Simultaneous optical parametric oscillation and sum-frequency generation within a single crystal for converting 1064 nm into 627 nm

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Abstract
We report a 1064-nm pumped optical parametric oscillator based on a single $KTiOAsO_4$ crystal that simultaneously generates the sum frequency of the pump and signal wavelengths, providing a 627 nm output with a high conversion efficiency.

Coherent radiation in the red part of the spectrum has important applications in several areas such as laser projection displays, photodynamic therapy in medicine and as a pump source for other lasers. Nanosecond Nd:YAG laser radiation was previously converted into red wavelengths by employing optical parametric oscillators (OPOs) based on the nonlinear crystals β-barium borate (BBO) or lithium triborate (LBO) [1]. Since the pump wavelength used in these devices is a harmonic of 1064 nm, the overall 1064-nm-to-visible conversion efficiencies are usually below 10 %. A nanosecond periodically-poled potassium titanyl phosphate (PP-KTP) OPO was recently reported [2]. Pumped by the second-harmonic of a Nd:YAG laser, this device achieves a 61 % conversion efficiency from 532 nm to the red spectral region. However, narrow aperture of PP-KTP limits the maximum input pulse energy.

Simultaneous phase matching of two nonlinear processes within the same nonlinear crystal have been used for efficient conversion of lasers to wavelengths that cannot be reached via a single nonlinear process. In particular, Ti:sapphire lasers have been upconverted to visible wavelengths by sum-frequency-generating OPOs (SF-OPOs) [3] and self-doubling OPOs [4] .

In this paper, we report a SF-OPO in which a single $KTiOAsO_4$ (KTA) crystal is employed for both parametric generation and SFG. The SF-OPO is pumped by a Q-switched Nd:YAG laser operating at 1064 nm. Type-II birefringent phase matching is employed to generate a *p*-polarized (horizontal, fast axis) signal beam at 1525 nm and an *s*-polarized (vertical, slow axis) idler beam at 3520 nm from a *p*-polarized pump beam as a result of parametric oscillation. SFG of an *s*-polarized beam at 1525 nm and *p*-polarized pump is simultaneously phase-matched for the same direction of propagation in the KTA crystal, again in a type-II polarization geometry. An intracavity retarder plate provides the required rotation for the signal polarization and a *p*-polarized sum-frequency beam at 627 nm is generated. This polarization geometry belongs to class-D SF-OPOs, as defined in Ref. [5]. The overall energy conversion efficiency of the two step process is 21%, and up to 8.3 mJ of red pulse energy has been generated.

Our experimental setup is shown in Fig. 1. The pump source is a 20 Hz flash-lamp-pumped Q-switched Nd:YAG laser operating at 1064 nm generating pulses of 14.7 ns duration (FWHM). The telescope lenses reduce the beam diameter of the pump beam almost 2.5-fold resulting in a 1.6 mm diameter beam ($1/e^2$ intensity point) with a divergence of 0.4 mrad.

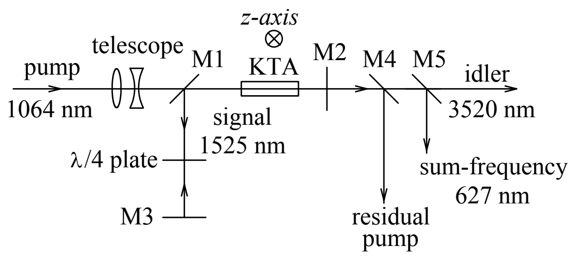

Fig. 1. Experimental setup of the SF-OPO.

The 4.8-cm-long L-shaped cavity is made up of three flat mirrors, M1, M2 and M3, which are high reflectors at the signal wavelength of 1525 nm. The pump beam enters the cavity through mirror M1 and exits the cavity through mirror M2 after making a single pass. Both of these mirrors are high transmitters at 1064 nm. An intracavity $\lambda/4$ plate acts as a polarization rotator to couple a portion of the *p*-polarized signal beam to *s*-polarization as the signal beam makes a double pass through this component upon reflection from mirror M3. The *s*-polarized component of the signal and the *p*-polarized pump produce the sum-frequency beam at 627 nm along the length of KTA. The red beam exits the cavity through mirror M2. The residual pump and red beams are separated from each other by dichroic mirrors M4 and M5. The idler at 3520 nm is mostly absorbed in mirrors M2, M4 and M5 which are made from BK7 glass. Only a small amount of idler, 0.4 mJ at the highest input energy, is measured after these mirrors.

Our SF-OPO is based on a 20-mm-long KTA crystal that is cut along the $\theta = 90^\circ$ and $\phi = 33^\circ$ direction. It has antireflection coatings for the signal and pump wavelengths on both surfaces. However, we determined that simultaneous SFG is most efficient for propagation along the $\theta = 90^\circ$ and $\phi = 30.1^\circ$ direction. This angle is very close to the value calculated using the Sellmeier coefficients given in Ref. [6] for parametric generation and the Sellmeier coefficients given in Ref. [7] for SFG. While the beams polarized along the slow axis (z-axis) experience no walk-off, the calculated walk-off angle associated with the beams polarized along the fast axis is small, with the maximum value being that of the sum-frequency beam which is 0.15º.

Fig. 2 shows the conversion efficiency of the red pulse as a function of the polarization rotation angle which is varied through the angular adjustment of the retarder plate. The pump energy is held fixed at 39.2 mJ. The peak conversion efficiency of 21 % is obtained at a polarization rotation angle of 36º. Above this optimum angle, the linear loss experienced by the intracavity signal field due to polarization rotation increases and the SF-OPO falls below threshold at 80º.

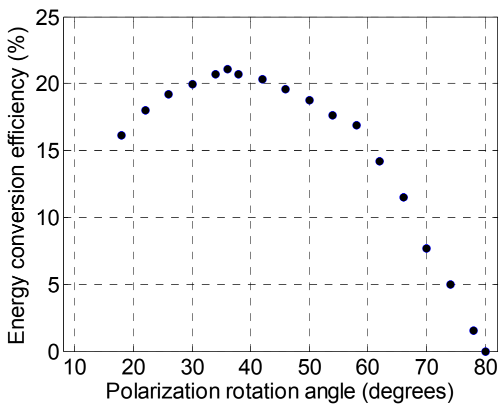

Fig. 2. Sum-frequency conversion efficiency as a function of the polarization rotation angle. Pump pulse energy is held fixed at 39.2 mJ.

Fig. 3 shows the sum-frequency pulse energy and pump depletion as functions of the pump pulse energy at the optimum polarization rotation angle of 36º. A maximum of 8.3 mJ sum-frequency energy is obtained at a pump energy of 39.5 mJ, corresponding to 21 % conversion efficiency and 37 % pump depletion. The threshold energy of the SF-OPO is 16.7 mJ.

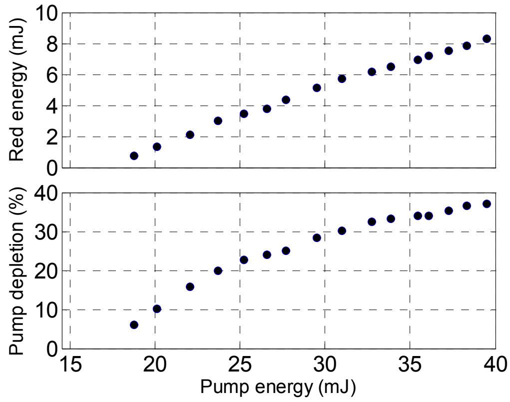

Fig. 3. Sum-frequency pulse energy and pump depletion as functions of pump pulse energy. Polarization rotation angle is held fixed at 36º.

In conclusion, we have demonstrated a 1064-nm pumped nanosecond SF-OPO that employs a single KTA crystal for both parametric oscillation and SFG. The 627 nm output energy is 8.3 mJ corresponding to a conversion efficiency of 21 %. To our knowledge, this is the first demonstration of a nanosecond SF-OPO. This device provides a simple and efficient method for converting high energy Nd:YAG lasers to a red wavelength.

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