Tunable continuous-wave doubly resonant optical parametric oscillator by use of a semimonolithic KTP crystal

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A temperature-tuned continuous-wave doubly resonant optical parametric oscillator (OPO) consisting of a semimonolithic KTP crystal and a concave mirror has been designed and built. Under single-axial-mode-pair operation, we obtained a combined output power of the signal and idler light fields up to 365 mW at a pump power of 680 mW. The output wavelength of the OPO can be temperature tuned by as much as 9 nm. We achieved 2.8-GHz continuous frequency tuning of the OPO by tuning the pump laser frequency. © 2002 Optical Society of America

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1. Introduction

In the past few years cw optical parametric oscillators (OPOs) have enjoyed renewed interest because of the improvement and the innovations of all the key optical components. First, the quality of nonlinear crystals was significantly improved, which made them capable to provide enough high nonlinear optical coefficients and low absorption loss to satisfy the requirements of a cw OPO. Second, the prompt progress on laser-diode-pumped all-solid-state lasers with higher frequency and intensity stability offers favorable pump sources. Moreover, the newly developed broadband high-reflection mirror[1] and advanced frequency-locking technique also promote the investigation of OPOs.

Mainly because of threshold constraint, most of the cw OPO devices are operated at the mode of doubly resonant oscillators (DROs), in which both signal and idler modes resonate simultaneously. Unfortunately, the wavelength-tuning range of a DRO is usually limited by the doubly resonating requirements. Although for singly resonant oscillators (SROs), in which either signal or idler mode resonates, the frequencies of the output fields can more easily be tuned over a larger range, and the pump thresholds are much higher than those of DROs. The threshold of a cw SRO OPO based on KTP, reported in 1993,[2] was well in excess of 1 W and, more recently, the threshold of a SRO OPO consisting of highly efficient quasi-phase-matched frequency conversion periodically poled lithium niobate was still around 1 W.[3]

In the development of cw OPO devices, type I nonlinear crystal with high conversion efficiency, for example, MgO:LiNbO$_3$, was frequently chosen. The cw OPOs with 105 and 385 mW combined signal and idler output power were achieved by Breitenbach *et al.*[4] and by Bode *et al.*,[5] respectively. The single-mode operation with high conversion efficiency of 81% and without mode hops was completed in Ref. 4. To obtain stable single-mode operation in a type I phase-matched OPO, the stability requirement of the cavity length must be rigorous.[6]

Compared with a type I OPO, the DRO OPOs that consist of type II phase-matched nonlinear crystals provide more tolerance of pump frequency and cavity length fluctuations because of the refractive-index difference between the signal and the idler light fields in crystals.[7] However, for many applications such as the generation of a quantum-correlated twin-beam and an Einstein–Podolsky–Rosen (EPR) beam, the continuous type II DRO OPOs are especially useful.[8,9] To overcome the frequency-tuning limitations, Colville *et al.*[10] and Lee and Wong[11] developed the dual-cavity DROs with LBO and KTP, respectively, cut for type II phase matching. In their systems, a polarizing beam splitter or a dichroic beam

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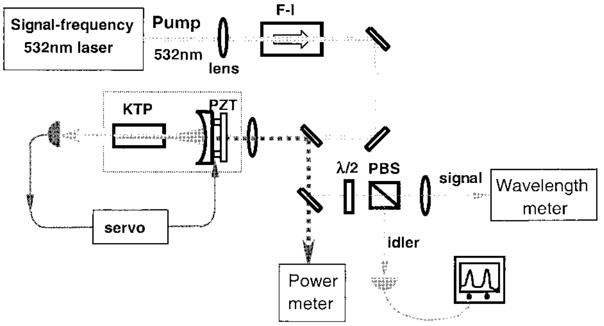

Fig. 1. Schematic of the cw OPO experimental arrangement.

splitter was inserted into the cavity to separate two subharmonic beams and then make them resonate in two independent cavities. The tuning behaviors of type I and type II phase-matched DROs have also been discussed in other publications.[6,7] Gibson *et al.*[12] and Ikegami *et al.*[13] experimentally demonstrated the wideband angular and moderate temperature-tuning properties of KTP crystal in DROs, respectively. Here we present a high-efficiency tunable DRO OPO with large wavelength tuning to as much as 9 nm for temperature tuning and an intense output power up to 365 mW.

2. Experimental Arrangement

Figure 1 is a schematic representation of the experimental arrangement, comprising a pumping laser diode, an intracavity frequency-doubled ring Nd:YVO_4/KTP laser, and a semimonolithic KTP DRO OPO. For the pump source of the DRO OPO, we designed and demonstrated a laser-diode-pumped cw frequency-stabilized and intracavity frequency-doubled ring Nd:YVO_4 laser. The fiber-coupling output diode laser that operates in the vicinity of 808 nm was used as the pump and was focused on Nd:YVO_4 with a waist of approximately 0.6 mm. We achieved frequency doubling by using a 5-mm-long, type II phase-matched KTP crystal. A Faraday rotator and a half-wave plate provide unidirectional operation and stable single-frequency oscillation. The temperature of the KTP was adjusted to ensure that the crystal acts as a full-wave plate for the fundamental mode. We observed continuous frequency tuning of 5.6 GHz by scanning the laser cavity length with a piezoelectric transducer (PZT).

The OPO cavity consists of a concave mirror M1 and a 2 mm × 5 mm × 7 mm flat–flat KTP crystal. Type II phase-matching KTP was chosen for its good optical quality, high damage threshold, wide temperature range, and angular tolerances. The crystal was cut at the angles of $\theta = 90°$ and $\phi = 23.5°$. One end of the crystal (inside the cavity) was antireflection coated at both 532- and 1064-nm wavelengths to minimize intracavity losses. The other end, which also served as a cavity mirror, had a coating designed to have high reflection at both 532 and 1064 nm. The input and output couplers are concave mirrors with 20-mm radius of curvature, coated for 97.7% reflection at 1064 nm and maximum transmission at 532 nm, and were located ~14 mm from the internal flat side of the crystal. Therefore the cavity is single ended for the signal and the idler, and it is a double-pass pump configuration that effectively doubles the interaction length.

A good overlap between the pump wave and the resonator mode is crucial for obtaining high conversion efficiency. Unfortunately there is no straightforward means to accomplish this in a double-pass pump configuration because the input mirror is significantly transparent to pump light. To achieve good mode matching, we replaced the input mirror with a 20-mm radius-of-curvature mirror coated for 2% transmission at 532 nm. For improved mechanical stability, we used only one mirror mount in the OPO cavity. We attached a PZT to the input and output mirrors to scan and to stabilize the cavity length. The crystal temperature can be adjusted with a Peltier thermoelectric cooler that is driven by a home-made temperature controller with a sensitivity of 0.01 °C. The pump wave was injected into the DRO OPO after it passed through an optical isolator that prevented backreflection into the laser. We analyzed the output wavelengths of the DRO OPO with a Coherent wavelength meter and a scanning Fabry–Perot cavity.

Although the double-resonance condition of an OPO leads to a significantly lower threshold and narrower linewidth than in a singly resonant OPO, it also results in wavelength-tuning complications. The DRO OPO must satisfy energy conservation, phase matching, and cavity resonance simultaneously for the signal and the idler frequencies.[14] The cavity's finesse and free spectral range determine the stability requirements of both the pump laser and the DRO OPO cavity length. The free spectral range of our OPO cavity with output at 1064 nm is 6 GHz. The cold cavity finesse and linewidth for the downconversion beams are 146 and 39.5 M, respectively, which we measured by injecting an IR beam into the DRO. The round-trip losses including the output coupling were 4.5%. Above threshold the DRO cavity linewidth equal to $(2^{1/2} - 1)^{1/2}$ times (from Ref. 7) the cold cavity linewidth, or 24.4 M in our experiment, is equivalent to a 3-dB width of 2.25 nm in cavity length. Therefore, both the pump laser frequency and the cavity length should be stabilized to satisfy the better than 24.4 MHz and 2.25 nm, respectively, requirements that can easily be met without difficulty with our experimental system.

Single-frequency stabilized operation of the device was achieved with the Pound–Drever–Hall technique.[15] Electro-optically phase-matched modulation was implemented directly onto the KTP crystal in the OPO. The leakage field from the high-reflection coated mirror of the OPO was monitored by use of a standard photodiode (ETX300), the output from which was used to provide the necessary error signal for the servo loop and hence to maintain the double-resonance condition.

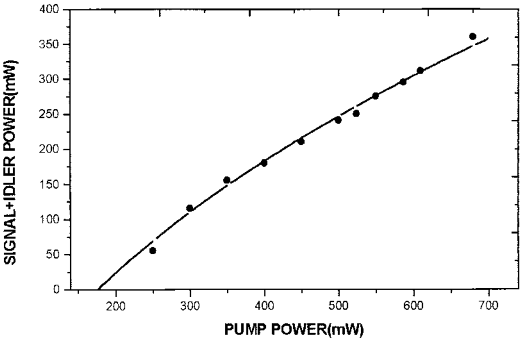

Fig. 2. Combined signal and idler output power as a function of the harmonic pump power at 532 nm. The dots represent data points, and the solid curve represents the calculations from theory. A linear slope efficiency of 66% was measured.

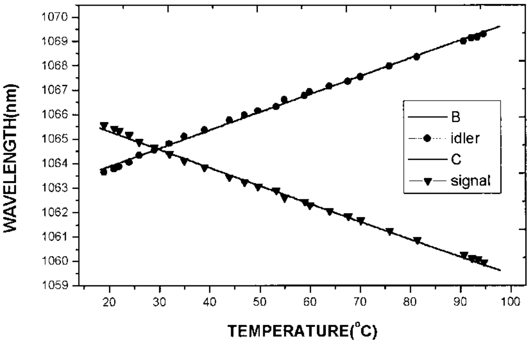

Fig. 3. Observed and calculated tuning for the semimonolithic KTP DRO as a function of temperature. The solid curve indicates the phase-matching condition calculated with Sellmeier equations. The dots represent idler data points, and the inverted triangles represent signal data points.

3. Experimental Results

The generated downconversion beams were separated from the injected second-harmonic beam by a dichroic mirror. Figure 2 shows the output power of the DRO in cw single-axial-mode-pair operation with respect to the harmonic pump power at 532 nm. A maximum 365 mW combined signal and idler output power with single-axial-mode-pair operation was achieved at a pump power of 680 mW, which is the highest output power reported so far for single-axial-mode-pair KTP DRO OPO to our knowledge. A linear slope efficiency of 66% was obtained and the pump threshold of DRO OPO is approximately 170 mW. Also shown in Fig. 2 are the calculated results of the output power that corresponds to the harmonic pump power at 532 nm. The calculation was carried out on the basis of the theory model given by Breitenbach *et al.*[4] By a simple combination of several equations, depending on the pump power and the threshold power, the output power of an OPO can be expressed by

$$P_{\mathrm{out}} = \frac{4T}{A + T}\,(\sqrt{P_{\mathrm{th}}P_{\mathrm{pump}}} - P_{\mathrm{th}}),$$

where T is the transmission coefficient of the cavity coupling mirror, A is the extraneous cavity loss coefficient, and P_{th} is the threshold pump power. The experimental results are in fairly good agreement with the theoretical expectation.

The output wavelength of the type II phase-matched DRO OPO was approximately tuned by the temperature. The temperature-tuning property of KTP is shown in Fig. 3, where the pump light frequency is set. We covered the signal and idler range from 1060.0 to 1069.3 nm. The solid curve indicates the phase-matching condition calculated with Sellmeier equations. The dots represent idler data points, and the inverted triangles represent signal data points. The temperature-tuning coefficient for our OPO was measured to be ~22.2 GHz/°C. The temperature-tuning range was limited only by the temperature that controlled the 19–94.7 °C range in the experiment. We measured the wavelength of the signal and idler waves by using the Coherent wavelength meter with 530-MHz resolution. Single-axial-mode-pair operation of the OPO was also confirmed with a confocal Fabry–Perot interferometer with a free spectral range of 750 MHz. Continuous frequency tuning for the signal and idler mode pair of 2.8 GHz without mode hops was achieved when we tuned the pump laser frequency. Figure 4 is a typical optical spectrum analyzer trace of the signal and the idler outputs of the locked DRO. Combining the laser frequency tuning with OPO temperature tuning with a spectral measurement greater than 9 nm, from 1060.0 to 1069.3 nm, can be smoothly covered with a DRO OPO.

4. Conclusion

In summary, we have demonstrated a broadband-tuned temperature doubly resonant optical parametric oscillator (OPO) using semimonolithic KTP pumped by an all-solid-state laser. The output wavelengths of the OPO can be temperature tuned up to 9 nm. We achieved a maximum of 365 mW combined signal and idler output power with single-axial-

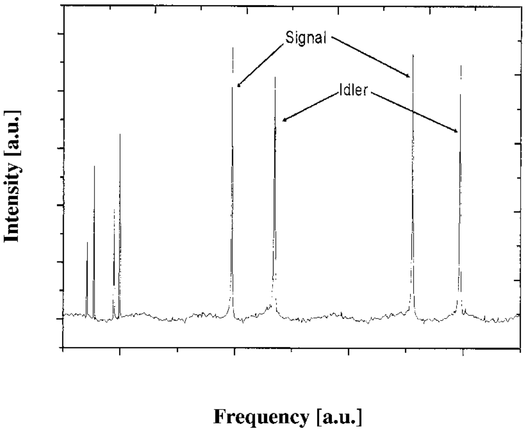

Fig. 4. Typical optical spectrum analyzer trace of signal and idler outputs as the DRO was locked. The free spectral range was 750 MHz.

mode-pair operation. The conversion efficiency from light to light was 53%. To our knowledge, the output power and the frequency-tunable range are both the highest values reported in publications for a temperature-tuned doubly resonant cw KTP OPO that operates at single-axial-mode-pair operation.

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