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Advances in Femtosecond Single-Crystal Sum-Frequency Generating Optical Parametric Oscillators

Kahraman G. Köprülü, Tolga Kartaloğlu, Yamaç Dikmelik, and Orhan Aytür

Department of Electrical and Electronics Engineering, Bilkent University,
TR-06533 Bilkent, Ankara, Turkey
Phone: 90-312-266-4307; Fax: 90-312-266-4126; e-mail: aytur@ee.bilkent.edu.tr

Upconversion of lasers to shorter wavelengths is commonly achieved by using second-harmonic generation (SHG)[1] or sum-frequency generation (SFG)[2] in conjunction with optical parametric oscillators (OPO's). The SHG or SFG crystal is usually internal to the OPO cavity to take advantage of the high intracavity field intensities. Recently, upconversion OPO's that use a single crystal for both parametric generation and SHG/SFG have been demonstrated.[3,4] These devices have achieved conversion efficiencies in excess of those utilizing a second crystal for SHG/SFG.

Here we report recent advances on the femtosecond single-crystal sum-frequency generating OPO.[4] Our OPO is based on a KTP ($KTiOPO_4$) crystal that is cut for noncritical phase matching (NCPM), and synchronously-pumped by a Ti:sapphire laser operating at a wavelength of 828 nm. At this wavelength, the KTP crystal is phase matched for a signal wavelength of 1175 nm in a type-II geometry; the corresponding idler wavelength is $2.8\,\mu$m. The KTP crystal is also phase matched for SFG of the pump and the signal beams to yield a blue output beam at 487 nm. However, a polarization rotation of the pump beam at the OPO input is necessary for this interaction to occur.

The pump laser has 180 fs long pulses at a repetition rate of 76 MHz. A ring cavity is constructed with four mirrors that are highly reflecting at the signal wavelength for the OPO. The 5-mm long KTP crystal is positioned at the intracavity focus. A half-wave retarder is placed at the input of the OPO to rotate the polarization of the laser beam. This configuration allows the input beam to be distributed between the OPO pump and the SFG input by an arbitrary ratio. This polarization rotation is necessary for both processes to be phase matched. The horizontally polarized component of the pump beam provides parametric gain whereas the vertically polarized component provides one SFG input, the other being the resonant signal field. The resulting sum-frequency beam exits the cavity through a dichroic cavity mirror, together with the residual pump beam. At the output of the OPO, the blue sum-frequency beam is separated from the residual pump beam with a dichroic mirror.

To achieve synchronization between the resonating signal pulse and the pump pulse, the length of the OPO cavity is adjusted using a cavity mirror mounted on a piezo-controlled translation stage. However, the vertically and horizontally polarized components of the pump pulse have different group velocities due to birefringence in the KTP crystal. As they propagate in the crystal, these components get separated from each other in the direction of propagation and arrive at the intracavity focus at different times. Since the signal pulse is synchronized with the horizontal component, it is out of synchronization with the vertical component. This results in a reduced efficiency for the SFG process. We calculate the group velocity mismatch between the horizontal and the vertical components of the pump as 330 fs/mm. Assuming the intracavity focus to be at the middle of the 5-mm long OPO crystal, the horizontal component needs to be delayed with respect to the vertical by 825 fs. To achieve this delay, we placed a 1.5-mm long KTP crystal at the input of the OPO. This crystal is also cut for NCPM but rotated 90° with respect to the OPO crystal; hence, there are no phase matched interactions. The time delay due to birefringence in the second KTP crystal is 600 fs (measured). With this compensation, parametric generation and SFG become nearly synchronous, leading to higher conversion efficiency to the blue.

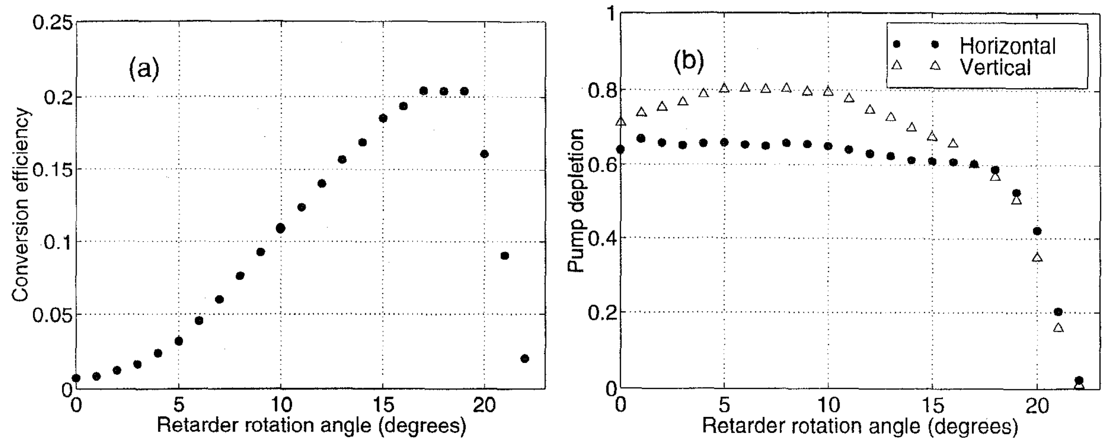

Figure 1: Conversion efficiency (a) and pump depletion (b) as functions of the retarder rotation angle.

Figure 1 shows the conversion efficiency and the depletion of the horizontal and vertical components of the pump beam as functions of retarder rotation angle when the input pump power is held constant at 485 mW. We obtain a maximum of 99 mW blue power at a retarder rotation angle of 18°, corresponding to 20% power conversion efficiency.

Figure 2 shows the conversion efficiency and the depletion of the horizontal and vertical components of the pump beam as functions of input pump power where at each power level the retarder angle is optimized to give the highest conversion. Figure 2(a) also shows conversion efficiency data for the case where group-velocity compensation is not done. We observe a 24% increase in the output power with compensation.

The coupled OPO and SFG interactions in our experiment can no longer be described with the usual three coupled-mode equations of second-order nonlinear interactions. In our case, the coupling between the two processes leads to a set of five coupled-mode equations. For monochromatic plane-waves under singly resonant operation, these equations can be expressed

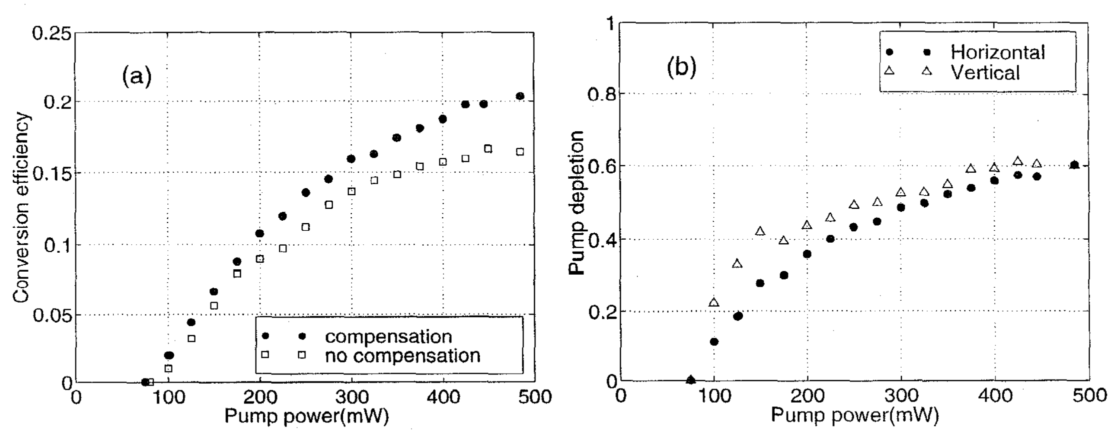

Figure 2: Conversion efficiency (a) and pump depletion (b) as functions of the input pump power.

in terms of real field amplitudes as

$$\frac{da_i}{dz} = \kappa_a a_p a_s \tag{1}$$

$$\frac{da_s}{dz} = \kappa_a a_p a_i - \kappa_b a_{sf} a_{rp} \tag{2}$$

$$\frac{da_p}{dz} = -\kappa_a a_i a_s \tag{3}$$

$$\frac{da_{rp}}{dz} = -\kappa_b a_{sf} a_s \tag{4}$$

$$\frac{da_{sf}}{dz} = \kappa_b a_s a_{rp}. \tag{5}$$

In these equations, κ_a and κ_b are the coupling coefficients of the OPO and SFG processes, respectively. These coefficients depend on the frequencies of the interacting waves and the effective nonlinear coefficients of the respective processes. The field amplitudes are normalized such that their squares correspond to photon flux densities for each field.

Analytical solutions to these equations are available only in the small-signal regime, where depletion of both the pump and the rotated pump fields are negligible. The small-signal gain in this case is

$$\frac{a_s^2(l)}{a_s^2(0)} = \cosh^2\left(\cos\alpha\sqrt{1-\beta^2\tan^2\alpha}\,\kappa_a a_t(0)l\right) \tag{6}$$

where $a_t(0)$ is the total pump field amplitude before polarization rotation, α is the polarization rotation angle (twice the retarder rotation angle), β is the ratio of the coupling coefficients κ_b/κ_a, and l is the interaction length. For the small-signal gain to be larger than unity, the condition $\beta\tan\alpha < 1$ should be satisfied.

The expression for the small-signal gain is valid only near the threshold. To determine the intracavity signal in steady-state, we solved the coupled-mode equations numerically using the Runge-Kutta-Fehlberg method. Based on the intracavity signal, the photon conversion efficiency to the sum-frequency, and the depletion of both pump components are calculated. We found that the results can be characterized in terms of three parameters, the nonlinear drive $(\kappa_a a_t(0)l)^2$, the polarization rotation angle α, and the ratio of coupling constants β. Our plane wave model is in qualitative agreement with the experiments, especially when we extend our model to include the Gaussian intensity profile of the pump beam.

In conclusion, we demonstrated that compensating for the group velocity mismatch between the orthogonal pump components increases the conversion efficiency of femtosecond single-crystal sum-frequency OPO's. Further improvement may be achieved with a setup where the amount of compensation is adjustable. Numerical modeling of the sum-frequency OPO yields a better understanding of the processes involved in the conversion.

1. R. J. Ellingson and C. L.Tang, Opt. Lett. **18**, 438 (1993).
2. E. C. Cheung, K. Koch, and G. T. Moore, Opt. Lett. **19**, 1967 (1994).
3. T. Kartaloğlu, K. G. Köprülü, and O. Aytür, Opt. Lett. **22**, 280 (1997).
4. K. G. Köprülü, T. Kartaloğlu, and O. Aytür, in *Conference on Lasers and Electro-Optics*, Vol. 11 of OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997) p. 457.