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Strong Bandwidth and Efficiency Improvement by Passive Pulse Shaping in Cavity-Enhanced OPCPA

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Abstract: An enhancement cavity can optimally reshape the small-signal gain across the interacting pulses of a chirped-pulse parametric amplifier, increasing the gain bandwidth dramatically while simultaneously boosting the conversion efficiency.

OCIS codes: (320.7110) Ultrafast nonlinear optics; (190.4970) Parametric oscillators and amplifiers

In recent years, optical parametric chirped pulse amplification (OPCPA) has emerged as a competitive means for providing high-power, few-cycle laser sources in the near- and mid- infrared required for high-field laser science. OPCPA allows the direct transfer of energy from a high-power, narrow-band pump source to a broadband signal source via a nonlinear crystal, with typical conversion efficiencies in the 10-20% range for few-cycle signal pulses. The conversion efficiencies are limited by temporal and spatial variation in small-signal gain, due to the bell-shaped intensity profiles and time-varying wave-vector mismatch of the interacting pulses.

In this paper we show that in cavity-enhanced OPCPA (c-OPCPA), proposed earlier as a means for storing and recycling pump light in OPCPA [1], the enhancement cavity naturally reshapes the pump pulses for optimal conversion efficiency, even for signal bandwidths exceeding the phase-matching bandwidth of the nonlinear medium. Efficiency approaching the quantum limit can be achieved, as well as effective gain bandwidths exceeding the single-pass acceptance bandwidth by up to an order of magnitude. Below, we provide a first theoretical and numerical analysis of this phenomenon, with simulations predicting over 50% conversion efficiency with a signal pulse exceeding the phase-matching bandwidth of the nonlinear medium by ~4 times.

In c-OPCPA, a high-Q cavity at the pump wavelength contains a parametric amplification crystal and allows light at the signal and idler wavelengths to exit, unreflected. Thus, the device is an enhancement cavity for the pump with a nonlinear loss element, since parametric conversion depends on the stored pump intensity. Light unconverted from pump to signal and idler after a pass through the nonlinear crystal remains in the cavity. Thus, temporal regions with low conversion (due to locally low pump intensity and/or large wave-vector mismatch) exhibit lower loss and therefore develop a higher pump intensity that compensates for the initially low gain. Three conditions, if met, allow full conversion of the incident pump pulse energy to the chirped signal and idler. First, the pump energy entering the cavity must equal the signal plus idler energy exiting. This balance occurs naturally after an initial period of cavity loading. Second, perfect impedance matching must take place for all temporal coordinates of the interaction, *i.e.*, the total cavity loss, $L(t) = L_{linear} + L_{nl}(t)$, must equal the transmission coefficient of the cavity input coupler, T, for all t. This allows all incident pump light to enter the cavity. Successful impedance matching depends on the initial conditions of the interaction. Third, the cavity Q must be large enough that the stored pump pulse provides enough parametric gain for significant conversion of pump to signal and idler at all t.

We conducted simulations to analyze the behavior of c-OPCPA with matched pump, signal, and cavity repetition rates, with narrowband pump and broadband chirped seed pulses of equal duration. With each round-trip through the cavity, the intracavity pump electric field is modified in amplitude and phase by (1) depletion of the pump intensity and phase adjustment due to the OPA process, (2) pump phase adjustment by self-phase modulation in the nonlinear

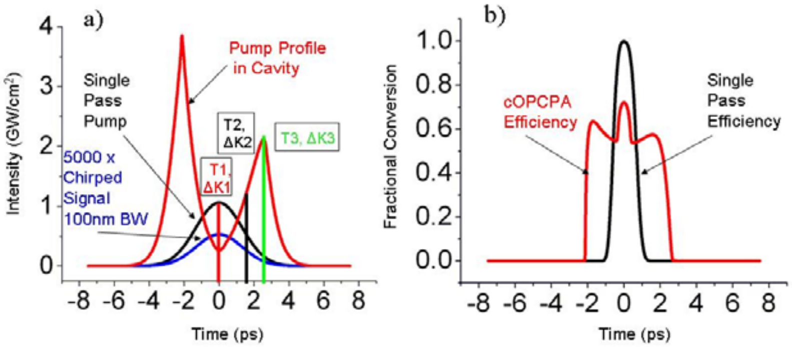

Fig. 1. a) Relevant intensity profiles. b) Conversion efficiency across the signal pulse for the c-OPCPA case (wider red curve) and the single pass case (narrower black curve).

crystal, (3) subtraction of fixed linear losses, and (4) combination of the intracavity field with the next pump pulse transmitted through the input coupler. The simulation is run until a steady-state intracavity pump power develops.

Figure 1 shows a simulation result for the case of 10-W, 3-ps, transform-limited pump pulses at 1037 nm and 1-mW, 3-ps, chirped signal pulses at 1550 nm with a bandwidth of 100 nm, which mix in a 5-mm PPLN crystal. The repetition rate is 80 MHz. These conditions allow enough gain for close-to-optimal single-pass OPCPA. In Fig. 1a the black and red curves are the incident and intracavity pump profiles, respectively. The blue curve is the chirped signal input, depicted here at 5000x its actual intensity for comparison on the scale of the pump pulses. Fig. 1b shows the fractional conversion of pump to signal as a function of time, with and without an enhancement cavity (red and black curves, respectively). In the single-pass case, gain narrowing limits the total conversion efficiency to 37%. The resulting bandwidth of the amplified signal is 38 nm at FWHM, slightly larger than the phase-matching bandwidth of the crystal, 24 nm, because of saturation. In comparison, the c-OPCPA case produces a signal pulse with 92-nm bandwidth and 52% conversion efficiency (Fig. 1a, red curve). At the center of the pump pulse (coordinate T1) where the wave-vector mismatch (ΔK1) is zero, the pump intensity of the incident pump pulse is already high enough for significant conversion of energy to the signal and the intracavity intensity builds up to an intensity slightly lower than that of the incident pulse. At coordinates further from the center (T2, T3), the intracavity intensity builds up more strongly, increasing to compensate for the lower small-signal gain due to the significant wave-vector mismatch, and the higher gain necessary for significant pump depletion due to the lower seed intensity. The above results were limited by impedance matching; the overall conversion efficiency can be increased to 71% by lowering the input signal power to 1 μW, allowing a more optimally impedance matched case.

As an illustration of the cavity's ability to adjust for different ratios of incident pump and seed intensity, Fig. 2a shows simulation results for quasi-monochromatic pump and signal pulses with varying incident seed power. Since gain is proportional to $\exp(I_p^{0.5})$, a small increase in intracavity intensity, requiring a small increase in enhancement, can increase the gain by an order of magnitude. In Fig. 2a, good conversion efficiency is obtained for input seed powers ranging 5 orders of magnitude. The highest conversion efficiency of 56% is achieved with ~1 μW of signal power, which allows the best impedance matching. The c-OPCPA technique, therefore, is quite flexible. The ability of the cavity to compensate for reduced seed power is ultimately limited by the amount of enhancement available from the cavity.

The ability of the cavity to allow high conversion efficiency even in the presence of significant Δk can be understood through the gain equation for the OPA process: $G(t) \approx 0.25\exp(2g(t)L) = 0.25\exp([\Gamma(t)^2 - (\Delta \mathrm{k}(t)/2)^2]^{0.5}L)$ [2]. As long as $\Delta k < 2\Gamma$, gain continues to be exponential. However, the maximum possible fractional conversion of pump power diminishes as Δk increases. Therefore, in a single-pass geometry, increased pump intensity cannot allow high conversion efficiency when Δk is large. In c-OPCPA, however, since the intracavity power is many times larger than the incident pump pulse power, only a small fraction of the intracavity power must be converted to signal and idler in order for the net conversion of incident pump energy to signal and idler to be large. For example, in the case of Fig. 1, above, only a few percent of the intracavity power at the wings of the pump pulse (where Δk is large) is converted to signal and idler, but the net conversion is large.

Fig. 2b summarizes simulations of c-OPCPA where the seed spectrum lies outside of the phase-matching bandwidth. In each case, the crystal is phase-matched at 1550 nm, with phase-matching bandwidth indicated by the dashed curve. Seed spectra of 10-nm bandwidth are launched at various center wavelengths. The results indicate that good conversion efficiency is possible over a range of wavelengths between 1.5 and 1.7 microns, covering a bandwidth an order of magnitude larger than the crystal phase-matching bandwidth.

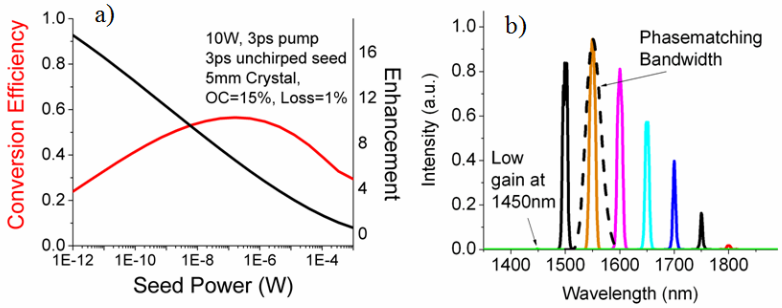

Fig. 2. a) Conversion efficiency and enhancement in c-OPCPA as the seed power is varied for an unchirped seed. b) Order-of-magnitude extension of the effective phase-matching bandwidth in c-OPCPA.

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