Multi-Wavelength, 1.5-10-μm Tunable, Tandem OPO

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Abstract: A systematic investigation of the tunability and efficiency of non-critically phase-matched (NCPM) and critically phase-matched (CPM) KTA OPOs using x- and y-cut crystals orientations has been conducted for the first time. Using our previously developed tandem, KTA-CdSe, OPO technology, we demonstrate a multi-wavelength, mid-infrared source capable of simultaneously delivering tunable radiation in four broad bands covering the range from 1.5 to 10 μm with high conversion efficiency.
OCIS codes: (190.4970) Parametric oscillators and amplifiers; (160.4330) Nonlinear optical materials

Introduction

The optical parametric oscillator (OPO) has always been considered as an attractive source of tunable coherent radiation extending well into the infrared. Nonlinear materials with high optical damage thresholds, such as KTP and its isomorphs, have had a significant impact on OPO technology. However, the long-wavelength limit of OPOs based on the isomorphs is limited by crystal transparency to approximately 5 μm.

For OPO operation further into infrared, only a few crystals with high transparency at long wavelengths are available, with CdSe, $ZnGeP_2$ and $AgGaSe_2$ among them. These crystals are semiconductors and have high absorption in the near-infrared region, which precludes direct pumping by well-developed, Nd-doped, 1-μm lasers. One alternative to direct Nd-laser pumping is a two-stage, or tandem OPO design, where the output of one OPO serves as the pump for another [1-4]. In references [1] and [2], $AgGaSe_2$ was used as a second-stage OPO material, with $LiNbO_3$ [1] and $KNbO_3$ [2] used in the first-stage, Nd-laser-pumped OPOs. The spectral range covered in [1] was between 2.6 and 6 μm with a maximum conversion efficiency of 1.75%. A tandem OPO configuration was also employed in [3] where a KTA OPO produced a 30% efficient source of 4-μm radiation, with tunability from 3.4 to 4.4 μm obtained by tuning the 2 μm KTP OPO pump source.

In our previous work [4], we reported a high-conversion- efficiency, tandem KTA-CdSe OPO source capable of covering the spectral range from 1.5 to 10 μm. In that work and the work reported here, the first OPO, using KTA, is pumped by a 1.053-μm, Q-switched Nd:YLF laser, and the idler output is used to pump the second, CdSe-based OPO. The CdSe OPO, operating with NCPM, provides signal and idler wavelengths in the regions 3.5-5 and 8-10 μm, respectively, through tuning of the pump wavelength. We show in Figure 1, solid lines, our calculated angle tuning curve for a Type II, x-cut KTA OPO pumped at 1.053 μm, where we limit the smallest angle to near the degenerate operating point. We also show in Figure 1 the calculated tuning of the CdSe OPO signal and idler, assuming the use of the KTA idler as the pump source.

We chose KTA because the material has much lower absorption loss than KTP at the OPO idler wavelength. In terms of damage threshold and nonlinearity, the characteristics of KTA are similar to those of KTP, based on reported operation with a 1.06-μm pump laser [5] and our experiments with a Ti:sapphire pump laser [6].

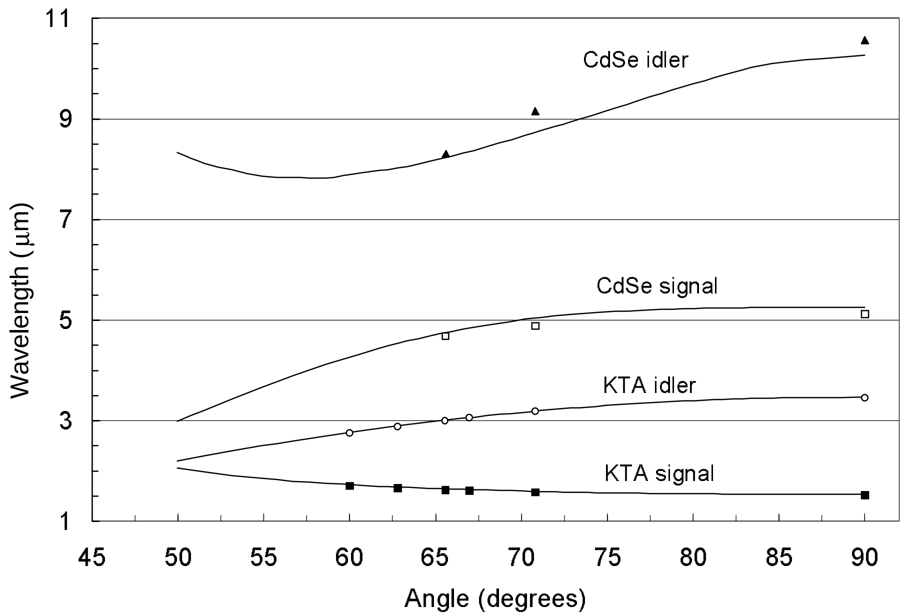

Fig. 1. Composite angle-tuning for x-cut KTA-CdSe tandem OPO. Solid lines are calculated and points are experimental.

With the availability of larger-aperture KTA crystals we have demonstrated angle-tuning of the first-stage OPO and subsequent tuning of the second-stage OPO to generate the range of wavelengths predicted in Figure 1 (see added data points). In our system, operation of the KTA OPO away from NCPM does not entail a substantial increase in threshold because the large pump spot size yields an aperture length longer than that of the crystal.

Experimental Setup and Results

Figure 2 shows a schematic layout of our experimental arrangement. This arrangement allows for up to four output beams simultaneously at different, although coupled, wavelengths. The present linear geometry may be improved by the use of a ring resonator [6] for the second-stage OPO to allow for more efficient outcoupling and separation of the beams.

The pump laser is a Q-switched, flashlamp-pumped, Nd:YLF stable-resonator oscillator with a 5x100-mm rod and an intracavity telescope. This is followed by a 6x100-mm rod, single-pass amplifier. The amplifier output has essentially the same beam quality and pulse width of the oscillator, which is 2 times the diffraction limit and 30 ns, respectively. A detailed description of the pump laser can be found in our earlier work [4].

The Nd:YLF pump laser was coupled with a single focusing lens to the first OPO. The singly resonant OPO cavity is a simple two-mirror, 3-cm-long, standing-wave resonator with pump feedback and 20% output coupling for the signal. The KTA crystal is placed in the center of this resonator on a rotation stage to allow angle tuning. We used several (see Table 1) KTA crystals, provided by Crystal Associates, Inc.

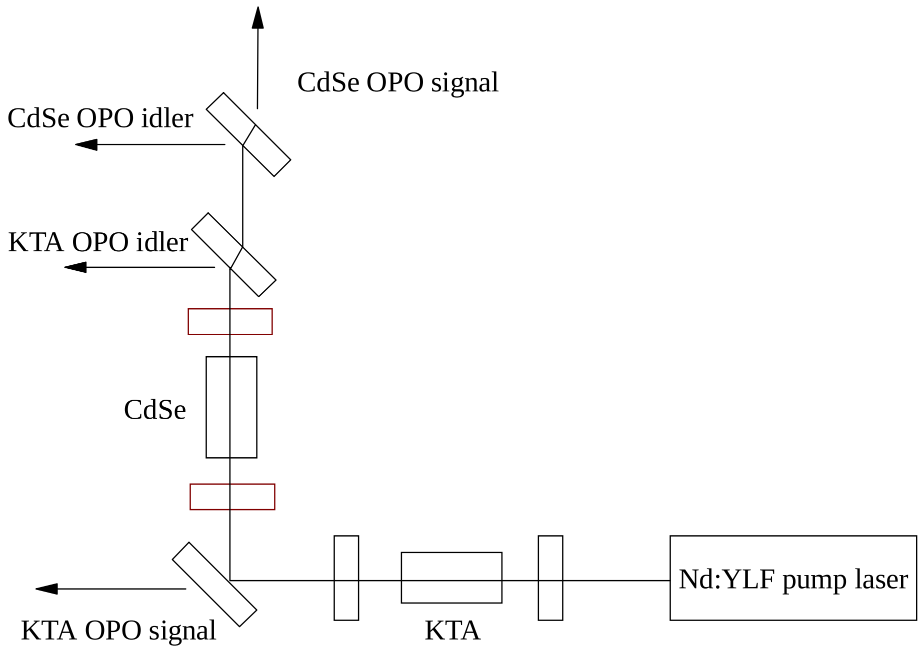

Fig. 2. Multi-wavelength, tandem OPO system arrangement.

Table 1. KTA crystal parameters.

KTA crystal #	Dimensions (w x h x l, mm)	Cut	Angle to z axis (degrees)
1	5 x 5 x 15	x	90
2	10 x 8(y) x 20	x	60
3	8(x) x10 x 15	y	70
4	8(x) x 10 x 25	y	90

Figure 1 shows the x-cut tuning data while Figure 3 shows the y-cut tuning data. In Figure 4 we plot experimental data on signal and idler output pulse energies for y-cut NCPM KTA and 66°, x-cut CPM KTA. The measured signal and idler wavelengths were 1.49 μm and 3.62 μm for NCPM and 1.61 μm and 3.06 μm for CPM. These and other wavelength data shown in Figure 1 are in good agreement with the calculated tuning curves. We took extensive tuning data for the KTA OPO with both x-cut and y-cut crystals. Combining our x- and y-cut data we have demonstrated KTA OPO signal wavelength tuning from 1.485 to 1.706 μm and idler wavelength from 2.751 to 3.620 μm. This tuning range is currently limited by our choice of available KTA crystals and optics.

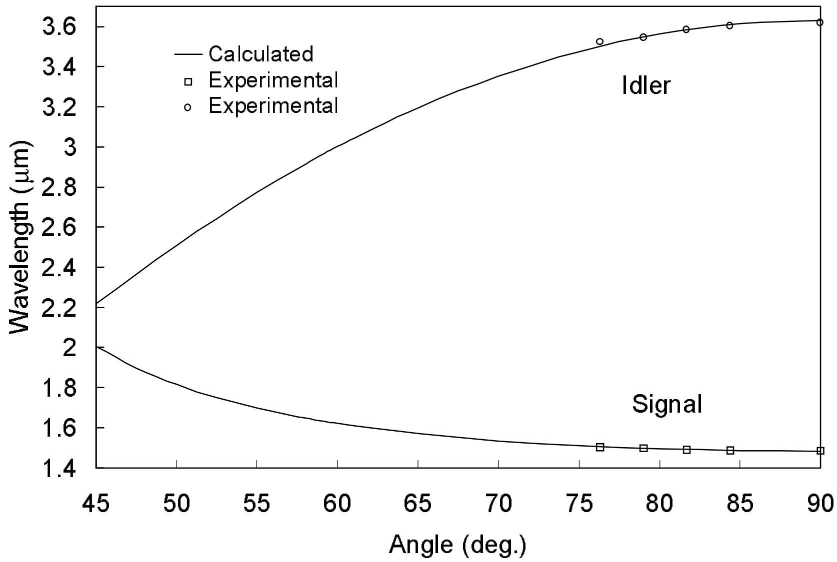

Fig. 3. Angle-tuning for y-cut KTA OPO.

The CdSe crystal used in the second-stage OPO has a relatively low surface-damage threshold, 60 MW/cm^2 for 50-ns pulses, but also a high nonlinear figure of merit, $d^2/n^3 = 2.4x10^{-23}$ $(m/V)^2$. The ability to operate with NCPM and use all the available crystal length for gain allows OPO operation at pump intensities well below the damage level. The ratio of nonlinear figure-of-merit to damage threshold is actually higher in CdSe than in the KTP-crystal family.

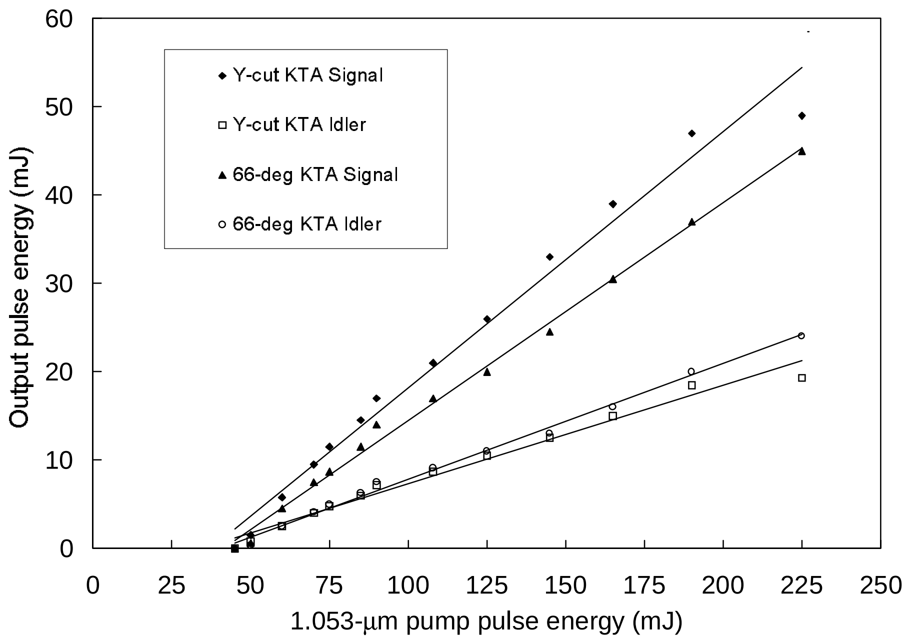

Fig. 4. Input/output data for KTA OPOs.

The CdSe crystal, provided by Cleveland Crystals, Inc., was cut for type II NCPM and is 35-mm in length, with a 10x10 mm cross section and AR coatings for the signal wavelength. The OPO cavity design is similar to that of the KTA OPO; the idler pump beam from the KTA OPO was directed into the cavity without any focusing. The input mirror is highly transmitting within the range from 3.2 to 3.6 μm and highly reflecting within the 4.7 to 5.3-μm range. The output mirror is highly reflecting for the pump wavelength and coated for ~70% reflectivity within the signal wavelength range.

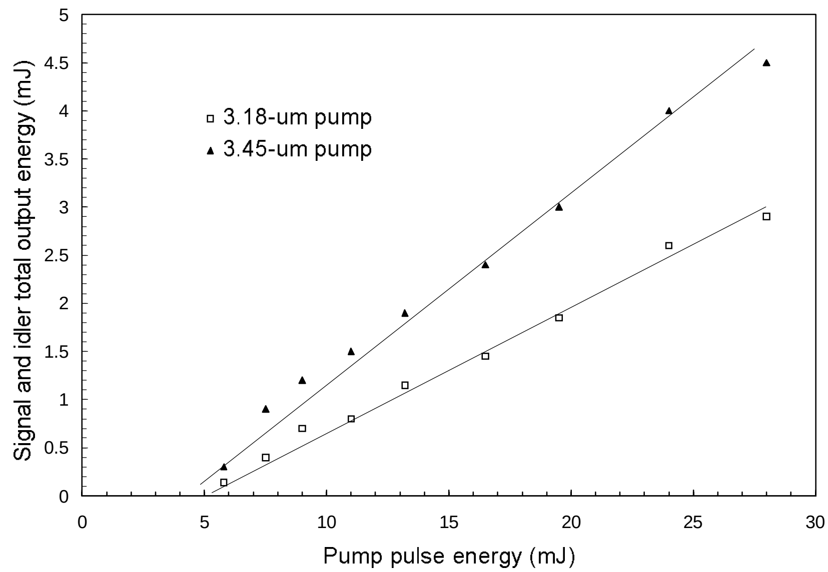

Fig. 5. Input/output data for CdSe OPO.

We show total (signal and idler) output energy versus pump energy in Figure 5 for 3.18 and 3.45 μm pump wavelengths with slope efficiencies of 13% and 20%, respectively. The CdSe signal wavelengths were measured with a grating spectrometer, lock-in amplifier, and HgCdTe photodetector system. Figure 2 shows CdSe experimental signal tuning data at 4.68, 4.88, and 5.12 μm and idler data at 8.31, 9.15, and 10.58 μm for corresponding KTA pump wavelengths of 3.45, 3.18, and 2.99 μm.

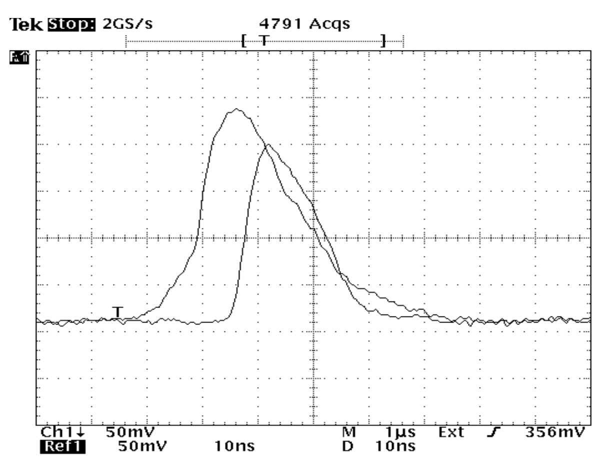

Fig. 6. 3 μm KTA idler (upper trace) and 5 μm CdSe signal (lower trace) pulse profiles.

Figure 6 displays the pulse waveforms for the KTA OPO idler, which was the pump pulse for the CdSe OPO, and the CdSe signal. The pulse durations were 17.5 ns and 14 ns for the KTA idler and CdSe signal, respectively, with a Nd:YLF pump pulse duration of 30 ns. As expected, the CdSe signal pulse is delayed and shorter than the pump pulse.

Future Prospects

Our future work will include broadening the tuning range by use of additional KTA crystals and the use of injection seeding techniques to control and narrow the emission linewidths. Optimization of output coupling and improved resonator optics should yield even higher efficiencies than already demonstrated.

Acknowledgments

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