Few-Cycle and Cavity-Enhanced Optical
Parametric Amplification

by

Aleem Mohammad Siddiqui

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Abstract

Optical parametric amplifiers have emerged as important optical sources by extending the properties of few-cycle laser sources, which exist only in materials with sufficiently large gain bandwidths, to wide array of spectral ranges. The work reported in this thesis relates to two areas for the continued development of optical parametric amplification based sources. First, we present a white light seeded, carrier-envelope stable, degenerately pumped OPA producing near transform-limited sub 7 fs, 3 μJ pulses at the driver wavelength from a long pulse, non-CEP stable Ti:sapphire regenerative amplifier. Problems to the spectral phase jump at the driver wavelength, 800 nm, were avoided by using a near infrared OPA to produce white light continuum down to 800 nm where the spectral phase is smooth. Secondly, enhancement cavities are used in conjunction with parametric amplifiers resulting in a new technique entitled, cavity-enhanced optical parametric chirped-pulse amplification (C-OPCPA). C-OPCPA increases the capabilities of nonlinear crystals and can allow continued scaling of parametric amplifier systems to high repetition rate. This work contains the first theoretical and experimental investigation of C-OPCPA. Numerically, passive pump pulse shaping of the intracavity pump power is shown to enable octave spanning gain. Experimentally, a first proof-of-principle experiment demonstrates a 78 MHz C-OPCPA with more than 50% conversion with under 1 W of incident pump power. A comparison to a single pass system shows improvements in the C-OPCPA of orders of magnitude in conversion efficiency and 3 fold increase in phase matching bandwidth in 10 and 20 mm periodically poled lithium niobate phase matched for parametric amplification with 1030 nm pump wavelength and a 1550 nm signal wavelength. A Yb-fiber laser based CPA system producing up to 5 W of 500 fs pulses comprises the pump source, and a Er-fiber laser the signal.

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Title: Professor of Electrical Engineering and Computer Science
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Chapter 1

Motivation

Few-cycle sources have found applications in many fields, including nonlinear spectroscopy, frequency metrology, and high field physics [42], and optical parametric amplification, due to its broad phase matching bandwidths and frequency tunability has enabled the generation of few-cycle pulses ranging from the visible to the IR [71, 15, 63, 19, 12, 11]. OPAs, requiring short pump and signal pulses, typically are pumped by either the fundamental wavelength or the second harmonic of an amplified titanium:sapphire (Ti:sapph) based system and seeded by continuum generation derived from the same source or by another few-cycle source synchronized to the pump. Pulse energies up to the micro-joule level with few-cycles have been reported [14].

Recently the applications of these sources, typically being nonlinear and intensity dependent, are requiring pulses with increasingly higher peak intensities [73, 42]. High field science, in particular high harmonic generation, requires highly energetic seed pulses in order to optimize an inefficient, though important process [10]. Optical Parametric Chirped Pulse Amplification (OPCPA) based systems, where a broadband seed is stretched to match the temporal duration of a narrowband pump, have allowed for the further scaling of the OPA process by avoiding parasitic nonlinear effects and crystal damage when high energy pump pulse are used [23] as illustrated in Figure 1-1. OPCPA sources seeded by Ti:sapph master oscillator-derived signals and pumped by high quality Ti:sapph, Nd- or Yb- based regenerative amplifiers have been successful in producing few cycle mJ pulses over a wide range [52, 2, 68, 72, 40, 28, 32, 55].
Figure 1-1: Optical Parametric Chirped Pulse Amplification (OPCPA) is the combination of OPA and chirped pulse amplification.

Increasing the repetition rate of parametric amplifiers is another important direction to further scale these systems and promote the advancement of their applications. In nonlinear spectroscopy, higher repetition rates would yield faster measurement times and higher signal levels. For frequency metrology, high repetition rates are important for many applications including astronomy and signal interrogation. Additionally, applications exist in high field science. In particular high harmonic generation can benefit by the increase in photon flux for the detection and application of the high harmonics [69].

For a fixed average pump power, as the repetition rate is increased, the peak power decreases, and therefore the conversion efficiency of the optical parametric process also decreases. Thus, in order to achieve significant conversion in a high repetition rate OPA/OPCPA, scaling the average power with repetition rate is essential. Much of the effort in developing high repetition rate OPA/OPCPAs has therefore focused on scaling the average power of the pump source. OPCPA systems, pumped with Ti:sapphire, Nd- or Yb- based regenerative amplifiers, are typically limited to the kHz range. Only recently have high repetition rate OPA systems with MHz repetition rates emerged, with design emphasis on the scaling of pump sources to high average power to achieve the required peak intensities [26, 60]. Also, powerful 100W Yb- fiber and thin disk pump sources are emerging with reports of OPCPA systems in the 10s of MHz [25, 37, 33]. Thus, while high-field science and other applications can benefit greatly by the increase in photon flux from high average power, high repetition rate...
OA/OPCPA sources, their development has been limited by the cost and complexity of scaling available pump sources.

Alternatively, we propose the use of an enhancement cavity to boost the nonlinear drive using moderate average power sources. In general, an enhancement cavity can be envisioned to improve nonlinearity by either being resonant with the pump as in Figure 1-2(a) or with the signal as shown in Figure 1-2(b). The latter case is the configuration for optical parametric oscillators (OPOs). The former case is a new configuration which we entitle, Cavity-Enhanced OPCPA (C-OPCPA). In C-OPCPA, pump pulses are coherently combined in a low finesse enhancement cavity transparent to signal and idler containing an OPA crystal in which a signal is amplified. If the pump has a narrow bandwidth (BW) and the seed is sufficiently chirped, the cavity passively shapes the intra-cavity pump profile in the time domain to attain more optimal conversion and increased bandwidth, overcoming limitations set by the bell-shaped pump intensity profile and the time-varying wave-vector mismatch of the interacting pulses. We have simulated octave-spanning gain showing the potential of this system [65].

Enhancement cavities have been useful in similar contexts. Yanovsky and Wise demonstrated the frequency doubling of fs Cr:forsterite oscillator pulses too weak for significant single-pass conversion efficiency [75]. Ilday and Kärtner proposed sub-harmonic cavity-enhanced OPCPA (C-OPCPA), in which pump pulses are built up in a passive, high-finesse enhancement cavity containing a nonlinear crystal, seeded at a sub-harmonic of the pump repetition rate. Thus, the pump pulse energy available
for single pass amplification of the seed is enhanced, increasing gain at the expense of repetition rate [36]. Additionally, Krischek et al. used an ultra-violet enhancement cavity containing a BBO crystal to generate entangled multiphoton states [41].

This thesis describes efforts in developing parametric amplifiers and cavity enhanced OPCA sources. In the first chapter, we discuss a degenerately pumped OPA that produces few-cycle, carrier-envelope-phase (CEP) stable laser pulses at the driver wavelength. We discuss the basic properties of parametric amplification including, gain conversion, phase matching and phase matching bandwidth. Additionally we present a novel OPA design that produces a less-than-three-cycle CEP stable pulse starting with a long wavelength CEP unstable source.

In following chapters we go into more detail with C-OPCPA. In Chapter 3 we lay down theoretical foundations by describing supporting simulations, discussing a comparison between single pass and C-OPCPA, introducing the concept of impedance matching, discussing the role of cavity phase and providing a load-line graphical explanations for an intuitive understanding of the cavity action. Additionally we motivate the potential for more than octave spanning gain. Furthermore we discuss a new instability modality, dispersion-induced depletion instabilities.

Chapter 4 and 5 describe experimental improvements and comparison between single pass and C-OPCPA. In Chapter 4, which details the experimental apparatus, we demonstrate the ability of C-OPCPA to extended the nonlinear conversion capabilities of a 20 mm periodically poled lithium niobate (PPLN) crystal, phase matched for parametric amplification, beyond limits set by the material properties, $d_{eff}$ and dispersion. This is done by comparing conversion efficiency and bandwidth to the C-OPCPA system and a single pass case. The cavity causes 10 times improvement in conversion efficiency with 4 times lower threshold as compared to the single pass case and a 3 fold increase in the bandwidth with limited pump power. In Chapter 5, we use the C-OPCPA setup with a 10 mm PPLN, to more carefully investigate bandwidth improvements and undesirable nonlinear effects. We show that within the full width half max (FWHM) tuning range, the cavity amplifies within the signal spectrum. Outside that range, spectrally broadened pump spectrum from self phase
modulation (SPM) resonates with the cavity causing the buildup of side-bands in the intracavity pump spectrum which contributes to the spectral distortion of the signal spectrum.
Many applications of ultrafast optics require pulses with durations down to the few-cycle limit [42]. In particular, time-resolved spectroscopy calls for the combination of short pulse widths and broad frequency tunability, while high harmonic generation and attosecond science also require control of the carrier envelope phase (CEP). Optical parametric amplifiers (OPAs) are powerful tools for the generation of widely tunable few-optical-cycle pulses since they can provide, under suitable phase-matching conditions, ultrabroad gain bandwidths [14]. In addition, OPAs offer the opportunity to produce pulses with passively stabilized CEP, exploiting the difference frequency generation process that occurs in the idler beam synthesis [7]. These favorable characteristics of OPAs have enabled their wide adoption for applications ranging from attosecond physics, to biology and chemistry.

Broad gain bandwidths are achieved in OPAs when the group velocities of signal and idler are matched [14]; this condition is satisfied either in the case of type I phase
matching at degeneracy, or in the case of non-collinear OPAs (NOPAs), when the idler group velocity is projected appropriately along the signal propagation direction. Using these concepts, a variety of broadband OPA schemes have been developed. Figure 2-1 shows a representation of a typical design for OPAs based on a regenerative Ti:Sapphire pump source which has been widely adopted for laboratory use. The OPA is pumped by either the fundamental frequency (FF) or by the second harmonic (SH) of Ti:Sapphire and seeded by white light continuum (WLC) derived from the same pump. The SH-pumped NOPA in the visible [71, 15, 63], the FF-pumped NOPA in the near-IR [19, 12] and the FF-pumped near-IR degenerate OPA [11] have all been demonstrated and allow nearly continuously coverage of the wavelength range from 500 to 2000 nm. Figure 2-2 show the amplified spectra of these OPA sources.

The only left gap in this range is the SH-pumped degenerate OPA, in the important frequency region around the 800-nm FF wavelength. This is due to the lack of a suitable broadband seed. In the work documented in this chapter we generate ultra-broadband pulses at 800 nm from an optical parametric amplifier (OPA) pumped by the second harmonic of a Ti:sapphire system and working at degeneracy. The OPA is seeded by a white-light continuum generated from a near-IR OPA pumped by the same laser. Nearly transform-limited sub-7 fs pulses, fully characterized in amplitude and phase, are obtained with a chirped mirror compressor. The system fills the gap around 800 nm for broadband continuum seeded OPAs pumped by Ti:sapphire-based sources as shown by the red curve in figure 2-2.

In this chapter, we first discuss the fundamental principles of nonlinear optics as they apply to parametric amplification and arrive at the basic governing equations for gain, bandwidth and tunability. We then discuss the innovative design concepts for the degenerately pump OPA system in this work which essentially enable us to produce a few-cycle, CEP-stable source starting with a CEP-unstable long pulse driver at the same wavelength. CEP-stability is passive, resulting from the use of the idler from a stage where the pump and signal, derived from the pump, have the same phase. Next we present the characterization of the CEP-stable few-cycle output, and finally we conclude.
Figure 2-1: A typical OPA source pumped by a regenerative Ti:sapphire amplification system. Either the fundamental wavelength or second harmonic of the pump is used to amplify a signal generated by the same pump in a nonlinear crystal phase-matched for optical parametric amplification. The seed signal can be derived from either white light continuum generation, optical parametric generation, or nonlinear processes. After the amplification, the signal is compressed.

Figure 2-2: Nearly continuous coverage of the electromagnetic spectrum from the ultraviolet to the mid-infrared range is possible with OPAs. The signal spectrum from Ti:saph pumped OPAs in three prior works are shown in green [16], blue [19], and yellow [11]. The signal spectrum from the OPA designed in this work shown in red [64] fills the gap around the driver pump wavelength, 800nm.
2.1 Fundamental Equations for Optical Parametric Amplification

As shown in Figure 2-3, optical parametric amplification is a second-order nonlinear process involving pump, signal and idler wavelengths in which energy is transferred from the pump to the signal and idler. The energetic pump and a weak signal are directed toward a nonlinear crystal and via a $\chi^2$ nonlinear interaction, energy is transferred from the pump to the signal and an idler is generated. The process conserves both energy and momentum. For the process to be efficient, phase matching must be achieved in that a given phase relation between the wave-vectors of the pump, signal, and idler must be maintained along the direction of propagation. Thanks to the high nonlinearity and broad phase matching bandwidths of available nonlinear crystals, parametric amplification has been successful in providing efficient, broadband amplification for a wide range of wavelengths from the visible to the infrared.

OPA is an instantaneous process involving virtual states arising from the coupling of pump, signal and idler wavelengths with a nonlinear polarization. Pump energy is not stored in the nonlinear crystal, unlike in amplification in active gain medium where pump energy is absorbed by the material through electron transitions to excited energy levels and where signal amplification arises through stimulated emission [1, 9, 66]. The amplification bandwidth in active gain medium is limited by homogeneous or inhomogeneous broadening mechanisms [70, 49, 66]. In OPAs, gain bandwidths, determined by phase matching and chromatic dispersion, have been significantly larger due to the use nonlinear crystals with favorable dispersion characteristics and beam geometries. Additionally, the absence of pump energy storage in OPAs problems arising from thermal issues such as thermal lensing are significantly mitigated [58, 66].
2.1.1 Nonlinear Optics

In this sub-section we provide a brief introduction to nonlinear optics (NLO) and discuss the fundamental equations of parametric amplification for few-cycle pump pulses [9, 62, 4, 22]. Nonlinear optics relates to the phenomena resulting from the modification of the optical properties of a material via the interaction of light. NLO involves optical processes that are induced as intense light passes through an optical medium such as a nonlinear crystal and most often involves frequency conversion, amplification, or signal generation. Due to the fact that most optical materials are non-magnetic, ie. $H = B/\mu_0$, the conduit of nonlinear optics is the optical polarization. The constitutive relationship between the induced polarization $\mathbf{P}$, an applied static electric field $\mathbf{E}$ is given by:

$$\mathbf{P} = \epsilon_0 \chi \mathbf{E} \quad (2.1)$$

where $\mathbf{P}$ and $\mathbf{E}$ are proportionally related through the linear susceptibility $\chi$, and the $\epsilon_0$.

The polarization, $P$, represents the density of electric dipole moments or charge displacement in a medium and therefore captures the movement of bound charges in NLO. Since the electric field from a propagating optical wave will induce both linear and nonlinear motion of bound charges in a nonlinear crystal, the optical polarization
can be reduced into both a linear and nonlinear component, and in general a tensor relationship between the polarization, $P$, and the electric field

$$P = \varepsilon_0 \left[ \chi^{(1)}E + \chi^{(2)}E^2 + \ldots \right] = P_L + P_{NL} \quad (2.2)$$

The polarization $P$ is a key source for the propagation of optical waves in nonmagnetic materials without free charges or electric currents through which NLO phenomena can be intuitively understood. A time varying propagating electromagnetic field must have a corresponding time varying polarization. Thus light generated through a frequency mixing process or otherwise nonlinearly modified in a nonlinear crystal must have an associate time-varying polarization induced in the medium. Additionally the harmonic motion of bound electrons can be absorbed into the linear portion of associated equations, while the anharmonic motion of the bound electrons remain unreduced. Thus, as derived elsewhere [9] the wave equation in nonlinear motion can be expressed as in Equation 2.3 below with $P_{NL}$ acting as a source term. This expression is consistent with Lamar’s theorem in that in charges accelerating through the time varying polarization are responsible for the creation of new radiation [9].

$$\nabla^2 E - \frac{n^2}{c^2} \frac{\partial^2 E}{\partial t^2} = \frac{1}{\varepsilon_0 c^2} \frac{\partial^2 P_{NL}}{\partial t^2} \quad (2.3)$$

This equation serves as the starting point for many nonlinear processes including second harmonic generation (SHG), sum frequency generation (SFG), difference frequency generation (DFG), self-phase modulation (SPM), parametric amplification (PA), and others. By considering time harmonic input fields, dropping of negligible terms and identifying identifying the polarization tensor element that relates components of the electric field and with consideration for phase matching, the equations for the mentioned nonlinear processes can be easily derived as will be done for parametric amplification in the next section.
2.1.2 Optical Parametric Amplification

In this section we outline the key steps in deriving the coupled nonlinear equations for parametric amplification, the main nonlinear effect of consideration in this work, as outlined in [14]. We consider first a linear polarized, monochromatic plane wave propagating in the z direction.

\[ E(z,t) = Re\{A(z)exp[j(\omega t - kz)]\} \]  \hspace{1cm} (2.4)

Assuming this wave, is the consequence of the nonlinear wave Equation 2.3, there must be a polarization source term modulating at the same frequency of the form shown below:

\[ P^{NL}(z,t) = Re\{P^{NL}(z)exp[j(\omega t - k_p z)]\} \]  \hspace{1cm} (2.5)

Inserting the above two equations into the nonlinear wave Equation 2.3, canceling time dependencies, and assuming the slowly varying approximation applies such that \( \frac{d^2A}{dz^2} \ll 2k \frac{dA}{dz} \), we can arrive at the following propagation equation, which will hold generally for typical nonlinear mixing processes.

\[ \frac{dA}{dz} = -j\frac{\mu_0 c \omega}{2n} P^{NL}(z) exp[-j(k_p - k)z] \]  \hspace{1cm} (2.6)

At this point, we assert specific requirements on the interacting fields pertinent for parametric amplification. Namely, we assume there interacting fields, pump, signal and idler, with respective frequencies \( \omega_p, \omega_s, \) and \( \omega_s \) such that \( \omega_p > \omega_s > \omega_s \), and energy is conserved, \( \omega_p = \omega_s + \omega_s \). Additionally, the \( i^{th} \) component of the nonlinear polarization can be expressed as:

\[ P_{i}^{NL} = \epsilon_0 \chi^{(2)}_{ijk} E_j E_k \]  \hspace{1cm} (2.7)

where \( \chi^{(2)}_{ijk} \) is the third rank, second order nonlinear nonlinear susceptibility tensor capturing the parametric process. Assuming a collinear process with parallel wave-
vectors, we can arrive at the following set of coupled equations:

\[
\frac{dA_i}{dz} = -j \frac{\omega_{eff}}{n_i} A_i^* A_p e^{j k z} \tag{2.8}
\]

\[
\frac{dA_s}{dz} = -j \frac{\omega_{eff}}{n_s} A_i^* A_p e^{j k z} \tag{2.9}
\]

\[
\frac{dA_p}{dz} = -j \frac{\omega_{eff}}{n_p} A_i^* A_s e^{j k z} \tag{2.10}
\]

where, \( d_{eff} \) is the nonlinear optical coefficient which captures the propagation direction and beam polarization, and \( \Delta k = k_p - k_s - k_i \) is the wave-vector mismatch. When a periodically poled nonlinear crystal is used, the sign of the crystal's nonlinearity is periodically flipped to match the half period of the wave-vector mismatch between the signal, pump, and idler during propagation. This allowing continued conversion from the pump to signal and idler when the wave-vector mismatch between the three field is 180°. This effect of periodically poled crystals is to decrease \( d_{eff} \) by \( 2/\pi \) and to adjust the expression for wave-vector mismatch to \( \Delta k = k_p - k_s - k_i - k_G \) where \( k_G = \frac{2\pi}{\Lambda} \), and \( \Lambda \) is the poling period.

We can see from the above set of equations that a coherent beating between signal and pump drive the creation of idler photons, and a coherent beating between idler and pump drive the creation of signal photons, while the beating between signal and idler deplete the pump. In order for the process to be efficient, a phase relationship must exist between pump signal and idler as captured by the phase matching conditions. If the phase matching conditions resulted in \( \Delta k \) being too large the phase term \( e^{-j \Delta k z} \) above would oscillate rapidly resulting in negligible conversion.

Assuming that the pump is not depleted, we can solve the above equations exactly as is done elsewhere for the growth in the signal and idler intensities during propagation in a crystal for a distance \( L \):

\[
I_s(L) = I_{s0} \left[ 1 + \frac{\Gamma^2}{g^2 sinh^2(gL)} \right] \tag{2.11}
\]
\[ I_i(L) = I_0 \left( \frac{\Gamma^2}{g^2 \sinh^2(gL)} \right) \]  

(2.12)

where, the small signal gain, \( g \), is given by:

\[ g = \sqrt{\Gamma^2 - \left( \frac{\Delta k}{2} \right)^2} \]  

(2.13)

\[ \Gamma^2 = \frac{2\omega_i \omega_a d_{eff} I_p}{n_i n_s n_p c_0^3} \]  

(2.14)

Assuming, that the large gain approximation is valid, that \( gL \gg 1 \), the signal gain can be expressed as:

\[ G = 1 + \frac{\exp(2gL)}{1 - (\frac{\Delta k}{2\Gamma})^2} \frac{\exp \left( 2\sqrt{\Gamma^2 - \left( \frac{\Delta k}{2} \right)^2} L \right)}{4} \]  

(2.15)

The above equation shows, that in the large gain approximation, the signal gain increases exponentially with crystal length, and exponentially with the square root of the pump intensity, and is degraded by wave-vector mismatch. In OPCPA, with Gaussian shaped pulses and large signal chirps, Equation 2.15 indicates that conversion limitations in the temporal wings arise from reduced pump intensity and increased wave-vector mismatch. However, the fact that pump intensity can be used to offset the reduction in gain due to wave-vector mismatch, implies pump pulse reshaping can lead to improved performance [51]. In Chapter 3, it will be shown that passive pump pulse shaping in Cavity-Enhanced Optical Parametric Chirped-Pulse Amplification (C-OPCPA) places pump energy in temporal regions where gain and conversion are reduced due to initially insufficient pump intensity.

Another favorable property of optical parametric amplifiers is their ability to preserve the carrier envelope phase (CEP) of the signal pulse, and achieve passive CEP-stability on the idler [7]. The CEP of an optical pulse can be denoted in the expression for the pulse electric field as,

\[ E(t) = A(t) \cos(\omega_c t + \phi_{CE}(t)) \]  

(2.16)
where $E(t)$ is the electric field, $A(t)$ is the envelope, $\omega_c$ is the carrier frequency, and $\phi_{CE}(t)$ is the CEP. The CEP represents the phase slip of the carrier electric field with respect to the envelope. CEP-stability is important for many applications that are phase sensitive including high-field science, spectroscopy, and high harmonic generation.

The influence of parametric amplification on the CEP can be seen by examining the evolution of the phase on pump, single and idler. Analytically exact solutions for these phases based on the equations of the fundamental parametric mixing process, 2.8-2.10, have been derived elsewhere [59] and are shown below:

$$\phi_s = \phi_s(0) - \frac{\Delta k z}{2} + \frac{\Delta k \gamma_s^2}{2} \int \frac{dz}{f + \gamma_s^2}$$  \hspace{1cm} (2.17)

$$\phi_i = \phi_i(0) - \phi_s(0) - \frac{\pi}{2} - \frac{\Delta k z}{2}$$  \hspace{1cm} (2.18)

$$\phi_p = \phi_p(0) - \frac{\Delta k}{2} \int \frac{f(z) dz}{f(z) + \gamma_s^2}$$  \hspace{1cm} (2.19)

where $\gamma_s^2 = \frac{\omega_s}{\omega_p} \frac{I_s(0)}{I_p(0)}$ is the ration of the initial signal photons to pump photons, and $f(z) = 1 - \frac{I_s(z)}{I_p(0)}$ is the pump depletion factor during propagation. The above equations indicate that for a phase matched process, $\Delta k = 0$, the phase of the signal and pump are preserved while the phase of the idler becomes, $\phi_i = \phi_i(0) - \phi_s(0) - \pi/2$, and is essentially the phase difference between the pump and signal within a constant factor. Thus, if the signal and pump have the same phase, for a phase matched process, the idler will achieve passive CEP-stability.

The potential for CEP-stability on the idler has been exploited in this work and many others by generating a seed derived from the pump source in a manner that preserves the phase of the pump. Typically, this process is white light continuum generation which retains the phase of the driver pulse while creating new frequencies and expanding the bandwidth [8]. When a seed generated in this manner is amplified in an OPA from the same pump source, the idler will have a constant phase.
2.1.3 Broadband Parametric Amplification

One of the main advantages of optical parametric amplifiers is the broad gain bandwidth that can be achieved. In a typical configuration a narrowband pump pulse is used to amplify either a broadly tunable signal or a wide bandwidth signal and a corresponding idler is generated. The expression for large gain in the presence of wave-vector mismatch, Equation 2.15, is essentially functionally dependent on the signal frequency, and can therefore be used to calculate the FWHM gain bandwidth. More generally, by Taylor expanding the expression for wave-vector mismatch with respect to variation in the signal frequency $\Delta \omega$, we can use the large-gain expression to arrive at an expression for the so-called phase matching bandwidth.

As calculated in [14] and as will be shown below, the phase matching bandwidth is proportional to the group velocity mismatch between signal and idler. Assuming perfect phase matching at a given signal frequency, a change in the signal wavelength from $\omega_s$ to $\omega_s + \Delta \omega$ will result in a change in the idler frequency from $\omega_i$ to $\omega_i - \Delta \omega$, do to the fact that $\omega_p = \omega_s + \omega_i$. The wave vector mismatch can then to first order be expressed as:

$$\Delta k \approx \frac{\partial k_s}{\partial \omega_s} \Delta \omega + \frac{\partial k_i}{\partial \omega_i} \Delta \omega = \left( \frac{1}{\nu_{gi}} - \frac{1}{\nu_{gs}} \right) \Delta \omega$$ (2.20)

Using the large gain expression, Equation 2.15, to determine the FWHM gain we arrive at the following expression for the phase matching bandwidth:

$$\Delta \nu = \frac{2(\ln 2)^{1/2}}{\pi} \left( \frac{\Gamma}{L} \right)^{1/2} \frac{1}{\left| \frac{1}{\nu_{gi}} - \frac{1}{\nu_{gs}} \right|}$$ (2.21)

The above expression shows that the phase matching bandwidth for a parametric amplifier is inversely proportional to the square root of the crystal length and is proportional to the 4th root of the intensity through the $\Gamma$ parameter. When the group velocity of the idler equals the group velocity of the signal, the above expression no longer holds and the wave-vector mismatch needs to be expanded to higher order, which results in the following expression:
\[ \Delta \nu = \frac{(\ln 2)^{1/4}}{\pi} \left( \frac{\Gamma}{L} \right)^{1/4} \frac{1}{\sqrt{\left( \frac{\partial^2 k_s}{\partial \omega_i^2} + \frac{\partial^2 k_i}{\partial \omega_i^2} \right)}} \]  

(2.22)

The above equations for the phase matching bandwidth indicate that broadband optical parametric amplifiers require that the signal and idler group velocities are equal. There are two general approaches to achieving signal-idler group velocity matching. Firstly, the signal and idler can be at the same frequency and polarization. In this case \( \omega_i = \omega_s = \omega_p/2 \). Since the signal and idler are the same, clearly the group velocities are matched and the OPA is said to be operating at degeneracy. The second method to achieve group-velocity matching is use of a non-collinear parametric amplifier. In this method an angle, \( \alpha \) is introduced as shown in Figure 2-3 between the signal and the pump such that the projection of the idler group velocity onto the signal direction equals the group velocity of the signal. This is satisfied when \( \nu_{gi} > \nu_{gs} \), which typically holds for type I phase matching in uniaxial crystals [14].

As mentioned in the introduction, employing degenerate and non-collinear amplifiers has successfully allowed for the generation of compressed amplified spectra from the visible to the infrared where either the fundamental wavelength of the Ti:sapphire source (800nm) or the second harmonic (400nm) was used. Specifically, in Figure 2-2, the green curve was generated in a non-collinear OPA pumped at 400nm, and the blue curve was generated in a non-collinear OPA pumped at 800nm, while the orange curve was generated in an OPA at degeneracy pumped at 800nm. The gap at 800nm remained due to lack of a suitable broadband and compressible seed source. The remaining sections of this chapter will describe the technique used to generate such a seed for amplification in a degenerate OPA pumped at 400 nm, and the characterization of the compressed output.

2.2 Parametric Amplification Design

As mentioned previously, in this work, we demonstrate a two-stage OPA scheme for the generation of few-optical-cycle pulses at 800nm starting from a 150-fs amplified
Ti:sapphire laser system. This system fills the gap around at the driver wavelength, 800 nm, for broadband continuum seeded OPAs pumped by Ti:sapphire based sources and seeded by white light continuum (WLC) generation (see Figure 2-2). Difficulties in realizing a compressible, ultra-broad spectrum at the driver wavelength are a consequence of the WLC generation process.

In WLC generation a short (100-fs) pump pulse is tightly focused into a transparent where the generation of new spectral components, both blue shifted and red shifted, results from a highly nonlinear interaction of the pump pulse and the transparent medium. While, multiple mechanisms have been proposed to contribute to the WLC process involving SPM, ionization-enhanced SPM, four-wave mixing, self-focusing, self-steepening, multi-photon absorption, and others, the influence of SPM plays a dominant role in the generation of new frequencies by imprinting a time varying phase or frequency chirp on the pump pulse profile [13, 27, 8, 30]. The frequency shift is given by:

$$\delta \omega = -\frac{d\phi}{dt} = -n_2 \frac{dI}{dt}$$

(2.23)

Thus, as shown in Figure 2-4(a), the red components ($\lambda > 800nm$) are generated in the leading edge and the blue components ($\lambda < 800nm$) in the trailing edge of the pulse [15], while no frequency components are generated at the unchirped central region of the pulse where the intensity is flat ($dI/dt = 0$). The temporal extent of the unchirped portion is further broadened due to nonlinear temporal and spacial effects. Free electrons are generated in a plasma channel at the peak of the pulse, and are thus able to influence the peak and trailing edge of the pulse, while the leading edge is undisturbed. The influence of the free electrons is to counter self-focusing from the Kerr nonlinearity. Thus, the leading edge of the pulse free from the influence of the plasma can be brought to a tighter focus through self-focusing increasing the intensity relative to the peak and trailing edge, leading to an asymmetric flattening of the pulse. Additional flattening of the pump pulse can occur from multi-photon absorption and self-steepening, steepening the edges and further confining the frequency chirp, asymmetrically, to the leading and trailing edges of the pulse [74]. This results in
broader spectral coverage by the tails with less energy due to more chirp in a smaller region of the pulse profile [4].

The unchirped portion is responsible for the prominent, rapid phase jump in the group delay spectrum as indicated in Figure 2-4(b) on the order of the pulse duration at the drive wavelength [15]. In fact, the WLC generated in a bulk medium presents a highly structured intensity and phase profile around the drive (800-nm pump) wavelength due to the high intensities, and the influence of nonlinearity and dispersion in optical processes including catastrophic self-focusing and wave breakup. Broad and compressible continuum has been primarily generated via WLC generation at spectra ranges far from the driver wavelength where the influence of SPM and dispersion in the leading and trailing edges lead to a smooth and undistorted amplitude and phase.

The creation of a suitable seed around the driver wavelength has thus remained problematic. Previous attempts of amplification at 800 nm of a supercontinuum generated in a photonic crystal fiber resulted in ultra-broad spectra, which were, however, not compressible due to the strong and highly structured chirp on the seed pulses [45, 5]. The design of the system presented here circumvents this problem by taking the three stage approach shown in Figure 2-5. Starting with a typical Ti:sapphire based pump source, first an NIR OPA is constructed to generate spectrum in the NIR. Secondly, this NIR wavelength is then used to create white light continuum down at 800nm where the spectral phase is smooth and compressible. Finally this suitable seed is amplified in a degenerate OPA pumped with the second harmonic of the Ti:sapphire source (400nm) and compressed down to few cycles.

More specifically, a FF-pumped near-IR OPA is used to generate either a signal at 1.3µm or an idler at 1.6µm, which in turn produces a WLC with well-behaved spectral amplitude and phase around 800 nm [57]. This WLC is then amplified in a broadband degenerate SH-pumped OPA and compressed by chirped mirrors to nearly transform-limited (TL) sub-7-fs duration. The system fills the gap around 800 nm for broadband continuum seeded OPAs pumped by Ti:sapphire based sources and seeded by WLC. Following this method, we achieve a pulse shortening by a factor of 20 with respect to the driving laser.
Figure 2-4: (a) In white light continuum generation in bulk media due to SPM the red components are generated on the leading edge and the blue components in the trailing edge. (b) A large jump in the group delay exist at the driver wavelength. The phase of the continuum generation spectrum is highly structured and distorted at the driver wavelength but smooth and compressible far from the driver wavelength.

Step 2: Use NIR wavelength to do WLG $\rightarrow$ Spectral phase down at 800 nm smooth

Step 1: Create a NIR wavelength

Step 3: Amplify spectrum at 800 nm $\rightarrow$ Compressible

Figure 2-5: Three-step method to generate a broadband compressible seed at the drive wavelength
Figure 2-6: (a) Experimental setup for the generation of few-cycle pulses at 800 nm: BS, beam splitters; VA, variable attenuator; WLC, white light continuum generation with either signal or idler from IR OPA; DCM, double chirped mirror; FS, fused silica glass prisms; BBO 1: second harmonic stage; BBO 2: OPA at 800 nm. (b) Setup for the two stage infrared OPA used for WLC generation; LPF, long pass filter; BBO 3 and BBO 4: near-IR OPA stages.

2.3 Implementation of Degenerate OPA Pumped at 800 nm

Figure 2-6 shows the scheme for the experimental setup. As shown in Figure 2-6(a), the system starts with an amplified Ti:sapphire laser system producing 150-fs pulses at 1 kHz (Quantronix Integra-C) with less than 0.3% pulse-to-pulse energy fluctuation. A fraction of the pulses is used to drive a two-stage FF-pumped near-IR OPA, with design similar to that reported in Kaindl et al. [39]. The first OPA stage, pumped with 60 μJ, is seeded by the WLC generated in a 3-mm-thick sapphire plate and employs a 5-mm-thick β-barium borate (BBO) crystal in a type II configuration (θ = 27°, φ = 30°). It provides 5μJ pulse energy with 1.5% rms fluctuations. The second stage is pumped with 100μJ energy and uses a 3-mm-thick BBO crystal in the same type II configuration. This stage produces signal energies up to 20μJ tunable from 1.2 to 1.6 μm (corresponding to an idler from 1.6 to 2.4 μm), with rms pulse to pulse fluctuations of 0.5%. Great care is taken to suppress amplification of parametric
superfluorescence in the second stage. To facilitate separation of the beams, a slightly non-collinear configuration is used for both OPAs; the non-collinear angle is however kept as small as possible to avoid angular dispersion in the idler beam when it is used for seeding. In principle, a single stage could be used for the near-IR OPA, however the two-stage design allows to achieve better stability, by driving into deeper saturation the second stage which had a conversion efficiency of pump into signal and idler of up to 30%.

Either the signal or the idler (in the latter case after rotating the polarization with a half-wave plate) of the near-IR OPA were used to generate the broadband WLC seed for the two stage SH-pumped degenerate OPA as shown in Figure 2-6(b). With the 1.3 μm signal, the WLC was generated in a 3-mm sapphire plate. The visible part of the optimized WLC spectrum is shown on a logarithmic scale as a blue dotted line in Figure 2-7(a) and provides a rather spectrally flat and stable seed around 800 nm. To measure the spectrum we used a calibrated optical multichannel analyzer (Ocean Optics HR2000). The SH-pumped degenerate OPA employs a single pass in a 1-mm-thick type I BBO crystal (θ = 29°, φ = 0°), pumped by 70μJ of the SH, to amplify the WLC up to 5 μJ. The resulting ultra-broadband spectrum is displayed as a green solid line in Figure 2-7(a): it spans from 670 to 950 nm. Also shown, as a black dashed line, is the frequency-dependent parametric gain, calculated in the plane wave approximation with monochromatic and undepleted 400-nm pump. For both calculation and experiment, the phase-matching condition was slightly detuned from degeneracy, resulting in a slightly broader gain bandwidth allowing for the generation of a broad, double-humped spectrum. The amplified signal spectrum fills the gain bandwidth provided by the OPA.

Alternatively, we also generated the WLC from the idler of the OPA, tuned to 1.6 μm; in this case, we used a 2-mm YAG plate instead of the sapphire plate. YAG was chosen, because we observed that YAG produces a WLC shifted to shorter wavelengths with respect to sapphire for the same drive wavelength. Since the idler of the near-IR OPA is at a longer wavelength, the use of YAG optimizes the WLC in the 800 nm range. The result was the broadband seed around 800 nm shown in
Figure 2-7(b) (blue dotted line). Owing to the small pump-seed angle and the narrow amplification bandwidth in the near-IR OPA, the angular dispersion of the idler beam is smaller than 1 mrad and is negligible in comparison to its divergence. Thus, the WLC had minimal spatial chirp. The idler of our near-IR OPA is CEP stable since it arises from a difference-frequency generation process between a pump and WLC seed which are derived from the same 800-nm Ti:sapphire source, thus with the same CEP fluctuations [7, 48, 20]. This CEP stability is expected to be transferred to the WLC [48, 20, 54] and to the amplified pulses. The idler-driven WLC is amplified by the same broadband SH-pumped OPA as the signal-driven one, and gives very similar performance both in terms of output energy and spectrum and is displayed as the green solid line in Figure 2-7(b)).

2.4 Characterization of Compressed Output

The laser pulses generated by this OPA design have a smooth spectral phase and are compressible. The advantageous property of WLC generation in bulk media that spectral phase is well-behaved originates from the generation process being dominated by an interplay of dispersion and nonlinearity. This is in contrast to the highly structured spectral phase delivered by supercontinuum generation in photonic crystal fibers that requires compression with greater spectral resolution [56, 24]. The spectral phase of the broadband OPA pulses is due essentially to linear dispersion in the sapphire/YAG plate (after the onset of the WLC), the 1-mm-thick BBO crystal and air. The green dashed line in Figure 2-8 shows the expected group delay (GD) of the amplified pulses. We designed a simple, high-throughput compressor consisting of two bounces on a pair of broadband double-chirped mirrors with compensating phase ripples [61], followed by fused silica wedges for fine dispersion tuning. The GD introduced by the compressor (red dash-dotted line in Figure 2-8) compensates for that of the pulses over a broad bandwidth.

The compressed pulses were characterized by Second Harmonic Generation Frequency Resolved Optical Gating (SHG-FROG) employing a 10 – μm BBO crystal.
Figures 2-9(a) and 2-9(b) show the experimental and retrieved SHG-FROG traces for the idler-derived case, while figures 2-9(c) and 2-9(d) report the retrieved temporal and spectral intensity and phase profiles. The measured 6.9 fs pulsewidth is very close to the 6.5 fs transform-limited duration. For the signal-derived case, with a slightly larger wedge insertion, we obtained a similar result with a pulsewidth of 6.8 fs. CEP stability was not characterized as it has been well established in similar works [7, 48, 20].

2.5 Conclusion

In this chapter, we have described the key features of the parametric process and we have demonstrated an ultrabroadband degenerate OPA generating nearly TL sub-7-fs pulses at 800 nm. Pulse durations limits were set by the phase-matching bandwidth of the final SH-pumped degenerate OPA stage. This system fills a gap in few-optical-cycle pulse generation from OPAs and achieves a shortening by a factor of 20 of the 150-fs driving pulse. It can be synchronized with other few-optical-cycle OPAs and used for high time resolution two-color pump-probe spectroscopy [12]. In addition, the use of the idler pulses to produce the WLC opens the possibility to generate in a simple way few-optical-cycle CEP stable pulses at 800 nm starting from a conventional non-CEP-stabilized, long-pulse system. This simple front-end may also, by energy scaling with further OPA stages [3], become interesting for CEP-dependent high-field science.
Figure 2-7: (a) Blue dotted line, logarithmic scale: WLC generated by the signal of the near-IR OPA single and seeding the 800nm OPA. Black dashed line: calculated gain bandwidth curve. Green solid line: amplified spectrum. (b) Same as (a), starting from the idler of the near-IR OPA.
Figure 2-8: GD composition of the idler-derived output. GD 1 (green dashed line) is the GD before compression, includes 1 mm BBO, 550 m YAG and 1.5 m air. GD 2 (red dashed-dotted) is the GD for the compressor, includes the GD from the chirped mirror pair. GD1 + GD2 (black line) is the total GD after compression.
Figure 2-9: (a) 128128 pixels FROG trace for the compressed, idler derived output. (b) Reconstructed FROG trace. (c) Intensity profile and phase vs. time retrieved from FROG. (d) Reconstructed intensity profile and phase vs. wavelength retrieved from FROG.
Chapter 3

Theoretical Analysis of Cavity Enhanced Optical Parametric Chirped Pulse Amplification (C-OPCPA)

In this chapter, we present a novel technique to improve the performance of optical parametric amplification by combining OPCPA with an enhancement cavity in a technique entitled cavity enhanced OPCPA (C-OPCPA) [65]. As shown in figure 3-1, we propose to coherently combine pump pulses in a low finesse enhancement cavity seeded at the full pump repetition rate, in contrast to the previous work [36] where multiple pump pulses were combined in the cavity resulting in amplification at a subharmonic of the repetition rate. Unlike optical parametric oscillation, the cavity is transparent to signal and idler and resonant with the pump, and a synchronized signal beam is amplified via OPCPA in the intracavity nonlinear crystal. Thus, pump energy that is not converted in a single cavity round trip remains in the cavity and is reused on subsequent passes.

We show that the enhancement cavity not only serves as a means to increase the effective pump power, but also naturally reshapes the pump pulses for close-to-
optimal conversion efficiency. Furthermore, we find the pump pulse self-shaping can extend the signal gain bandwidth to several times the phase-matching bandwidth of the OPA crystal, while maintaining good conversion efficiency. C-OPCPA thus can extend the boundaries of high-repetition-rate parametric amplifier technology in several aspects simultaneously. By extending this technique to OPCPA systems with phase-matching bandwidths already broadened through group-velocity matching, we show that greater-than octave-spanning gain bandwidths can be realized. As an example, periodically poled lithium niobate (PPLN) degenerately pumped at 1 μm wavelength is shown to support direct single-cycle pulse amplification with good conversion efficiency. The possibility of extremely broad gain bandwidths is a key motivation for this work.

Below, we provide a conceptual introduction and numerical analysis of this technique. First we address conversion efficiency limitations in single pass OPCPAs. Then turning to C-OPCPA, we motivate the role of the cavity by introducing the concept of impedance matching. We contextualized the performance of a C-OPCPA system by comparing it to the performance of a single pass amplifier. Within the context of low SPM we discuss the possibility of octave spanning gain. Next we analyze the action of the cavity locking mechanism, which ensures matching of the cavity free spectral range with the pump laser repetition rate. We show that the action of the cavity lock is to compensate for nonlinear phase and ensure proper loading of pump power. This feature ensures octave spanning gain even in the presence of large SPM. We present an intuitive graphical analysis. And finally, we describe a new kind of instability that arises in the context of C-OPCPA, dispersion induced depletion instability, which results from the interplay of the group velocity walk-off between pump and signal/idler and conversion, and address conditions for stable cavity operation.
3.1 Conversion Efficiency Limitations in Single Pass Optical Parametric Chirped Pulse Amplifiers

Scaling of parametric amplification is achieved by combining OPAs with chirped pulse amplification to create optical parametric chirped pulse amplifiers (OPCPAs) [23]. As shown in Figure 3-2, in OPCPAs a narrowband pump source with sufficiently long duration and a broadband signal pulse chirped to match the pump pulse duration are directed toward a nonlinear crystal phase matched for parametric amplification. Energy scaling is achieved in this arrangement since high energy pump pulses can be made sufficiently long so that the peak intensity is below the onset of crystal damage or undesired nonlinearities. In this way, additional pump energy can be converted to signal, whereas a conventional OPA would be limited in its energy handling due to excessively high peak intensities. OPCPA designs have enabled the scaling of broadband parametric sources, but suffer from limitations due to the Gaussian shaped profiles and time dependent wave-vector mismatches [59, 53].

In OPCPA if the signal pulse is sufficiently chirped such that the group velocity walk off between the pump, signal and idler is small compared to the pulse duration, the so-called local approximation holds where each temporal coordinate can be considered as a separate monochromatic parametric interaction with the pump and signal fields set by the envelope functions, and the signal wavelength set by the time-wavelength mapping associated with a heavily chirped pulse. The local approximation limit is valid as long as the signal is sufficiently chirped such that dispersive propagation effects are negligible, which is commonly seen in ultra-broadband OPCPA.
pumped by picosecond pulses [59, 51]. The gain that the signal experiences at each point in time can thus be calculated using the gain expression for monochromatic beams derived in the previous chapter, Equation 2.15, with a temporal dependence:

\[
G \approx \frac{1}{4} \exp \left( 2\sqrt{\Gamma(t)^2 - \left( \frac{\Delta k(t)}{2} \right)^2} \right)
\]

where \( L \) is the crystal length. This expression holds in the limit of low (< 20%) pump conversion and large gain (> 10). The small-signal gain, \( g(t) \), has time-dependence through the intra-cavity nonlinear drive, a function of intra-cavity pump intensity, \( \Gamma(t) I(t)^{1/2} \), and the local wave-vector mismatch, \( \Delta k(t) \) [14]. \( \Delta k(t) \) is the local wave-vector mismatch taken between the pump wavelength and the corresponding time varying signal/idler wavelengths. \( \Delta k(t) \) remains unchanged during propagation. As seen from the above equation, the gain drops as the wave-vector mismatch increases and as the available pump intensity decreases. In a large signal analysis, the achieved conversion depends on the gain and also to a lesser extent on the signal level present.

In OPCPA with Gaussian pump and signal pulses, the central temporal coordinate/wavelength typically coincides with the location of the peak pump intensity and is locally phase matched, \( \Delta k(0) = 0 \), as shown in Figure 3-2. The signal gain at each point in time/wavelength can be determined by the above expression and thus has a maximum value at the central temporal coordinate and reduces in the wings due to a drop in pump intensity and an increase in wave-vector mismatch. Since each point in time corresponds to a wavelength, a reduction of the conversion in the wings corresponds to a reduction in bandwidth. Thus, limitations in bandwidth and conversion in C-OPCPA are set by the conversion efficiency reduction at the wings of Gaussian pump and signal pulses due to a drop in pump/signal intensity and an increase in wave-vector mismatch away from the central temporal coordinate. Even when enough gain is available to saturate the amplifier, OPCPA systems experience low conversion efficiency and spectral gain narrowing due to the temporal non-uniformity of the small-signal gain, a result of both the bell-shaped pump intensity profile and the time-varying wave-vector mismatch of the interacting pulses [53, 51, 59].
As seen from the above large gain expression, reduction in gain from wave-vector mismatch can be compensated by an increase in pump intensity. Thus pump pulse shaping can potentially mitigate these effects by placing more pump energy where the wave-vector mismatch is high [51]. Figure 3-3 shows possible pump profile shapes to optimize signal conversion for varies signal pulse conditions. For a square monochromatic signal pulse, perfect conversion can be attained at each point in time with a square monochromatic pump pulse. When a broad band signal with a chirp is introduced, the pump profile can be correspondingly adjusted to optimize the gain with a parabolic shape. However, with Gaussian pulses and broadband, chirped signal, the pump must take on a so-called conformal profile, increased pump intensities in the wings and improving overall conversion efficiencies [51]. The generation of such unusual pump pulse profiles is difficult and lossy with standard techniques. And, in any case, 100% conversion is not possible in the presence of wave-vector mismatch. Since, for monochromatic waves, wave-vector mismatch reduces the maximum possible conversion, a conformal pump shape can only optimize overall conversion and is not able to achieve 100% conversion at each point in time.

However, in C-OPCPA the use of an enhancement allows for the attainment of conformal pump profiles and achieving conversion efficiencies beyond limitations set by the parametric process approaching perfect conversion. As will be discussed below, a conformal shape is achieved since temporal coordinates with initially less conversion due to wave-vector mismatch or reduced intensities develop more intracavity pump pulse and offset the initial low conversion. The pulse shaping in C-OPCPA is thus achieved passively. Also, perfect conversion efficiency is possible even in the presence of wave-vector mismatch since a fractional conversion of the intracavity pump power, which can be many times larger than the incident pump power, can correspond to a large conversion with respect to the incident pump beam.
Figure 3-2: Conversion efficiency limitations in single pass optical parametric chirped pulse amplification

Figure 3-3: Just as a flattop seed and pump pulse combination maximizes conversion efficiency in OPA (a), conformal profiles in OPCPA (b,c) maximize conversion efficiency while also increasing the range of wavevector mismatches (and thus frequencies) that can be amplified efficiently.
3.2 Impedance Matching in C-OPCPA

In a C-OPCPA setup, unconverted pump light after a pass through the nonlinear crystal remains and builds up in the cavity. The dynamics of the C-OPCPA system can be understood by first considering the buildup in a linear cavity as shown in Figure 3-4(a). The power developed in the cavity and the power reflected from the input coupler are described by the standard equations,

\[ P_{\text{buildup}} = \frac{T \times P_0}{1 - \sqrt{R} \times (1 - L)} \]  

(3.2)

\[ P_{\text{reflected}} = \left| \sqrt{R} - \frac{\sqrt{(1 - L)T}}{1 - \sqrt{R(1 - L)}} \right|^2 \times P_0 \]  

(3.3)

where \( T \) and \( R \) are the transmission and reflection coefficients of the input coupler, \( L \) is the cavity loss, and \( P_0 \) is the incident pump power. When the incident pump beam is directed toward the input/output coupler, power develops in the cavity and is dissipated through the loss element and a reflection develops according to the above equations. Since energy is conserved, the total of the reflected power and dissipated power equals the incident power. Also, as the loss decreases, the intracavity pump power increases. For a particular value of loss when \( L = T \), the impedance matched condition, the reflected power vanishes and the intracavity power is enhanced by a factor of \( 1/T \). Under these conditions, all of the power incident on the cavity is dissipated through the cavity loss.

In C-OPCPA, the loss element is captured by the conversion via parametric amplification to signal and idler. The loss element is thus nonlinear and time varying. Since, in OPCPA, a broadband seed pulse is strongly chirped to match the temporal duration of a narrowband pump pulse, each temporal coordinate can be treated as a parametric interaction between locally quasi-monochromatic waves [51]. Thus, \( L_{NL}(t) \) equals the local conversion, \( L_{NL}(t) = G(t) \times I_{s0}/I_{p0} \times (\omega_p/\omega_s) \), where \( \omega_n \) and \( I_{n0}(t) \) are the frequencies and initial intensities. And, the temporal behavior of the nonlinear loss in C-OPCPA depends only on the local gain, \( G(t) \) in Equation 3.1,
and is a function of time varying pump intensity, seed intensity and wave-vector mismatch.

Once the steady state of the cavity is reached after multiple round trips, the sum of the newly transmitted and recycled pump power provides just enough gain to convert the new light that enters the cavity. Thus, temporal coordinates with low incident pump intensity and/or large wave-vector mismatch (i.e., which initially have low small-signal gain) experience greater intra-cavity enhancement. The goal in C-OPCPA is to arrive at a condition closest to impedance matching for all temporal coordinates such that all of the incident pump power is dissipated in the nonlinear loss element, i.e., converted to signal and idler. Our simulations, below, show that an enhancement cavity with a sufficient Q-factor and a proper ratio of incident pump and seed powers naturally arranges for conditions close to this: pump power builds until the loss balances the newly injected pump power with each round trip, while good adherence to the impedance matching condition, $L(t) = T$, on average, allows nearly all of the pump light incident upon the cavity to enter, unreflected.

### 3.3 Performance Improvements of C-OPCPA Neglecting the Influence of the Cavity Locking Mechanism

We conducted numerical simulations capturing parametric amplification and cavity loading in order to analyzed the dynamics of the C-OPCPA process and compare the results to the single pass case. Gaussian pump and signal pulses were used with matched pump, signal, and cavity repetition rate and with matched pump and chirped seed duration. The C-OPCPA simulation is shown schematically in Figure 3-5. With each cavity round trip the following steps are applied: the intracavity pump electric field is added to the incident pump transmitted through the input coupler, modified by propagation through the OPA crystal, and then linear losses are applied. The nonlinear propagation, including self-phase modulation (SPM), and is
Figure 3-4: (a) An enhancement cavity resonant with the pump with a linear loss. (b) In C-OPCPA the loss is due to conversion of the pump to signal and idler via parametric amplification. Therefore the loss is nonlinear and time varying.
calculated via the fourth-order RungeKutta method. The spectrally dependent wave-vector mismatch is calculated from the crystal Sellmeier equations and implemented as a time-dependent function, $\Delta k(t)$.

Our choice of material and laser parameters, below, ensures that dispersive pulse broadening is negligible and group-delay mismatch between pump, signal, and idler pulses is less than one-tenth their durations. Our approach is thus consistent with the local approximation, allowing dispersive propagation terms to be dropped. The simulations run for multiple round trips ensuring that the steady-state values are attained. The resulting analysis captures valid steady state solutions within the context of the local approximation even when effects due to pulse walk-off are considered, however, instabilities do arise when all temporal dynamics are accounted for. As will be shown in a later section, instabilities due to the effect of walk-off can be easily stabilized with sufficient pump filtering.

It is important to note that the influence of the cavity locking is not considered here and the value of $n_2$ is kept low. A low value of $n_2$ is not entirely unrealistic considering the development of negative $n_2$ materials [ ]. This section, therefore, addresses the fundamental limitations and performance of parametric amplification in an enhancement cavity resonant with the pump laser source. High values of $n_2$ and the role of cavity locking are addressed in a later section.

### 3.3.1 Simulation and Comparison of Single Pass OPCPA and C-OPCPA

As a point of comparison, the single pass case was simulated with a 6 ps transform-limited pump pulse train at 1037 nm and a 2 $\mu$W, 6 ps, chirped signal pulse train at 1550 nm with 100 nm band-width, which mix in a 5-mm-long PPLN crystal at 80 MHz repetition rate. The average power of the pump pulse train was scanned and the resulting conversion and amplification bandwidth are shown in Figure 3-6. The optimal conversion for gain saturation in this case of 43% occurs with a bandwidth of 53 nm at 50 W incident pump power. We conducted a similar simulation for a
Ain(t)=i TVx A_{\text{incident}}(t)

A_{\text{intra}}(t) - \text{cavity}

\begin{align*}
A_{\text{in}}(t) &= i T^{1/2} A_{\text{incident}}(t) \\
R^{1/2} &\quad \text{OPA + SPM + Dispersion} \\
\text{Loss} &
\end{align*}

Figure 3-5: Schematic of iterative simulation capturing temporal dynamics.

C-OPCPA system with experimentally reachable parameters assuming a system comprised of a Yb-fiber amplifier pump and a spectrally broadened Er-fiber oscillator seed source. The chosen parameters where identical to the optimized single-pass OPCPA, calculated above, except that for the single pass case the incident pump power was 5-times-higher, required for saturated single-pass gain. The C-OPCPA simulation yielded a higher conversion efficiency of 68% and a broader bandwidth of 103-nm. The pump mode had a waist of $\omega_0 = 40 \mu m$ in both cases.

Figure 3-7 shows a comparison of the intensity profiles and the fractional conversion profiles from pump to signal/idler for the single pass and C-OPCPA. In both cases, $\Delta k = 0$ for 1550-nm signal wavelength, which is aligned to $t = 0$. The broader fractional conversion profile of the C-OPCPA case compared to the single-pass case shown in Figure 3-7(b) illustrates the advantage of C-OPCPA: In the single-pass case, conversion mostly occurs under the peak of the corresponding Gaussian pump pulse and so gain narrowing limits the total conversion efficiency of incident pump to signal and idler to 43%. The resulting bandwidth of the amplified signal is 52 nm (FWHM), slightly larger than the calculated phase-matching bandwidth of 44 nm because of broadening due to amplifier saturation [14]. In comparison, the C-OPCPA
Figure 3-6: Single pass parametric amplifier simulation with a 6 ps transform-limited pump pulse train at 1037 nm and a 2 μW, 6 ps, chirped signal pulse train at 1550 nm with 100 nm band-width, which mix in a 5-mm-long PPLN crystal at 80 MHz repetition rate.
case produces a signal pulse with 103-nm bandwidth and 68% total conversion efficiency. Thus, with C-OPCPA we attain twice the bandwidth and $1.6 \times$ greater conversion efficiency at 1/5-th the incident pump power.

### 3.3.2 Performance Improvements through Passive Pulse Shaping

The intra-cavity pump profile obtained via passive pulse shaping in the enhancement cavity (Figure 3-7(a), red curve) enables the improved performance and resembles that of a conformal profile. Figure 3-8 shows how the intracavity pump pulse profile develops as the cavity is loaded. At the center of the incident pump pulse, where the wave-vector mismatch is zero and intensity is peaked, $g(t)$ is relatively high, and cavity equilibrium requires an enhancement of only 2. At the wings, however, the cavity must respond to the relatively low $g(t)$ of the incident pulse, due to significant wave-vector mismatch and low intensity, by building up more intracavity power. In other words in the wings, the enhancement is large because the loss is low. The resulting double-peaked intra-cavity pulse allows for more uniform conversion over its duration, increasing efficiency and eliminating gain narrowing.

The chirp of the signal pulse consequently has a separate purpose: the mapping of frequency to time allows the cavity to respond to the nonuniformity of the gain spectrum by further enhancing the pump intensity at the temporal coordinates where there is wave-vector mismatch. Thus, the initially lower gain at frequencies where the wave-vector mismatch is large is offset by higher gain from increased pump intensity. The small-signal gain is thus made uniform in both time and frequency. The resulting conformal-type pump profile shape allows for both higher-than-normal conversion efficiency compared to the single pass case, since the pump depletion is uniform in time, and also wider gain bandwidth, since the gain is also made uniform in frequency, even in the presence of significant wave-vector mismatch.

It is important to note that the cavity can shape the pump pulse to a conformal-like pulse shape and optimize conversion is a unique property of how the parametric
Figure 3-7: Simulated C-OPCPA with a 10 W, 6 ps, transform-limited pump pulse train at 1037 nm and a 2 W, 6 ps, chirped signal pulse train at 1550 nm with 100 nm bandwidth, which mix in a 5-mm-long PPLN crystal at 80 MHz repetition rate. The pump and signal beam waist is $\omega_0 = 40 \mu m$. For comparison, optimized single-pass OPCPA is simulated with identical parameters except for a higher, 50 Wpump power. Cavity parameters are $T = 10\%$ and $L_{\text{linear}} = 1\%$ (a) Intensity profiles of seed (multiplied by 107) and pump in single-pass case and incident, and intracavity pump profiles in cavity-enhanced case. (b) Fractional conversion efficiency (conversion of incident pump to signal and idler) versus time for the single-pass case compared to the cavity-enhanced case. The fractional intracavity conversion is also shown.
interaction changes with wave-vector mismatch. Figure 3-9(b) shows that for each quasi-CW parametric interaction, the peak conversion efficiency shifts to longer propagation lengths as the wave-vector mismatch increases. This shift can be offset by increasing the pump intensity. When this happens, the peak conversion efficiency with respect to the original pump intensity increases and shifts to shorter propagation lengths. Thus, for a fixed propagation length, pump intensity can be used to compensate for wave-vector mismatch in the parametric interaction. This is not true for all non-linear optical processes. In second harmonic generation, for example, the peak conversion efficiency shifts to shorter propagation lengths, as shown in Figure 3-9(a). Thus, when the pump intensity is increased, the peak increases, but shifts to shorter propagation lengths. Thus, for SHG, an increase in pump intensity cannot be used to compensate for wave-vector mismatch for a fixed propagation length.

Figure 3-10 further illuminates the effect of the cavity on OPCPA. Figure 3-10(a) shows the conversion efficiency as a function of propagation of three pump and signal fields at the coordinates $T_1 = 0$ ps, $T_2 = 3$ ps, and $T_3 = 5$ ps shown in Figure 3-7 for the single-pass case. Since the signal is chirped there is also a time-frequency map and the three coordinates have increasing values of wave-vector mismatch. We see
from Figure 3-10(a), that in the single-pass case for a fixed propagation length it is not possible to simultaneously optimize conversion efficiency for all three coordinates (wave-vector mismatches). The effect of the cavity, however, is to increase the pump field at the later times, T2 and T3, to make up for the lower conversion efficiency. Thus, we see in Figure 3-10(b) that the effect of the cavity is to align the peak conversion efficiencies so that it is possible to optimize the conversion across the pulse for a fixed propagation length.

### 3.3.3 Impedance-Matching in C-OPCPA Systems

At impedance matching for an input/output coupler with a transmission T, the reflection vanishes and the enhancement factor settles to 1/T, as all of the incident pump power is dissipated in the loss element. In C-OPCPA, the loss is nonlinear and time-varying but due to the large signal chip the impedance matching can be evaluated at each temporal coordinate. Figure 3-11(a) shows the reflected power at the input coupler. In this example, \( L_{NL}(t) \cdot T = L_{linear} \) on average, and therefore the system is well impedance matched, as manifested by the low total reflected power across the temporal axis. This result was obtained by tuning the seed power to 2 \( \mu W \): since the ratio of incident pump and seed intensity determines the amount of enhancement
necessary for equilibrium to be reached, the seed intensity is an experimental knob for controlling the intra-cavity conversion, $L_{NL}$, and therefore the average impedance matching. At two temporal coordinates, $L_{NL}(t) = T - L_{linear}$, exactly, recognizable in Figure 3-11(b) by where the black dashed line ($T - L_{linear}$) and the fractional intra-cavity conversion (red dashed curve) intersect, and manifested in Figure 3-7(a) where the reflected power has local minima. (Note, we find the reflected power at $t = -2$ ps does not go to zero, as expected, due to the effect of SPM.) As manifested by the low reflected power, even with the degree of variation of $L_{NL}(t)$ seen in Figure 3-7(b), impedance matching is good on average. These results suggest that well impedance-matched conditions can be obtained over a wide range of amplifier designs, using $T$ and the seed intensity as design parameters.

It is important to note that fractional conversion of the incident pump pulse (Figure 3-7(b), solid red curve) is high while the intra-cavity fractional conversion (Figure 3-7(b), dashed red curve) is low, since it only takes a small amount of intra-cavity conversion to balance the pump power transmitted into the cavity with each round trip. Low intra-cavity conversion is crucial to the cavities ability to extend the OPA.

Figure 3-10: Conversion efficiency for the 3 temporal coordinates from Figure 3-7 for the single pass case (a) and the cavity enhanced case (b). $T1 = 0$ ps, $T2 = 3$ ps, $T3 = 5$ ps
Figure 3-11: (a) Reflection from an initially empty cavity. Progression of the reduction in reflected intensity (black curves). The final steady state reflection profile (red). (b) Steady state loss (red) including nonlinear loss from the parametric conversion and linear losses. Static input coupling (IC) value for the cavity (black). The intersection (blue arrows) indicates the impedance matched temporal coordinates. At these coordinates perfect conversion, i.e., zero reflection, is possible, limited only by nonlinear phase effects.

Gain bandwidth significantly beyond the phase-matching bandwidth. Equation 3.1 for $G(t)$ indicates that the effect of $\Delta k$ mismatch can be compensated by an increase in $\Gamma$ through an increase in pump intensity. However, it is a feature of OPA that the maximum obtainable fractional conversion efficiency drops quickly as the ratio $\Delta k/2\Gamma$ approaches unity [59, 51]. Therefore, in single-pass OPA, maximum conversion efficiency limitations imposed by $\Delta k$ directly limit the system efficiency. In contrast, C-OPCPA achieves high conversion efficiency with low intra-cavity conversion. In fact, as $\Delta k$ increases, the cavity responds with increased enhancement and lower intra-cavity fractional conversion, ensuring the limitations on maximum obtainable fractional conversion efficiency are not reached. Instead, the cavity finesse, damage threshold, and/or SPM limit the build-up of intensity and the system performance. Finally, low intra-cavity conversion also eliminates the phase shifts due to $\Delta k$ that would otherwise be impressed upon the pump during its depletion, ensuring full cavity loading.
3.3.4 Potential for Octave Spanning Gain

The capability of C-OPCPA to extend gain bandwidth while boosting conversion efficiency can be employed in a wide range of OPCPA systems. A particularly dramatic result can be obtained when it is used in conjunction with a group-velocity matched, degenerate OPA system which already has a phase-matching bandwidth that spans a significant fraction of an octave in single-pass configuration, eg.[50]. For example, using cavity parameters similar to those of the example above, but with signal and idler wavelengths equal at 2.06μm, we have calculated that the C-OPCPA technique can be used to extend the gain bandwidth to 1.3 octaves: noting that the cavity can offset the effect of moderate wave-vector mismatch, the OPA crystal poling period can be chosen to bias the wave-vector mismatch versus wavelength such that the maximum deviation of Δk from zero is minimized over the largest possible wavelength range (see red curve in Figure 3-12(a)).

Figures 3-12 and 3-13 illustrate the tuning capability and signal gain bandwidth that can be achieved if the interaction is phase-matched at 1.55μm. Figures 3-12 summarizes simulations of C-OPCPA with 100-nm seed pulses centered throughout the 1.5 – 3.4μm range. In each case, the seed pulse is appropriately stretched to match the pulse duration of the pump, and the PPLN OPA crystal is phase matched at 1.55μm. These results highlight the ability of the cavity to efficiently amplify the seed pulse when the parametric conversion process is phase mismatched: while the phase-matching bandwidth (dashed line) covers only narrow regions around 1.55μm and 3.07μm, efficient conversion of incident pump to signal plus idler (ranging from 27 to 78%), occurs over the full 1.5 – 3.4μm range. These results are possible due to the ability of an increased nonlinear drive to exactly compensate for reductions in gain due to wavevector mismatch when the intracavity conversion is low. Since low intracavity conversion is the natural operating point of the cavity, amplification without phase matching is possible. These results highlight an additional practical capability of C-OPCPA: wide tunability covering a greater-than-octave bandwidth, using a single nonlinear crystal and without realignment necessary. For example, if
the WLC is stretched to a much longer duration than the pump pulse, the device can be tuned to efficiently amplify a different wavelength by simply adjusting the delay between pump and seed pulses by means of a delay stage.

In addition to octave tunability, the cavity can amplify all the above wavelengths if they are contained in a single pulse as shown in Figure 3-13. The C-OPCPA device has more than an octave of tuning range and can amplify a signal pulse over the range $1.5 - 3.4\mu m$ (-10 dB bandwidth), with a conversion efficiency still as high as 53%. In comparison, the phase-matching bandwidth (-10 dB) when phase matched for $2.06\mu m$ signal (i.e., at degeneracy) covers only $1.7 - 2.6\mu m$. Using conventional OPA crystals, C-OPCPA, therefore, could provide the first amplification technique with gain bandwidth spanning over an octave.

3.4 Influence of the Cavity Phase on System Dynamics

In the previous study, two key assumptions were made. First, the influence of cavity locking was neglected and, secondly, a value of $n_2$ of $3.2 \times 10^{16} \text{cm}^2/\text{W}$ was used which can potentially be a factor of 10 lower than a typical value for PPLN. Since, in principle excessive $n_2$ can be compensated with negative $n_2$ materials and cavities can be engineered to be more stable, the utility of the previous analysis resides in addressing specifically the fundamental limitations in using an enhancement cavity to improve the performance of parametric amplification. We have shown that enhancement cavities extend the capabilities of parametric amplification by passive pulse shaping in the limit where local approximation holds. In this section we investigate the impact of the C-OPCPA system performance when Hänsch-Couillaud cavity locking is included in the model and when large values of $n_2$ are used. By considering intra-cavity phase effects on cavity loading, we will show that the degradation of C-OPCPA system performance when large values of $n_2$ are used can be compensated by the action of the cavity locking which imparts a phase on the intracavity pump pulse that on average
Figure 3-12: Demonstration of wide tunability: amplification of 100-nm wide seed pulses at center wavelengths spanning 1 to 4μm. (a) Amplified signal spectrum (multicolor series) labeled with the fractional conversion to signal and idler. The phase-matching gain bandwidth (dashed black) and wave-vector mismatch (red, units on the right) are also shown. (b) Pump intensities at corresponding temporal coordinates mapped to signal wavelength.
Figure 3-13: C-OPCPA, pumped at 1.03 μm, seeded around the degeneracy point with bandwidth covering 1.4 to 3.5 μm, and phase matched at 1.5 μm. Input coupler T =10%. (a) Wave-vector mismatch (red), phase-matching bandwidth (black, dashed), and amplified signal (blue). (b) Corresponding intracavity pump intensity profile.
cancels that of SPM.

### 3.4.1 Influence of High $n_2$ on C-OPCPA Performance without Cavity Locking

In the previous analysis, by neglecting the action of the cavity locking we are implicitly assuming that the cavity is interferometrically stable with respect to the pump laser cavity such that at low pump powers when nonlinear phase effects in the enhancement cavity are negligible, the pump power is fully loading at each temporal coordinate and is limited only by intracavity losses. However, at high powers when intracavity nonlinear conversion occurs, a phase profile develops on the intracavity pump arising from the parametric process and from self phase modulation. These phase effects can degrade cavity loading as can be seen through the expression for the enhancement in the presence of a phase shift:

$$E = \frac{T}{|1 - R^{1/2} \times \alpha \times e^{j \delta}|^2} = \frac{T}{|1 - R \times \alpha - 2R^{1/2} \times \alpha \times \cos(\delta)|^2} \quad (3.4)$$

In the above equation, T and R are the transmission and reflection coefficients of the input/output coupler. $\alpha^2 = 1$ - total cavity loss, and can be though of as the cavity absorption coefficient. And $\delta$ is the total residual phase which could originate from beam propagation and/or nonlinear effects. The effect of a phase shift through the $\cos(\delta)$ term is to simply lower the enhancement and reduce the power that enters the cavity. Phase effects, thus, prevent proper loading of the incident pump power in the cavity and limit impedance matching.

In C-OPCPA, the sources of nonlinear phase shift are parametric conversion and self phase modulation (SPM). Phase shifts from parametric amplification are relatively low since the they are proportional to the fractional pump depletion which is low compared to the intracavity pump pulse in C-OPCPA. SPM, however, is particularly detrimental since the resulting phase shifts are strongest at high intracavity powers. Temporal coordinates with initially low conversion may never attain the full enhancement necessary to drive up the conversion due to intensity dependent, self-
phase-modulation-induced phase shifts manifesting during the build up process that limit pump power loading. Thus, under the conditions of an interferometrically stable enhancement cavity, the relative strength of parametric conversion, $d_{\text{eff}}$, compared to self phase modulation, $n_2$, determines the ability of the cavity to load pump power and overcome limitations set by the gain profile in parametric amplifiers. This is illustrated by the blue and black curves in Figure 3-14 which shows the intracavity pump profile, reflected pump profile, fractional conversion and intracavity pump phase for various simulation conditions. The blue curves correspond to the simulations in the previous section except with 20% less power. A 100 nm wide signal is amplified in C-OPCPA system with 8 W of pump power, a 10% output/input coupler and a 5 mm PPLN. The black curves correspond to simulated results when the same parameters are used except that $n_2$ is increased by a factor of 10. As shown in the figure, the fractional conversion is substantially decreased due to the high $n_2$ and overall the conversion efficiency is lowered from 75% to 26%.

The source of the limitations is revealed by considering the phase of the intracavity pump power after the input/output coupler. In the absence of intracavity phase, the intracavity field just reflected from the input/output coupler will coherently combine with the fraction of the incident pump field just transmitted through the coupler. Since the transmitted field is equal to the incident field scaled by the transmittivity and phase shifted by $\pi/2$, $(A(t)_t = jt \times A_{\text{in}}(t))$, at resonance and neglecting nonlinear phase shifts the intracavity field is phase shifted by $\pi/2$ with respect to the incident field. When nonlinear effects are included, deviations of the intracavity phase from $\pi/2$ limit loading of the pump pulse as shown in Figure 3-14(d). For the simulation case where $n_2$ is small (blue curve) the phase deviation is bounded around $\pi/2$. The anti-symmetric shape of the phase profile indicates that the phase contributions from parametric amplification are larger than from SPM and that the wave-vector mismatch reverses sign at $t=0$. High conversion is achieved since the moderate phase profile allows cavity loading as indicated by the low reflected pump profile and the large double peaked intracavity pump profile. When a large $n_2$ is used however, the phase effects from SPM cause large deviations of the intracavity phase as shown by
Figure 3-14: C-OPCPA simulations with 8W pump power, T=10%, L=5mm for the case of low $n_2$ and no locking (blue curves), high $n_2$ and no locking (black curves), and high $n_2$ and locking.
the black curve in Figure 3-14. That the largest phase deviations are the center of the pulse where the most intracavity pump power is located indicates that SPM dominates the nonlinear phase effects over parametric amplification, although the influence of parametric amplification is seen in the local increase in phase to the left of \( t = 0 \). In that range the effects of SPM are canceled somewhat by the oppositely signed phase effects of parametric amplification. The conversion efficiency decreases because the phase effects of SPM limit cavity loading as indicated by the large reflected pump profile and the wingless low intracavity pump profile. Only at the range of temporal coordinates where the phase effects of SPM are mitigated by the phase effects of parametric amplification is there any appreciable conversion.

### 3.4.2 Analysis of the Cavity Locking

Although large \( n_2 \) degrades system performance in the above simulation, the action of the cavity lock can be used to compensate the nonlinear phase responsible for the reduced performance. The cavity locking technique used in this work, the Hänisch-Couillaud method, produces an error signal that is proportional to the total roundtrip phase shifts experienced by the intracavity pulse. This error signal is feedback to a piezo mounted cavity mirror which counteracts the roundtrip phase by imparting its own phase through the mirror displacement. The total cumulative internal phase shift in the cavity can then be made zero or tuned to an offset value.

Figure 3-15 depicts the Hänisch-Couillaud method. The polarization of the linearly polarized incident pump beam is rotated by an angle \( \theta \) so that most of the incident field is oriented along the principle axis of the cavity while a small fraction of the field is oriented along the perpendicular axis. A loss element which influences only the perpendicular component of the field, such as a polarizer or an optical window oriented at Brewster angle for the principle axis, is placed in the cavity. As the cavity moves through a resonance, an ellipticity is introduced on the reflected beam due to the different phase shifts imparted on the principle field component which is resonant with the cavity and the perpendicular component which is influenced by the polarization dependent loss element. Shifts in the ellipticity are measured in a
balanced polarization analyzer which produces an error signal with a zero crossing, which is used as a feedback signal to a piezo-mounted mirror which finely adds a phase from the mirror displacement, \( \exp(jk\Delta z) \), to the intracavity pump pulse.

If the polarization dependent loss in a C-OPCPA setup is a perfectly absorbing polarizer, then the reflection along the perpendicular axis, \( x \), is simply the incident beam along the perpendicular, \( y \), axis reflected off the input/output coupler while the reflection along the principle axis is influenced by the field built up in the cavity. If \( E_0 \) is the incident field and \( \theta \) is the incident polarization angle, the the reflected beam components can be expressed as:

\[
E'_y = E_0 \sin(\theta) \sqrt{R}, \quad E'_z = E_0 \cos(\theta) \frac{j \sqrt{T}}{1 - \sqrt{R} \alpha e^{j\phi}},
\]

where \( \alpha^2 = 1 - \text{loss} \) is the absorption of power in the cavity capturing both linear loss
and nonlinear loss, and \( \delta \) is the total roundtrip phase which includes the nonlinear phase shifts, \( \delta_{NL} \), and cavity phase shifts from the mirror displacement, \( \delta_{Cavity} = k\Delta z \).

For a given value of \( \delta_{Cavity} \), the values \( \alpha^2 \) and \( \delta_{NL} \) evolve as the pump power develops in the cavity. When steady state is reached, the amplitude and phase of the reflected field along the principle axis is determined by using the above equation with the final values of \( \alpha^2 \) and \( \delta_{NL} \). Overall, the optical processes stabilize with a few hundred roundtrips, while the cavity phase which is controlled through the displacement of the piezo can only be adjusted on a considerable slower time scale. Thus, the motion of the piezo adiabatically traces out steady state solutions functionally dependent on the cavity phase and accessible through the cavity dynamics. Additionally, since the cavity dynamics are dependent on the stored intracavity power the ultimate steady state solution attained by the cavity is path dependent allowing for the possibility of hysteresis.

The polarization analyzer consists of a half-wave plate (HWP) and a quarter-wave plate (QWP) followed by a polarizing beam splitter (PBS). The outputs of the PBS are directed to a balanced photo detector which measures the difference, \( I_a - I_b \).

As seen from the equations above, which determine the ellipticity of the reflected beam, when \( \delta_{RT} \) is zero \( E_x^r \) is in phase with \( E_y^r \) and the reflected beam is linearly polarized. Therefore, since linear polarization indicates optimal round trip phase, the QWP and the HWP should be aligned so that the powers, \( I_a \) and \( I_b \), from the polarization analyzer balance at linear polarization, i.e. the zero crossing in the error signal corresponds to resonance. If the fast axis of the QWP is set at \( 45^\circ \) with respect to the PBS, \( I_a \) will equal \( I_b \) if the reflected beam is linearly polarized regardless of orientation with respect to the fast axis. This occurs since for linear light the QWP will induce an ellipticity such that the major and minor axes of the ellipse are along the slow and fast axis of the QWP. The PBS is oriented \( 45^\circ \) with respect to the fast axis and the slow axis. Each output port of the PBS will, therefore, have equal contributions of field from the field component along the slow axis and the fast axis of the QWP, and so the signal will balance. In practice, if the polarization dependent loss is not perfectly extinguishing, both wave plates are needed. For simplicity we
only consider the QWP.

With proper polarization analyzer orientation, the error signal can be calculated with the Jones matrices as has been done in the original work [29]:

\[ I_a - I_b = I^{(i)} 2 \cos \theta \sin \theta \frac{T \alpha^2 \sin \delta}{(1 - \alpha^2)^2 + 4 \alpha^2 \sin^2 \frac{\delta}{2}} = T I^{(i)} \frac{\alpha^2 \delta}{(1 - \alpha)^2} \] (3.6)

where the second equality holds in the limit of small \( \delta \). Since \( \alpha^2 = 1 - \text{loss} \), in the limit of small \( \delta \), we have:

\[ I_a - I_b = T I^{(i)} \left( \frac{1 - \text{loss}}{\text{loss}^2} \right) \delta \] (3.7)

The above analysis applied to monochromatic wave. In C-OPCPA, under the conditions of the local approximation, each temporal coordinate will settle to a value of \( \text{loss}(t) \) and \( \alpha(t) \) causing the reflected beam to have a time dependent ellipticity. The outputs of the PBS would eject power at each point in time consistent on the time dependent ellipticity. The slow response time of the photodiodes would then integrate the PBS output. The resulting error signal is essentially the integration of Equation 3.7 over time:

\[ HC \text{ Error Signal } \propto T \int I^{(i)}(t) \left( \frac{1 - \text{loss}(t)}{\text{loss}(t)^2} \right) \delta(t) \, dt \] (3.8)

The above expression confirms that the HC error signal is essentially a weighted average of the phase across the pulse. This signal is then used in a feedback loop to control the cavity phase which influences the roundtrip phase. If the error signal is locked to zero, then the "average" roundtrip phase across the pulse will be vanish, facilitating cavity loading.

The above error signal expression is valid when the cavity reflection is referenced to a pure reflection from the output coupler. This assumption may not hold if the polarization discriminating element does not perfectly extinguish the field. Also rather than a loss, the polarization element may introduce a birefringence so that when the desired axis is on resonance the other axis is off resonance. In both cases, the po-
larization discriminating intracavity element allows for some cavity loading along the low finesse axis which will introduce offsets and asymmetric, which could limit the range of accessible cavity phases.

3.4.3 Incorporating Cavity Locking into the Simulation

The HC error signal and feedback loop with proportional gain was implemented in the simulations as shown in Figure 3-16. The green curves in Figure 3-14 show the simulated results for the same parameters with a large value of $n_2$. As indicated by the phase, the action of the cavity results in the phase of the cavity being pushed up, resulting in proper cavity loading as evident by the low reflection profile and the winged intra-cavity pump shape, allowing intracavity pulse shaping to overcome gain limitations. Figure 3-17 shows the total conversion, the average and total enhancement, and the relevant phase shifts (average, cavity, nonlinear and roundtrip) as the pump power builds up in the cavity for the corresponding simulation results in Figure 3-17. These results show the influence of phase effects during the buildup process on the C-OPCPA system performance. For the case of low $n_2$ and no cavity locking, as power accumulates the average round trip phase is low allowing a total enhancement and conversion to build up. With a high $n_2$ and no cavity locking, SPM accumulates as power develops limiting the enhancement and resulting in low total conversion. When both high $n_2$ and cavity locking are implemented, the effects of SPM are canceled. The cavity loads without the lock for the first 60 round trips and a nonlinear phase develops which rejects power as evident by a reduction in enhancement. After the lock is turned on, the cavity phase counter acts the nonlinear phase effects, keeping the average roundtrip phase low and thereby allowing high enhancement with a total conversion close to the case of low $n_2$. The total enhancement is lower while the average enhancement is higher. This is due to the fact that more power is coming in at the center and less in the wings. Not all temporal coordinates can be compensated resulting in a slightly reduced bandwidth.

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Figure 3-16: Schematic of iterative simulation capturing temporal dynamics incorporating feedback of the Hansch-Coulliard (HC) error signal into the cavity phase.
Figure 3-17: Total conversion, average and total enhancement, and cavity, nonlinear and roundtrip phase for conditions of low and high $n_2$ and locking.
3.4.4 Influence of SPM and Cavity Locking on Prospects for Octave Spanning Gain

Figure 3-18 and Figure 3-19 show the influence of cavity phase on broad tuning. The case of low $n_2$ and no locking, high $n_2$ and no locking, and high $n_2$ and locking are shown. The time profiles for conversion, enhancement, and phase are shown in Figure 3-18, while the average values are shown in Figure 3-18. The influence of SPM drastically reduces conversion due to a large phase and low enhancement across the tuning range when locking is not implemented compared to the low $n_2$ case. However, when the lock is applied, more conversion is realized between $1.5\mu m$ and $3\mu m$ compared to the low $n_2$/no locking case. Higher conversion is realized since the cavity locking is able to cancel phase effects through the cavity phase whereas for the low $n_2$/no locking case the wave-vector mismatch is highest for this range of wavelengths, limiting loading and conversion. Specifically, the phase profiles in Figure ?? show the influence of the phase and the action of the cavity. The phase for the intracavity pump pulses for the high $n_2$/locking case center around $\pi/2$ for the entire center-wavelength tuning range, while for the low $n_2$/no locking case, the phase profiles rise across the center-wavelength range where the wave-vector mismatch is the highest. At around $3.5\mu m$, however, for the high $n_2$/locking case, while the average intracavity phase is $\pi/2$ allowing high conversion for temporal coordinates where the phase is close to $\pi/2$, the phase fluctuation are large enough to limit conversion to only a narrow range of temporal coordinates, limiting the bandwidth. Thus peak conversion is higher compared to the low $n_2$/no locking case, but the bandwidth is reduced.

Figure 3-20, shows that influence of high $n_2$ and cavity locking on the prospects of octave spanning gain. The blue curves in the figure show the previous results. Without cavity locking, high $n_2$ limits conversion to a narrow range near the phase-matched wavelengths (black curves). The cavity lock, however, is able to bias the intracavity pump phase so that proper cavity loading and high conversion are maintained across the interacting pulses (red curves). Figure 3-21 show the same information except
Figure 3-18: C-OPCPA simulations with 8W pump power, T=10%, L=5mm, phase matched at 1.55 μm for various signal wavelengths for the case of low $n_2$ and no locking (blue curves), high $n_2$ and no locking (black curves), and high $n_2$ and locking. The fractional conversion, enhancement profile, and phase profile are represented vs wavelength/temporal coordinate.
Figure 3-19: C-OPOCPA simulations with 8W pump power, T=10%, L=5mm, phase matched at 1.55 μm for various signal wavelengths for the case of low $n_2$ and no locking (blue curves), high $n_2$ and no locking (black curves), and high $n_2$ and locking. Total conversion, total enhancement and average phase are shown vs signal wavelength.
Figure 3-20: C-OPCPA simulations depicting octave spanning gain with 8W pump power, T=10%, L=5mm for the case of low $n_2$ and no locking (blue curves), high $n_2$ and no locking (black curves), and high $n_2$ and with locking (red curves). The intracavity pump profile (a), reflected pump profile (b), fractional conversion (c) and intracavity pump phase profile are shown above.

plotted vs. wavelength rather temporal coordinate. Thus the action of the cavity preserves the possibility of octave spanning gain.

### 3.5 Graphical Analysis - Load Line Solutions

More insight into the operation of the cavity can be achieved by looking at the response of the cavity to a CW input. This can be done graphically as shown in Figure 3-22, which corresponds to a CW solution for the peak powers for the example
Figure 3-21: C-OPCPA simulations depicting octave spanning gain with 8W pump power, T=10%, L=5mm for the case of low $n_2$ and no locking (blue curves), high $n_2$ and no locking (black curves), and high $n_2$ and with locking (red curves). The signal spectrum (a), intracavity pump spectrum (b), and phase spectrum (c) are shown above. The wave-vector mismatch and the phase matching gain bandwidth (PM BW) at 2.03 $\mu$m and 1.55 $\mu$m are also shown in (a).
case of C-OPCPA discussed in Figure 3-7 and the previous section. This analysis
neglects the effects of nonlinear phase shifts, but is still valid since the OPA phase is
zero for a phase-matched interaction and the influence of the cavity lock is to minimize
the cumulative roundtrip phase.

The red curve (a) in Figure 3-22 shows the intra-cavity power build-up (x-axis) as a
function of $\alpha^2$ (y-axis) of the cavity. $\alpha^2 = 1 - \text{loss}$ accounts for all linear and
nonlinear cavity losses and is essentially the absorption coefficient for the intra-cavity
elements. For curve (a) $\alpha^2$ is a free parameter and for a given $\alpha^2$ a particular value of
intra-cavity pump light will build up. $\alpha^2$ varies from 0 to 1 and as $\alpha^2$ increases there
is less absorption in the cavity and more field builds up. To find the CW operating
point we need to determine the value of $\alpha^2$ at which the cavity operates.

The black curve (d) in Figure 3-22 shows the absorption factor in the cavity as a
function of intra-cavity power. Both the losses from the cavity due to linear loss and
due to nonlinear power-dependent loss from the OPA process are captured in the
absorption function. The curve dips to zero for a phase-matched OPA process when all the pump light is converted to the signal and idler. When there is a wave-vector mismatch the dip shifts to higher intensities and rises from zero because of the behavior of the parametric interaction. This is shown in curve (e) in Figure 3-22.

The operating point for CW pump, signal and idler waves in the c-OPCPA process
is determined by the intersection of the red curve (a) and the black curve (d). At
this intersection, the particular intra-cavity power developed in the cavity results in
an absorption parameter of the cavity elements that support the required intensity.

Once the operating point is determined, the efficiency with respect to the input
pump power is determined from curve (b) in Figure 3-22. For the case in the figure,
the CW conversion efficiency is 46%. The conversion efficiency is calculated for all
points on (a) by taking the ratio of the intra-cavity power to the input power times the
non-linear loss from the OPA conversion. In principle, the operating point should be
near the maximum of curve (b) since this is the most optimally impedance matched
point.

The graphical solution to the C-OPCPA for the CW case can be extended to
visualize the dynamics in pulsed operation with a chirped signal pulse since each point in time is treated as a separate CW interaction. With this in mind, we can see that when a narrow-band pump and chirped signal interact in c-OPCPA, each point in time is represented by a curve similar to the one shown in Figure 3-22. Figure 3-22, for example, is the curve for t=0 for the case of Figure 3-7 where then pump and signal pulses have their highest intensity and the wave-vector mismatch is zero. As we shift from away from t=0 to earlier or later times, the pump and signal intensities reduce, and the wave-vector mismatch increases. The reduction in pump intensity causes curve (a) and (b) to shift to the left since less power is available to build up in the cavity. Also, the reduction in signal intensity causes curve (d) to shift to the right and the increase in wave-vector mismatch causes curve (d) to shift up and toward curve (e).

By monitoring how the operating point shifts as the curves corresponding to the cavity shift to the left and the absorption curves shift to the right, we can see how the efficiency changes in time. We see that times away from t=0 the operating point can shift through the maximum of (b) over and past the optimal impedance matched points for both earlier and later times. Thus, the efficiency profile for c-OPCPA with a chirped signal pulse as a function of time has two peaks as shown in Figure 3-7(b). Times slightly advanced or delayed from the phase-matched center are more optimally impedance matched so the conversion efficiency increases away from t=0.

3.6 Dispersion Induced Depletion Instabilities

A key assumption in the analysis of C-OPCPA is that the narrow pump pulse was long enough and the broadband signal was sufficiently chirped so that each temporal coordinate could be treated independently. This allowed the use of a time-varying wave-vector mismatch and permitted the neglect of temporal walk-off between interacting pulses, greatly simplifying the simulation. The chirping requirement is also necessary to avoid phase effects due to walk-off and dispersion, which prevents proper loading of the pump in the cavity and limits the system performance, when
Figure 3-22: Relevant curves for a C-OPCPA with a 10% OC, 4% loss, and 5 mm PPLN crystal. The peak pump power is, $1.2 \text{GW/cm}^2$ which corresponds to a 5 W 3 ps pump signal at 80 MHz. The signal 1 mW in 3 ps. Curve a) is the built up power as a function of $\alpha^2$ for a fixed input power. Curve b) is the converted power efficiency with respect to the input pump power. Curve c) indicates the input pump power. Curve d) is the loss coefficient function for the cavity which includes non-linear and linear loss for a phase matched OPCPA process, and curve e) is a similar curve where the OPCPA process has a wave-vector mismatch. The intersection between a) and d) indicates the operating point of the c-OPCPA.
short pulses are used. Additionally, the chirping requirement increases with the BW of the signal. By implementing the full temporal dynamics, a new kind of instability, dispersion-induced depletion instability, naturally arises due to the interplay of pump depletion and dispersion when pulse durations longer than the pump to signal/idler walk-off lengths are used. We analyze these instabilities in this section.

Employing detailed simulations by including the effects of walk-off and dispersion, we have found that for pulse durations longer than the walk-off length between the pump and signal/idler a natural instability manifests itself which can cause the breakup of the stored intra-cavity pump pulse. This new kind of instability for C-OPCPA systems is related to the interplay of pump depletion and material dispersion and could potentially occur in other scenarios where resonant cavities are used to enhance nonlinear processes such as high harmonic generation.

Figure 3-23(a) shows the simulated intra-cavity pump profile for a scenario where depletion instabilities arise when long pulses are used. 1\(\mu\)m, 40\(\mu\)J pump pulses are used to amplify 1.55\(\mu\)m, 0.6\(p\)J, 100nm BW signal pulses with > 70% conversion efficiency. The pump and signal pulse durations are 80 ps. The cavity has a 10% input/output coupler. The PPLN crystal is 5 mm long. And the repetition rate is 80MHz. After > 600 iterations the instability appears on the intra-cavity pump profile as shown in Figure 3-23(a) and magnified in Figure 3-23(c) (red dashed line). In each subsequent pass through the crystal, the interplay of dispersion and intra-cavity pump depletion causes the instability to further grow, resulting ultimately in the pulse breakup shown in Figure 3-23(c).

In order to understand the underlying gain mechanism for the instability, we conducted open-cavity propagation simulations of the parametric amplifier with a sinusoidal perturbation added to a flat-top pump pulse with a peak intensity corresponding to the steady state of the closed cavity. We analyzed the results to determine the conditions under which modulation growth takes place. Figure 3-24 shows the numerically simulated propagation of pump, signal and idler pulses with durations \(\sim 100\times\) the pump-signal and pump-idler walk-off lengths. The modulation period was 0.57 ps. Figures 3-24(a)-(c) show the amplitude of the modulation on the pump,
Figure 3-23: a) Depletion instability appearing on the intra-cavity pump profile after $> 600$ iterations. b) Instability zoomed in from 1b (red-dashed). Steady state intensity profiles of the intra-cavity pump (red-solid), signal (blue), and idler (olive) resulting after breakup, i.e. the instability is allowed to continue to grow until the pump pulse profile appears as a train of short pulses.

The DC field amplitude of the pump, and the phase of the modulation on the pump, respectively. Figures 3-24(d)-(f) show the amplitude of the modulation on the signal and idler, the DC field amplitude of the signal and idler, and the phase of the modulation, respectively. The simulation shows that for the given modulation period, at the onset of depletion of the DC pump field, the modulation on the pump grows and is delayed in phase. Additionally, the modulation amplitudes on the signal and idler grow exponentially and shift during the propagation due to parametric amplification and group velocity walk-off. Thus, under these conditions, gain exists for a modulation on the intra-cavity pump at the modulation frequency chosen.

The gain mechanism for the instability can be understood by considering the effects of parametric amplification, walk-off, and seeding conditions throughout the propagation. At the beginning of the crystal, a sinusoidal modulation on the pump causes the signal and idler to experience increased gain at the peaks of the perturbation. Thus initially the signal and idler develop a ripple that is in phase with that on the pump. However, due to walk-off and parametric amplification, the ripple on the signal and idler advances in phase and grows exponentially in amplitude as the pulses
propagate. Eventually, the pump pulse starts to deplete. If walk-off were not present, the ripple on the pump pulse would tend to flatten since the peaks of the perturbation would deplete faster than the troughs due to the peaks of the amplified signal/idler fields lining up with the peaks on the pump. However, because of the walk-off, the peaks of the amplified signal/idler fields can seed at different phases relative to the perturbation on the pump at the onset of depletion. For certain combinations of modulation period and walk-off rate, the peaks of the signal and idler modulations coincide with the troughs of the pump modulation at the end of the crystal where pump depletion is strong and signal/idler intensities are large. When this happens, depletion is greatest at the troughs of the pump modulation because these troughs are seeded by the peaks of the signal and idler. Thus, the troughs are depleted faster than the peaks, and the modulation on the pump grows in amplitude while the DC field of the pump is depleted. This modulation period corresponds to the natural resonance of the depletion instability. From our simulations we determined this period to be 0.57 ps. Through this mechanism in a single roundtrip, the amplitude of the modulation on the pump is increased while the average value of the pump intensity is reduced due to conversion to signal and idler. After propagation through the crystal, the signal and idler exit the cavity and the intra-cavity pump pulse is combined with a clean pump pulse at the input/output coupler which restores the DC value of the pump pulse to the steady state value while the modulation amplitude is unaffected. The new pre-crystal pump pulse and a clean signal pulse are then directed toward the crystal to repeat the process and the modulation on the pump continues to grow with each round trip.

Thus, we have identified a new type of modulation instability which occurs in C-OPCPA. This depletion instability could potentially compromise the C-OPCPA scheme when signals with large bandwidths requiring large chirps are used. However, since the pump pulse is narrow band, we have found in our simulations that a properly chosen intra-cavity notch filter for the pump is sufficient to suppress this instability and ensures proper system performance. The analysis here provides a design criterion for the pass band of such a filter by identifying the resonance of the instability, and
Figure 3-24: a) Offset value of intra-cavity pump. b) Amplitude of modulation on pump. c) Phase of pump modulation. d) Offset value of signal (blue)/idler(green) fields. e) Amplitude of modulation on signal (blue)/idler(green). f) Phase of modulation on signal (blue)/idler(green).

thus putting a lower limit on the pump pulse durations that can be used.

### 3.7 Conclusion

In conclusion, we have presented a new approach to boosting gain, conversion efficiency and gain bandwidth for high-repetition-rate OPCPA systems. C-OPCPA optimizes the temporal profiles for the nonlinear interaction, compensating the effects of wave-vector mismatch and gain narrowing by increasing pump intensity where there is low conversion efficiency. Simultaneously, through an increase in effective pump power, it boosts nonlinear drive. These are important results for the development of practical high-repetition-rate OPA systems. The pulse shaping is passive and self-optimizing. Gain bandwidths can be extended well beyond the phase-matching bandwidth of the OPA material, thus opening the door to direct amplification of
octave-spanning sources and extending the performance of existing OPA materials. In our recent experimental effort, we have observed the amplification of 1.56 $\mu m$ pulses at 78 MHz repetition rate in a C-OPCPA setup. Further experimental progress will be reported elsewhere.
Chapter 4

Conversion Efficiency and Bandwidth Extension Beyond Material Limitations of a 20 mm PPLN in a C-OPCPA System

In the previous chapter, we presented a theoretic description of technique of the Cavity Enhanced Optical Parametric Chirped Pulse Amplification (C-OPCPA) in which pump pulses are coherently combined in a low finesse enhancement cavity transparent to signal and idler containing an OPA crystal in which a synchronized signal beam is amplified. We demonstrated that if the pump and seed are sufficiently chirped, the cavity passively shapes the intra-cavity pump profile to attain more optimal conversion and increased bandwidth (BW), overcoming limitations set by the bell-shaped pump intensity profile and the time-varying wave-vector mismatch of the interacting pulses. Our numerical analysis predicted octave spanning gain BW at high conversion efficiency and high repetition rate using the C-OPCPA with low average pump power sources [65], illustrating the potential of the system to efficiently amplify few cycle sources without the need for pump power scaling.

Even if octave spanning gain is not desired, however, the utility of C-OPCPA
is in its ability to extend the capabilities of existing nonlinear crystals beyond their material properties. In parametric amplification for a fixed crystal length, pump source, and signal source, conversion and bandwidth experience limitations from the nonlinear coefficient driving the process, $d_{eff}$, and from dispersion characteristics. C-OPCPA overcomes this by treating the parametric process as a loss mechanism which can be impedance matched through a cavity's output coupler value. The relation between intracavity loss, $L$, and the output coupling value, $T$, determines system performance. When $L$, consisting of both a linear contribution and a nonlinear time varying component from the intracavity conversion process, equals $T$ at all temporal coordinates, the cavity is perfectly impedance matched (IM) and therefore the reflected power vanishes and the enhancement factor, i.e., the ratio between the intracavity power and input power, becomes $1/T$. At IM, all incident pump power is dissipated in the loss element, the nonlinear loss is maximized, and conversion is optimal. Reaching a condition closest to IM is the main issue for maximum conversion in C-OPCPA. Demonstration of the extension of crystal capabilities by evaluating IM will illustrate the utility of the system and is a first step in the direction of octave spanning gain.

Toward this end, we have conducted two detailed sets of experiments with two crystals phase matched for parametric-amplification, a 20 mm crystal and a 10 mm crystal. The experiments were done sequentially with the 20 mm crystal being used initially. In the next chapter, the 10 mm crystal, with a larger phase matching bandwidth was used to carefully evaluate bandwidth extension. This chapter addresses the experiments with the 20 mm crystal where the emphasis was to demonstrate high conversion efficiency. Here, we present an experimental study of impedance matching and performance improvements in the first experimental demonstration of a C-OPCPA system. We show more than 50% conversion efficiency of coupled pump light at a high repetition rate (78 MHz) and an increase in the tuning bandwidth by a factor of 4 beyond the phase matching bandwidth. C-OPCPA enables significant parametric amplification under conditions where an equivalent amount of pump power used in a single-pass configuration would lead to negligible conversion. Through comparison
with the single-pass case, we evaluate the underlying impedance-matched conditions and relate them to the C-OPCPA performance.

First, we present an overview of the experimental apparatus, providing an overview of the pump, signal and cavity. A more detailed description of the subsystems are presented in the Appendix. We describe characterization of the coupling coefficient and loss. Then for the 20 mm crystal used in this study, we compare single-pass and C-OPCPA and analyze impedance matching under phase matched conditions. And finally we quantify bandwidth improvements. The performance improvements illustrate the ability of the cavity to improve the capabilities of the 20 mm PPLN crystal used.

4.1 Experimental Apparatus

To demonstrate the C-OPCPA concept, we constructed the experimental apparatus shown schematically in Figure 4-1. A Yb-doped fiber laser (YDFL) centered at 1.03μm seeds the OPCPA pump chain and produces up to 5-W average power 500 fs pump pulses, and an Er-doped fiber laser (EDFL) centered at 1.56μm serves as the C-OPCPA signal. Both lasers have a 78 MHz repetition rate to match the free spectral range of the enhancement cavity (ring cavity) with a finesse of 25 containing the PPLN crystal. The cavity is locked to the YDFA via the Hänisch-Couillaud scheme [29], and the YDFL and EDFL are locked via electronic synchronization [38, 46]. This apparatus, outlined below, allowed proof-of-principal experiments to explore optimization, scaling of cavity parameters, and limitations of the c-OPCPA technique. The result of the c-OPCPA demonstration at 1.5μm is the highest conversion efficiency amplifier at 78 MHz with low average power pump sources based on a parametric process. In the following, we provide details of the subsystems comprising the C-OPCPA apparatus.

The EDFL signal source is based on a soliton design and is shown in Figure 4-2. The EDFL has a free space section containing a piezo mounted mirror to electronically control the repetition rates. The output of the EDFL is amplified in a home built
EDFA to the 50mW and is directed toward the cavity for amplification. The electronic synchronization scheme locking the EDFL and the YDFL is shown in Figure 4-3 and consists of two loops. A fast loop which is a phase lock loop for the 9GHz harmonic of the repetition rates allows for tight synchronization of the two lasers, and a slow loop which is a phase locked loop for the fundamental harmonic of the repetition rate allows for temporal overlap of the signal and pump lasers. The measured timing jitter between the pump and signal is \(~40\) fs and is sufficiently bounded giving the duration of 500 fs of the pump source.

The YDFA is a CPA system consisting of a similariton mode-locked fiber laser shown in Figure 4-4, a grating stretcher shown in Figure 4-5, a home-built Yb-doped fiber pre-amplifier, a commercial 10W IPG fiber amplifier, and a grating compressor shown in Figure 4-6. As described below a grating stretcher/compressor pair is employed to generate the 10 nJ pulse pump pulse energy, however, this source can be replaced by an all fiber source at a later stage using double cladding pump technol-
Figure 4-2: Erbium doped fiber laser (EDFL) based on a soliton design with a free space section.
The YDFL provides 500fs, 78MHz, with a wavelength range from 980nm to 1100nm. A 7nm portion of this spectrum, is stretched to 1ns in a grating stretcher, shown in figure 6b, consisting of two 1800 lines/mm gold coated gratings with a 1:1 telescope comprised of two 50cm lenses placed between. The output of the stretcher is directed to a homemade fiber pre-amp and is amplified to > 10mW, which is the required power to seed the 10W commercial IPG amplifier. The spectrum output of the IPG amplifier can attain average powers of up to 8W without nonlinear spectral distortions. Finally the output of the IPG amplifier is compressed in a grating compressor pair consisting of two 1750lines/mm. The 2nd and 3rd order dispersion are set to cancel the dispersion of the stretcher and fiber amplifier, and pulse durations down to 500fs with 7W average power are attained. The 7W, 500fs, 78MHz source provides pulses with 125nJ energy, which while not enough for sufficient single pass conversion, can proved enough gain when loaded into the cavity with a modest enhancement of 10 to allow for significant depletion of the intra-cavity pump. The pulse duration of 500fs is narrow band enough to avoid dispersive effects such as cavity filtering, and pump/signal walk off. In addition the pulses duration can be tuned
to optimize the c-OPCPA conversion efficiency by introducing a hard aperture in the grating stretcher.

The design of the enhancement cavity is shown in Figure 4-7. The cavity is a ring consisting of folding mirrors with high reflectivity at the pump wavelength, an input coupler for the incident pump, and two curved mirrors allowing for a tight focus at the location of the PPLN crystal. The pump is directed to the input coupler though a mode matching telescope assembly to allow for optimal coupling into the cavity. The curved mirrors are transparent at the signal wavelength, allowing one to be used for injection of the seed and the other for removal of the amplified signal as shown in the figure. The cavity length is set to match the repetition rate of the fiber lasers, and the separation of the curved mirrors determines the spot size at the crystal location. The birefringence of the PPLN crystal is sufficient to introduce a polarization dependent
Figure 4-5: Free space grating stretcher
Figure 4-6: Free space grating compressor
resonant condition and thus can be used to impart an ellipticity on the reflected beam provided that the incident beam has a component along both the tangential and sagittal axes. Thus, a HC error signal can be derived from the reflected beam without the addition of additional cavity elements such as a thin film reflector at Brewster's angle to impart a polarization-dependent loss. The error signal derived from the polarization of the reflected beam from the cavity is used to lock the cavity to the YDFL and is shown in Figure 4-8. The optics employed in the cavity should allow a finesse of 25. The optics are all designed to withstand at least 100-W average power under the beam focusing conditions of the cavity.

The EDFL signal pulses are stretched to \(~3\) ps using 5 m of single-mode fiber. The large seed pulse chirp and the chosen delay between pump and signal pulses optimized conversion efficiency for a well phase-matched 4-nm segment of the seed.
Figure 4-8: Hänsch-Couillaud (HC) signal and cavity transmission measured through leakage from a cavity mirror as a voltage is applied to a piezo mounted cavity mirror.
spectrum centered at 1565nm. This resulted in only $\sim 20\mu W$ of seed power overlapping the gain window set by the pump. The pump and stretched seed pulses are simultaneously injected into a 78-MHz cavity with 10% output coupler, resonant with the pump pulses, and containing a 20-mm-long periodically poled lithium niobate (PPLN) crystal anti-reflection (AR) coated at the pump, signal and idler wavelengths. We chose the PPLN because its large $d_{eff}$ value enables the use of low pulse energy at high repetition rate. Two telescopes were used to focus the pump and seed beams into the PPLN and match the closed cavity mode diameter of 100µm.

4.2 Calibration and Assessment of Cavity Loss and Coupling Efficiency

The above mentioned experimental apparatus was used to evaluate the performance of the C-OCPA. The optimal performance of the system is attained when the fractional conversion of the intracavity power matches the power transmission of the cavity input/output coupler (T) achieving conditions of impedance matching. Under the condition of impedance matching, the reflected beam vanishes and the intracavity enhancement factor reaches the value of $1/T$. Impedance matching and system performance can thus be evaluated by monitoring the intracavity power, the reflected power and the signal power under various seeded and unseeded scenarios as shown in Figure 4-9. By monitoring these quantities while the cavity is locked or while the cavity piezo is slowly scanned, the performance of the C-OCPA system can be quantified and the underlying cavity dynamics can be observed.

In addition to the signal power, intra-cavity power, and reflected power, it is essential to calculate the coupling efficiency (CE) into the cavity to quantify cavity performance. Higher-order modes are completely rejected by the cavity when locked on the fundamental mode. This uncoupled light does not contribute to conversion and so the total conversion efficiency to signal and idler needs to be scaled by the CE. In principle, however, the CE can be improved to be close to 100% with accurate
Intra-cavity leakage

PPLN amplified signal

Figure 4-9: The reflected power, intra-cavity pump power, and amplified signal power are monitored to evaluate the C-OPCPA performance and observe cavity dynamics spatial control of the input beam, and does not represent a fundamental limitation to the C-OPCPA technique.

To evaluate CE, we adjusted the intracavity linear loss while monitoring the reflected and intracavity powers with low incident pump power. As shown in Figure 4-10, as the intracavity linear loss in a linear cavity is increased, the reflected power passed through a minimum while the enhancement monotonically decreased. At the minimum point of reflected power, the total loss equals the IM value and the enhancement experienced by the coupled light equals the inverse of the output coupling value. In the case of perfect coupling efficiency, the reflection when there is impedance matching should vanish. Any non-zero value of reflected power at the impedance matched condition is a result of uncoupled light. The reflected power at this value is the uncoupled amount since otherwise it would vanish. The CE is therefore equal to one minus the ratio of the reflected power at this operating point to the incident pump power.

In the case of the cavity in this experiment, the linear loss was adjusted via aperture loss through an intracavity iris (see Figure 4-1) which did not significantly disturb the cavity mode since the maximum introduced loss matched the output coupling value of only 10%. When the iris was close the reflection passed through a mini-
Figure 4-10: Enhancement (black) and reflection coefficient (red) for an enhancement cavity as the loss is varied. At the impedance matched point the reflection is zero and the enhancement monotonically decreases as the loss is increased.

Figure 4-11 further illustrates how the coupling efficiency was determined. The reflected power is shown in 4-11(a), and the intracavity power in 4-11(b) as a voltage is applied to a piezo to displace a cavity mirror. The red curves correspond to a scan when the iris is closed at the impedance matched condition with no signal present, the green curves correspond to when the iris is open and no signal is present, and the blue curves correspond to when the iris is open and the signal is being amplified. As shown in the figure, when the piezo is scanned a dip in the reflected power and spike in the intracavity power occurs when the resonant condition of the cavity is met and power builds up in the cavity and is dissipated through loss. Major dips/spikes correspond to coupling into the fundamental mode, while minor dips/spikes correspond to coupling into higher order modes. Outside the cavity resonances, no power builds in the cavity and the full incident beam is reflected. When the signal is not present the re-
flected power and enhancement diminish when the iris is closed. The dip in reflection with the iris open corresponds to dissipation of incident pump light into linear losses. Since the total loss is low the enhancement is high. If the losses were zero, then there would be no dip in the reflected power and the intracavity power reach its highest value. As we add more loss by closing the iris the reflection reaches the minimum and the total loss (linear + iris) matches the output/input coupler at 10%. As shown in the figure, the dip corresponds to 55% coupling efficiency as determined from the zero power level and the maximum power level. When the cavity is seeded under the conditions of the figure, the dip in reflection/spike in enhancement is between the unseeded and impedance matched level, demonstrating the operation of the cavity.

Once the coupling efficiencies were determined, the cavity losses were evaluated by measuring the reflection and enhancement vs. incident pump power as shown in Figure 4-12. The green curve in Figure 4-12 shows the conversion to super-fluorescence. Figure 4-13 shows the intracavity pump at various incident pump power levels. For low pump power the spectrum scales linearly, however, at high pump power the spectrum experiences nonlinear effects. At the highest incident pump power of 1.3 W, the distortion of the intracavity power spectrum (Figure 4-13) is primarily due to conversion to superfluorescence but is also suggestive of slight self-phase modulation. The aforementioned observations, indicate that at low incident pump power levels, the cavity responds linearly since the effects of parametric amplification and SPM are low. Thus, accounting for coupling efficiency, an enhancement of 30 with a reflection of 70% is consistent with an intracavity linear loss of 2-3%

4.3 Comparison of Single Pass Optical Parametric Amplifier for Comparison to C-OPCPA

We first performed single-pass parametric amplification using the same C-OPCPA setup of Figure 4-1 without closing the enhancement cavity, i.e., the output coupler was removed. Figure 4-14(a) shows the amplified signal power and the conversion to
Figure 4-11: Reflection traces (a) and intracavity pump power (b) as the piezo supporting a cavity mirror is scanning for conditions of seeded, unseeded and impedance matched through an intracavity iris.
Figure 4-12: (a) Shows for the case where no signal is present the intracavity enhancement, the conversion to superfluorescence, and the percent reflected power. An enhancement of 30 with a reflection of 70% accounting for CE is recorded, consistent with an intracavity linear loss of 2-3%.

Figure 4-13: Intracavity pump spectrum for various incident average power levels under unseeded operation. For low values of average incident pump power, the intracavity pump spectrum scales linearly, and for high values the spectrum is distorted.
signal as a function of pump power and Figure 4-14(b) shows the seed (dashed line) and amplified signal spectra (blue solid) when 4 W of pump power were used. With 4 W of 500 fs pump pulses and ~20μW of seed power, we were able to convert 5% of the pump power into signal at 78 MHz. Accounting for the idler at 3.03μm which was fully absorbed in a BK7 collimating lens, we estimate that the total pump depletion was 8%. Thus, with the same 4 W of intracavity power, the nonlinear loss in the closed cavity is expected to be 8% as well. If we allow for 2% linear losses from components in the cavity, i.e. mirrors and AR coatings on the PPLN, then the total intracavity loss can thus be tuned to 10%. Thus, a 10% output coupler is suitable for IM. Additionally, the single pass experiment shows that sufficient amplification can be achieved before crystal damage occurs at the desired power levels.

Turning to seeded operation of the C-OPCPA apparatus, with only 1.3 W of incident pump power, 210 mW of the pump power is depleted into the signal and we estimate 105 mW is depleted into the idler. The resulting signal spectrum is shown by the red solid line in Figure 4-14(b). In contrast, only 1.3 mW of amplified signal is observed in the single-pass configuration with this pump power (see 4-14(a)), which is 2 orders of magnitude lower. Allowing for 55% CE, with an effective available pump power of only 650 mW we are able to achieve nearly 45% pump depletion for a 78 MHz source. As discussed below, even though the intracavity conversion is
Figure 4-15: Intracavity pump spectra for seeded C-OPCPA (red) and unseeded C-OPCPA (black).

much less than 45%, cavity enhancement with good average IM enables the dramatic conversion efficiency improvement with respect to the coupled incident pump. The high conversion efficiency and the clean spectrum of the signal is also aided by the seeding lowering the intracavity power below the threshold of SPM related effects. As shown in Figure 4-15, the spectrum of the intracavity pump power under conditions of seeding is clean and distortion free.

For quantitative evaluation of the C-OPCPA performance and the underlying impedance matching mechanism, we measured the total conversion to signal and idler and the enhancement versus incident pump power (including uncoupled light), as shown in Figure 4-16 on the left. For comparison the single pass conversion is plotted along with the C-OPCPA results on the right panel. This figure reveals several features of the high repetition rate C-OPCPA. Firstly, this figure demonstrates the cavity's ability to passively maintain high conversion in response to factors that reduce conversion. As the pump power increases from zero, the net conversion efficiency
quickly increases and saturates at ~ 50% for > 0.4W. Accordingly, the enhancement is first high (~ 26) and then quickly reduces to ~ 10 or less for > 0.4W. The cavity naturally employs increased enhancement to offset low incident power, thus maintaining intracavity peak intensity and conversion over a wide range of incident pump power. The passive self-adjustment results in the incident power threshold for amplification being ~ 5 times less compared to that of the single-pass amplification.

Secondly, this curve allows us to characterize the IM operating point of the C-OPCPA system. Conversion of > 50% is observed between 0.4 and 1 W of incident pump power where the enhancement ranges from 11.4 to 7.4. The intracavity power spans 2.2 W to 4 W. The variation in enhancement across this range is low and close to 10 which is consistent with the IM with a 10% output coupler. According to the single pass measurements with 4 W of pump power, the total conversion is ~ 8%. Thus, the nonlinear loss in the cavity at this power is also ~ 8%. Additionally, the linear loss is ~ 2%, allowing the total intracavity loss to match the IM value of 10%. The maximum C-OPCPA conversion of 55%, however, is observed at 0.4 W of incident pump power. Accounting for CE, the intracavity power at this operating point is 2.2 W, significantly lower than the value predicted in the single-pass case. The discrepancy possibly comes from the mode mismatch between a single-pass pump beam and the cavity mode. A slightly larger beam size at the PPLN for the single-pass case would shift the single-pass conversion curve to higher pump powers. Nevertheless, the trend observed in Figure 4-16 is quantitatively consistent with the IM analysis.

The advantage of using a cavity stems from increased effective nonlinear drive by recycling the pump power. The incident power required to achieve the desired intracavity pump power is reduced by the IM enhancement factor, which is 10 in this case. Thus, under IM, the enhancement factor for the intracavity process significantly reduces the pump average power requirements. Additionally, only a fraction of the intracavity power is converted and is subsequently replaced by the next injected incident pump pulse. Thus a small fractional conversion of the intracavity pump power results in a large conversion of the incident pump power. In the absence of linear losses for a 10% OC as in this case, an intracavity pump power level that allows
a 10% single pass total conversion yields 100% conversion of coupled pump light in the C-OPCPA case. With 3% linear loss, ideally 70% conversion is achievable (30% into linear losses). Here, we have shown 55% conversion with only 400 mW of incident pump power. Nonlinear and dispersive effects play a role in limiting conversion as does temporally non-uniform IM due to non-uniform pulse intensity profiles, but further improvements are expected as the cavity losses are reduced. Finally, we note that the pump pulse self-shaping mechanism addressed in the previous chapter is impeded in this work by group-velocity walk-off effects. By appropriately adjusting system parameters, (increasing pulse durations, and average pump power or reducing the output coupler transmission), we expect to demonstrate BW improvement due to pump pulse self-shaping in future work.

4.4 Demonstration of Bandwidth Extension

Although a more complete study of bandwidth extension is presented in the next chapter, to complete the analysis of performance improvements in a C-OPCPA with a 20 mm crystal we characterized the bandwidth. As a first step in demonstration of BW improvements of C-OPCPA as compared to single pass (SP) we show effi-
cient conversion in the presence of a wave-vector mismatch large enough to make SP conversion negligible. This is equivalent to extending the wavelength tunability well beyond the phase matching BW. The same system parameters as in the above conversion efficiency measurements were used: The Yb- fiber based CPA pump source, having 500 fs pulses centered at 1034 nm, produced up to 4 W of average power. The Er-doped fiber signal source, centered at 1560 nm with 20 nm BW, had 2mW of average power and was stretched in 100 m of fiber to attain a 10 ps duration. The enhancement cavity containing a 20 mm long PPLN and a 10% output coupler. Since the signal wavelength is fixed, the phase matched wavelength was tunned while monitoring converted power to evaluate bandwidth changes. The method is explained in more detail in the next chapter.

Figure 4-17 shows the BW improvement as determined by observing conversion into signal and idler while varying the phase-matching by temperature tuning the PPLN with the pump and chirped seed temporal overlap fixed at their peaks. The green curve in Figure 4-17(b) shows actual phase matched wavelength as the temperature is tuned as observed from superfluorescence spectra. For C-OPCPA, 750 mW of coupled pump power was used. Since the phase matching BW is intensity dependent, the SP pump intensity was chosen to be 4W to match the intracavity power at the optimally phase-matched temperature for the C-OPCPA case, allowing a fair comparison. As the phase matching wavelength is tuned the SP conversion efficiency drops off as shown in Figure 4-17(b). The phase matching BW at fwhm is observed to be 10-nm. In C-OPCPA, the cavity responds to the initially reduced conversion from wave-vector mismatch by increasing the enhancement from 3 to 7 (see Figure 4-17(c)) making available more intracavity pump power and maintaining the nonlinear process. The resulting effect is that the conversion into signal and idler is maintained over the entire tuning range (Figure 4-17(b)).

The central wavelength of the amplified signal is fixed in SP determined by the overlap of the gain window set pump and the highly chirped seed, however in C-OPCPA as the temperature is tuned, more optimally phase matched signal wavelength are brought under the gain window set by the pump pulse due to pump and signal
walk off. Thus the central wavelength of the amplified signal spectrum shifts as shown by the black curve in Figure 4-17(c). The corresponding signal spectrum is shown in Figure 4-18. Although other nonlinear processes may contribute to the output signal spectrum, the dominant mechanism responsible for the distortion is group velocity walk off which is avoided in the next chapter by limiting the signal bandwidth to 2.5 nm.

For the conditions of this experiment we are still able to quantify the BW improvement. Across the range from 1543 nm (T=130) to 1570 nm (T=170) the central wavelength of the amplified signal spectrum matches that of the seed, and we observe the cavity compensating wave-vector mismatch at the desired wavelength and maintaining uniform conversion while the SP rolls off. At T=170, beyond the phase matching BW, the SP has < 1% conversion while the C-OPCPA case has more than 40%. Importantly, at T=200 the amplified signal spectrum is centered at 1571 nm while the phase matching wavelength is at 1593 nm, beyond the phase-matching BW by a factor of 4.2.

4.5 Conclusion

In conclusion, by a fair comparison to single pass measurements we have demonstrated, for the first time, significant conversion efficiency and bandwidth improvement in OPCPA by use of an enhancement cavity. The C-OPCPA lowered the threshold for amplification by a factor of 5, and had nearly 50% overall conversion efficiency and the bandwidth was extended by a factor of 4 compared to the single pass case. We analyzed these results in the context of impedance matching identifying the linear and nonlinear losses while noting the 1/T enhancement factor of 10. While the material properties, $d_{eff}$ and dispersion, limit single pass parametric amplification, the C-OPCPA technique extends the capabilities of the 20mm PPLN used by passively loading power in the cavity in response to either reduced incident pump power or increased wave-vector mismatch by increasing the enhancement factor. The results taken as a whole validate that the concept of IM in C-OPCPA systems applies even
Figure 4-17: a) Conversion to signal+idler for C-OPCPA and single pass case vs. PPLN temperature. b) Enhancement, phase matching wavelength and the central wavelength of the amplified signal vs. PPLN temperature.
Figure 4-18: Amplified signal spectra as the phase matching condition is tuned via the temperature. The numbers in the upper right corner of each panel is the temperature in °C.
in cases where the local approximation is not valid.
Chapter 5

Bandwidth Improvement Beyond Phase Matching in C-OPCPA System with a 10 mm Crystal in the Presence of Parasitic Nonlinearities and Metastable States

In Chapter 3, we have shown that in Cavity-Enhanced OPCPA (C-OPCPA), the cavity passively shapes the intra-cavity pump profile in the time domain to attain more optimal conversion and increased bandwidth (BW), overcoming limitations set by the bell-shaped pump intensity profile and the time-varying wave-vector mismatch of the interacting pulses. We simulated octave-spanning gain showing the potential of this system. In the Chapter 4, we have demonstrated conversion efficiency and bandwidth improvements beyond the crystal capabilities, showing that the concept of impedance matching in C-OPCPA systems applies even in cases where the local approximation is not valid. While the experimental study with a 20 mm crystal yielded encour-
aging results, group velocity walk-off between pump and signal allowed considerable 
spectral distortions and center-of-mass wavelength shifts as more optimally-phase 
matched signal wavelengths were brought under the gain curve set by the pump. In 
the phased-matched wavelength tuning study in this chapter, the signal bandwidth 
was further narrowed to avoid the effects of group-velocity walk off. Additionally, 
shorter, larger aperture crystal was used to demonstrate a larger bandwidth and to 
facilitate alignment.

In this chapter, we present a detailed study of bandwidth improvements of the C-
OPCPA system with a 10 mm crystal in the presence of a wave-vector mismatch large 
enough to make single-pass conversion negligible while also improving the bandwidth 
by a factor of 3.3 beyond the phase-matching bandwidth. Unlike in the previous chap-
ter, the signal source is limited to a 2.5 nm bandwidth. Here, we will describe our 
method to characterize the gain bandwidth. Since single-pass is not possible with our 
setup with a 10 mm crystal do to limited gain, we use scaled single pass data from 
the 20 mm crystal and numerical simulations to compare the experimental perfor-
mance of the C-OPCPA system. We show that the performance of our system, with 
limited input power, is on par with a theoretical single-pass configuration with sub-
stantially greater power. We successfully, demonstrate the key feature of C-OPCPA, 
namely, that enhancement can be used to compensate wave-vector mismatch. This is 
shown despite parasitic effects, arising from pulse walk-off and self-phase modulation, 
degrading optimal performance.

5.1 Method of Bandwidth Characterizing

A major goal of this work is to provide a detailed characterization of the gain band-
width of the C-OPCPA system and compare that to the single-pass case. Ideally, in 
order to measure the gain, the seed source would have either a wide center-wavelength 
tuning range or produce broad-bandwidth pulses compressed to within the pump 
pulse/intracavity pump pulse duration. However, the signal source in this demon-
stration experiment had a FWHM bandwidth of only 13.5 nm, which is less than the
phase-matching bandwidth of 20 nm for the crystal. Thus, since the laser sources in our demonstration experiment were too narrowband, we interrogated the BW dependence by adjusting the phase-matching conditions over a broad range of wave-vector mismatches while also further reducing the input signal bandwidth by bandpass filtering. By adjusting the phase-matched wavelength with fixed and narrowband pump/signal/idler wavelengths, we were able to show an extension of the wavelength tunability of an optical parametric amplifier well beyond the phase-matching BW.

The expression for large-signal parametric gain in the presence of wave-vector can be used to evaluate the gain realized through either phase-matched-signal wavelength tuning or center-signal wavelength:

\[ G(t) \approx \frac{1}{4} \exp(2gl) = \frac{1}{4} \exp \left( 2\sqrt{\Gamma^2 - (\Delta k/2)^2} L \right) \]

where \( L \) is the crystal length. This expression holds in the limit of low (\(<\sim 20\%\)) pump conversion and large gain (\(>\sim 10\)). The small-signal gain, \( g \), dependence on the nonlinear drive is a function of the pump intensity, \( \Gamma(t) \sim I(t)^{1/2} \) and the local wave-vector mismatch, \( \Delta k \) [14]. Since we are considering periodically-poled nonlinear crystals, the wave-vector mismatch itself is given by:

\[ \Delta k = 2\pi \left( \frac{n(\lambda_p,T)}{\lambda_p} - \frac{n(\lambda_s,T)}{\lambda_s} - \frac{n(\lambda_i,T)}{\lambda_i} - \frac{1}{\Lambda} \right) \]

\[ = \frac{2\pi}{c} \left( n(\omega_p,T)\omega_p - n(\omega_s,T)\omega_s - n(\omega_i,T)\omega_i - \frac{1}{\Lambda} \right) \]

where \( \Lambda \) is the poling period of the crystal and \( T \) is the crystal temperature. For a given \( \Lambda \), \( T \), and pump wavelength a signal and corresponding idler wavelength exists, the phase-matched wavelength, such that \( \Delta k = 0 \) and which maximizes the gain. Deviations in the signal wavelength from the phase-matched wavelength increase the magnitude of \( \Delta k \) and thus reduce the gain establishing a functional dependence which comprises the signal tuning range, the signal bandwidth over which there is appreciable conversion, and the gain bandwidth, the wavelength range that can be amplified simultaneously. Both of these quantities are related to the phase matching
The PMB is determined by using the Taylor expansion of $\Delta k$ with respect to a variation in the signal frequency $\Delta \omega$ in the the large-gain expression to determine the full with at half max (FWHM) gain. As calculated in [14] the phase-matching bandwidth is proportional to the group-velocity mismatch between signal and idler. Assuming perfect phase-matching at a given signal/idler frequency, $\omega_s/\omega_i$; a change in the signal frequency from $\omega_s$ to $\omega_s + \Delta \omega$ will result in a change in the idler frequency from $\omega_i$ to $\omega_i + \Delta \omega$, due to the fact that $\omega_p = \omega_s + \omega_i$. The wave-vector mismatch can then to first order be expressed as:

$$
\Delta k = -\frac{\partial k_s}{\partial \omega_s} \Delta \omega + \frac{\partial k_i}{\partial \omega_i} \Delta \omega = \left( \frac{1}{v_{gi}} - \frac{1}{v_{gs}} \right) \Delta \omega \tag{5.3}
$$

Using Equation 5.1, the FWHM phase-matched bandwidth can then be determined as:

$$
\Delta \omega = \frac{2(\ln 2)^{1/2}}{\pi} \left( \frac{\Gamma}{L} \right)^{1/2} \frac{1}{\frac{1}{v_{gs}} - \frac{1}{v_{gi}}} \tag{5.4}
$$

The relation of gain vs. phase-matched-signal and gain vs. center-signal wavelength can be seen by considering the variation of the wave-vector mismatch for a phase-matched process as the signal frequency, crystal temperature, and grating period are adjusted. By Taylor expanding $\Delta k$ we determine this variation to be:

$$
\Delta k(\omega + \Delta \omega, T + \Delta T, \Lambda + \Delta \Lambda) = \frac{\partial \Delta k}{\partial \omega} \Delta \omega + \frac{\partial \Delta k}{\partial \Delta T} \Delta T + \frac{\partial \Delta k}{\partial \Lambda} \Lambda = \left( \frac{1}{v_{gi}} - \frac{1}{v_{gs}} \right) \Delta \omega + \frac{\partial \Delta k}{\partial \Delta T} \Delta T + \frac{\partial \Delta k}{\partial \omega} \Lambda \tag{5.5}
$$

By setting $\Delta k = 0$, we are able to determine, the amount the signal frequency must shift to offset the effects of tuning the temperature and grating period, and to maintain phase-matching. This signal frequency offset, $\Delta \omega_{PM}$, the frequency shift of the phase-matched wavelength, is given by:
If the signal frequency is held constant, for a change in the phase-matching conditions by $\Delta T$ and $\Delta \Lambda$, the wave-vector mismatch changes by an amount:

$$
\frac{\partial \Delta k}{\partial \omega} \Delta T + \frac{\partial \Delta k}{\partial \omega} \Delta \Lambda = - \left( \frac{1}{v_{gi}} - \frac{1}{v_{gs}} \right) \Delta \omega_{PM}
$$

(5.6)

The large signal gain to first order depends only on the wave-vector mismatch. The wave-vector mismatch and thus the large-signal gain change by an amount dependent on the frequency deviation of the signal wavelength from the phase-matched signal wavelength. Thus, by tuning the phase matched condition and monitoring the phase matched wavelength (i.e. through a superfluorescence spectrum) rather than tuning signal wavelength we can determine and compare the bandwidth performance of the parametric processes in this study.

5.2 Modification of C-OPCPA Experimental Parameters to Optimize Bandwidth Tuning

The experimental setup, shown in Figure 5-1 and described in detail in Chapter 3 and Appendix A, was used to perform the measurements described in this chapter. To summarize: the pump source is a Yb-fiber chirped-pulse amplifier system producing 500 fs pulses centered at 1034 nm with up to 4 W of average power. The signal source is an Er-doped fiber laser/amplifier centered at 1545 nm. Both laser sources have a 78-MHz repetition rate and are synchronized via electronic feedback. The enhancement cavity containing a periodically poled lithium niobate crystal (PPLN) phase matched for parametric amplification is locked to the pump source via the Hänsch-Coullaud locking scheme. As indicated in the figure, the bandwidth performance of the C-OPCPA system is established by measuring the dependence of the conversion as
Figure 5-1: Experimental setup. Since the signal wavelength was fixed and narrow band, the amplification bandwidth was monitored by adjusting the phase matched wavelength.

the phase matched wavelength is adjusted either by grating selection or temperature tuning.

Several experimental parameters where adjusted from the system configuration in the previous chapter to optimize tuning performance, namely, the signal bandwidth was made more narrowband, the 20mm crystal was replaced by a shorter, 10mm, crystal with a larger aperture, and the 10% output coupler was replaced with a 5% output coupler. The signal spectrum is shown in Figure 5-9 and is limited in bandwidth to 5 nm by a narrowband filter. This was done to avoid the amplification of out-of-band signal wavelengths. In the previous Chapter, the examination of phase-matched-wavelength-tuning was obscured by more optimally phase-matched signal-wavelengths entering under the temporal gain window set by the pump pulse. The group-velocity mismatch of the signal and pump thus allowed a range of signal wavelengths to interact with the pump pulse and since the unfiltered signal had significant power in the wings of the spectrum as shown in Figure 5-9(b) on a logarithmic scale, the center-of-mass wavelength of the amplified signal spectrum was distorted and shifted in the direction of phase-matching, as the phase-matched wavelength was tuning. Under conditions of the largest wave-vector mis-match, we observed that the central-of-mass wavelength of the amplified signal had shifted by 21nm (from 1550
to 1571nm, when the phase-matched wavelength was 1594nm) whereas the phase-matching bandwidth was 10 nm for the crystal used (20mm PPLN). By limiting the signal to a 2.5 nm bandwidth which is smaller than the phase-matching bandwidth (20 nm for a 10 mm crystal), the signal power is isolated to a limited range as shown on the logarithmic scale in Figure 5-9(b). The band-limited signal is better suited to demonstrate the bandwidth extension of C-OPCPA, generating clean amplified signal spectrum over the FWHM tuning bandwidth.

Additionally, the crystal choice in the previous chapter (Thorlabs OPO3) was challenging to work with because of its small aperture, which barely accommodated the cavity mode, and significantly complicated alignment. Instead, here we use a large aperture PPLN (2 by 2 mm) with a 10 mm length (HC Photonics). The shorter crystal length is also useful for attaining broader overall bandwidths since the starting phase-matching bandwidth is larger. Figure 5-3, shows the conversion efficiency and enhancement vs. coupled pump power for a 5% and 10% output coupler. In both cases reduced coupled power is compensated by enhancement, but a 10% does not
provide enough enhancement to maintain conversion. In fact, as shown in Figure 5-3, the enhancement is greater than the impedance matched value of 10, \(1/T = 1/10\%\), for the range of coupled pump powers, which indicates insufficient nonlinear drive for impedance-matching. However, as shown in Figure 5-3 a 5% output coupler increases the available enhancement and drives the C-OPOCPA into saturation. Also good impedance-matching is achieved as the impedance-matched enhancement of \(1/5\% = 20\) is attained at under 0.5 W. Thus, for a 10 mm PPLN used in this study, an output coupler transmission of \(T=5\%\) was chosen.

wavelength by calculating at the center of mass wavelength of the superfluorescence while the cavity is unseeded, and allowing maximum intracavity power. Unseeded, maxim conversion occurs where the wave-vector mismatch is zero allowing us to determine the phase matched wavelength from the super-fluorescence. Figure 5-4(a) shows representative super-fluorescence spectra, and figure 5-4(b) shows how the center of mass wavelength changes as the temperature is tuned for a fixed grating period.
5.3 Comparison of Bandwidth Tuning in C-OPCPA to the Single-Pass Case

As previously mentioned, the single-pass and C-OPCPA bandwidths in this study were evaluated by monitoring the amplified signal power as the phase-matched wavelength was tuned by adjusting the grating period and the crystal temperature. In the case of the 20 mm PPLN a single grating of 30 μm was used with temperatures ranging from 100 – 200°C to access a range of phase-matched signal wavelengths from 1530 – 1593 nm. In the case of the 10 mm PPLN, three poling periods of 29.9, 30, and 30.1 μm, and a temperature range of 100 – 200°C, made accessible phase-matched wavelengths spanning from 1520 – 1620 μm. The phase-matched wavelength was determined by calculating the center-of-mass wavelength from the superfluorescence (SF) spectrum as shown in Figure. Since the pump source had insufficient power to generate SF, the cavity was locked to the pump while unseeded allowing the maximally-enhanced intracavity pump power to drive the SF generation. From the resulting spectra, the phase-matched wavelength for a given temperature and poling period was determined since under conditions of no signal, the maximum gain in C-OPCPA will occur at the phase-matched wavelength. Conversion from the pump is negligible since the SF power is small and so any possible influence of pulse shaping can be ignored.

As in Chapter 4, a single pass parametric amplifier was established by removing the input/output coupler of the cavity allowing the full 4 W of pump power to be directed toward the PPLN and overlapped with the signal in the crystal for amplification. Since the same coupling optics used to deliver the pump beam into the cavity mode were used to focus the beam in the single-pass case, the mode size of the pump in the C-OPCPA and single pass case was similar. However, a crystal length of 10 mm was not sufficiently long to allow for measurable conversion. Alternatively, we used the 20 mm crystal and measured the conversion into signal as the phase-matched wavelength was tuned, as was done previously. The resulting single-pass FWHM bandwidth of 10 nm was subsequently measured, with a maximum conversion of less

135
than 8%. Since these results are in the low conversion limit, the measured single-pass bandwidth equals the phase-matching bandwidth. The phase-matched bandwidth for the 10 mm can then be determined by scaling the measured bandwidth for crystal length and determined to 20 nm. The p

Having determined the mapping of poling period and temperature to phase-matched wavelength, the C-OPCPA system performance was evaluated by monitoring both the amplified signal power and the intracavity pump power as determined by measuring the residual leaked pump power through a cavity mirror while the phase-matching conditions were tuned. The experimental results are summarized in Figure 5-5. Figure 5-5(a) shows the converted signal power and fractional conversion to signal and idler when 1.25W of coupled incident pump power was used. The blue curve shows the total signal power across its entire spectral range. However, in these measurements, spectral components are generated outside the signal bandwidth from parasitic nonlinear processes with lower threshold than the intended one. Thus, to isolate the effects of C-OPCPA within the signal band, spectral components outside the bandwidth of the input seed spectrum from 1540nm to 1550nm where numerically filtered for each acquired spectra. The resulting spectrally filtered conversion curve is plotted as the red curve in Figure 5-5(a). As shown in the figure, we take the FWHM bandwidth of the C-OPCPA system from the spectrally filtered conversion curve as determined from the red curve to be 60 nm. As a comparison, the phase matching gain is shown as the black dashed curve in the figure with normalized units. The actual conversion in the single pass case was very small. Thus, C-OPCPA dramatically increases the conversion to more than 60% and extends the tuning range by a factor of 3.

Figure 5-5(b), shows the response of the cavity in the presence of the wave-vector mismatch as the phase-matched wavelength was adjusted. The basic mechanism in C-OPCPA is demonstrated. As the phase-matched wavelength is tuned, the wave-vector mismatch increases, which would cause the conversion to roll of in the single-pass case. The cavity, however, responds to this increase in the wave-vector mismatch by increasing the enhancement. As the conversion to signal and idler initially drops, more
Figure 5-4: (a) Superflorescence spectrum for a fixed grating in the 20 mm PPLN as temperature is tuned in an unseeded C-OPCPA setup with 10% output coupler. Also shown is the correspondence between center of mass phase matched wavelength and temperature for the given spectra in. (b) Superflorescence spectrum for a set of poling periods and temperatures for the 10 mm PPLN as temperature is tuned in an unseeded C-OPCPA setup 5% output coupler.
Figure 5-5: (a) Output signal power/conversion to signal+idler in the C-OPCPA setup for 800 mW of coupled pump power (blue curve) vs. phase matched wavelength. The total conversion is shown in the blue curve. The conversion only in the signal bandwidth (spectrally filtered) is shown in the red curve. (b) Corresponding intracavity pump power vs. phase matched wavelength.
intracavity power builds up in the cavity, compensating the wave-vector mismatch and maintaining conversion efficiency over an extended range. The actual enhancement varies from around 8 at the central-wavelength and reaches a maximum value near 12 at 1.61 μm. Although the conversion into the signal band is small, the total nonlinear conversion is 20%. However, in Figure 5-3(b), which shows conversion and enhancement for Δk = 0 as the coupled pump power is reduced, the conversion approaches 20% when the enhancement approaches 60 or higher. A similar value of conversion is achieved for different enhancements. In Figure 5-3(b), a low incident pump power results in high enhancement and high intracavity power with low intracavity conversion. In that case, an enhancement of 60 with total nonlinear conversion of 20% corresponds to an intracavity conversion of 20%/60 = .3%, if linear losses are neglected. In Figure 5-5(b), however, the incident pump power is high and the enhancement is comparatively lower while the intracavity conversion is high. In that case, an enhancement of 11.5 with total nonlinear conversion of 20% corresponds to an intracavity conversion of 20%/11.5 = 1.7%, if we neglect linear loss. Thus, the parasitic nonlinear process, which is responsible for the conversion in Figure 5-5(b), limits the enhancement below the threshold needed to drive parametric amplification in the signal bandwidth. In a later section we will discuss the nonlinear process.

Even if the nonlinear process were avoided, spectral narrowing and distortion of the cavity mode could limit the enhancement to below the threshold needed to drive parametric amplification when the wave-vector mismatch is large. Unseeded, we observed that the maximum enhancement achieved was 18 with no appreciable conversion to super-fluorescence, the intracavity power was ~ 20W with ~ 1.3W of coupled incident pump power, where the coupling-efficiency was evaluated at low incident pump power. In Figure 5-3(b), however, as the incident pump power is reduced, the enhancement rises well above 20, reaching nearly 60. There are two possible contributions to the limited enhancement at high incident pump powers. First, temporal phase effects due to SPM, could put a large, varying phase profile on the intracavity pump preventing loading as was discussed in Chapter 3. Secondly, spatial phase effects from SPM could put a spatial phase profile on the intracavity pump
acting as a nonlinear lens. This could distort the cavity mode and reduced the coupling efficiency, effectively limiting enhancement. Also, when depletion of the pump from parametric conversion is significant, the effects of spacial and temporal phase, and spatial pump depletion from parametric amplification could limit enhancement, and should be considered in evaluated the maximum achievable enhancement in a C-OPCPA system.

5.4 Comparison to Numerically Simulated, Depletion-Optimized Single-Pass OPA

We evaluated the experimental performance of the C-OPCPA system with phase-matched wavelength tuning to a numerically simulated, single-pass OPA pumped with the depletion-optimizing pump intensity, specific for a given value of wave-vector mismatch. Figure, 5-6, shows how the conversion to signal and idler varies as the pump intensity is increased, for a 1 ps, transform limited pump pulse, and a 10 ps signal pulse with a 36 nm bandwidth. A long, chirped signal pulse was chosen such that in a 1 ps window the signal had a bandwidth of 2.5 nm. This allows us to run simulations close to the experimental conditions (0.75 ps, near transform limited pump pulses, 1-2ps, 5 nm signal pulse) without having to optimize the time delay between signal and pump. The depletion-optimizing pump intensity is the value of initial pump intensity which allows for the maximum conversion of pump into signal and idler. The value of the depletion-optimizing pump increases with increasing wave-vector mismatch, while the total conversion of an OPA pumped with the depletion-optimizing pump intensity drops as the wave-vector mismatch increases. These facts are confirmed by the results in Figure 5-6. Only the first maximum in conversion was chosen, since as the incident pump intensity is increased, saturation and back conversion is period with temporally local pump intensity and is thus asynchronous at different temporal coordinates. Thus every local maximum other than the first is corresponds to highly structured, in intensity and phase, pump and signal pulses.
Figure 5-6: Conversion to signal and idler as incident pump power is increased for single pass OPA corresponding to the experimental conditions with a 10 mm PPLN. The black curve corresponds to a phase-matched wavelength of $\lambda_{PM} = 1.55$ (i.e. $\Delta k = 0$) and the red curve corresponds a phase-matched wavelength of $\lambda_{PM} = 1.55$ (i.e. $\Delta k \neq 0$)

Only the first maximum corresponds to a realistic single-pass parametric amplifier, and thus correspond to the best case performance single-pass amplifier for the given experimental conditions and wave-vector mismatch.

The black curve in Figure 5-7(a) shows the achieved conversion efficiency of a single-pass OPA pumped with the average power shown by the black curve in 5-7(b), which is the depletion-optimizing pump intensity described above. Also shown in the figure are the total conversion, intracavity conversion, intracavity enhancement and wave-vector mismatch. The comparison of the C-OCPA results to the maximum conversion possible for variable pump shows the advantage of the C-OCPA system. As indicated above, conversion in the depletion-optimized single-pass case is peaked at 20% with a pump power higher than the intracavity pump power in the C-OCPA which was already enhanced by a factor of 9 compared to the incident coupled pump power. The C-OCPA case has a conversion efficiency of 60% with considerably lower
incident pump power. As the phase-matched wavelength is tuned, the depletion-optimizing pump intensity is increased as shown in Figure 5-7(b) in order to track the maximize conversion possible. Under these conditions, the depletion-optimized single-pass case has roughly one third the conversion and twice the bandwidth as the experimental C-OPCPA case. The experimental C-OPCPA case, however, has roughly a 30% larger gain-bandwidth product with a fixed intensity pump intensity with a substantially smaller average power. The C-OPCPA performance is based on passively adjusting enhancement, whereas the depletion-optimized single-pass case requires large variable power pump source.

The performance advantage achieved in the C-OPCPA system can be seen through the intracavity pump power and the intracavity conversion curves in figure 5-7. The intracavity power increases by 50% at the end of the tuning range to compensate for up to 3e - 31/\mu m of wave-vector mismatch. The large conversion efficiency attained (\approx 30\%) over the tuning range results from the fact that only a small amount of intracavity conversion is required to have high overall conversion. As shown in figure 5-7(a), the power converted from the intracavity pump pulse in a single round trip is more than 5%. However since the enhancement is 8, the conversion with respect to the incident pump is high. The cavity maintains a high level of intracavity power to boost the nonlinear drive. The peak intensity of the intracavity pump pulse is sufficient to allow a 5% conversion thus reducing the amplitude of the pump pulse after propagating through the crystal. The peak intensity of the pump pulse is then restored to the original level after it is combined with a new pump pulse entering and the process is repeated on the next iteration. Since a 5% output coupler is used, high conversion is achieved through impedance matching, where as the depletion-optimized single pass case faces conversion limits set by phase-matching.

5.5 Parasitic Nonlinear Effects

In the above mentioned analysis gain is achieved well beyond the calculated phase matched bandwidth, however at the extremities of the tuning range, new frequency
Figure 5-7: (a) Conversion efficiency with respect to incident coupled pump (blue curve, diamond symbols) and intracavity pump (red curve, square symbols) of the experimental C-OPCPA setup into the signal/idler bandwidth range vs. phase matched wavelength. Conversion efficiency into signal and idler for the single-pass case pumped with depletion-optimizing pump intensity (black curve). (b) Intracavity pump power in the C-OPCPA setup (blue curve, diamond symbols). Wave-vector mismatch for each phase-matched signal wavelength (green curve, square symbols). Pump power for the depletion-optimizing pump intensity for the conversion efficiencies in (a).
components are generated outside the signal bandwidth range, since at the edges of the tuning range, the low conversion results in high intra-cavity power which is able to drive parasitic nonlinear processes. These nonlinearities, which involve the interplay of SPM, parametric amplification and cavity dynamics, result in the creation of new signal/idler wavelengths, that are outside the bandwidth of the signal, and thus should not be consider in evaluating conversion efficiency as the phase matching conditions are tuned. When appropriate filtering is applied, the tuning range of the C-OPCPA system is narrowed somewhat as shown by the red curve in figure 5-8(b). This curve, however, captures the pertinent C-OPCPA dynamics that result in a tuning bandwidth of 60nm FWHM, while separating additional parasitic effects. In the following we characterize the parasitic nonlinearities and describe experimentally observed behavior. Overall, the spectral output is robust against the parasitic nonlinear effects for most of the tuning range from 1.52 m to 1.57 m. This can be seen through the center of mass wavelength for the filtered and unfiltered amplified spectrum as the phase matched wavelength is tuning, shown in figure 5 below. The filtered response maintains the center of mass wavelength into the spectral range of the signal, while in the unfiltered response the nonlinearities tend to shift the center of mass wavelength closer to the phase matched wavelength. A significant deviation of the center of mass wavelength between the filtered and unfiltered response only occurs beyond 1.57 m which is at the edge of the tuning range.

From the wavelength range of 1.54um to 1.57um, the cavity maintains the conversion into the signal with little parasitic effects. However, beyond 1.57um, the intra-cavity pump power increases from 10 W to 14 W sharply while the conversion into signal drops. In this range, two effects are contributing to the reduction in conversion. Firstly, the magnitude of the wave-vector mismatch exceeds what the cavity can compensate, and so the intra-cavity pump power simply approaches the maximum possible. Secondly, the increased intra-cavity pump power leads to nonlinear phase effects due to SPM which limit cavity loading, and drives parasitic nonlinear processes which result in conversion into wavelengths outside the input signal bandwidth. For this reason, the measured signal power (blue curve) extends via an elbow
Figure 5-8: (a) Output signal power/conversion to signal+idler in the C-OPCPA setup for 800 mW of coupled pump power (blue curve) vs. phase matched wavelength. The total conversion is shown in the blue curve. The conversion only in the signal bandwidth (spectrally filtered) is shown in the red curve. (b) Center of mass wavelength for the unfiltered amplified signal (blue curve) and filtered signal (red curve).

Beyond 1.58, while the filtered signal power drops sharply at 1.57.

Figure 5-9 shows representative amplified signal spectrum and the phase matched gain for the C-OPCPA setup under different phase matched conditions, and figure 5-10 shows the corresponding intra-cavity pump power when seeded and unseeded. When the cavity is unseeded the maximum intra-cavity pump power is loaded in the cavity. Because of SPM, the spectrum of the pump broadens and effectively loads the cavity, which is locked to the central pump wavelength, with new pump spectrum beyond the initial spectrum. The cavity, which can be thought of as a Fabry-pero cavity having a transmission bandwidth and a free spectral range, will capture the generated pump spectrum that satisfies the resonant condition which is periodic with the cavity free spectral range. The intra-cavity pump spectrum, therefore, develops side bands as pump wavelengths resonant with a free spectral range and within the reflectance bandwidth accumulate in the cavity.

The figures taken together illustrate aspects of the parasitic nonlinear process. For the case of a), b) and c) in figures 5-9 and, which correspond to the phase matched wavelengths of 1.53 m, 1.55 m, and 1.58 m, there is sufficient intra-cavity
conversion to keep the built-up intracavity power below the threshold level of the parasitic nonlinear effects. The slight shift in the center of mass wavelength can be accounted for by considering that more optimally phase matched signal wavelengths in the signal bandwidth are amplified in the gain window provided by the pump pulse. In d), however, the extreme-case of wave-vector mismatch with a phase-matched wavelength of 1.62 m results in the creation of a distinct spectral region not present in the input signal. The structured spectrum of the intracavity pump power may play a role. The excessive intracavity pump power result in a prominent side band in the pump spectrum due to the effects of SPM on the intracavity pump and the filtering effects of the cavity. The pump effectively has dual wavelengths separated by 25 nm. The effects of parametric amplification using a dual wavelength pump and using a signal wavelength far from the phase matched wavelength may play a role in the generation of new signal spectrum localized closer to the phase matched wavelength as shown in d).

5.6 Conclusion

In this work we have experimentally demonstrated significant conversion in the presence of wave-vector mismatch beyond the phase matching conditions. And have thus demonstrated the key dynamics of a C-OPCPA system in that enhancement can be used to compensate for wave-vector mismatch to maintain conversion. By using narrow band sources and adjusting the phase matching conditions, we were able to characterize the a gain bandwidth of 60 nm with up to 30% conversion efficiency with a 10 mm crystal using only 800 mW of incident pump power. A single pass parametric amplifier, under similar conditions, but with the maximum pump intensity available with the experimental setup did not result in any conversion.

Thus, we established an experimental comparison by using a single pass amplifier with a crystal twice as long. By appropriately scaling the results we showed that the C-OPCPA bandwidth exceeds the phase matched bandwidth by a factor of 3.3. Additional comparisons to detailed single pass simulations, show that the tuning
Figure 5-9: Amplified signal spectrum (red) and relative gain (blue) for phase matched wavelengths of 1.53 $\mu m$ (a), 1.55 $\mu m$ (b), 1.58$\mu m$ (c), and 1.63 $\mu m$ (d). The offset wavelength is relative to 1.55 $\mu m$. 
Figure 5-10: Figure 7. Intracavity pump power spectrum corresponding to signal spectra in figure 6 with a signal present (blue) and when the signal is blocked (red) for phase matched wavelengths of 1.53 μm (a), 1.55 μm (b), 1.58 μm (c), and 1.63 μm (d).
response with the C-OPCPA system presented in this work performs on par with a single pass system that uses an optimized pump power at each signal wavelength. The C-OPCPA system achieves the same level of performance with a fixed power pump source at 1/20th the power level.
Chapter 6

Future Work

Optical parametric amplifiers have emerged as important optical sources by extending the properties of few-cycle laser sources, which exist only in materials with sufficiently large gain bandwidths, to wide array of spectral ranges. The work in this thesis relates to the continued development of OPAs and C-OPCPAs, where we address new designs for generating compressible spectrum, circumventing prior difficulties, and where we present a new method to dramatically increase conversion efficiency and bandwidth beyond material limitations. Specifically, we have developed a white light seeded, CEP, degenerately pumped OPA (DOPA) producing near transform-limited sub-7-fs pulses at the driver wavelength from a long-pulse, non-CEP-stable Ti:sapphire regenerative amplifier. Problems arising from the spectral phase jump at the driver wavelength, 800 nm, were avoided by using a near infrared OPA to produce white light continuum down to 800 nm where the spectral phase is smooth. Additionally, we have proposed C-OPCPA as a way to increase the capabilities of nonlinear crystals and continue scaling parametric amplifier systems to high repetition rate. This work contains the first theoretical and experimental investigation of C-OPCPA, where we have shown that passive pump pulse shaping of the intracavity pump power can lead to potentially octave spanning gain, and have measured orders of magnitude improvement in conversion efficiency and and 3-fold improvement in phase matching bandwidth in 10 and 20 mm PPLNs. In this section, the future use, challenges and limitations will be discussed.
6.1 Future Uses of 800 nm OPA

The DOPA system described in this work successfully produced 7-fs, CEP stable pulses at the driver wavelength of 800 nm thus allowing continues coverage from the visible to the infrared with few-cycles, laser pulses generated by OPAs pumped by regenerative Ti:sapphire sources and seeded by white light continuum. Previously, a second-harmonic-pumped, non-collinear OPA (SH-OPA) covered the visible range, a fundamental wavelength pumped degenerate OPA (FF-OPA) covered the NIR range, while a fundamental wavelength pumped non-collinear OPA (FF-NOPA) covered the IR range. Only the spectral range around 800 nm, the driver wavelength, remained unfilled. The SH-DOPA, in this work, fills the gap in the spectrum at the driver wavelength. This source can naturally extend to many applications that employ Ti:sapphire pumped OPAs, and can be incorporated into existing optical systems. The source can provide up to several $\mu$J of energy for use in CEP stable or unstable dependent ultrafast pump/probe spectroscopy at 800 nm [ ]. Additionally the source, which has passive CEP stability, could be used as a seed source for a high power attosecond driver [ ].

A particularly unique application is the coherent combination of few-cycle sources from OPAs to produce single cycle or sub-cycle optical wave-forms [47]. A common Ti:sapphire pump source can be used to construct OPAs producing few cycles, CEP pulses across the full spectrum from visible to infrared can be constructed, allowing the possibility of wavelength multiplexing via coherently combining multiple OPA outputs. The common pump source and congruous design of the OPA stages greatly reduce the complexity of the synchronization methods. Manzoni, et. al. in [47] were successfully able to coherently combine a blue pumped NOPA and the blue pumped DOPA, presented in this work, in a system using a common Ti:sapphire pump source and common seed from white light continuum generation. The resulting spectrum was nearly octave spanning from 520 nm to 1000 nm and had a nearly single cycle sub 4-fs pulse duration. Further wavelength multiplexing by incorporating additional OPAs could generate even shorter, sub-wavelength optical wave-forms.
6.2 Technical Challenges and Limitations in C-OPCPA Systems

The basic operating principle of C-OPCPA is to achieve optimal nonlinear conversion, by treating parametric amplification as a loss element in an enhancement cavity. Power develops in the cavity until sufficient nonlinear drive is achieved such that the converted pump power in a single pass is replaced by pump power transmitted through the input/output coupler. Thus, intracavity pump reaches levels that result in a fractional conversion but yield large conversion compared to incident pump, and at impedance matching the intracavity loss equals the transmission, 100% conversion is attained and the cavity reflection vanishes.

The C-OPCPA system presented in this work was a proof-of-principle experiment demonstrating the key features of the system, namely, that enhancement can be used to compensate wave-vector mismatch. Although these results are encouraging, continued development of C-OPCPA sources needs to address the limitations and technical challenges observed in the first C-OPCPA measurements presented here. Namely, limitations due to group velocity walk-off, linear losses, parasitic nonlinear losses, spatial effects, damage threshold, and cavity locking dynamics need to be considered carefully in future implementations. We address some of these considerations below.

6.2.1 Linear losses

Linear losses can severely limit system performance by simply depleting pump power that would otherwise be used to drive the nonlinear process. This is particularly dramatic when the losses are a substantial fraction of the input/output coupler transmission, T. In the 10 mm C-OPCPA system, where a 5% input/output coupler was needed, a 1.5% loss value cut the maximum conversion by 25%. Additionally, excessive linear losses reduce bandwidth, since linear losses reduce the maximum enhancement a cavity can achieve and compensation of wave-vector mismatch (increasing bandwidth) requires enhancement. Thus, a reduction in enhancement from linear
losses corresponds to a reduction in bandwidth. In our case, the linear losses reduced the maximum enhancement from 78 to 46 (use of linear enhancement factor). Since \( g \sim \sqrt{\Gamma^2 - (\Delta k/2)^2} \) and \( \Gamma \sim I_p \), in order to maintain \( g \) as \( \Delta k \) increases, \( I_p \sim \sqrt{\Delta K} \). Since \( \Delta k \) is proportional to frequency/bandwidth in a GVD limited process, here, the loss in enhancement thus corresponds to a \( \sqrt{78/46} - 1 \) or 30\% loss in bandwidth. Thus, cavity losses must be kept to a minimum in order to preserved bandwidth performance particularly when low values of \( T \) are needed.

6.2.2 Group-Velocity Walk-off

Passive pulse shaping in C-OPCPA allows for the cavity to realize optimal gain profiles, but can only be realized with adequately chirped pulses satisfying the local approximation. Ross, et. al [59] advised that the pulse durations must be at least 3 times the pump-signal walk off time for the local approximation to be valid. This is required to avoid walk-off-induced distortions of the pulse profiles. For the system in this work, the minimum pulse duration is 1.5ps which correspond to a transform limited duration for a 2.7 nm signal pulse and a 1.2 nm pump pulse. In this work the pump pulse was 500 fs in 6 nm, and the signal pulse was 1.3 ps in 2.5 nm. A short pump pulse duration was needed in this work to reach an intracavity peak intensity in the range 1 - 2GW/cm² to drive the nonlinear conversion. Clearly, walk-off was a factor in these experiments presented here. Ideally, longer narrowband pump pulses should be used in a future design. Scaling the pump source in the current setup (5W, 500 fs, 80 MHz) for peak intensity, a 1.5ps, 15W source would be more suited to avoid walk-off and demonstrate pump pulse shaping for the cavity used in this setup.

Another factor for consideration is the chirp rate. It is possible that the chirp rate must be limited to avoid the interaction of spectral regions neighboring in time. A chirp rate of 20nm/ps was used by Ross [59] in addressing the local approximation; however, at the maximum rate of 160 nm/ps the distortion was not severe. Further study is required to clarify this point when considering octave spanning gain. In scaling the current system, an upper limit of chirp rate of 20nm/ps would require 50ps pulses with 500 W average power, while a 160 nm/ps would require 6.25 ps
pulses with 62.5 W average power.

6.2.3 Parasitic and Destabilizing Nonlinear Process

Parasitic nonlinear processes observed in this work, which are related to unwanted SPM broadened pump spectrum resonant with the cavity and destabilizing nonlinear processes including dispersion-induced depletion instabilities can interfere with system performance. These processes can be avoided by the insertion of a narrowband pump filter. An ideal filter would be a few nm wide with high transmission to avoid adding linear losses at the pump wavelength of the enhancement cavity, which would degrade system performance. Additionally negative $n_2$ materials could be tailored to counteract the influence of SPM [].

6.2.4 Cavity Coupling

The coupling factor is directly proportional to system performance, since uncoupled light is rejected and does not contribute to conversion. In this work more than 50% geometric coupling was achieved. At high intracavity power (> 13W), however, mode distortion was observed by the changing shape of second harmonic (green) pump light. Nonlinear processes in the crystal can add a phase curvature at the crystal location. SPM produces a phase that follows intensity, while parametric amplification produces a phase profile that increases with pump depletion and wave-vector mismatch. These processes could reduce the coupling factor at high levels of enhancement and can therefore reduce bandwidth, since bandwidth extension required enhancement. Additionally, the conversion process could distort the cavity mode at high levels of intracavity conversion and degrade coupling and limit maximum conversion. Coupling efficiency optimization, and possibly adaptive mode-matching schemes [], are important considerations for future C-OPCPA designs.
6.2.5 Crystal Damage Threshold

Although no crystal damage was observed during cavity operation, damage could be an issue for large bandwidth C-OPCPA systems with sufficient chirp so that the local approximation applies. In our simulations, the maximum pump intensities can be 2-3 times as large as the average peak intensity. In other OPA systems, the pump intensity is often set close to the damage threshold to generate the optimal conversion \([\cdot]\). In a C-OPCPA system, if the average intracavity intensity needs to be brought near the damage level, pulse shaping could lead to pulse damage. Damage considerations and crystal robustness \([\cdot]\) are additional factors for consideration.

6.3 Alternative Utilizations for C-OPCPA

The choice of pump and signal wavelength for the current C-OPCPA setup in this work was made based to the dispersion properties of PPLN. However, high average power pump sources near 1 \(\mu\text{m}\) are increasingly more available and can be exploited in OPA systems when ultrabroad bandwidths are less of a consideration. C-OPCPA systems, may have more impact in applications at pump wavelengths where suitably large average power sources are unavailable. In particular mid-infrared OPOs and OPAs based on GaAs, GaSe, CGA, ZGP, ZnSe and ZnS have been demonstrated with pump wavelengths ranging from 2-3\(\mu\text{m}\) \([43, 21, ?]\).
Appendix A

Experimental Design

As stated in previously, the system overall is comprised of a Yb- fiber CPA pump chain, Er- fiber signal source, and resonant enhancement cavity with an intracavity periodically poled lithium niobate (PPLN) crystal phase-matched for parametric amplification. The successful operation of the system relied on the careful design and construction of the laser/optical subsystems, and the electronic/optical synchronization control loops. Fiber laser sources and amplifiers were constructed due to their stable operation and good beam quality. Cavity coupling was maximized due to the need of high incident pump power, and optical components were chosen to minimize loss since linear loss degrades overall conversion, particularly when high values of enhancement are needed. Laser synchronization needed to be sufficiently tight to ensure proper temporal overlap of pump and signal. And finally, cavity locking, which due to the tandem nature of complex optical designs, essentially combines and magnifies the instabilities of the underlying subsystems and required an adequate locking margin. A high degree of robustness of the subsystems was essential to ensure stable operation of the overall C-OPCPA apparatus and without which the measurement and characterization of the new C-OPCPA dynamics would have been obscured. In this chapter we present a detailed description of the experimental apparatus and subsystems used for the C-OPCPA demonstration measurements.
A.1 Experimental Layout

The experimental layout is shown in Figure A-1, and an overview of the system is detailed in Chapter 4. The the signal source lasers and elements of the pump chain including pump source lasers, grating stretcher, and pre-amplifier where integrated on an enclosed 3 ft by 5 ft 2 inch thick on one optical bread board. The grating compressor and cavity where integrated on a second enclosed 3 ft by 5 ft 2 inch thick optical bread board. The main pump amplifier, IPG 10-W polarization maintained fiber amplifier, was mounted off the optical table. Both bread boards were enclosed with plexy glass and where placed on acoustical insulating foam (McMaster Carr) which consists of layers of lead and foam to insulate against air currents and vibrations ensuring a high degree of passive stability. Environmental control (temperature and humidity) of the lab was sufficient to ensure consistent operation of the enclosed subsytems.

The signal was delivered via single mode fiber (SMF28) to the C-OCPA setup for amplification. Similarly the stretched pre-amplified pump was delivered via fiber to the IPG amplifier which in turn was delivered by fiber via the IPG’s large mode area output cord to the grating compressor. Since both the signal source laser and enhancement cavity were locked to the pump master oscillator, coarse delay access was given via a delay-stage-mounted cavity mirror accessed through a long hex-driver for the signal oscillator and via a simple delay line for the enhancement cavity.

A.2 Pump and Signal Laser sources

Mode locked Yt- doped and Er- doped fiber lasers (YDFL, EDFL) were chosen due to the suitability of 1μm and 1.55μm as pump and signal wavelengths and the stability and good beam quality afforded by fiber lasers and fiber components. Schematic of the YDFL and EDFL are shown in Figure A-2. The YDFL serves as the master oscillator for the system to which the cavity and EDFL are locked. The repetition rates of the YDFL and EDFL were both matched to 78 MHz. The EDFL, however, has a piezo-mounted cavity mirror on a delay stage allowing fast/fine and coarse
Figure A-1: a) The Er- signal source and the Yt- seed and pump stretcher where integrated on an enclosed 3 ft by 5 ft optical bread board. b) The enhancement cavity, pump compressor, and Hänsch-Coulaud detection where integrated on another enclosed 3 ft by 5 ft optical bread board
Figure A-2: a) Pump seed laser: a 78 MHz Yb-fiber laser with Similariton mode locking. b) Signal laser: an 78 MHz Er-fiber laser with Soliton mode locking. The cavity is mounted in a sigma configuration to accommodate a piezo mounted mirror to control the repetition rate for synchronization of the signal to the pump.

cavity length adjustments.

While the pulse shaping mechanism for each laser is different and determined by the dispersion characteristics of fiber and dispersion elements in the laser cavities, the mode locking in both lasers was achieved via polarization additive pulse mode-locking (P-APM) whereby the saturable absorption mechanism is achieved through an intensity dependent rotation of the instantaneous polarization ellipse of an optical pulse. As shown in Figure A-3 taken from [17], the polarization ellipse of the peak of an intracavity optical pulse is rotated due to nonlinearity during propagation in the fiber, whereas the wings of the pulse, with reduced intensity are not affected. With a suitably oriented polarizer, the peak experiences less loss than the wings, reinforcing its shape. This mechanism can effectively reduce the loss of pulsed operation over continuous wave operation for the laser resulting in mode-locking. It acts as a fast saturable absorption mechanism and makes both fiber lasers self-starting. The origin of this mechanism arises from left and right circularly polarized components of a propagating elliptically polarized beam each experiencing intensity dependent propagation delays, which result in a pure rotation of the polarization ellipse as is analogously observed in the linear optics of optically active materials (birefringence).
The nonlinear rotation mechanism is instantaneous [9]. Thus, P-APM can be considered to arise from Kerr and birefringent nonlinearity occurring during propagation in optical fiber [17].

The design of the EDFL laser used in this study is shown in Figure A-2(b) and a partial list of components is shown in Table A.1. The laser operates in the Soliton mode-locking regime and is based off the the 200 MHz EDFL specified in [18]. The laser specified in that study, a 200 MHz Soliton mode locked EDFL, was used with a sufficient length of single mode fiber (SMF28) added to the laser cavity to achieve a 78MHz repetition rate. The additional fiber was added before the gain fiber to avoid access nonlinearity. Also, the free space portion was put in a $\sigma$-bend configuration. A 50 cm long highly doped gain fiber was used with cumulative anomalous group-velocity dispersion (GVD) of $-10,000 \text{ fs}^2$. The other fibers in the cavity are SMF with a cumulative GVD of $-50,000 \text{ fs}^2$. The collimator pigtail lengths were each 10 cm, and approximately 1.5 m of SMF28 was added to reduce the repetition rate. While the pulse shaping and stabilization mechanism is dominated by Soliton propagation in the fiber laser, P-APM initiates and contributes to the stability of the mode-locking. Half-wave plates (HWP) and quarter-wave plates (QWP) were thus positioned to adjust the nonlinear polarization state to find and optimize mode-locking. A free space isolator was used to ensure unidimensional lasing. The output spectrum is shown in Figure A-4 and the output power was 35 mW with 500 mW of pump power.

The $\sigma$-bend was added with the insertion of a QWP and piezo mounted mirror after the polarizing beam splitter (PBS). Rather then a linear free space section,
the sigma cavity allows the beam path to retrace its path for a short distance. The beam exiting the starting collimator passes through waveplates and through the PBS and a QWP. After reflecting off the piezo-mounted mirror and passing again through the QWP, instead of going straight through the PBS, the beam is reflected, since its polarization has rotated after accumulating 2 passes through the QWP, and continues toward the second collimator closing the loop. The utility of the σ-cavity is that a linear displacement of the piezo mounted mirror will not misalign the system and so this mirror can be used in both course and fine adjustments to match the repetition rate of the YDFL.

The YDFL shown in Figure A-2(a) follows the design in [44] except two gratings are used in a double pass geometry instead of four in a straight through configuration. A partial list of components is shown in Table A-2. In this design the collimated beam reflecting from the grating compressor is directed slightly downward, separating it from the incoming beam, toward a pick off mirror and directed through an isolator into a collimator to complete the loop. The fiber components all have normal dispersion and positive nonlinearity and thus don’t support solitons. Instead the YDFL operates in a Similariton regime [35] where self-similar propagation occurs in the normal dispersion fiber such that a parabolic pulse profile is accompanied with a monotonically increasing chirp. This is followed by both spectral gain narrowing in the gain fiber and compression in the grating compressor, which reset the pulse for self-similar evolution in the normal dispersion fiber. Because of the large pulse stretching involved, the peak intensity and nonlinear-phase-shift is lower when compared to Soliton evolution for the same pulse energy. This allows Similariton fiber lasers to attain higher pulse energies compared to Soliton lasers, avoiding both wave-breakup from high dispersion and nonlinearity and peak power limitations in P-APM, which arises in part to the saturation of the saturable loss due to the interferometric nature of the polarization rotation and also to pulse break up due to periodic perturbations [67, 31].

In the design of the YDFL for this setup, a 60 cm piece of Yb- doped gain fiber was used. The total length of single mode fiber from the passive fiber components in-
Figure A-4: a) Spectrum from the EDFL signal source. The full spectrum is shown in red. A filtered and amplified portion of the full spectrum shown in black is used as the signal for the C-OPCPA setup. b) Intensity autocorrelation of the signal for the C-OPCPA setup, the black curve in a)

including collimator pigtails, WDM, and couplers was 2.3 m. The fiber components and bulk optics all contribute a normal dispersion value to the cavity dispersion totaling 48,000 $fs^2$. The total normal dispersion is compensated in the grating compressor which has 600-lines-per-mm grating pair at 30° with a nominally 3.5 cm separation. The net dispersion is slightly positive at 3000 $fs^2$ [34]. QWPs and HWPs were positioned to initiate and stabilize mode-locking via the P-APM mechanism. A free space isolator was used to enforce the lasing direction. The output spectrum is shown in Figure A-4 with an output power of 50 mW pumped with 550 mW of pump power.

A.3 Pump Source Chain

The YDFL seed is amplified in a conventional chirped-pulse amplification system to provide pulses with up to 7-W average power and durations down to 500 fs to be used as the C-OPCPA pump. An overview of the system consisting of a grating stretcher, a home-built Yb-doped fiber pre-amplifier, a commercial 10-W fiber amplifier, and a grating compressor is shown in Figure A-6, where the output and input
Table A.1: Partial parts list for EDFL and YDFL

<table>
<thead>
<tr>
<th>Part</th>
<th>EDFL</th>
<th>YDFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain Fiber</td>
<td>Coractive ER 614</td>
<td>Coractive Yb164</td>
</tr>
<tr>
<td>Diode Laser Pump Source</td>
<td>JDSU 30-7602-660</td>
<td>JDSU 30-7602-660</td>
</tr>
<tr>
<td>Single Mode Fiber</td>
<td>SMF28</td>
<td>HI1060</td>
</tr>
<tr>
<td>Pigtail Collimator</td>
<td>OZ LPC-02-1550-6/125-S-1.3-3.9AS-60-X-3-1-SP</td>
<td>OFR CFS-T-2-1030</td>
</tr>
<tr>
<td>WDM</td>
<td>Lightel 980/1550</td>
<td>Lightel 980/1050</td>
</tr>
<tr>
<td>Free Space Isolator</td>
<td>OFR IO-3D 1550</td>
<td>OFR IO-3D 1030</td>
</tr>
<tr>
<td>Wave Plates</td>
<td>MeadowLark NQ-050-1550, NH-050-1550</td>
<td>MeadowLark NQ-050-1030, NH-050-1030</td>
</tr>
<tr>
<td>Polarization Beam Splitter</td>
<td>Newport 05FC16PB.9</td>
<td>Newport 05FC16PB.7</td>
</tr>
<tr>
<td>Gratings</td>
<td>Thorlabs 600 lines/mm</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure A-5: a) Spectrum from the EDFL signal source. The full spectrum is shown in red. A filtered and amplified portion of the full spectrum shown in black is used as the signal for the C-OPCPA setup. b) Intensity autocorrelation of the signal for the C-OPCPA setup, the black curve in a)
power levels of each stage are indicated. The amplification stages each needed sufficient seed intensity to suppress amplified spontaneous emission (ASE) which could degrade amplification by drawing power away from the main pump pulse train into an incompressible incoherent background radiation level. Additionally, the commercial 10-fiber amplifier used (IPG YAR-LP-SF) required a minimum input power of 10 mW to avoid damage \( \left[ \right] \). In the following paragraphs we characterize the stages comprising the pump source amplification chain.

The YDFL output needed a large stretching factor in order to avoid excessive nonlinearity in the high average power fiber amplifiers which can add a highly structured incompressible phase to the spectrum from SPM. Consequently we employed a grating stretcher/compressor pair to stretch and compress the YDFL by a factor of 1000. The grating stretcher design is shown in Figure A-7 \( [6] \) and consists of a pair of gratings with 1800 lines/mm between which is placed a telescope consisting of a pair of lenses with focal lengths of 50 cm. The lenses reverse the path followed by spectral components compared to a grating compressor allowing for a perfect cancellation of the phase form the complementary grating compressor if matching 1800 lines/mm gratings are used. However, the high efficiency gratings (\( > 96\% \) reflectivity) used in the compressor had 1752 lines/mm gratings, so the parameters specified in Table A.2 were used. The grating separation and angle for the the stretcher and compressor.
Figure A-7: Grating stretcher design. The use of lenses reverses the optical delays compared to a grating stretcher and thus a grating compressor in a standard configuration can be used to perfectly compress the output of the stretcher.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stretcher Design</th>
<th>Compressor Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident Angle</td>
<td>$\Theta = 65^0$</td>
<td>$\Theta = 58.8$</td>
</tr>
<tr>
<td>Diffracted Angle</td>
<td>$\Theta' = 71.3863^0$</td>
<td>$\Theta' = 71.6581^0$</td>
</tr>
<tr>
<td>Separation</td>
<td>$L = 20\text{cm}$</td>
<td>$L = 20.5\text{cm}$</td>
</tr>
<tr>
<td>Focal length</td>
<td>$f = 50\text{cm}$</td>
<td></td>
</tr>
<tr>
<td>GVD</td>
<td>$\beta_2 = -2.458146e + 007\text{fs}^2$</td>
<td>$\beta_2 = 2.458146e + 007\text{fs}^2$</td>
</tr>
<tr>
<td>TOD</td>
<td>$\beta_3 = 5.035982e + 008\text{fs}^3$</td>
<td>$\beta_3 = -5.049670e + 008\text{fs}^3$</td>
</tr>
<tr>
<td>FOD</td>
<td>$\beta_4 = -2.007293e + 010\text{fs}^4$</td>
<td>$\beta_4 = 2.016970e + 010\text{fs}^4$</td>
</tr>
</tbody>
</table>

Table A.2: Grating stretcher and compressor parameters and the resulting dispersion coefficients

were adjusted to optimize the compression. The values for second, third, and forth order dispersion for the stretcher and compressor are also listed in Table A.2. Figure A-8 shows the calculated pulse profile after stretching and after compression when a 200 fs Gaussian pulse is used. In the experiment, the grating compressor is also optimized to minimize the effects of the fiber from the fiber pre-AMP and the 10-W IPG amplifier.

Figure A-9 shows the spectrum at various intermediate stages of the pump chain in (a)-(c) and the autocorrelation of the final compressed output in (d). The spectrum of YDFL output is shown by the black curve in (a) which is directed to the stretcher. The limited aperture imposed by the 2 inch optics used in the stretcher selects a 7 nm portion of the YDFL output shown by the red curve in (a). After the stretcher
only 1.1 mW of pump power remains and thus a fiber pre-amplifier is used to attain 13 mW which is above the minimum required seed power to avoid damage in the IPG fiber amplifier. The pre-amplifier output is shown in (b). The final output after compression is shown in (c) for various setpoint levels, where the spectrum is shown to be free from distortions. As shown by the autocorrelation in (d), we achieve compression down to 500 fs with 7-W average power.

### A.4 Laser Synchronization

Tight control of the temporal overlap between pump and signal sources is necessary to ensure proper operation of the C-OPCPA system. Specifically, the timing jitter between pump and signal must be constrained within a small fraction of the pulse durations used in the setup to ensure stable operation of the C-OPCPA setup. Since the shortest pulse duration in the setup is 500 fs from the pump pulse, we set a target timing jitter to be within 10% of that value or 50 fs. This was achieved with the scheme depicted in Figure A-10 where the phase difference of the repetition rate was fed to a piezo-mounted mirror in the EDFL. The mirror (10 mm in diameter and 1 mm thick) was attached with crystal bond to a piezo (PI PL055.21) to a copper rod.
Figure A-9: a) Output spectrum of the YDFL (black). Spectrum after the grating stretcher (red). b) Spectrum after the home made fiber pre-amplifier. c) Spectrum of compressed output at various power levels. d) Intensity autocorrelation of the compressed pump.
Figure A-10: Schematic of synchronization electronics achieving 40-fs timing jitter. A synchronized time trace, photographed, is shown in the lower left corner.

(1 inch long 1 inch diameter).

In the scheme in Figure A-10, temporal overlap of the pulse trains is achieved by locking the phase difference of the fundamental repetition frequency at 78 MHz and of the 115th high order harmonic of the repetition frequencies corresponding to 9 GHz. The phase locked loop corresponding to the fundamental repetition frequency, the slow loop, is used to impart large delays between the pulse trains since a 2\pi phase shift at the fundamental corresponds to a full period of the repetition rate. For the phase lock loop at 9 GHz, the fast loop, however, a 2\pi phase shift corresponds to a delay which is only a small fraction of the full repetition period. The fast loop therefore has high temporal resolution but imparts ambiguity in the absolute delay between the pulse trains. A combination of both the fast and slow loop is used to achieve the required pulse delay control in a series of steps. First, the slow loop is used to overlap the pump and signal pulses. Then, while the slow loop is still activated, the fast loop is closed to achieve a tight lock with low timing jitter. While both loops are closed the resulting timing jitter has contributions from both the fast loop and also the more loosely locked slow loop. Thus, finally, the slow loop is opened and the lowest possible timing jitter is achieved. The fast loop will allow for fine adjustment of the delay if needed.
A portion of the output power of each laser is directed to a pair of 80 MHz photodiodes and a pair of 10 GHz photodiodes from which the phase error signals are derived. The photodiodes convert an optical pulse train to an rf pulse train from which the desired harmonic frequency component is accessed through appropriate bandpass filtering. Phase differences are detected by mixing the appropriate frequencies in a rf mixer and lowpass filter. The slow loop is fairly straightforward to construct and is comprised of two 80MHz EOS photonic GaAs photo diode, standard 7dBm frequency mixer, and standard rf components. The fast loop required more sensitive electronics and higher amplification. A detailed specification is shown in Figure ??.

10mW of power from each laser were coupled into two separate 10GHz amplified EOS GaAs photodiodes. Microwave cavity filters were used to filter out the high-order-harmonic repetition frequencies near 9GHz, which were subsequently amplified with 60dB in low noise, high-gain rf amplifiers. The outputs of the amplifiers were mixed in a high sensitivity phase detector and the error signal was derived from the low pass filtered output. The error signals from the slow and fast loops were combined in the summing junction of the loop-filter by BNC cables. The slow or fast loop was closed or opened by simply plugging in or removing a BNC cables. Delays were generated by controlling the DC offset on the loop filter. The offset on the loop filter controls the phase offset of the corresponding lock. Thus, when the slow loop was closed, delays on the order of the repetition period were imparted by the loop. However, when the fast loop was closed find control was possible.

The timing jitter was measured by looking at the voltage fluctuations in the locking error signal when just the fast loop was closed. Figure A-12 shows the unlocked and locked mixer output of the fast loop. Since the voltage output of a mixer is proportional to a phase, period oscillation in the mixer output corresponds to $1/9$GHz=0.11 ns. Normalizing away the scan rate, we can apply the following formula to calculate
the timing jitter.

\[
\begin{align*}
t_{jitter} & = V_{rms} \times \left(\frac{1}{dVolts/dt}\right) \times \left(\frac{2\pi \times \text{Cycles}}{\Delta T}\right) \times \left(\frac{1}{2\pi \times f_o}\right) \\
& = 1.26mV \times \left(\frac{\mu s}{0.1190V}\right) \times \left(\frac{2\pi \times 4}{114.7\mu s}\right) \times \left(\frac{1}{2\pi \times 9GHz}\right) \\
& = 41.0fs
\end{align*}
\] (A.1)

(A.2)

Thus, the locking electronics have a residual timing jitter of 41 fs which is sufficiently small for the C-OPCPA experiments.

Figure A-13 and A-14 shows the frequency response of the locked output and the open loop gain of the locking loop respectively. As shown in Figure A-13(a), with high proportional gain a resonance occurs at 7 kHz which is also noticeable in the time domain as shown in Figure A-13(b). By investigating the contributions to the loop gain we are able to determine the source of this ringing. The black curves in A-14(a) and (b) correspond to the displacement response of the piezo-mounted mirror and piezo driver in the EDFL laser cavity as measured in an interferometer. The piezo response rolls off at around 100 kHz, but is resonant-free only up to 10kHz. The loop filter has proportional and integral gain, and bandwidth of the loop filter exceeds 10 MHz. Over the bandwidth range in the figure, the loop filter contributes a $90^{\circ}$ phase shift and an attenuation of amplitude. From the phase response we can see that that $135^{\circ}$ of phase shift is accumulated around 10 KHz and is dominated.
Figure A-12: a) Unlocked mixer output between the 9GHz harmonic of pump and signal lasers (red). Mixer output when the loop is closed (black), i.e. locked. b) Time derivative of the unlocked mixer output in a).

by the piezo and piezo driver. The ring and locking bandwidth while limited by the piezo and piezo driver is adequate for the purposes of the C-OPCPA experiment.

A.5 Geometric Mode Matching into Optical Cavity

The coupling efficiency is an important parameter in C-OPCPA since the system performance scales with only the fraction of coupled pump light. Uncoupled pump light is completely rejected from the cavity and does not contribute to system performance. In Chapter 4 we described how the coupling efficiency was characterized. Clearly, a high initial coupling efficiency, requiring proper telescope design and optimal alignment, is important to utilized all available pump power. For the system in this study, the final realized coupling efficiency of 55% was measured by looking at the ratio of reflected power to incident power with an impedance matched intracavity
Figure A-13: a) RF spectrum of the locked mixer output. b) Locked mixer output.

Figure A-14: Open loop gain (a) and phase (b) of the pump/signal synchronization feedback loop.
loss. In principle, alignment can be optimized by minimizing the reflected power at impedance matching through the adjustment of the telescope lenses. This proved to be exceedingly difficult since moving the lenses any appreciable distance would break the lock. Additionally, for a given telescope design, the coupling depends on the telescope alignment and the cavity alignment. Thus adjustments of the cavity necessarily followed adjustments of the telescope. Repeatedly making adjustments that could only be evaluated when the cavity was locked proved difficult to optimize coupling. To avoid these difficulties we developed a method to achieve alignment with the cavity unlocked. In this section, we describe the cavity design and the techniques employed to optimize the coupling efficiency of the incident pump light into the lowest order cavity mode.

The enhancement cavity is in a ring configuration where the total path length, 384 cm, is chosen such that the free spectral range matches the repetition rate of the source lasers, 78 MHz, and consists of a pair of curved mirrors both having a radius of curvature of 50 cm and separated by 57.2 cm. Additional flat mirrors served as folding optics. The layout of the enhancement cavity shown is shown in Figure A-15. As is typical of cavities of this type, the section of the optical cavity between the short separation of the curved mirror, the focusing arm, has the location of the tight focus, and the section between the long separation of the curved mirrors, the collimated section, has the loose focus. A PPLN crystal is placed between the curved mirrors in the short section where the tight focus is located.

The cavity design was chosen such that the waist of the cavity focus was \( \omega_0 = 80 \mu m \) corresponding to a Rayleigh range of 40 mm. This length was chosen to match the initially anticipated crystal lengths of 20 mm or longer, although shorter crystals were ultimately used, and to avoid spatial shaping effects from combination of nonlinear conversion and diffraction. Figure A-16, show the calculated waists in the tangential and sagittal planes at the tight focus and loose focus as a function of the curved mirror separation. The angle of approach of a circulating cavity mode on the curved mirror which is responsible for the astigmatism was made as small as possible within the physical constraints of the crystal housing. As shown in the figure, the
cavity waist is a parabolic shaped function of the curved mirror separation. The value near the maximum cavity waist was chosen since this corresponds to a configuration with high stability. The slope is zero and so perturbations of the curved mirror separation would not influence the waist size. Additionally, the astigmatism is the weakest near the maximum.

A high geometric coupling efficiency factor was achieved by both starting with an optimized initial telescope design and by properly aligning the optical components to maximize coupling. A two lens telescope was constructed to maximize coupling of the incident pump beam after the compressor. The output beam of the IPG fiber amplifier had good beam quality and a waist of 1.16 mm. The beam quality was preserved after the compressor. After the compressor the incident pump beam is directed through the input/output coupler, then toward the first curved mirror, and after which the beam is brought to a focus in the nonlinear crystal. The function of the telescope is to relay the collimated incident pump beam such that it matches the cavity mode at the crystal. In terms of beam parameters, the telescope must ensure
Figure A-16: a) Cavity waist in the focusing section in the tangential (black) and segital (green) planes vs curved mirror separation. b) Cavity waist in the collimated section in the tangential (black) and segital (green) planes vs curved mirror separation.

that the size and position of the waist of the incident beam after reflecting off the first curved mirror matches that of the cavity mode.

Figure A-17 shows the distance to focus and the focused waist size after the the curved mirror as a function of $L_3$, the distance from the lens closest to the cavity to the output coupler. The telescope was designed such that the focal length of the first lens is $f_1 = 30$ cm and the second lens is $f_2 = 20$ cm and the lens separation is 49 cm. As indicated in the figure, for specific value of $L_3 = 46.2$ cm, the distance to focus, 27 cm, and the focus waist, 84.9$\mu$m, matches that of the cavity mode. In practice, achieving this alignment can be difficult, however, since the focused waist varies linearly with $L_3$ while the distance to the focus changes minimally around 27 cm over a large change in $L_3$, proper scanning of lense parameters can achieve optimal coupling into the lowest order cavity mode.

Proper alignment is achieved with the ability to quickly scan the lens positions and image the achieved cavity mode. Figure A-15 illustrates the rational behind the aliment procedure. Coupling into the cavity mode can be equivalently viewed as matching the collimated waist at its position in the cavity and at its position before the input/output coupler. The later position can be determined since backward propagating of the cavity mode from the first curved mirror through the input/output
Cavity Waist vs Distance To Focus Close Match with f
1=30cm, f2=20cm
for a Fixed Repetition Rate L1=26.5cm L2=48.945cm

(28.6, 85.7) 27.05
80
27.00 (46.1,27) 100
26.95
(27, 84.89
26.90
26.85
26.80
(20-
26.75.
60-
26.70 b) 50 25 26 27 28 29 26.65
10 10
200
Distance To Focus (cm) L3 (cm)

Figure A-17: a) Cavity waist in the tangential (black) and segital (green) planes vs curved mirror separation. b) Red curve: distance to focus after mode matching lenses, f1 and f2. Black curve: waist at the focus.

Figure A-18: a) Beam profile before the cavity at position 1 in Figure A-15. b) Beam profile at position 2 (collimated section) when the cavity is blocked. c) Beam profile at position 2 (collimated section) when the cavity is locked.

coupler will lead to a focus outside the cavity which is equivalent in terms of beam parameters to the collimated waist. The collimated waist inside the cavity can be imaged by appropriately placing a pellicle beamsplitter and relying the leakage beam toward a CCD camera. When the cavity is locked, the leakage beam from the pellical will give a direct measure of the cavity mode in the collimated arm. A CCD camera placed at the focus of this beam will directly image the cavity mode in the collimated arm.

Thus, by placing a CCD camera before the output/input coupler and after the peliccal, the optimal lens positions and alignment is realized when that the beam image at the CCD after the pelical matches when the cavity is locked and unlocked and
also matches the beam image at the CCD camera before the input/output coupler. To find the optimal configuration, the lens positions were systematically adjusted monitoring the beam images at the two CCD camera positions when the cavity was unlocked. Less frequently, the cavity would be aligned and locked and the CCD images would be compared. The utility of this method is that it allows extensive exploration and evaluation of the alignment condition while the cavity is unlocked.

Figure ? shows the measured beam images for the optimal case. Afterwards, the geometric mode matching was further characterized by using a beam profiler (micrometer mounted knife edge and power meter) to accurately measure the beam at the tight focus when the crystal was removed. The acquired profile is shown in Figure A-19 confirming the matching to the cavity mode size.

Figure A-19: Measured waist after incident beam reflects off the first curving using the knife edge technique vs. propagation distance
Bibliography


