Energy exchange between orthogonally polarized waves by cascaded quasi-phase-matched processes.

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ABSTRACT

By identifying appropriate quasi-phase-matching (QPM) conditions in z-cut congruent lithium niobate, we demonstrate simultaneous QPM of type-I (ooe) and higher order type-0 (eee) second-harmonic-generation, which share a common second harmonic wave. We demonstrate this experimentally at 1064nm, and show that cascading between these processes occurs. The cascading can result in energy exchange between the cross-polarized fundamentals, indicative of an equivalent 3rd order process. The nonlinear phase shifts and transfer functions resulting from this cascading are explored numerically.
Keywords: Nonlinear Optics, Lithium Niobate

1. INTRODUCTION

Cascaded second-order optical nonlinearities have been of interest for some time as they have the potential to provide the nonlinear phase shifts and transfer functions suitable for optical switching and processing. Implementing these processes in ferroelectric optical materials such as lithium niobate and KTP allows tailoring of the phase matching conditions by domain engineering. The introduction of waveguides by well established techniques such as proton exchange and metal indiffusion is also readily achieved in these materials. In this presentation we demonstrate a new cascaded process realized by simultaneously phase-matching two wavelength equivalent, yet distinct second harmonic processes in periodically poled lithium niobate. This results in energy exchange between crossed polarized fundamental fields which are coupled by a common second harmonic, and we demonstrate this experimentally. Simultaneous, and almost simultaneous (offset) phase matching, also results in some new nonlinear phase-shift dynamics which are explored numerically.

2. TWO COLOUR CASCADING

Two colour cascading refers to a class of parametric processes which involve interactions between two wavelengths, namely a fundamental field and its second harmonic[1]. Interest in these processes was sparked by De Salvo *et al*[2] who demonstrated that an effective nonlinear refractive index, fundamentally a 3rd order phenomenon, arises from the cascading of fields in an efficient but slightly phase-mismatched second order process. In birefringent crystals type-I (fundamental components orthogonal to the second harmonic) and type-II (one fundamental component orthogonal and one co-polarized with the second harmonic) phase-matchings are utilized, with type-II processes being of key interest in optical processing as the phase-shifting and switching behaviour can be controlled by the separable orthogonal fundamentals[3,4]. In domain engineered ferroelectrics such as periodically poled lithium niobate (PPLN), type-0 (all fields are co-polarized) as well as type-I and type-II quasi-phase-matchings can be realized, and the phase-matching can actually be tailored via domain engineering to produce optimal nonlinear phase-shifts[5]. With the right conditions cascading between two collinear and wavelength equivalent, yet distinct phase-matched processes can be realized in periodically poled lithium niobate. This is achieved by fabricating a poling period which satisfies both type-I QPM on the lithium niobate d_{31} nonlinear coefficient and a higher order type-0 QPM on the lithium niobate d_{33} nonlinear

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coefficient. The poling period required for second harmonic generation (SHG) is found from the quasi -phase-matching condition,

$$\Delta k = k^{2\omega} - 2k^{\omega} - G_m = 0 \tag{1}$$

where $k^{\omega,2\omega} = \frac{n^{\omega,2\omega}\omega,2\omega}{c} = \frac{2\pi n}{\lambda}$ are the wave-numbers for the participating fields, and G_m is the contribution from the QPM structure which for periodic poling is the m^{th} order inverse lattice vector of the period Λ,

$G_m = \frac{2\pi m}{\Lambda}$. Rearranging gives us the required QPM periods,

$$\Lambda = \frac{m\lambda}{2(n^{2\omega} - n^{\omega})} \tag{2}$$

For periodic inversions with a 50% duty cycle the odd QPM orders (*m=1,3,5,…*) provide nonzero nonlinear gain. In lithium niobate the type-0 case has all fields polarized on the extraordinary refractive index (eee), whereas the type-I case has the fundamental field polarized in the ordinary refractive index (ooe). Temperature dependant Sellmeier relations are used to calculate these refractive indices. Fig. 1 shows the required poling periods for type-I SHG and the 5^{th} and 7^{th} order periods for type-0 SHG as a function of temperature at 1064nm (Sellmeier relations taken from ref. 6). It is seen that quasi-phase-matching of both the type-I process and the 5^{th} order type-0 SHG can be achieved with a period of 32.2µm at a temperature of ~515K, as well as the type-I process and the 7^{th} order type-0 with a period of 45.75µm and at a temperature of ~452K.

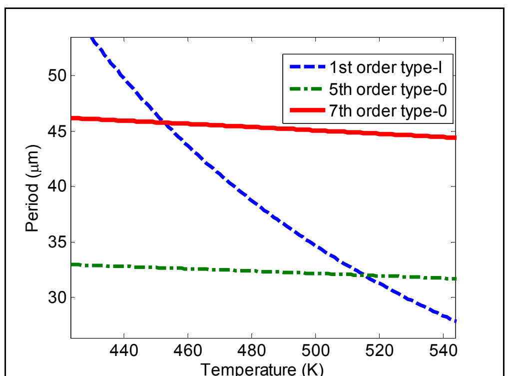

Fig. 1. QPM periods for 1^{st} order type-I and 5^{th} and 7^{th} order type-0 SHG for a 1064 nm fundamental wavelength in lithium niobate as a function of crystal temperature.

In our case we have chosen the 7^{th} order type-0 phase matching as the 45.75µm could be made more accurately and also the nonlinearities of the two processes are almost equivalent, given that in lithium niobate d_{31}=4.7 pm/V d_{33}=30 pm/V,

$$d_Q = \frac{2d}{m\pi} \rightarrow \frac{2d_{31}}{\pi} \approx \frac{2d_{33}}{7\pi} \tag{3}$$

The coupled field equations for simultaneous type-0 and type-I SHG, adopting the Cartesian coordinates of the crystal axes (propagation in the *x* direction with polarizations in the *y* and *z* directions), may be written as,

$$\frac{dE_y^{\omega}}{dx} = -i\sigma_1 E_z^{2\omega} E_y^{\omega*} \exp\left(-i\Delta k_I x\right) \tag{4}$$

$$\frac{dE_z^{\omega}}{dx} = -i\sigma_2 E_z^{2\omega} E_z^{\omega*} \exp\left(-i\Delta k_0 x\right) \tag{5}$$

$$\frac{dE_z^{2\omega}}{dx} = -i\sigma_3 (E_y^{\omega})^2 \exp\left(i\Delta k_I x\right) - i\sigma_4 (E_z^{\omega})^2 \exp\left(i\Delta k_0 x\right) \tag{6}$$

Here the vectors *E* are the electric fields propagating in the *x*-direction whose superscript denote the optical frequency and the subscript denote the polarization with respect to the crystal axes. Δk_0 and Δk_I are the residual phase-mismatches in the system for the type-0 and type-I processes respectively, given as $\Delta k_{0,1} = k_e^{2\omega} - 2k_{e,o}^{\omega} - G_{m=7,1}$. The nonlinear parameters σ are given by:

$$\sigma_1 = \sigma_3 = \frac{d_{31}}{\lambda n_o} \text{ and } \sigma_2 = \sigma_4 = \frac{d_{33}}{7\lambda n_e}$$

where n_o and n_e are the ordinary and extraordinary refractive indices of lithium niobate at the fundamental wavelength λ. Eq. 6 (the second harmonic field) can be integrated analytically if depletion is ignored. However numerical integration of all 3 coupled equations is necessary to simulate the cascading between the three fields. Numerical simulations were carried out for the case of temperature detuning. One of the features of the simultaneous type-0 and type-I SHG process in PPLN is that the type-I process has a much narrower temperature acceptance bandwidth than the type-0. This allows for interplay between the two processes across the temperature detuning bandwidth. The relative phase of the two fundamental fields is also an important factor in how the two processes interact. Fig. 2 shows the temperature detuning behaviour for simultaneous SHG from equal type-I and type-0 processes in PPLN. The simulations were performed for a crystal length of 100 domains (4.5mm) and the amplitudes of the input fundamentals were chosen to produce 30% depletion at the phase-matching temperature.

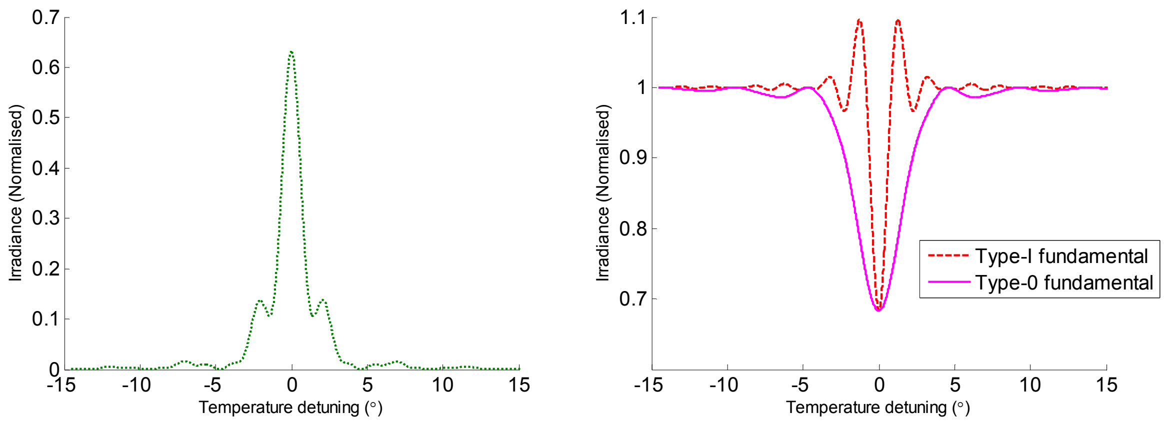

Fig. 2. Temperature detuning curves for SHG, for simultaneously phase-matched type-0 and type-I SHG with in-phase fundamentals in 4.5 mm long PPLN crystal. Left: SHG detuning. Right: Fundamental detuning.

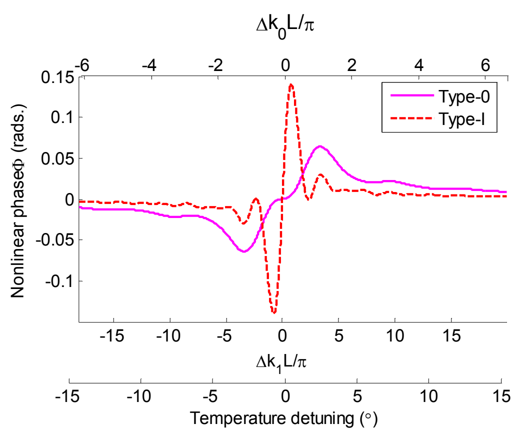

Fig 3. Nonlinear phase-shifts of simultaneously phase-matched type-0 and type-I processes in PPLN.

In the plots on the left of Fig. 2, we see the case for in-phase fundamentals. The detuning curve for the SH is representative of the superposition of the two individual processes with differing bandwidths, which would individually have *sinc*^{2} detuning functions. For the narrower-temperature-bandwidth, type-I fundamental, energy exchange from the SH field produced by the broader-band type-0 phase matching can be seen. This is accompanied by an enhanced nonlinear phase-shift of the type-I fundamental at detunings of $\Delta k_1 L \approx \pm\pi$, as shown in Fig. 3. This is due to a larger SH field being available, produced by the broader-band type-0 SHG, compared to that of a single SHG process. Introduction of a π/2 phase-shift between the two fundamentals (circular/elliptical input polarization) can inducing parametric back conversion for the case where the magnitudes of the fundamental components are different. In this case the stronger fundamental prevails and energy from the strong fundamental couples into the weaker fundamental via the second harmonic field. This is facilitated by the weaker fundamental being in-phase with the SH field allowing for difference frequency mixing. The progression of this cascading at simultaneous phase-matching ($\Delta k=0$) is shown in Fig 4. The simulated results are presented which a total input power normalized to a value of '2' being shared in various ratios between the type-0 (*e*) and type-I (*o*) components. The simulations have been presented in this fashion so as to correspond to our experimental case, where the ratio of power in the orthogonal polarization components was controlled by rotating a half-wave-plate with respect the crystal axes. For a pure *o* or *e* wave, as in the top left of Fig. 4, the usual SHG curves are seen. However when we have contributions from both the *o* and *e* polarizations, we see cascading from the strong fundamental to the weak fundamental via the second harmonic. When equivalent magnitudes of *o* and *e* components are launched the coupling remains static as the π/2 phase-shift between the two fields results in suppression of any SHG.

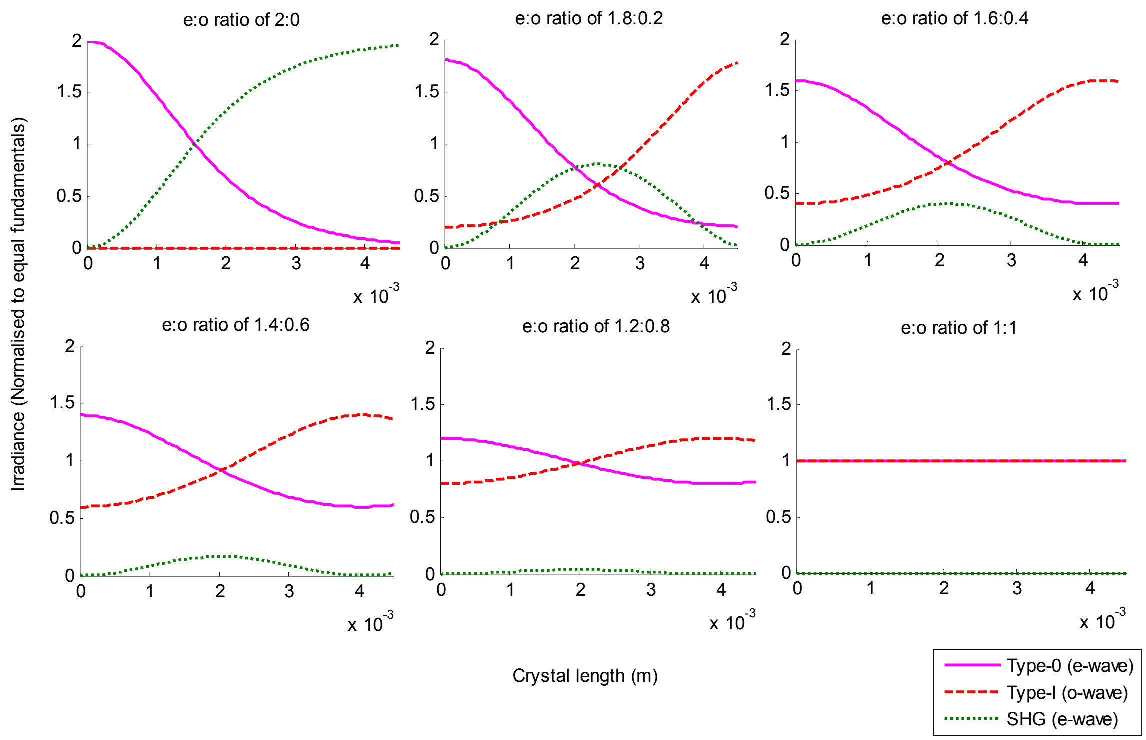

Fig 4. Simultaneously phase matched type-0 and type-I SHG with π/2 phase-shifted fundamental components. The process is shown with various ratios of the type-0: type-I fundamental input powers. Cascading is observed when energy from the dominant e-wave fundamental field couples to the weaker o-wave fundamental field via the second-harmonic.

3. CRYSTAL FABRICATION

The PPLN crystals used for these experiments were fabrication using laser micromachined topographical electrodes as first reported by Reich *et al*[7]. The machining was performed with a Spectra-Physics Hurricane system, producing 100fs pulses at 800nm centre wavelength. The pulse energy used was 3μJ and focusing was performed using a 10x objective. Aerotech stages were used to position and translate the sample. Once a periodic array of grooves were machined in the +z crystal surface high voltage poling was performed in the usual fashion, a liquid poling cell with a programmable voltage supply as demonstrated by Myers[8]. The laser machined grooves provide the isopotential required for domain nucleation and growth, as illustrated by the finite element simulation of Laplace's equation shown in Fig. 5. Fig 6 shows the etched –z face of 45.75μm period PPLN crystal fabricated using this technique.

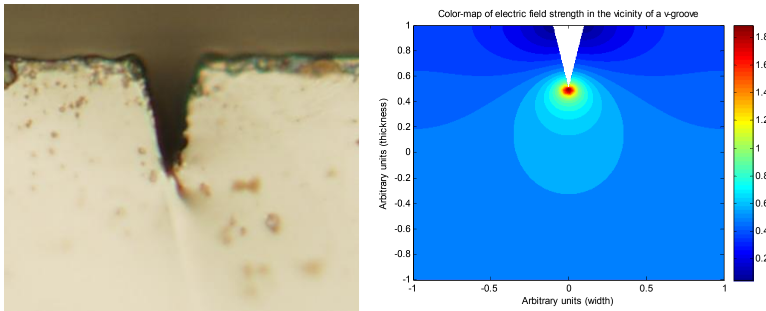

Fig. 5. Left: Crossection of laser machined V-groove in lithium niobate. Right FEM simulation of Laplace's equation for a V-groove geometry. The colourmap indicate the electric field strength in the neighbour hood of a groove, where the top surface is held at the poling potential.

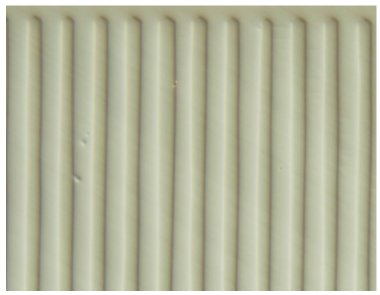

Fig 6. Domains on the –z face of a 45.75 µm period PPLN crystals, revealed by soft etching and phase-contrast microscopy.

4. EXPERIMENT-RESULTS

The experimental measurements where carried out using a lab built Q-switched Nd:YVO_4 laser providing ~1kW of peak power, as shown in fig. 7. Waveplates were used to control the input polarization and a Glan cube was used to resolve the output polarization. The temperature tuning was automated using a Eurotherm controlled oven for the PPLN crystal.

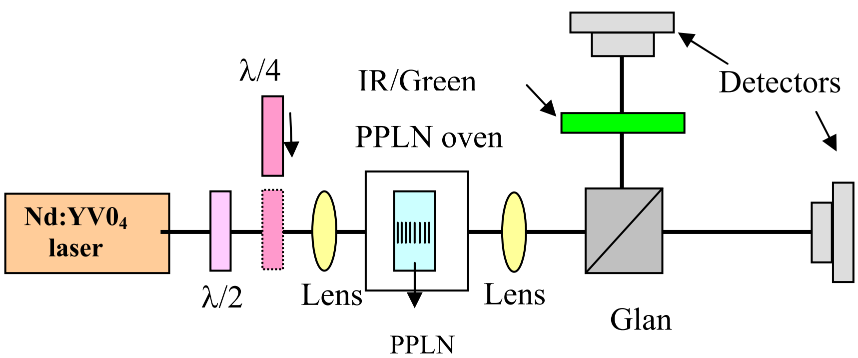

Fig. 7. Experimental setup for simultaneous SHG in PPLN.

By setting the laser polarization to be incident on either the y-axis or the z-axis the SHG temperature detuning curves of the type-0 and type-I SHG could be measured individually, as shown in Fig 8. The individual SHG detuning curves closely resemble the expected sinc^2 form, and the nonlinear efficiency of the two processes was very similar as intended from Eq. (3).

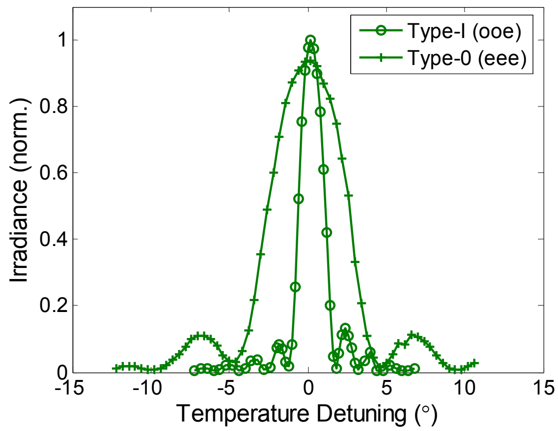

Fig 8. Temperature detuning curves for type-I (1st order QPM on d_{31}) and type-0 (7th order QPM on d_{33}) SHG of a 1064.5 nm laser in 45.75 μm period PPLN. Each curve is measured separately with either a pure type-0 or type-I polarization being set as the input. Irradiance has been normalized to peak SH irradiance of the type I process.

The temperature detuning results for the simultaneous processes is shown in Fig 9. A maximum depletion of 6% of each fundamental was measured in the experiments and the simulation was adjusted for comparison. Both the SHG and the fundamental depletion showed very good agreement with the simulations, validating the coupled wave approach from Eqs (4-6).

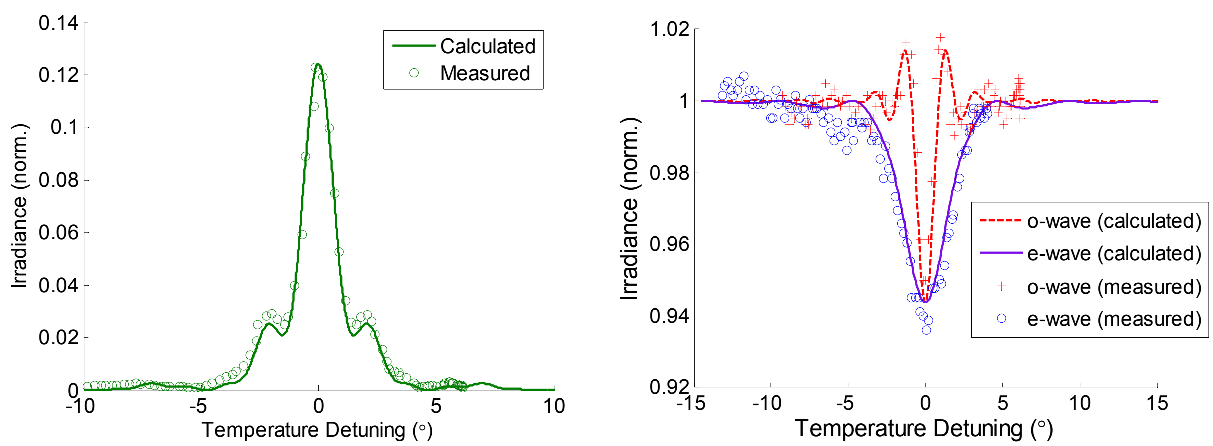

Fig. 9. Experimental temperature detuning curves for simultaneously phase-matched SHG. Left: SHG detuning. Right: Fundamental detuning.

The cascading of the π/2 phase-shifted fundamentals with varying ratios of the irradiance in the *o* and *e*-wave fundamental polarizations was also explored. The experimental data recorded for the weaker o-wave component when temperature detuning for an input ratio of 7:3 (e:o) is shown in the left Fig. 10. As expected from simulations, we see parametric gain at zero detuning due to the cascading from the strong fundamental to the second harmonic and then back to the weaker and orthogonal fundamental. The measured relative gain for a variety of *o:e* ratios is shown in the right of Fig. 10.

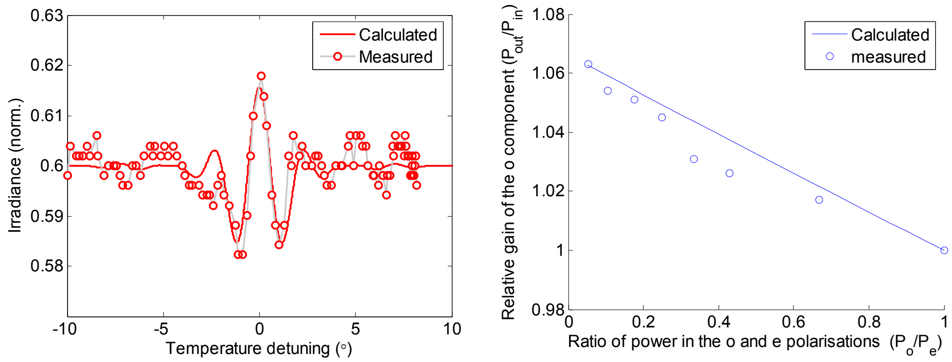

Fig. 10. Left: Temperature detuning curve for the weaker o-wave component cascaded in a 7:3, *e:o* input ratio. Parametric gain is observed at zero detuning. Right: Measured relative parametric gains for various input ratios.

5. CONCLUSION

We have reported on experimental studies of the cascaded interaction between two cross-polarized fundamental waves under condition where each fundamental wave is involved in separate phase-matched SHG processes but with a common second-harmonic wave. The energy exchange between the two fundamental waves can be observed when the two SHG processes are simultaneously phase-matched. The effect has been compared with the dependences obtained from the developed numerical calculations. We expect the same effect will be even more easily observed with short (picosecond or femtosecond) pulses, with an additional consideration that the crystal length be chosen so that the effects due to group-velocity mismatch between *o* and *e* polarizations do not become an overriding factor. The advantage of the proposed interaction is its instantaneous character due to the nonlinearities involved being of the second order.

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