Guided wave optics in periodically poled KTP: quadratic nonlinearity and prospects for attosecond jitter characterization

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Mode locked lasers can inherently generate pulse trains with very low timing jitter—down to the attosecond (as) level or even lower [1–4]. As a result, they are excellent candidates for applications where timing accuracy is of extreme importance, such as high-speed analog-to-digital conversion and precise timing synchronization.

The low jitter characteristics of various kinds of mode locked lasers have been well documented [5–9]. Although the measured jitter has been very low in all of these studies, theoretical limits are still much lower, indicating that either there are unmodeled additional sources of noise, or the measurement techniques lack enough resolution. As a result, in order to verify the ultralow timing fluctuation property of mode locked lasers, and to exploit it for timing purposes, first and foremost, one has to be able to precisely evaluate their jitter performance.

A variety of methods have been devised for this purpose. Optical cross correlation is one of them [10]. Recently, it was experimentally demonstrated that a balanced optical cross correlator could show unprecedented precision in measuring the timing jitter of optical pulse trains [11]. In this scheme, the two pulses whose relative jitter is to be measured are projected onto orthogonal polarizations and then launched into a quadratic nonlinear crystal. Due to the group velocity mismatch, the two polarizations travel along the crystal at different speeds. A dichroic coating at the end facet discriminates the fundamental harmonic (FH) against the second harmonic (SH). The SH signal is measured by the first detector of a balanced receiver, and the reflected FH fields travel backwards and generate a new SH signal that will be measured by the second detector of the receiver. The length of the crystal is chosen to provide a one-pass delay between the two FH fields, approximately equal to their pulse widths. If the two pulses are initially arranged to overlap temporally with each other at the end facet, it will correspond to the zero crossing point on the differential output trace of the balanced detector, assuming no depletion of the FH pulses. The amplitude of the electrical signal from the balanced receiver is henceforth proportional to the temporal difference between the center of gravity of the pulses. In the presence of timing jitter, the varying electrical signal from the receiver provides the jitter statistics at high precision, since the balanced scheme by nature removes effects of amplitude fluctuations from the measured electrical signal.

The orthogonality of the polarizations (type II operation) is essential to ensure that the electrical signal will vanish whenever one of the signals ceases to exist, henceforth resulting in background-free operation. Moreover, large phase matching (PM) bandwidth is crucial to guarantee efficient second-harmonic generation (SHG) of ultrashort laser pulses. In this regard, periodically poled potassium titanyl phosphate (PPKTP) is the nonlinear material of choice, since it has a large type II PM bandwidth in the telecom C band (1530–1565 nm) at room temperature [12].

In Ref. [11], using bulk PPKTP, a SH conversion efficiency of 0.4% was obtained in the telecom band. The cross correlation method was later applied to measure the timing jitter of free running mode locked lasers down to a resolution of 470 attosecond (as) for an offset frequency range of 10 kHz–10 MHz [3]. However, obtaining resolutions at the attosecond level requires two orders of magnitude improvement in SH signal detection, which is currently not feasible with the typical tens of milliwatts FH power levels. As a result, we seek to use waveguides instead of bulk crystals to significantly improve the efficiency of the SHG process, in order to reach a resolution of a few attoseconds.

Although guided wave SHG has previously been demonstrated in KTP, those studies were either of type I [13] or in segmented waveguides [14]. To the best of our knowledge, this is the first time that...
tinuous waveguides in electric field poled KTP are utilized to demonstrate type II SHG. The SHG process in the nonsegmented devices studied in this Letter exhibits an overall pulse mode efficiency of 36%, a 90-fold improvement over previous bulk crystal results [11]. This will pave the way to few- and eventually subattosecond resolution in timing jitter measurements of optical pulse trains, as well as precision timing distribution in large scale facilities [15].

The quasi-phase-matching grating in KTP for type II SHG was designed for the optical telecom C band by electric field poling at a period of 113.64 μm. The grating period was chosen based on the best estimate of the combined bulk and modal indices. Since the orthogonal excitation fields are polarized along the y and z axes of the KTP crystal, the effective nonlinearity is $d_{eff} = (2/\pi)d_{24}$.

After the grating fabrication, the PM curve was observed in the S band (1460–1530 nm). Figure 1 shows the measured intensity profiles (after denoising) of FH TE, FH TM, and SH TE guided modes for 1505 nm wavelength, where the maximum SH light was generated. In analogy to planar lightwave circuit parlance, hereafter, we refer to the states of polarization as TE and TM for the respective electric fields parallel and perpendicular to the sample surface.

The measured SH power ($P_{SH}$) versus total (both polarizations) FH power ($P_{FH}$) at the output of the waveguide is depicted in Fig. 2; they are related by $P_{SH} = 0.029P_{FH}^2$, as determined by a quadratic fit to the measurement results [11]. This will pave the way to few- and eventually subattosecond resolution in timing jitter measurements of optical pulse trains, as well as precision timing distribution in large scale facilities [15].

To measure losses, we applied a Fabry–Perot fringe technique, as explained elsewhere [16,17]. At 1505 nm, this resulted in coefficients of electric field linear attenuation of $\alpha'_{1,2} = 0.39$ and 0.36 cm$^{-1}$ for the FH TE and FH TM modes, respectively. We approximated the SH TE loss by the FH TE value, meaning $\alpha''_3 = \alpha'_{1}$. The observed loss values are higher than expected (<1 dB/cm) and may indicate some fabrication defect in the particular sample under study, which will be addressed in future.

Type II guided mode SHG can be described by the coupled mode formulation of sum frequency generation ($\omega_3 = \omega_1 + \omega_2$) [18]:

$$dA_1/dx = -j\kappa_1 A_2 A_3^* \exp(-j2\Delta kx) - \alpha'_{1} A_1,$$  

$$dA_2/dx = -j\kappa_2 A_3 A_1^* \exp(-j2\Delta kx) - \alpha'_{2} A_2,$$  

$$dA_3/dx = -j\kappa_3 A_1 A_2^* \exp(+j2\Delta kx) - \alpha'_{3} A_3,$$  

in which $m=1$, $m=2$, and $m=3$ are the respective indices of the FH TE, FH TM, and SH TE guided modes—Figs. 1(a)–1(c), respectively. The relation $\omega_3/2 = \omega_1 = \omega_2 = \omega$ holds between angular frequencies, and $\Delta k$ is the phase mismatch. $A_m$ are field amplitudes in units of W$^{1/2}$.

From Fig. 1, the normalized electric field mode profiles of the waveguides, $E_m(y,z)$, expressed in units of $\Omega^{1/2}$ m$^{-1}$, that satisfy

$$(n_m/2)\sqrt{\varepsilon_0/\mu_0} \int \int |E_m(y,z)|^2 dydz = 1$$

can be extracted. Due to the weakly guided nature of the modes, the effective indices of the guided modes, $n_m$, are approximately equal to the bulk material values.

The extraction of the nonlinear coupling coefficients $\kappa_m$, defined by

$$\kappa_1 = \kappa_2 = (\omega \varepsilon_0 d_{eff}/2) \int \int E_1^* E_2 E_3 dydz,$$  

$$\kappa_3 = \omega \varepsilon_0 d_{eff} \int \int E_1 E_2^* E_3 dydz,$$  

and expressed in units of W$^{-1/2}$ m$^{-1}$, follows from the measured mode profiles (Fig. 1), in conjunction with the bulk material nonlinear coefficient $d_{24} = 3.6$ pm/V [19]. This results in $\kappa_{1,2} = 0.13$ and $\kappa_3 = 0.27$ W$^{-1/2}$ cm$^{-1}$. At other wavelengths, values as low as 1.9 and 1.4 pm/V are also reported for $d_{24}$ [20].

By solving Eqs. (1)–(3) and trying to create a theoretical curve that overlaps with the measurement results of Fig. 2, one can then estimate how much the nonlinear coefficient is modified, if any. We obtain good agreement between theory and experiment by increasing the value of $d_{24}$ by 3%. This is well within
the uncertainties in our calculations, suggesting that most likely the nonlinear characteristics of the material are not altered by the fabrication of nonsegmented waveguides. To evaluate the timing precision of the optical cross correlator that can be built based on the PPKTP waveguide presented here, we consider the photodetection process when the device operates in the pulsed mode.

For the SH detection process, we designed a balanced transimpedance amplifier based photoreceiver. The transimpedance amplifier has a transimpedance gain of 2 MHz over the DC band–23 MHz. The bandwidth enables complete noise measurement—up to Nyquist frequency—of mode locked lasers with repetition rates as high as 44 MHz. The Simulation Program with Integrated Circuit Emphasis (SPICE) simulations of our designed TIA show an integrated output referred rms voltage noise of \( \approx 19 \text{ mV} \) over the frequency range of 1 Hz–23 MHz.

As an example, let us consider, an erbium-doped fiber laser that generates a train of \( \tau = 200 \text{ fs} \) optical pulses at a repetition rate of \( f_r = 44 \text{ MHz} \), with an average power of 15 mW. By conservative measures, if only one third of the light can be coupled in, there will still be \( P_{aw} = 5 \text{ mW} \) of excited FH in the waveguide. At 1560 nm wavelength, the group indices are \( n_{g1,2} = 1.7505 \) and 1.7926. For the aforementioned erbium-doped fiber laser pulse duration, a length of \( L = 2 \text{ mm} \) is needed for the two orthogonally polarized pulses to walk through each other, as described above. If Eqs. (1)–(3) are solved for the 2 mm length using the previously explained experimental parameters, a normalized conversion efficiency of \( \eta_0 = 1.6 \% / (W \text{ cm}^2) \) will be obtained. For the above laser parameters, this translates to \( \eta = \eta_0 L^2 P_{aw} / (f_r) = 36\% \) conversion efficiency in the pulsed operating mode, which is 90 times larger than the previous bulk results [11]. There, a zero crossing slope of \( \approx 25 \text{ V/ps} \) was measured. As a result, the 2 mm long guided wave device will have an estimated slope of larger than 2.25 V/fs. Dividing the 19 mV output noise of the TIA by the 2.25 V/fs slope, the timing resolution of the apparatus is estimated to be \( \approx 8 \text{ as} \).

It is worth mentioning that by setting the loss coefficients to zero and then solving Eqs. (1)–(3), one will obtain a maximum attainable normalized conversion efficiency of \( \eta_{\text{max}} = 1.9 \% / (W \text{ cm}^2) \). This is only 20% higher than the 1.6%/(W cm²) reported above, indicating that due to the short 2 mm length of the required crystal for the cross correlator, the effect of losses is not significant, and the device is nearly optimal for the current structure of waveguide mode profiles.

In conclusion, continuous (nonsegmented) waveguides in electric field periodically poled KTP is used for what we believe to be the first time to demonstrate type II second harmonic generation in the optical telecom S band. The next phase will include slight modification of the period of the electric field poling to shift the peak of the phase matching curve to the telecom C band. Also, by modifying the structure of the guided modes, it is possible to increase the mode overlaps, henceforth obtaining the same nonlinear performance at even lower power levels. The combination of the guided wave PPKTP SH generation studied here and the photoreceiver that is currently under development in our laboratory, will realize an integrated device for precision measurement of the timing jitter of optical pulse trains at the attosecond level. This will be instrumental not only in fundamental studies such as noise characterization of lasers, but also in diverse applications, including but not limited to optical synchronization and timing distribution, photonic analog-to-digital conversion, and extraction of precision microwave signals from mode locked lasers.

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References