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Engineering of effective quadratic and cubic nonlinearities in two-period QPM gratings

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Quasi-phase-matching (QPM) by electric-field poling in ferroelectric materials, such as LiNbO₃, is promising due to the possibilities of engineering the photolithographic mask, and thus the QPM grating, without also generating a linear grating. A proper design of the longitudinal grating structure allows for distortion free temporal pulse compression, so that the QPM grating can be used for beam-tailoring, broad-band SHG and soliton steering.

At lowest order the effect of QPM is to eliminate the phase mismatch and average the quadratic (or cubic) nonlinearity, resulting in an effective $\chi^{(2)}$ nonlinearity experienced by the slowly varying (on the scale of the coherence length) averaged field, which is reduced by a factor of $\pi/2$. At the next order QPM induces cubic nonlinear self- and cross-phase-modulation, an equation for the averaged field. This induced nonlinearity is a result of non-phase-matched coupling between average field and higher order modes of a fundamentally different nature than the intrinsic material Kerr nonlinearity. So far it was shown how the induced $\chi^{(2)}$ nonlinearity affects the amplitude and phase modulation of cw waves, and still supporting solitons. However, in conventional materials with single-period QPM the cubic corrections were small. Here we show analytically and verify numerically how the average $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities can be engineered by modulating the QPM grating, such as, e.g., to make their effects equally strong.

We consider a linearly polarized electric field $\mathbf{E}(z,t) = \mathbf{E}_0 \exp[i(k_0 z + \omega t)] + \mathbf{E}_2(z) \exp[i(k_2 z + \omega_2 t)] + \mathbf{E}_0 \exp[i(k_0^* z + \omega_0 - \omega_2 t)]$, propagating in a lossless QPM $\chi^{(3)}$ medium under conditions for type I SHG. Then the dynamical equations take the form

$$\frac{dE_0}{dz} + i \chi_0 \omega_0 E_0 E_0^* e^{-i\phi} = 0,$$

$$\frac{dE_0}{dz} + i \chi_1 \omega_1 E_0 E_0^* e^{-i\phi} = 0,$$

where $\chi_0 = c_{33} \alpha_0 g_{11}(\lambda_0)$, $E_0(z)$ is the slowly varying amplitude of the fundamental wave (FW) with frequency $\omega_0$, refractive index $n_0$, and wavevector $k_0$, and $E_2(z)$ is the second harmonic (SH) with refractive index $n_2$ and wavevector $k_2(z)$.

\[ i \frac{dE_0}{dz} + \eta_0 \omega_0^2 E_0 E_0^* + \eta_2 \omega_2 E_2 E_2^* - 2\gamma_0 |E_2|^2 E_2^* = 0, \]

\[ i \frac{dE_0}{dz} + \eta_0 \omega_0^2 E_0 E_0^* - 2\gamma_0 |E_2|^2 E_2^* = 0, \]

where $\eta_0 = -\eta_2 = \Delta k = n_2 - n_0$, $\Delta k < n_2$, is the effective mismatch for matching to the SH peak next to the FW peak, as illustrated in the close-up in Fig. 1 (right). The nonlinearity coefficients are given by

$$\eta_2 = \chi_3 (f_1 (z) + \pi/2),$$

$$\gamma_0 = \chi_3 (f_2 (z) - 2\Delta k_0 z) + 4\chi_0 (f_3 (z) + \pi/2),$$

with frequency $\omega_2$, refractive indices $n_2$, and wavevectors $k_2(z)$ and $E_2(z)$.

Following the approach of we obtain the final equations for the average fields, which includes the induced cubic nonlinear term:

\[ i \frac{dE_0}{dz} + \eta_0 \omega_0^2 E_0 E_0^* + \eta_2 \omega_2 E_2 E_2^* - 2\gamma_0 |E_2|^2 E_2^* = 0, \]

\[ i \frac{dE_0}{dz} + \eta_0 \omega_0^2 E_0 E_0^* - 2\gamma_0 |E_2|^2 E_2^* = 0, \]

\[ \eta_2 = \chi_3 (f_1 (z) + \pi/2), \]

\[ \gamma_0 = \chi_3 (f_2 (z) - 2\Delta k_0 z) + 4\chi_0 (f_3 (z) + \pi/2), \]

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CTuA15

Generation of <4 cm⁻¹ transform-limited pulses in IR by difference frequency mixing of stretched pulses

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In our previous paper we have presented the theoretical background and experimental verification of narrow-bandwidth pulse generation via difference frequency mixing. The tunability of generated narrow-bandwidth pulses was restricted to rather narrow wavelength range in the proximity of 1 µm, which is not of great practical interest.

In the present contribution we report on generation of narrow-bandwidth pulses within 3–5 µm wavelength region that can be applied to highly selective time-resolved vibrational spectroscopy.

As a pump source we used a picosecond Ti:Sapphire laser system delivering 800-nm wavelength pulses with duration of 1.8 ps and energy of 1.5 mJ. A part of the laser output was frequency doubled and used to pump an optical parametric generator-amplifier (OPA/A), which produced ~1.3-ps pulses in 470–2600-nm wavelength range. The idler wave of the OPA/A was used as a seed for subsequent difference frequency (DF) mixing/parametric amplification pumped by 800-nm pulses.

In the first series of experiments we generated the difference frequency in a conventional way. Laser and seed pulses were mixed in a 7-mm-thick KTA crystal without stretching. The DF pulses that were produced had a bandwidth of 12.3 cm⁻¹ (Fig. 1). We measured duration of amplified seed pulse to be 1.2 ps (Fig. 2). Computer simulation of the process has shown that both DF pulse and amplified seed have similar duration when group velocity mismatch is as small as in our case. With this assumption we estimate the time-bandwidth product of the IR pulses to be ~0.43, which is very close to the time-bandwidth product of transform-limited Gaussian pulses. We measured the IR pulse energy of 70 µJ at 3 µm and 25 µJ at 5 µm, with pump pulse energy of 1.2 mJ.

In the second set of experiments, pump and seed pulses were stretched in two separate gratings to ~8 ps duration. The stretcher for the pump pulses was fixed whereas that for the seed had adjustable grating incidence angle, stretcher length and automatic delay compensation. The pulses were mixed in a 15-mm-thick KTA crystal. The bandwidth of generated DF pulse was a function of the seed stretcher length and had a minimum at the point where the chirp of pump and seed was calculated to be equal. The narrowest DF bandwidth of 3 cm⁻¹ was observed at 3 µm. The pulses at longer wavelengths had a bandwidth of ~4 cm⁻¹ (Fig. 1). Duration of the amplified seed pulse was measured to be 4.6 ps (Fig. 2). Again, according to computer simulation the amplified seed and IR pulses have nearly the same duration. With this assumption we again estimate the time-bandwidth product of the IR pulses to be 0.4–0.5. With the pump energy at the THG stage of 550 µJ the energy of generated IR pulse ranged from 3 µJ at 5 µm to 35 µJ at 3 µm.

In conclusion, we have generated transform-limited pulses of <4 cm⁻¹ bandwidth, tunable in the range of 3–5 µm. Further extension of the tuning range requires pump wavelengths longer than 800 nm since existing IR transparent crystals exhibit one- and/or two-photon absorption, which results not only in energy loss but also in heavy thermal lensing.

CTuA15 Fig. 1. Spectrum profiles of conventional (squares) and narrow-bandwidth (circles) difference frequency pulses.

CTuA15 Fig. 2. Autocorrelation traces of amplified idler pulses in conventional (squares) and narrow-bandwidth (circles) difference frequency mixing.

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Thermally stable third harmonic generation using type I LBO

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The third-harmonic light sources of Nd:YAG/ Yb:Lasers have begun to be utilized for drilling via holes in printed circuit boards according to the progress of high-density fabrication. Fast rise-time in burst mode operation and high pulse energy stability are required for the light source in this industrial use. Because of simple construction and less optical component requirement, type 1 STG-type 2 THG(LBO) scheme has often been used for the third-harmonic generation. However it has unstable rise-time property in high average power operation.

CTuA16 Fig. 1. The fundamental and THG output waveform for type 2 THG LBO. Crystal temperature is 80, 50, and 34°C, respectively.