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Research Article

Mid-Infrared Tunable Intracavity Singly Resonant Optical Parametric Oscillator Based on MgO:PPLN

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In this paper, we demonstrated a continuous-wave intracavity singly resonant optical parametric oscillator based on periodically poled MgO:LiNbO3 (MgO:PPLN) pumped by a diode-pumped Nd:YVO4 laser at 1064 nm. The singly resonant optical parametric oscillator only outputs the idler light as its cavity high reflectivity was coated at the signal light. When the temperature was controlled at 120°C and the grating period set at 30.5 μm for the MgO:PPLN, a maximum idler output power of 1.27 W and central wavelength at 3251 nm were obtained under an incident diode pump power of 12.4 W, corresponding to the conversion efficiency of 10.2%. By changing the temperature and the grating period of MgO:PPLN crystal, widely tunable mid-infrared spectra from 2.95 to 4.16 μm were achieved.

1. Introduction

3~5 μm wavelength range mid-infrared (mid-IR) laser sources have attracted considerable attention, owing to their wide range of applications, such as atmospheric, pollution monitoring, remote sensing, and differential absorption lidar (DIAL) [1–5]. Continuous-wave (CW) especially single-frequency mid-infrared laser sources have an important application in high-resolution spectral analysis [6]. At present, two typical technical routes to achieve the 3~5 μm laser are direct stimulating radiation and nonlinear frequency transition. It is regarded as a potential way for generating a mid-infrared laser where the optical parametric oscillations (OPO) are pumped by diode-pumped solid-state lasers. Many continuous-wave and Q-switch tunable infrared lasers based on OPO were achieved by tuning the period, temperature, angle, and other parameters [7–11]. Recently, there are a number of reports on CW extracavity OPO (EOPO) pumped by well-refined solid-state lasers and fiber lasers [12–15]. Compared with this extracavity OPO, intracavity OPO (IOPO) is characteristic of high energy density in nonlinear medium, compact structure, and multiple round trips of pump light to increase the effective interaction length [16–20]. Hence, the output power and optical-optical conversion efficiency of IOPO are higher than EOPO. The singly resonant optical parametric oscillator (SR-OPO), whose only one wave is in resonance within the optical cavity, is more stable and of higher maximum output power than the doubly resonant OPO (DR-OPO). In 1997, the CW intracavity SR-OPO has been first reported by Colville et al. [21]. A KTP crystal pumped by a Ti:sapphire laser in the intracavity SR-OPO and a total output power of 400 mW in the infrared were obtained.

For birefringent phase matching and the output wavelengths are controlled with angle or temperature tuning of the refractive indices. These tuning techniques are limited by the angular acceptance, the walk-off of Poynting vector, and the beam deviation. However, in quasi-phase matching, the nonlinear susceptibility is modulated periodically to compensate for dispersion. The quasi-phase matching (QPM) can alleviate limitations of birefringent phase matching [22]. Temperature and angle can be used for tuning a QPM

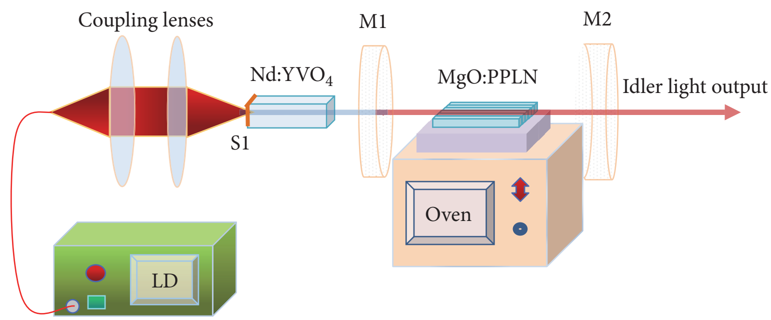

Figure 1: Schematic diagram of LD end-pumped intracavity singly resonant optical parametric oscillator setup.

interaction. Moreover, control of the grating vector can also tune an output wavelength of QPM. There are many literatures about the periodically poled ferroelectric crystals reported, such as periodically poled $LiTaO_3$ (PPLT), periodically poled $KTiOPO_4$ (PPKTP), and periodically poled $RbTiOAsO_4$ (PPRTA) [23–25]. Periodically poled lithium niobate (PPLN) is an ideal and the most comprehensive crystal for the OPO process. In 2003, Abitan and Buchhave reported an intracavity CW SR-OPO based on periodically poled lithium niobate (PPLN) as the nonlinear medium [26]. In 2004, a tunable intracavity CW PPLN SR-OPO pumped by diode-pumped ring-cavity Nd:YAG laser was demonstrated and the idler tunable range was from 2.3 to 3.9 μm [27]. In 2012, Sheng et al. reported an output power of 1.54 W at 3.66 μm using a fold cavity and in-band pumped intracavity SR-OPO with an absorbed pump power of 21.9 W and an optical conversion efficiency of 7.0% [4]. Li et al. generated a maximum signal output power of 2.48 W at 1586 nm and an idler output power of 1.1 W at 3232 nm with a total optical-to-optical conversion efficiency of 31% [28].

In this paper, a tunable CW intracavity singly resonant OPO based on periodically poled $MgO:LiNbO_3$ (MgO:PPLN) driven by a diode-pumped $Nd:YVO_4$ laser at 1064 nm in a simple linear cavity was reported. Through changing the grating period from 28.5 μm to 31 μm and the temperature from 30°C to 150°C, a tunable idler output spectra range from 2.95 μm to 4.16 μm was obtained. A maximum idler output power of 1.27 W and a conversion efficiency of 10.2% were achieved at a temperature of 120°C and a grating period of 30.5 μm for MgO:PPLN.

2. Experimental Setup Design

The experimental setup of our intracavity MgO:PPLN SR-OPO was shown in Figure 1. The pump source is a fiber-coupled laser diode at 808 nm with a core diameter of 100 μm and a numerical aperture of 0.22. The LD output beam was focused into a 0.3% $Nd:YVO_4$ using two coupling lenses with focal lengths of 30 mm and 100 mm. The focused beam spot was about 330 μm in diameter. The a-cut $Nd:YVO_4$ crystal we used was $3 \times 3 \times 10\,mm^3$ in size and its entrance face (S1) was antireflection (AR) coated at 808 nm and high reflection (HR) coated at 1064 nm. With the rising of LD pump power, the thermal effects became more and more unignorable, which would drop in output power. In order to relieve the thermal effects, $Nd:YVO_4$ was wrapped with indium foil and mounted tightly in a water-cooled copper heat sink. And the refrigerant water had been maintained at the temperature of 18°C throughout the experiment.

The flat mirror M1 of SR-OPO was AR ($T = 98.7\%$) coated at fundamental wavelength of 1064 nm, HR ($R > 99\%$) at the signal wavelength around 1.4–1.7 μm, HR ($R > 99\%$) coated at wavelength from 3.2 to 4.2 μm, and partial reflection (PR) coated with the reflectivity fluctuating between 30 and 99% at wavelength from 2.9 to 3.2 μm. The output concave mirror M2 with a radius of curvature of 150 mm was HR ($R > 99\%$) coated in the range of signal wavelength around 1.4–1.7 μm and at fundamental wavelength of 1064 nm and high transmittance (HT) coated at the idler wavelengths around 2.9–4.2 μm. Therefore, the fundamental cavity consisted of S1 of $Nd:YVO_4$ crystal and M2, and the OPO cavity consisted of M1 and M2. Therefore, the signal wave was closed in the OPO cavity and only output the idler wave.

MgO:PPLN we used was AR coated at the fundamental wavelength of 1064 nm ($R < 0.5\%$) and the signal wavelength (1430–2128 nm, $R < 1\%$) and idler wavelength (2128–4800 nm, $R < 5\%$) on both light pass surfaces. It contains seven different periodically poled gratings with periods of 28.5, 29, 29.5, 30, 30.5, 31, and 31.5 μm, respectively, with dimensions of $50 \times 8.6 \times 1\,mm^3$ and MgO doping concentration of 5% mol. Only the first six periods were used as OPO operation was limited by the cavity coating. To realize the temperature tuning, the MgO:PPLN was installed on a servo-controlled oven. A temperature controller and the servo-controlled oven consist of a temperature control system whose tuning temperature of OPO crystal is from 0 to 150°C. The oven was put on an adjusting mount with six degrees of freedom for alignment of the system and period tuning.

3. Results and Discussions

The idler wavelength of SR-OPO output wavelength changed with the period of the inverted domain by shifting the position of the MgO:PPLN wafer. In our experiment, the signal wavelength can be successfully measured; however, the idler wave with the wavelength longer than 3.5 μm was out of

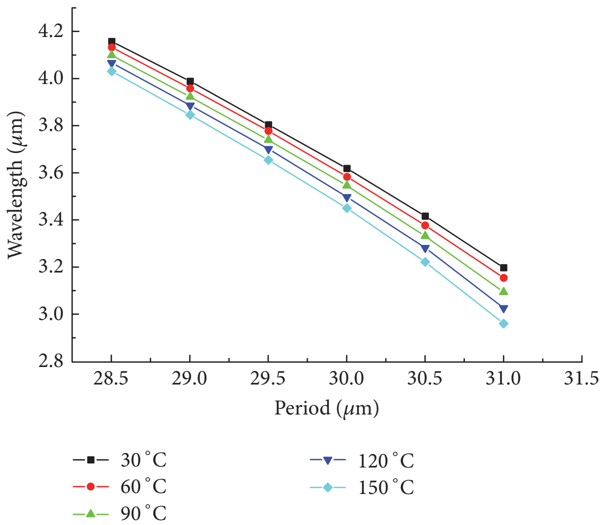

FIGURE 2: The tuning curves of the SR-OPO system versus the grating period of the MgO:PPLN crystal at different controlled temperature value.

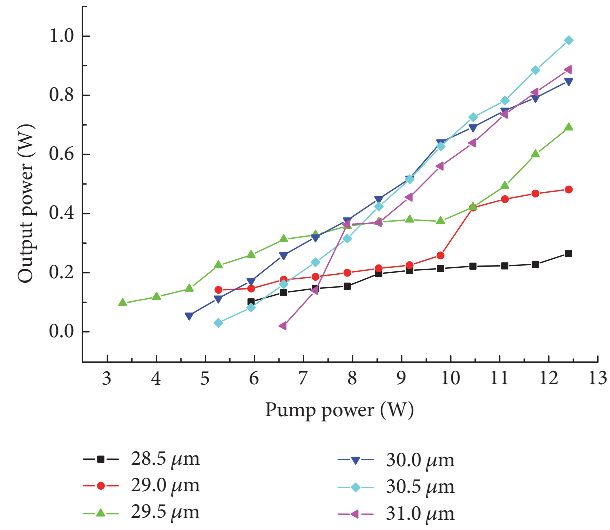

FIGURE 3: The idler output power versus incident pump power with different domain period (T = 30°C).

the response range of the optical spectrum analyzer we used. The idler wavelength can be determined, since it is related to the pump and signal wavelength according to the equations:

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}, \tag{1}$$

where λ_p, λ_s, and λ_i are the wavelengths of pump, signal, and idler, respectively. The calculated idler wavelength as a function of the grating period of 28.5 to 31.0 μm based on different MgO:PPLN temperature values was shown in Figure 2. It is obvious that the idler wavelength can be continuously tunable in the range of 2.96 μm (at the domain period of 31.0 μm and the temperature of 150°C) to 4.16 μm (at the domain period of 28.5 μm and the temperature of 30°C).

The OPO setup was optimized at an incident pump power of 12.4 W with different grating period at the MgO:PPLN temperature of 30°C. Figure 3 shows the idler output power versus incident pump power. The output power was measured with the incident pump power tuned down from 12.4 W. Using different grating periods of MgO:PPLN of 28.5, 29, 29.5, 30, 30.5, and 31 μm at 30°C, maximum idler output powers of 0.27, 0.48, 0.69, 0.85, 0.99, and 0.89 W were obtained, respectively, when the incident pump power was 12.4 W. The maximum idler output power and the diode-to-idler conversion efficiency were in a sustained uptrend with the grating period varying from 28.5 to 30.5 μm, but it decreased at 31 μm. The output wavelength shortened and the single photon energy increased for idler wave with grating period of MgO:PPLN crystal tuned from 28.5 to 30.5 μm; therefore, the idler output power and conversion efficiency increased. Furthermore, the output power dropped at the grating period of 31 μm due to the high transmission loss of cavity mirror. The transmittance of mirror M1 at idler wavelength at 3201 nm reached 40%, which led to larger cavity loss and the drop of output power at the domain period of 31 μm.

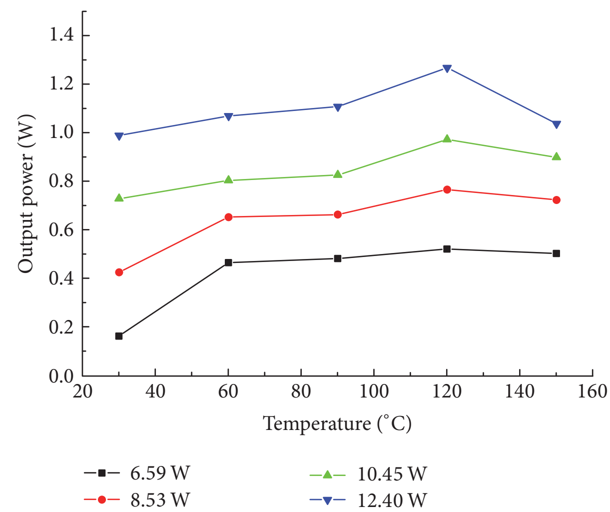

FIGURE 4: The idler output power with temperature tuning under different incident pump power.

The idler output power of OPO versus the temperature of MgO:PPLN crystal at 30.5 μm grating period was shown in Figure 4. The output power of OPO process increased with increasing of temperature while it decreased when the temperature exceeded 120°C. The single photon energy of idler also increased with the increasing of MgO:PPLN temperature below 120°C. The idler wavelength was 3224 nm for MgO:PPLN temperature controlled at 150°C; the transmittance of OPO input mirror (M1) at this waveband was also up to 37% and led to large cavity loss and then resulted in a drop of output power for temperature controlled at 150°C. Under an incident pump power of 12.4 W, a maximum idler output power of 1.27 W was obtained at the temperature controlled at 120°C and the grating period of 30.5 μm, corresponding to

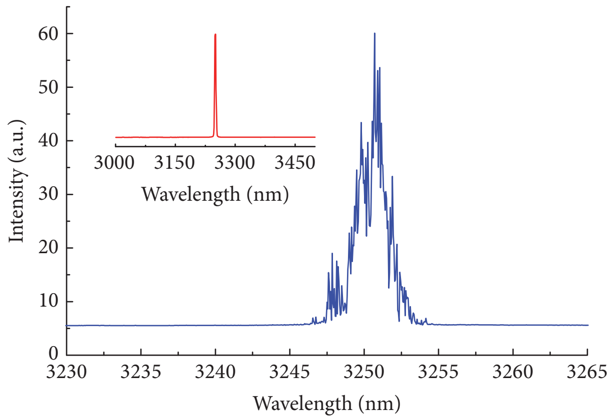

Figure 5: The idler spectrum of MgO:PPLN crystal at the temperature of 120°C and the grating period of 30.5 μm.

the conversion efficiency of 10.2%. We did not increase pump power further to prevent the damage of OPO crystal, while there was great potential for higher idler output power with more powerful pump power.

The output idler wavelength of the intracavity MgO:PPLN SR-OPO at the temperature of 120°C and the corresponding grating period of 30.5 μm were measured by a monochromator. Figure 5 shows measured spectrum with a resolution of 0.05 nm, and the inset shows the spectrum of same wavelength with a resolution of 1 nm and a range from 3000 to 3500 nm. It can be seen that the idler central wavelength was 3251 nm with the line width of about 2 nm.

4. Conclusions

In conclusion, we have experimentally demonstrated a compact continuous-wave intracavity SR-OPO based on MgO:PPLN crystal. A diode-pumped Nd:YVO_4 laser is employed as the pump laser centered at 1064 nm of this SR-OPO. By changing the grating period and the temperature of MgO:PPLN, widely tunable mid-infrared spectra from 2.95 to 4.16 μm of idler light were obtained. At the temperature of 120°C and the grating period of 30.5 μm, a maximum idler output power of 1.27 W was achieved under an incident pump power of 12.4 W with the diode-to-idler conversion efficiency up to 10.2%. The central wavelength of idler wave was 3251 nm and the line width was about 2 nm.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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