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可调谐 Nd∶YVO_4/MgO∶PPLN 连续中红外光学参量振荡器

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摘　要:报道了一种基于 Nd∶YVO_4/MgO∶PPLN 的高效连续单谐振连续中红外光学参量器.采用 LD 泵浦的输出波长为 1 064 nm 的连续 Nd∶YVO_4激光器作为入射光,经过 MgO∶PPLN 晶体进行非线性频率转换.理论分析了非线性晶体的周期、温度对光学参量振荡量输出波长的影响.提出采用紧凑的平平腔结构,利用多周期的 MgO∶PPLN 晶体(29.52～31.59 μm),产生宽带可调谐的中红外激光,其信号光调谐范围为 1.48～ 1.63 μm;闲频光调谐范围为 3.0～3.8 μm.结果表明:在 MgO∶PPLN 的极化周期为 30.5 μm,温度为 100℃的条件下,当 808 nm 泵浦光功率为 8.06 W时,获得最高 760 mW 的信号光和 360 mW 的闲频光输出,对应光光转换效率为 13.9%.

关键词:中红外激光;光学参量振荡;周期极化铌酸锂;连续激光

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Tunable Continuous-wave Nd∶YVO_4/MgO∶PPLN Optical Parametric Oscillator Generating Mid-infrared Laser

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Abstract: An efficient tunable, continuous-wave, mid-infrared, intra-cavity singly resonant Nd∶YVO_4/MgO∶PPLN optical parametric oscillator is presented. A laser-diode-pumped 1 064 nm laser is taken as the incident light and a MgO∶PPLN crystal is used for frequency conversion. The variation of the mid-infrared output wavelength with the grating period and temperature of nonliear crystal is investigated. The grating period of multi-grating MgO∶PPLN chip is from 29.52 to 31.59 μm by a step of 0.5 mm. The tuning wavelength of the signal light is from 1.48 to 1.63 μm and that of the idle light is 3.0 to 3.8 μm. A maximum signal power of 760 mW and idler power of 360 mW are obtained under a pump power of 8.06 W at 808 nm, with corresponding to a total optical efficiency being 13.9% when the grating period is 30.5 μm.

Key words: Mid-infrared laser; Optical parametric oscillator; MgO∶PPLN; Continue-wave

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0　Introduction

Optical parametric oscillators（OPO）has lots of significant advantages，such as high efficiency，widely tunable rang，simple structure and high reliability. In recent years，many important breakthroughs have been made in the research of OPO[1-3]. OPO can be divided to singly resonant OPO（SRO）and doubly resonant OPO（DRO）[4-5]. SRO has some advantages in spectral and power stability and tuning ability compared to DRO. Typically，OPO can also be classified into the intra-cavity and the extra-cavity [6-7]. It is noticed that the energy density and pump threshold of the intra-cavity is better than that of the extra-cavity[8-9]. Therefore，the intra-cavity singly resonant optical parametric oscillator（ICSRO）[10] shows extremely low pump threshold，high down-conversion efficiency and output power. Up to now，quasi-phase matching（QPM）is a technique for achieving similar results to those with phase matching of nonlinear interactions，in particular for nonlinear frequency conversion. Many plane-concave cavity and double-concave cavity were used to realize ICSRO [11-12]. The QPM OPO based on a MgO：PPLN as nonlinear medium is a potential solution for obtaining 3～5 μm mid-infrared radiation to meet the specific requirements，such as the spectral measurement，remote sensing and so on[13-14]. Although high power of signal and idle was achieved，it was found that the beam quality was not satisfying.

In this paper，a plane-plane ICSRO was used to obtain both signal and idle laser output in order to get a good beam quality. With the different poled periods of the nonlinear medium [15]，the tuning wavelength range of signal light from 1.48 to 1.63 μm and the tuning range of the idle light from 3.0 to 3.8 μm were realized. Under a pump power of 8.06W at 808 nm，a maximum signal power of 760 mW around 1.55 μm was obtained at the grating period of 30.5 mm. The idler power of 360 mW around 3.5 μm has been obtained at the same time，with corresponding to a total optical efficiency being 13.9%.

1　Theoretical analysis

First of all，according to the law of energy and momentum conservation，the three waves（pump，signal and idler waves）inside OPO should meet the equations as follows

$$1/\lambda_p=1/\lambda_s+1/\lambda_i \tag{1}$$

where λ_p is the wavelength of the pump light；λ_s and λ_i is the wavelength of the signal light and the idler.

The conservation of momentum of a collinear phase-matched is below

$$\boldsymbol{K}_p=\boldsymbol{K}_s+\boldsymbol{K}_i \tag{2}$$

in which $\boldsymbol{K}_p$，$\boldsymbol{K}_s$，$\boldsymbol{K}_i$ are the wave vector of the pump，the signal and the idler waves. At the beginning，in the case of a collinear quasi phase matched OPO，it is obvious that the grating period Λ and the refractive index of the periodically poled crystal are considered as a function of the temperature T. Secondly；different grating periods will generate different wavelengths due to the wave-vector mismatch Δk [16]. Here the relation between the wave-vector mismatch Δk and the grating period Λ is given as follow

$$\Delta k=\frac{n_e(\lambda_p,T)}{\lambda_p}-\frac{n_e(\lambda_s,T)}{\lambda_s}-\frac{n_e(\lambda_i,T)}{\lambda_i}-\frac{1}{\Lambda(T)} \tag{3}$$

where $n_e(\lambda_p, T)$ is the extraordinary refractive index of the crystal used at the wavelength λ and the temperature T. $n_e(\lambda_p,T)$ is the extraordinary refractive index at the pump wavelength，and $n_e(\lambda_s,T)$) and $n_e(\lambda_i, T)$ are the corresponding quantities for the signal and the idler waves. The conservation of momentum yields the phase-matching condition $\Delta k=0$.

Usually，the domain grating period Λ is given at a specific temperature. Nevertheless，for different elevated temperatures，since the nonlinear crystal would expand in the propagation direction，the grating period increases at the same time. Here the poled period of crystal can be described by the thermal-expansion coefficients α and β with the temperature T based on the domain grating period at 25℃[17]，$\Lambda_{25^\circ\mathrm{C}}$

$$\Lambda(T)=\Lambda_{25^\circ\mathrm{C}}[1+\alpha(T-25^\circ\mathrm{C})+\beta(T-25^\circ\mathrm{C})^2] \tag{4}$$

where $\alpha=1.543\ 10^{-5}\ \mathrm{K}^{-1}$ and $\beta=5.331\ 0^{-9}\ \mathrm{K}^{-2}$. The Sellmeier equation for lithium niobate was measured by Dieter H. Jundt[13]，which describes the relation of the refractive index，temperature and wavelength [17-18]

$$n_e=a_1+b_1f+\frac{a_2+b_2f}{\lambda^2-(a_3+b_3f)^2}+\frac{a_4+b_4f}{\lambda^2-a_5}-a_6\lambda^2 \tag{5}$$

Besides，the temperatures T expressed in degrees Celsius and the temperature parameter f is given by

$$f(T)=(T-T_0)(T+T_0+2\times271.16)=(T-24.5^\circ\mathrm{C})(T+570.82) \tag{6}$$

The parameters for the Sellmeier equation are showed in the Table 1.

Table 1 Sellmeier fitted parameters

Parameter	Value
a_1	5.355 83
a_2	0.100 473
a_3	0.206 92
a_4	100
a_5	11.349 27
a_6	$1.533\ 4\times10^{-2}$
b_1	4.629×10^{-7}
b_2	3.862×10^{-8}
b_3	-0.89×10^{-8}
b_4	2.657×10^{-5}

Combining the equations above, we assumed that the pump wave is at 1 064 nm and then calculated the theoretical signal wavelengths curve of OPO versus the temperature, which is depicted in Fig. 1. Obviously, at a specific poled period of the MgO∶PPLN, the wavelength of signal light goes up with the increase of the temperature. But the wavelength of the idle light decreased simultaneously. What's more, as shown in Fig. 1, the larger grating period makes the longer signal wave and short idle wave. Accordingly, we can design an OPO system emitting the specific wavelengths by controlling the temperature and the grating period of the nonlinear crystal.

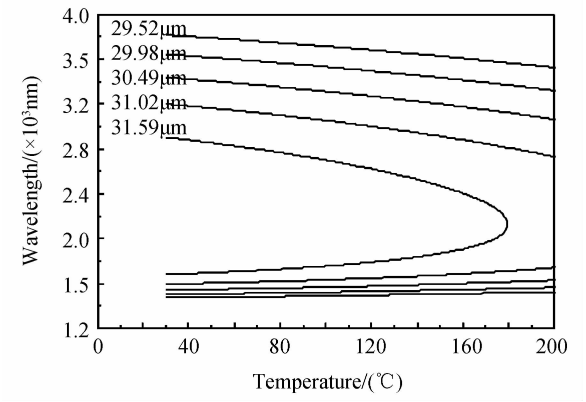

Fig. 1 The OPO tuning curves with a 1064nm pump

2 Experimental setup

The experimental setup is sketched in Fig. 2. The laser diode taken as the pump source is an 808 nm fiber-coupled diode laser array with a fiber core diameter of 200 μm and a numerical aperture of 0.22. The output beam from the fiber was imaged through a couple lenses system with a ratio of 1∶2 for achieving an effective diameter of 400 μm, which is equal to the fundamental laser mode size inside the resonator. The plane-convex lenses were coated at 808 nm with a total transmission about 96%. A $3\times3\times16.5$ mm^3 α-cut Nd∶YVO$_4$ crystal with 0.5at.% Nd-doped was taken as the laser crystal. Its entrance face was coated for antireflective (AR, $T>98\%$) at 808 nm and highly reflective at 1 064 nm (HR, $R>99.5\%$). The other face is AR ($R<0.2\%$) coated at 1 064 nm and 808 nm to eliminate the cavity loss due to the interface. The crystal length is evaluated at the beginning to ensure sufficient absorption of non-polarized pump laser. The OPO cavity with a length of 35 mm was formed by two plane-plane mirrors, M$_1$ and M$_2$. The output coupler M2 with one facet was HR coated at 1.06 μm and partial-reflection (PR) with 13% transmission at 1.53 μm and AR coated at 3～5 μm, and the other facet was AR coated at 1.53 μm and AR at 3～5 μm. One facet of M1 was AR coated at 1.06 μm($R<1\%$) and HR coated at 1.53 μm ($R>99\%$) and HR coated at 3～5 μm, and the other facet was AR coated at 1.06 μm and 1.53 μm and 3～5 μm. A MgO∶PPLN crystal with a dimension of $40\times10\times10$ mm^3 was chosen as the nonlinear medium. It contains five different grating periods from 29.52 μm to 31.59 μm by a step of 0.5 μm. Both faces of the crystal are AR coated at 1 064 nm pump, 1.4～1.8 μm signal and 2.6～4.8 μm idler

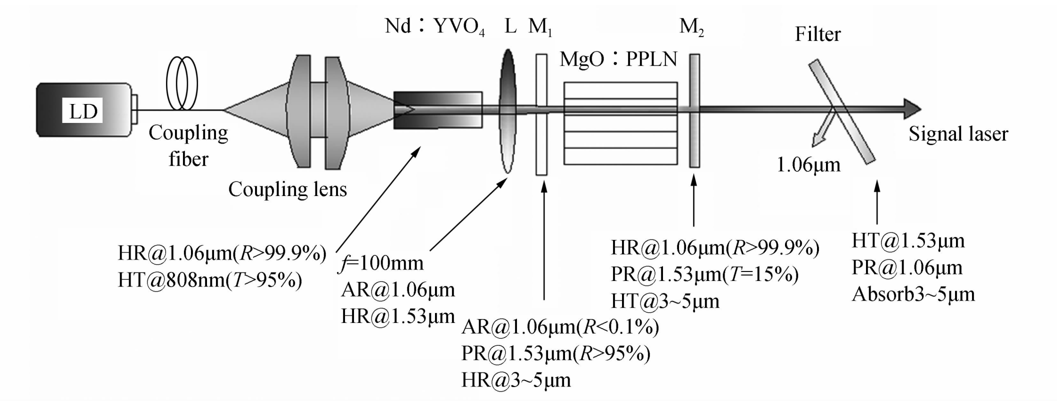

Fig. 2 Schematic illustration of the pumped intra-cavity SRO

wavelength ranges. What is important, a focus lens L with a focal length of 100 mm, which was AR coated ($R<0.2\%$) at 1.06 μm on both sides, was inserted to make the beam size of 1 064 nm laser smaller for the purpose of sufficient pump intensity and mode matching of the pump, the resonant signal and idle laser[6]. In addition, it was beneficial to make the beam size and the location of 1064 nm laser waist insensitive to the variation of the thermal focal length of Nd ∶ YVO$_4$ crystal as the variation of pump power. The filter was HR coated at 1.06 μm ($R>99\%$), AR coated at 1.53 μm ($R<1\%$) and absorbed at 3～5μm for obtain the pure 1.5 μm laser output.

To avoid the photorefractive effect making the crystal damage, controlling the high temperature is good for long time laser operation. Thus the MgO ∶ PPLN crystal was set inside an oven with the accuracy of ±0.01℃, which can be tuned at wide temperature range of (30～180)℃. On the other hand, the Nd ∶ YVO$_4$ crystal was wrapped with indium foil and mounted in a copper block with an thermoelectric cooler kept at about 17℃ during the experimental operation.

3 Experimental results and discussions

With a MgO ∶ PPLN as the nonlinear crystal, the stable mid-infrared lasers operation were achieved inside a singly resonant optical parametric oscillator. The laser spectrums of the mid-infrared lasers, at the temperature range of (30～180)℃, were shown in Fig. 3 and Fig. 4, among which, the dot lines and the solid lines indicated the measured and calculated results, respectively. As shown in these figures, the measured spectrums (measured by Zolix Inc., Omni-λ500) presented very good agreements with the theoretical results. These experimental results suggested that our calculations can be applied to build a mid-infrared laser system with a specific wavelength.

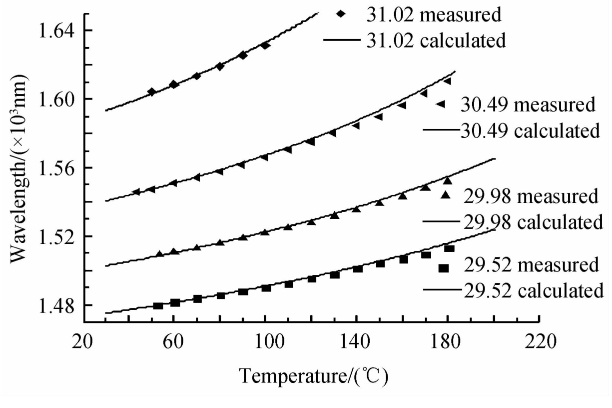

Fig. 3 The experimental signal wavelengths versus the temperature

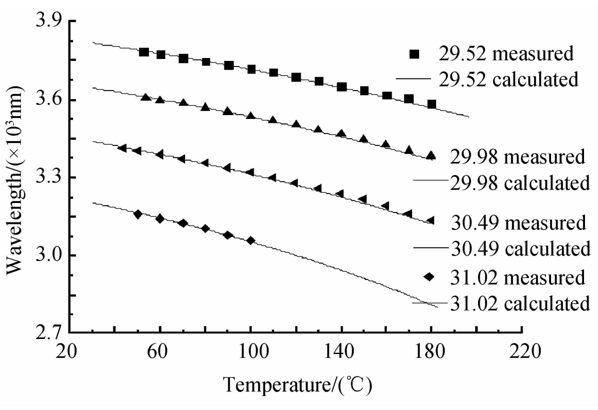

Fig. 4 The experimental idle wavelengths versus the temperature

Additionally, under the crystal operation of a poled period of 31.02 μm and 100℃, the wavelength of the signal light was displayed in Fig. 5, which was measured using a grating spectrometer (Zolix Inc., Omni-λ500) providing a spectral resolution of 0.2 nm. As marked in Fig. 5, the center wavelength of the laser was located at 1 631.4 nm, with a bandwidth (full width at half maximum) of about 0.3 nm.

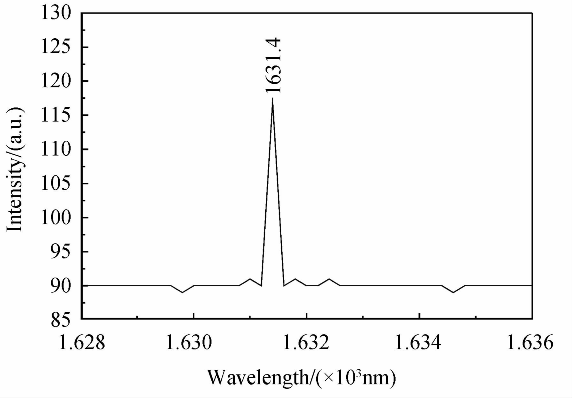

Fig. 5 The wavelength of the output signal light

The output characteristics of mid-infrared laser at 1.53 μm were experimentally investigated under different output couplers (OC) of 8.5%, 15.5% and 18%. The relationship between average signal output power and incident pump power at 808 nm were shown in Fig. 6. It can be seen from it that the highest average output power of 760 mW was achieved at the pumping power of 8.06 W with the OC of 8.5%. The output power was improved about 50% compared to that of 18%. Under different output couplers, the thresholds of the mid-infrared laser were observed about 3.2, 4.5 and 6.7 W, respectively. It was noticed that the decrease of OC was beneficial to improve the power intensity for effective frequency conversion.

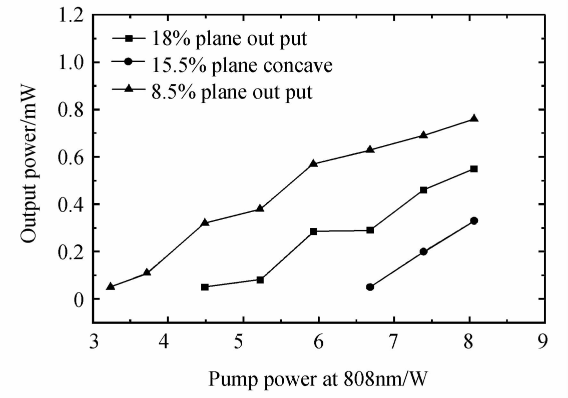

Fig. 6 Output signal power versus pump power at different OC

Fig. 7 presented the output power at the signal wavelength and idle wavelength with the poled period of 31.02 μm at 100℃ under the optimum OC. A maximum signal power of 760 mW and idler power of 360 mW has been obtained under a pump (808 nm) power of 8.06 W, with corresponding total optical efficiency of 13.9%. Moreover, since the pump power intensity was under the damage threshold of PPLN crystal, there is room for improving the output power. As shown in Fig. 7, it is obvious that the output power of signal is twice than that of idle due to the quantum efficiency. A good beam quality was obtained in out plane-plane ICSRO. The M_2 factors are about 1.99 and 1.46 in *X* and *Y* directions, respectively, measured by knife-edge technique. The asymmetry of the M_2 factor in two directions is possibly attributed to the small error caused by the focal lens. The power stability of the 1.5 μm laser was measured by a Model LPM-100 power meter and the fluctuation was about 5% at the maximum output power during 30 min of operation. This fluctuation may attribute to the variation of temperature in the laser and nonlinear crystal.

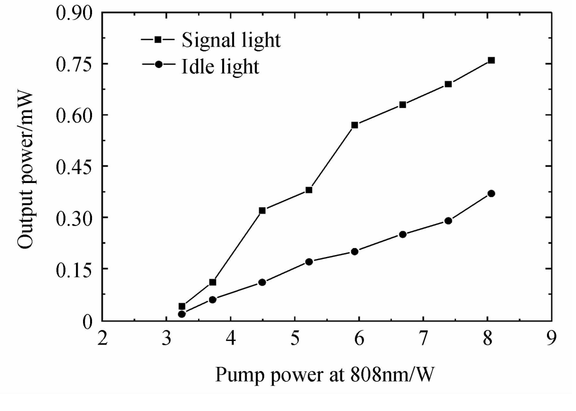

Fig. 7 The output power of signal and idle at the grating period of 29.98 μm

4 Conclusion

In summary, an optical parametric oscillator, based on a multi-periods MgO∶PPLN chip varied from 29.52 to 31.59 μm , was carried out. The mid-infrared laser from 1.48 to 1.63 μm was generated in this laser system, whose corresponding idler beam is from 3.0 to 3.8 μm. A maximum signal output power of 760 mW and idler power of 360 mW have been obtained with a pump power at 808nm of 8.06 W, under a poled period of 30.5 mm, with corresponding total optical efficiency being 13.9%. The flat-flat ICSRO presented a good beam quality, which indicates that it will be widely applied for many optical instruments as laser sources.

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