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Temperature-tuned difference-frequency mixing in periodically poled $KTiOPO_4$

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Abstract. We report difference frequency generation and temperature-tuned phase-matching in the nonlinear optical material periodically poled $KTiOPO_4$ (PPKTP). We generated 12 μW of radiation tunable around 1.6 μm by difference-frequency mixing of the outputs of a frequency-doubled Nd:YLF laser at 523 nm (240 mW) and a tunable Ti:sapphire laser near 760 nm (340 mW). A temperature tuning rate of 0.73 nm/°C for the generated wavelength and a FWHM temperature acceptance bandwidth of 6.9 °C cm was observed. The effective d_{33} coefficient was estimated to be ∼ 5 pm/V.

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The use of periodically poled materials for quasi-phase-matching (QPM) has recently had a considerable impact in the field of nonlinear optics [1]. QPM permits access to the highest nonlinear coefficients of a material (e.g. d_{33} in $LiNbO_3$, $KTiOPO_4$, $RbTiOAsO_4$), and hence can provide greater conversion efficiency than possible with traditional birefringent phase-matching. In addition, with suitable grating selection, essentially any wavelength combination within the transparency range of the material may be phase-matched in a noncritical geometry.

While the pioneering work into QPM focused principally on periodically poled lithium niobate (PPLN), other materials, notably periodically poled $KTiOPO_4$ (PPKTP) and its isomorphs, have recently been successfully developed. PPKTP has been demonstrated in the efficient frequency doubling of both pulsed and continuous-wave (cw) Nd:YAG lasers [2, 3], second-harmonic generation with simultaneous femtosecond pulse compression [4], and femtosecond optical parametric oscillators (OPOs) for photon division [5]. In cw applications, periodically poled $RbTiOAsO_4$ (PPRTA) has been used in a singly resonant OPO [6].

Flux-grown KTP, now a well-established nonlinear optical material, has been successfully poled by using millimeter-thick samples [7]. KTP has the advantages of a higher laser damage threshold and higher resistance to photorefractive damage than PPLN. It has a coercive field about 10 times lower than that of $LiNbO_3$, which allows fine pitch gratings to be easily produced due to limited domain broadening during the poling process [7]. These properties, along with room-temperature operation, make PPKTP an attractive alternative material to PPLN for a wide range of applications.

In this communication, we report what we believe to be the first demonstration of difference-frequency generation (DFG) in PPKTP. Importantly, while conventional birefringent phase-matching in KTP is insensitive to crystal temperature, we find that in the case of QPM, KTP demonstrates a useful degree of temperature tuning. We show from theory that the degree of tunability varies with pump wavelength, and so anticipate the application of PPKTP to widely temperature tunable DFG and high average power OPOs.

1 Experimental setup

Our single-grating periodically poled crystal was prepared from a sample of flux-grown KTP (9 mm long by 1 mm thick) by patterning a photoresist grating with a period of $\Lambda = 9.55\ \mu m$ upon the c− face. The sample was first ion-exchanged in 100% $RbNO_3$ on the c− side for 3.5 h at 355 °C prior to patterning, in order to create a low-conductive RTP layer at the surface where the domains can easily nucleate [7]. The sample was then poled by applying three 6-ms-long pulses at 2.5 kV, with KCl used as liquid electrodes. The poled interaction length of the crystal is 5 mm with the end faces polished and left uncoated.

The experimental set up is as shown in Fig. 1. The PPKTP crystal was pumped by two collinear, continuous-wave laser beams: one at a fixed wavelength, $\lambda_p = 523$ nm, the other, λ_s, tunable around 760 nm. The source at 523 nm is an all-solid-state, diode-pumped Nd:YLF laser with an intracav-

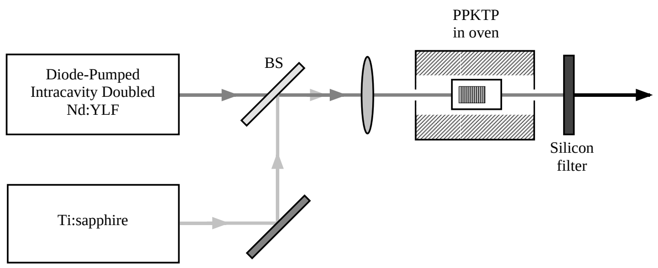

Fig. 1. Schematic of the experimental setup (BS, beamsplitter)

ity KTP doubler giving an output power of a few hundred mW. The tunable source is a Ti:sapphire laser configured as a standing-wave bow-tie resonator, and is itself pumped by an argon-ion laser. A three-plate birefringent tuner allows coarse tuning of the multi-axial-mode (~ 20 GHz bandwidth) output from 750 to 850 nm. When operating around 760 nm, the Ti:sapphire laser provides an output power of a few hundred mW.

The two beams were combined using a dichroic-coated beamsplitter which transmits the green light and reflects the red. The combined beams were then focused into the crystal using a single 50-mm-focal-length lens, resulting in beam waists of 11.5 μm and 16.9 μm for the green and red beams, respectively. The PPKTP was mounted in a temperature-controlled oven which could vary the crystal temperature from room temperature to over 100 °C.

2 Results

Figure 2 shows the tuning range of the wavelength generated as the PPKTP crystal temperature is varied over a range of 80 °C, while the Ti:sapphire wavelength was simultaneously tuned to maintain optimum conversion. Over this temperature range the Ti:sapphire wavelength is varied from 767 nm to 755 nm, corresponding to a variation in the DFG wavelength, λ_i, of 1649 nm to 1707 nm. The corresponding tuning rate for the generated wavelength is 0.73 nm/°C. This is consistent with the value calculated from the $\partial n/\partial T$ data from Wiechmann et al. [8]. $\partial\lambda_i/\partial T$ is calculated from the quasi-phase-matching condition

$$\frac{n_p(T)}{\lambda_p} = \frac{n_s(T)}{\lambda_s} + \frac{n_i(T)}{\lambda_i} + \frac{1}{\Lambda}\,, \tag{1}$$

where $n(T) = n(25\,°\mathrm{C}) + \partial n(T - 25\,°\mathrm{C})/\partial T$ and T is the crystal temperature.

The uncertainty in published Sellmeier data for KTP and the uncertainty in the grating period result in predicted wavelengths that are offset from the experimental results. However, we found that Sellmeier data published by Fan et al. [9] predicted the closest wavelengths, which were within ~ 9 nm at Ti:sapphire wavelengths.

The temperature acceptance bandwidth of the interaction was then measured by fixing the Ti:sapphire wavelength while the crystal temperature was varied. Figure 3 shows two experimental bandwidth measurements, together with a theoretical curve based on the temperature-dependent index data from [8]. Experimental data for two different Ti:sapphire wavelengths (and hence different temperatures of peak conversion) are shown; the circles and diamonds correspond to Ti:sapphire wavelengths of 761 nm and 753 nm and peak temperatures of 63 °C and 111 °C, respectively.

It is well known that for the case of tightly focused Gaussian beams, the acceptance-bandwidth curve deviates from the ideal sinc^2 shape associated with collimated beams, and, for example, comprehensive analyses have been carried out by Boyd and Kleinman [10] and Guha et al. [11]. The tight focusing of the red, $\xi_s = 1.34$, and green, $\xi_p = 1.75$, beams resulted in the asymmetry of the experimental data as shown in Fig. 3. The theoretical curve in Fig. 3 is a normalised plot of the function h_s as defined in [11, eq. (15)], as a function of temperature (assuming small depletion of the waves at λ_p and λ_s). In [11], h_s is defined as a function that shows the relative DFG efficiency, as a function of phase mismatch, for the general case of unequal confocal beam parameters. The present calculation is based on a Ti:sapphire wavelength of 767 nm, a poled interaction length of 5 mm, and the above beam focusing parameters. In order to plot h_s as a function of temperature in the present case, the phase mismatch Δk

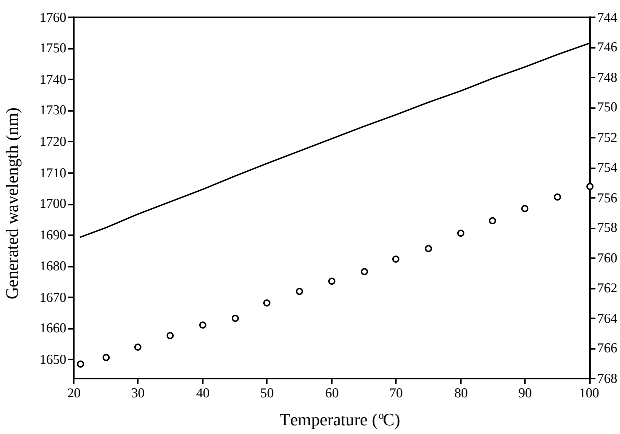

Fig. 2. Temperature tuning of PPKTP. The *solid line* shows the predicted temperature tuning based on [8]

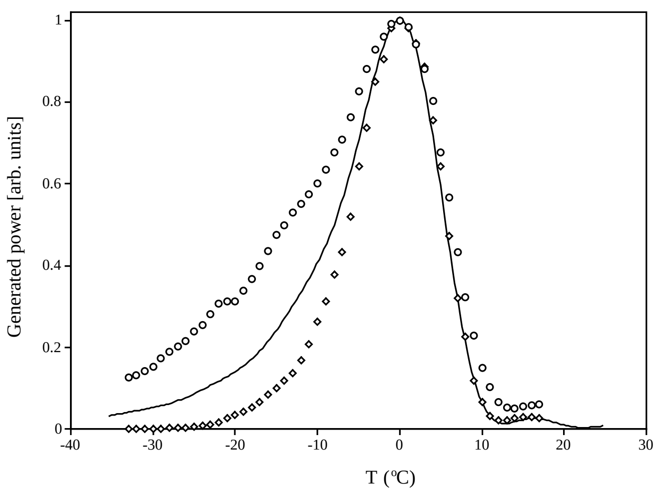

Fig. 3. Temperature acceptance bandwidth of PPKTP. The *solid line* shows the theoretical prediction based on [11]. Experimental curves, *circles* and *diamonds*, correspond to temperatures of 63 °C and 111 °C, corresponding to Ti:sapphire wavelengths of 761 nm and 753 nm, respectively

has been related to the temperature deviation, ΔT, from the phase-matching temperature by

$$\Delta k = 2\pi \left(\frac{1}{\lambda_p} \frac{\partial n_p}{\partial T} - \frac{1}{\lambda_s} \frac{\partial n_s}{\partial T} - \frac{1}{\lambda_i} \frac{\partial n_i}{\partial T} \right) \Delta T \ , \qquad (2)$$

where the $\partial n / \partial T$ values are from [8].

The asymmetry observed in Fig. 3 results from a spread in the wavevectors in the focussed beams. Different wavevector components phase-match at different temperatures resulting in the broadening of the temperature acceptance bandwidth and an offset in maximum conversion from $\Delta k = 0$. In this experiment the maximum conversion occurs at $\Delta k = -5.5\,\text{cm}^{-1}$ ($\Delta T = 4\,°\text{C}$).

The theory in [11] predicts a FWHM temperature acceptance bandwidth of 6.9 °C cm, which is close to the experimental values of 6.0 °C cm and 10 °C cm. This agreement suggests that the full 5-mm interaction length contributes to the DFG process. The difference between the two experimental bandwidths is not explained by the theory in [11], which predicts similar bandwidths for each case. We note that, strictly, this theory describes only deviations from conventional phase-matching and does not include the periodic domain inversion of the PPKTP. An improved model that includes the periodic poling may explain this difference. Otherwise the discrepancy could be due to a thermal gradient between the crystal and thermocouple inside the oven.

The power of the DFG wavelength was measured by using a calibrated germanium photodetector, after the input beams had been removed by a silicon blocking filter. For input powers of 240 mW at 523 nm and 340 mW at 767 nm, we measured a maximum generated power of 12 μW at 1644 nm. These measurements, along with our measured beam waists of 11.5 μm and 16.9 μm for the green and red beams, respectively, allow us to estimate the value of the effective d_{33} coefficient. A simplified calculation based on a plane-wave approximation results in an effective d_{33} of $\sim 5\,\text{pm/V}$. This calculation assumes that the pump and signal beams are not substantially depleted by conversion to idler. However, a more detailed calculation based on [12, eq. (10)] results in an effective d_{33} value of $\sim 4\,\text{pm/V}$.

We have extended the theoretical predictions, based on data by Fan et al. to determine the degree of tunability for OPOs based on PPKTP. Using a Nd:YAG laser at 1064 nm as the pump source, we predict accessible wavelengths ranging from $\sim 1.6\,\mu\text{m}$ up to the transparency limit of KTP. This is obtainable by using a single grating and a temperature variation of $\sim 200\,°\text{C}$.

3 Summary and conclusions

In summary we have demonstrated difference-frequency generation and temperature tuning of PPKTP. We observed a tuning rate of 0.73 nm/°C for the generated wavelength, which is a useful rate compared to the rapid tuning observed in PPLN, and a generated power of 12 μW (1.6 μm) for input powers of 240 mW (523 nm) and 340 mW (767 nm). The value of the effective d_{33} coefficient was estimated to be $\sim 5\,\text{pm/V}$. From our studies, and our experimental data, we anticipate that PPKTP will prove to be a significant nonlinear material for the near- and mid-infrared, not only for DFG but also for OPOs, and will have considerable flexibility through a combination of grating-period and temperature tuning. Indeed, sensitivity to temperature tuning can be engineered to suit requirements through appropriate design of the grating period [1]. The high damage threshold of the bulk material together with the relatively large aperture available with PPKTP should allow, in particular, future application to high-average-power, pulsed and continuous-wave tunable OPOs.

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