2-μm singly resonant optical parameter oscillator

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We experimentally realize a singly resonant optical parameter oscillator (OPO) which operates at the degenerate point of $KTiOPO_4$ (KTP) crystal. A thin film plate polarizer (TFP) is used as the output coupler to obtain linearly polarized 2.12 μm laser. A maximum output power of 2.2 W at 2.12 μm is obtained from a near-degenerate, type-II KTP OPO by utilizing a Q-switched diode-pumped Nd:YAG laser operating at 5 kHz.

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All solid-state mid-infrared lasers have attractive applications in areas of laser radar, chemical detection, remote-sensing, etc. Linearly polarized 2-μm laser can be expanded to mid-infrared area by utilizing $ZnGeP_2$ (ZGP)[1]. In 1990, Guyer *et al.* reported a novel way to produce linearly polarized 2.12-μm laser[2]. They designed a non-resonant optical parameter oscillator (OPO) by utilizing a type II matched $KTiOPO_4$ (KTP) crystal in which only the degenerate down conversion from 1.06 μm to 2.12 μm occurred. Kalmani *et al.* reported the experimental realization of the novel cavity with the maximum output power of 380 mW at 2 μm by periodically poled KTP (PPKTP)[3]. However, significant developments of 2-μm laser by OPO have been made mainly in terms of doubly resonant oscillators with KTP or PPKTP[4−8]. The watt-class singly resonant OPO (SR-OPO) by which linear polarization at 2 μm can be generated has scarcely been reported. In our experiment, a SR-OPO which operates at the degenerate point of KTP crystal is designed utilizing a Q-switched linearly polarized 1.06-μm Nd:YAG laser. The KTP crystal is chosen as the nonlinear crystal because of the high transmittance between $0.35-2.8$ μm and high damage threshold. As a result, a linearly polarized 2.12-μm laser with an average output power of 2.2 W is obtained by utilizing a 25-mm-long KTP crystal.

The experimental layout of the OPO is schematically shown in Fig. 1. The Nd:YAG laser contains two flat mirrors (M2, M4), two identical pump modules, two identical acousto-optic modulators (AOMs), a 90° polarization rotator, and a thin film plate polarizer (TFP) with high reflectance for s-polarization at 1.06 μm. M2 has high reflectance at 1.06 μm and antireflectance at 2.12 μm. M4 has partial reflectance ($R = 60\%$) to avoid optical damage when tuning the OPO operation. The pump module consists of a 4-mm-diameter, 100-mm-long Nd:YAG rod pumped by five close-coupled continuous wave (CW) diode arrays[9]. The two pump modules are set as close as possible and a 90^o quartz rotator is placed between them to compensate the thermally induced birefringence. For a flat-flat cavity, the position of beam waist is in the surface of the flat mirror. Therefore, the two AOMs are placed orthogonal and close to the pump module to hold off the high pump gain for Q-switching operation.

The OPO cavity consists of two flat mirrors (M1, M3), a TFP at 2.12 μm, and a KTP crystal. M1 has high reflectance at 2.12 μm; M3 with antireflectance at 1.06 μm has high reflectance at 2.12 μm. The 4×5× 25 (mm) dual-wavelength antireflection-coated KTP crystal with the cut angle of 51.7° is type II phase-matched. As shown in Fig. 2, the degenerate point at 2.12 μm corresponds to a phase matching angle of 51.7° at the temperature of 100 °C. The length of KTP in our experiment is limited for the big walk-off angle (46.27 mrad).

The SR-OPO utilizes a 2.12-μm TFP as the output coupler, which is different from conventional OPOs. As we know, one of signal wave and idler wave must oscillate in the OPO cavity to achieve singly resonant operation. But for 2.12-μm operation, the signal wavelength is almost the same as the idler one. That means the

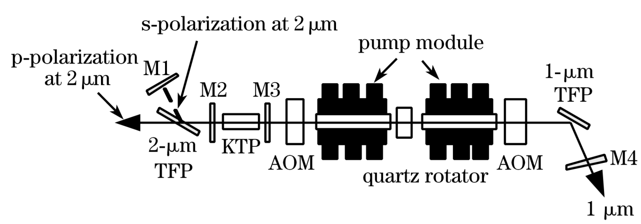


Fig. 1. Experimental configuration of the compound OPO cavity.

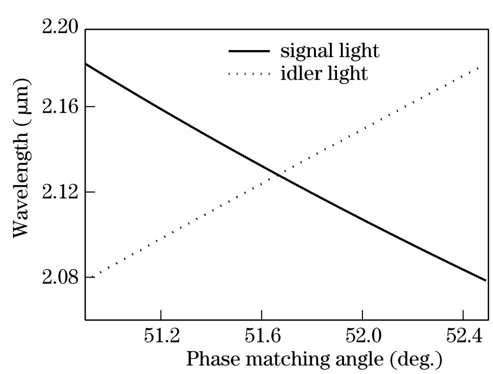


Fig. 2. Turning angle of an OPO pumped by a 1.06-μm laser and utilizing a type-II KTP crystal.

two waves only can be separated by a TFP. As shown in Fig. 1, the s-polarization 2.12-μm light oscillates in OPO cavity between M2 and M3 and p-polarization 2.12-μm light is almost all coupled out by the 2.12-μm TFP. The 1.06-μm laser and OPO cavity are designed carefully to get good beam quality of 1.06 μm. Based on the measurement of the pump module thermal focal length, the cavity lengths of 1.06-μm cavity and OPO cavity are designed by *ABCD* ray propagation matrix. The calculated fundamental mode radius versus the thermal focal length of Nd:YAG rod is shown in Fig. 3. The cavity length of 1.06-μm resonator and OPO cavity are designed to be 900 and 50 mm, respectively.

In our design, one broad stable zone is obtained. That means the Nd:YAG laser is still stable at high pump power. The KTP crystal is mounted in an oven whose temperature is precisely controlled at 100 ±0.1 °C.

At first, we operated the 1.06-μm laser without KTP crystal. The average output power of 1.06 μm was about 76 W at the pump power of 660 W. The beam quality was measured by a laser beam analyzer (M^2-200, Spiricon Inc.), as shown in Fig. 4. We obtained the good beam quality ($M^2 \approx 6$) at 1.06 μm by optimizing the cavity parameters.

KTP crystal mounted in an oven was placed close to M2, which was the place of the 1.06-μm laser beam waist. We obtained the maximum output power of 2.2 W of linearly polarized 2.12-μm laser with 73-W output power at 1.06-μm when the KTP crystal was added in the OPO cavity. The threshold pump intensity is estimated by[10]

$$P = \frac{P_{\mathrm{out}}(1+R)}{f t_{\mathrm{p}} \pi M^2 \omega^2 (1-R)},$$

where P_{out} and R represent the output power of Nd:YAG laser and the reflectance of the output coupler, respectively; f, t_{p}, M^2, and ω represent the repetition rate, pulse width, beam quality factor, and beam radius of Nd:YAG laser, respectively. When 2.12-μm light appears, P_{out} is about 70 W. f and t_{p} are measured to be 5 kHz and 92 ns, respectively. M^2 is estimated to be 6 and ω is 0.2 mm. According to these parameters, the threshold pump intensity is estimated to be about 81 MW/cm^2. That means the threshold is still high for our OPO cavity. The stable SRO cavity is derived from the thermal focal length induced in the KTP crystal pumped by a 1.06-μm laser. Figure 5 shows the output power of a 2.12-μm laser versus the 808-nm diode pump power. The slope efficiency of the OPO is about 22% according to the experimental result. This indicates that the compound SRO has a good prospect to generate high power of linearly polarized 2.12-μm laser by improving the beam quality of the 1.06-μm laser and increasing the reflection of the mirror M4.

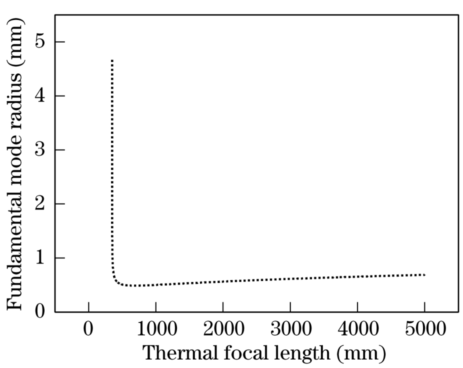
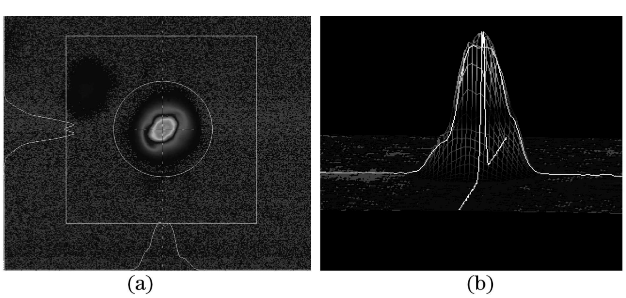


Fig. 3. Diameter of beam in the Nd:YAG crystal versus thermal focal length.



(a) (b)

Fig. 4. (a) Two-dimensional and (b) three-dimensional laser beam profiles with 76-W output at 1.06 μm.

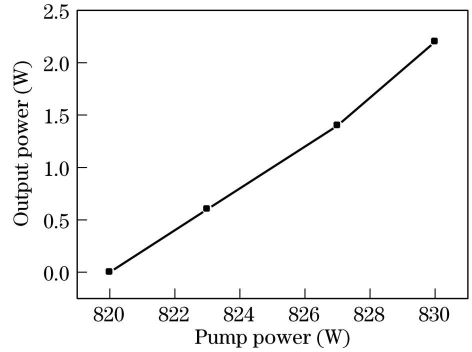


Fig. 5. Average output power of 2.12-μm laser versus diode pump power.

In conclusion, a SR-OPO which operates at the degenerate point of KTP crystal is experimentally demonstrated. A TFP is used as the output coupler to obtain linearly polarized 2.12-μm laser. A maximum output power of 2.2 W at 2.12 μm is obtained from a near-degenerate, type II KTP OPO by utilizing a Q-switched diode-pumped Nd:YAG laser operating at 5 kHz.

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