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Extra-cavity, widely tunable, continuous wave MgO-doped PPLN optical parametric oscillator pumped with a Nd:YVO_4 laser

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ABSTRACT

An extra-cavity, widely tunable, and continuous wave (CW) singly resonant optical parametric oscillator (SRO) based on MgO-doped periodically poled lithium niobate (PPMgLN) has been developed. A Nd:YVO_4 laser pumped by 808 nm laser diode array (LDA) is used as the pump source. The threshold value of the SRO system is only 1.86 W at 1064 nm. 1101.1 mW of idler output at 3.217 μm and 2004.3 mW of signal output at 1.590 μm have been achieved when the pump power is 8.76 W, and this corresponds to a total (idler + signal) optic–optic conversion efficiency of 35.5%. The periods of the domain structure on the PPMgLN wafer can be changed by shifting the PPMgLN crystal, thus enabling a widely tunable mid-infrared spectrum of 3.026–4.485 μm, and signal wavelengths widely tunable in range of 1.395–1.641 μm. Along with the signal and idler light, the visible and near-infrared spectrum (697.5–820.5 nm, 603.6–645.5 nm, 532 nm, 421.3–463.3 nm) is observed. This OPO system is compact, simple and operated at room temperature.

1. Introduction

The continuous wave optical parametric oscillator (OPO) has recently been established as a practical and efficient source of tunable near- to mid-infrared radiation [1–4]. The relative merits of singly resonant optical parametric oscillator (SRO) and doubly resonant optical parametric oscillator (DRO) have been understood for many years. SRO offers superior amplitude and spectral stability at the cost of a higher oscillation threshold. However, DRO offers a much lower oscillation threshold but generally has much lower spectral and amplitude stability [5,6]. In the CW regime, much work has gone into stabilizing DRO; but even with complex control loops and careful cavity design, continuous tuning is still limited to <10 GHz [7]. The first CW SRO was reported in 1993 based on a custom-built resonantly-doubled singly-frequency Nd:YAG pump laser with KTP, but tuning was impossible [8]. However, it demonstrated the key result of stable SRO behavior from a CW OPO device, and provided motivation for making CW SRO based on simpler device.

In recent years, the introduction of the congruent periodically poled lithium niobate (PPLN) crystal with a high nonlinear coefficient has lowered significantly the threshold for parametric processes and has increased their efficiency. Singly resonant, high efficient OPO systems based on PPLN and diode-pumped lasers have been demonstrated in both pulsed and CW regimes [9,10]. These devices are significant for applications including spectroscopy, atmospheric sensing and laser radar. However, its high coercive force and sensitivity to photorefractive effect limit its use in miniaturization of practical devices and high power applications. Compared to PPLN, the congruent PPMgLN crystal would be preferred. In this paper, we report an extra-cavity, CW, and widely tunable SRO based on PPMgLN. In contrast to the ring cavity [11], the symmetric linear cavity is very compact, simple and easy to adjust.

2. Properties of the nonlinear crystals

The first PPLN crystal was made of undoped congruent lithium niobate (CLN). However, CLN is subject to green-induced infrared absorption [12] and photorefractive damage at temperature below 150 °C, and suffers from high coercive field that limits the thickness of poling to about 0.5 mm (as shown in Table 1). In order to solve these drawbacks, two improvements are introduced: (1) growing stoichiometric (or near stoichiometric) lithium niobate (SLN) and lithium tantalite (SLT); (2) adding MgO to the crystal with typical 5% molar doping level (PPMgLN or MgO:cPPLN).

Periodically poled MgO-doped stoichiometric lithium tantalite (MgO:$LiTaO_3$) is a remarkable nonlinear material for CW OPO because of increased resistance to the photorefractive effect [13].

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Table 1
The properties of nonlinear crystals.

Crystal	Nonlinear coefficient (pm/V)	Photorefractive damage threshold	Optical damage threshold (532 nm)	Coercive field kV/mm	Length (mm)	OPO spectral range
PPLN	15–17	Low	Low	21	50	0.35–5 μm
Congruent PPMgLN	25.2	Moderate	Moderate	4.5	50	0.35–5 μm
Stoichiometric $MgO:LiTaO_3$	10	High	High	1.7–4.5	–	Visible, near-IR
PPKTP	16.7	High	High	2	20	–

However, most of papers focused on the visible and near-IR CW OPO rather than mid-infrared CW OPO. Other candidate for high-energy OPO devices is periodically poled $KTiOPO_4$ (PPKTP), which has high resistance to photorefractive effect and low coercive field. But the small nonlinear coefficient and short length (at present 20 mm) compared to PPMgLN means that the high oscillation threshold becomes unacceptably high for the PPKTP crystal. Of all the above crystals, the congruent PPMgLN crystal would be perfect. It has attractive material prosperities for quasi-phase-matched (QPM) devices, due to its greatly improved resistance to photorefractive damage, optical damage threshold and larger nonlinear coefficient.

Using the energy conservation law, the momentum conservation law and the Sellmeier equation of the PPMgLN crystal, we can obtain the tuning characteristic of this crystal. To the PPMgLN crystal, a Sellmeier equation for the extraordinary index of 5% MgO-doped congruent lithium niobate was obtained by O. Paul [14] as

$$n_e^2 = a_1 + b_1 f + \frac{a_2 + b_2 f}{\lambda^2 - a_3^2} + \frac{a_4 + b_3 f}{\lambda^2 - a_5^2} - a_6 \lambda^2 \tag{1}$$

In this equation, n_e is the extraordinary refractive index and λ is the wavelength of the generated light. The fitting parameters included in the equation are given following. $a_1 = 5.319725$, $a_2 = 0.09147285$, $a_3 = 0.3165008$, $a_4 = 100.2028$, $a_5 = 11.37639$, $a_6 = 1.497046 \times 10^{-2}$, $b_1 = 4.753469 \times 10^{-7}$, $b_2 = 3.310965 \times 10^{-8}$ and $b_3 = 2.760513 \times 10^{-5}$. f is the temperature parameter, and for temperatures T expressed in degrees Celsius, f is given by

$$f = (T - 24.5)(T + 570.82) \tag{2}$$

Take the periods of 27.4–31.4 μm for example, we calculated the tuning curves of the PPMgLN OPO system with many periods, as displayed in Fig. 1 ($T = 20$ °C). At room temperature, we can change the periods of the PPMgLN wafer and enable a widely tunable spectral range.

3. Experiment setup

The experimental setup was shown schematically in Fig. 2. The pump source of the OPO system was a $Nd:YVO_4$ laser. This laser was pumped by a fiber-coupled LDA with a center wavelength of 808 nm at 25 °C. The pump light was collimated and focused by focusing optics to a $YVO_4/Nd:YVO_4/YVO_4$ (3 mm:4 mm:3 mm) bonding crystal. The a-cut 0.5 at.% Nd^{3+}-doped $Nd:YVO_4$ crystal used in the experiment had a thickness of 4 mm. The crystal was wrapped with indium foil and mounted at a thermal electronic cooled (TEC) copper block, and the temperature was maintained at 20 °C. One side of the laser crystal (M_1) was anti-reflection (AR) coated at the pump wavelength of 808 nm and high-refection (HR) coated at the fundamental wavelength of 1.06 μm ($R > 99.9\%$) to act as a cavity mirror of the laser (input mirror); the other side was AR coated at 1.06 μm to reduce the cavity loss. The output coupler (M_2) had a transmission of 30% at 1.06 μm, and the cavity length was about 95 mm.

The resonator of the OPO system was consisted of two plane-concave mirrors (M_3, M_4) with 200 mm a radius-of-curvature, which were separated by 65 mm. The input (M_3) mirror had a HR coating at the signal radiation ($R > 99.8\%$ at 1.4–1.6 μm), a HR coating at the idler radiation ($R > 99\%$), and a high transmission (HT) coating ($T > 90\%$ at 1.064 μm) at the pump light; the output mirror (M_4) had a HR coating at the signal wavelength ($R = 95\%$ at 1.4–1.6 μm), a HT coating at the idler wavelength ($T > 95\%$ at 3.2–4.2 μm), and a HR coating at the pump light ($R > 99.8\%$ at 1.064 μm). We could deduce this OPO system was SRO. A lens with focal length of 50 mm was used to focus the pump beam into the PPMgLN crystal. The 5% MgO-doped PPLN crystal (HC Photonics Corp.) had an interaction length of 50 mm and a thickness of 1 mm. The crystal was of multi-grating form with 20 domain polling periods ranging from 27.6 to 31.4 μm with a constant step of 0.2 μm. The domain duty factor was about 50%. The crystal faces were broadband AR coated at 1.4–1.6 μm ($R < 2\%$), 3.2–4.2 μm ($R < 5\%$) and 1.064 μm ($R < 1.5\%$). During the experiment, the PPMgLN wafer was kept working at room temperature by putting it onto a copper stage to keep temperature unchanged. No additional heating facility was used.

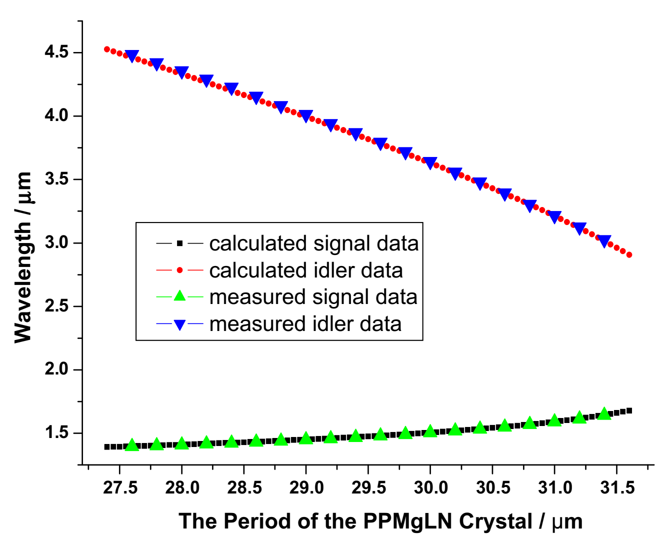

Fig. 1. The tuning curves of the OPO system versus the period of the PPMgLN crystal ($T = 20$ °C).

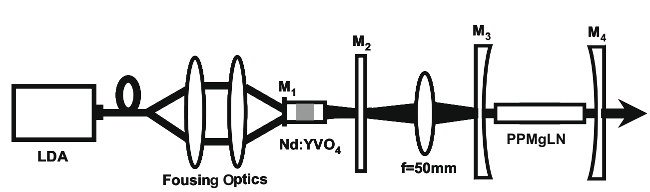

Fig. 2. Schematic of the PPMgLN OPO system.