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High-power, high-repetition-rate mid-infrared generation with PE-SRO based on a fan-out periodically poled MgO-doped lithium niobate

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ABSTRACT

We present a high-average-power, pulsed mid-infrared pump-enhanced singly-resonant optical parametric oscillator (PE-SRO) using a fan-out periodically poled MgO-doped lithium niobate (MgO:PPLN). The pump laser is a Q-switched Nd:YAG laser with a repetition rate of 10 kHz. When the pump power was 22.0 W, a maximum idler output power of 3.4 W at 3781.4 nm was obtained. The thermal guiding effect caused by signal absorption was observed and the crystal heating power was measured with a new method.

1. Introduction

Tunable mid-infrared (MIR) lasers (3–5 μm) are attractive for a variety of applications such as laser spectroscopy, imaging laser radar and MIR countermeasures [1]. The methods for generating MIR lasers include the solid state lasers with Er:YAG crystal [2], chemical DF lasers [3] and diode lasers with GaInAsSb/AlGaAsSb media [4]. Quasi-phase-matched (QPM) OPOs based on MgO:PPLN, with the ability of converting single-wavelength near-infrared (NIR) lasers into continuously tunable MIR lasers efficiently, have become increasingly promising approach for MIR laser sources [5,6].

In recent years, research on MgO:PPLN OPOs mostly focused on those operated in the continuous-wave (CW) regime [7–10]. CW OPOs with high-power output have been developed [8,9]. Nevertheless, when CW OPOs with high finesse operate in high-power levels, the intra-cavity average power would be extremely high. This power heats the crystal and cause thermal effects, which degrades the OPOs' conversion efficiency and output beam quality [10,11]. Consequently, the crystal heating power induced by intra-cavity laser absorption was investigated in detail [11].

On the other hand, pulsed OPOs with high-average-power output are often desirable in applications where rapid pulsing is required. For instance, repetition rate about 10 kHz is required to produce an image frame in a reasonable time in applications for imaging laser radar. Besides, tunable MIR laser sources with a repetition rate >10 kHz are also candidate sources for MIR countermeasures, i.e., jamming heat seeking missiles, in which high-repetition rate is necessary to jam effectively [12]. N. Dixit obtained 140 mW output power of 10 kHz pulsed idler at 3.47 μm with a pump power of 1.92 W using 1-mm-thick MgO:PPLN [13]. P.D. Mason obtained 2.2 W of idler output power around 3.85 μm with a pump power of 18.7 W operating at 10 kHz and finally obtained 3.7 W of idler power based on polarization recombination with a total pump power of 36.5 W [14]. For pulsed OPOs, the peak power intensity of pump laser in the nonlinear crystals would be hundreds of times to that in CW OPOs. So the output average power is limited in case of laser damage of crystals. In order to decrease pump power intensity in the crystals, large pump beam waist should be applied for crystals with large apertures. In addition, the intra-cavity peak power of pulsed OPOs is much higher, which would absolutely cause severe crystal heating and thermal effects. Research on this is important for pulsed OPOs with high-power output.

In this work we used a 2-mm-thick fan-out MgO:PPLN crystal to construct a pump-enhanced singly-resonant optical parametric oscillator (PE-SRO) operating at a repetition rate of 10 kHz. For a pump average power of 22.0 W, the maximum idler output average power at 3781.4 nm arrived at 3.4 W. The signal output wavelength showed significant shift to longer direction, corresponding to a rise of 23 °C in crystal temperature. The crystal heating power induced by laser absorption was measured to be 4.8 W with a new method.

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We adopted a linear cavity configuration for QPM OPO, as shown in Fig. 1. The homemade Q-switched Nd:YAG laser was used to pump the QPM OPO, which generated a near diffraction limited laser output (M^2 ~ 1.5). The pump source could produce a maximum output power of 32 W at 1.064 μm with 60 ns pulses at a repetition rate of 10 kHz. In order to prevent feedback, an optical isolator, as shown in the dashed box in Fig. 1, was placed in-line after the pump laser. The isolator was actually constructed in-house, which was composed of 2 half wave plates (HWP1 & HWP2), 2 thin film polarizers (TFP1 & TFP 2) and a 45° Faraday rotator. Another function of the isolator was to polarize the beam. The polarization of the pump beam was set parallel to the z-axis of the crystal. The maximum pump laser after the isolator decreased to 22.0 W. In the experiment the pump laser kept the maximum output and a variable attenuator was applied to change the pump power with keeping the pump beam characteristics (i.e., beam quality, pulse width, pointing) constant.

The nonlinear crystal utilized in the experiment is a periodically poled 5 mol% MgO-doped congruent lithium niobate (MgO:PPLN) with a dimension of $30\times12\times2$ mm^3 in the x, y, and z directions respectively (supplied by HC Photonics Corporation), which possesses higher photorefractive damage threshold [15]. The crystal was fan-out periodically poled with grating periods varying from 26.9 to 29.5 μm continuously across the y-axis. The pump beam was loosely focused to yield a beam waist diameter of 0.6 mm in the MgO:PPLN crystal by a convex lens with a focal length of 800 mm. The end faces of the MgO:PPLN crystal were AR coated for signal, idler and pump (R<1%@1.3–1.5 μm, R<1.5%@3.6–4.7 μm, and R<2%@1.064 μm). The crystal was placed in a temperature control oven and operated at 80 ± 0.1 °C.

The OPO mirrors were designed for pump-enhanced singly-resonant OPO (PE-SRO) operation (only signal resonated), which would attain low oscillation threshold [16]. The symmetric flat–flat OPO resonator has a physical length of 65 mm. The input coupler of the OPO cavity M1 was highly transmitted (HT) coated at 1.064 μm, highly reflected (HR) coated in signal waveband 1.3–1.5 μm (R>99.9%) and HR coated in idler waveband 3.6–4.7 μm (R>99.0%). The output coupler of the OPO cavity mirror M2 is a coated CaF_2 substrate, then HR coated at 1.064 μm, HR coated in signal waveband (R>99.5%) and HT coated in idler waveband (T>98.0%). Idler would mostly be extracted from M2. The filter M3 (HR at signal, pump and HT at idler) after M2 was used to separate the idler from the signal and residual pump.

In the experiment, the MgO:PPLN crystal was first pumped at a grating period of 29.35 μm. For the PE-SRO design, the pump laser double passes the gain-media, which reduces the oscillation threshold. The threshold was found to be 5.8 W, corresponding to a peak pump power intensity of 3.4 MW/cm^2. This is about 3 times to the predicted result by theory [16]. The resonant signal beam radius for flat–flat cavity would be several times to pump beam, which rapidly decreased spatial mode couple coefficient between pump and signal. This might account for the increased oscillation threshold in the experiment. With pump power a little more than threshold, the wavelength of signal was measured to be 1475.8 nm and idler was deduced to be 3813.1 nm. This result is in excellent agreement with the theoretically predicted one derived from the Sellmeier equations for 5 mol% MgO-doped congruent LN [17]. As the residual pump power leaking from M2 was too low and could be ignored, the pump reflected by the thin film polarizer TFP1 of the isolator (As shown in Fig. 1) was measured to be the depleted pump.

Fig. 2 shows the idler output and Fig. 3 shows the pump depletion efficiency as pump power increased from 0 to 22 W and back to 0 W. There was a step increase of the idler output from 1.5 W to 3.0 W and depletion efficiency from 35% to 70.4% when the pump power was increased to 17.9 W. We also measured the beam quality of the idler by measuring the size of laser spot using the knife-edge method and hyperbolic fitting the data. The M^2 factors of idler were 3.2 with 16.3 W pump and 2.0 with 22.0 W pump respectively. As the input and output couplers of the OPO resonator were both HR at signal wavelength, the intra-cavity circulating signal power was extremely high. The MgO:PPLN crystal absorbed the signal power and then thermally induced optical guiding appeared with pump power above 17.9 W. The thermally guiding could greatly enhance the mode overlap among mixing waves and thus increased the parametric conversion efficiency and beam quality sharply [18]. The adverse thermal effects in the conventional view [10,11] was surprisingly helpful in increasing parametric efficiency and idler beam quality in our experiment. The reason for this was that the absorption-induced crystal heating in references [10] and [11] mainly caused beam distortion, which was disadvantageous to beam quality of output, just like the condition with pump power of 16.3 W in our experiment. While the pump power increased above 17.9 W in our experiment, the increased crystal heating was sufficient to turn the disadvantageous beam distortion effect into the optical guiding effect in our OPO, which was advantageous to improve the OPO parametric efficiency and idler beam quality. Slight hysteresis occurs for idler output and pump depletion efficiency when pump power decreased back to 0 W, which is another evidence for thermal guiding effect.

The idler output and pump depletion efficiency arrived at 78% and 3.4 W respectively with the maximum pump power of 22.0 W. Idler wavelength shifted to 3781.4 nm for crystal heating, which would be studied in detail next. Idler output didn't arrive at the saturation with the maximum pump power, which implies that further scaling of idler output is possible as pump power increases. On the other hand, if pump power increases, laser damage of the MgO:PPLN crystal must be considered. In our future experiment, we can apply larger pump beam diameter (>1 mm) in the crystal with 2 mm thickness, which would lower the pump intensity effectively and protect the crystal from laser damage.

To further characterize the power stability of our OPO, we recorded the time evolution of the output power for a time period of 750 s with the maximum pump power of 22 W. Fig. 4 shows the temporal stability of the idler output power. The instability of the output is about ±3.5%, which shows the OPO output has a good temporal stability.

In generally, a flat–flat cavity is a critical unstable resonator, which is sensitive to cavity mirror misalignment and will suffer bad temporal stability. But our OPO showed good performances on these. We submit this to the thermal guiding effect of the nonlinear crystal too. The thermal guiding induced by signal absorption inside the resonator made

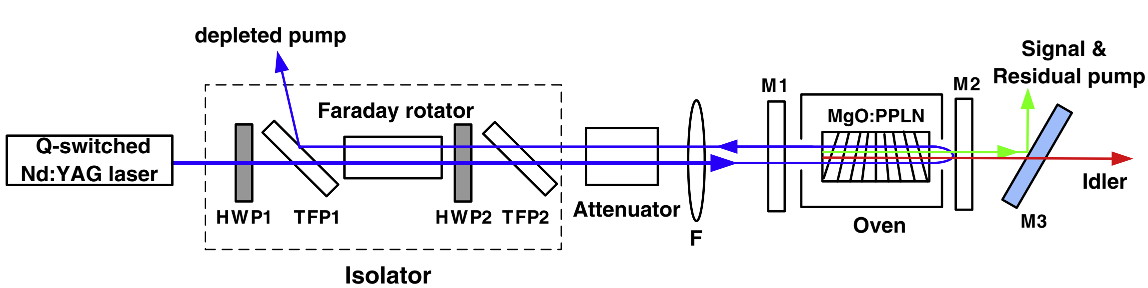

Fig. 1. Schematic of experiment setup of the MgO:PPLN OPO. HWP1 and HWP2: half wave plate, TFP1 and TFP2: thin film polarizer, F: focal lens, M1: input mirror, M2: output mirror, and M3: filter.