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Stable, high-average-power, continuous-wave singly resonant optical parametric oscillation based on angle-polished MgO:PPLN

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Abstract: We report a stable, high-power, continuous-wave (cw) optical parametric oscillator (OPO) pumped at 1064nm by a commercial Nd:YVO_4 solid-state laser. The oscillator is singly resonant, based on an angle-polished MgO-doped periodically poled $LiNbO_3$ (MgO:PPLN) in a four-mirror ring cavity. Maximum output idler up to 2.15 W is achieved at 3069.1 nm with 9.8 W of pump power, corresponding to a pump-to-idler conversion efficiency of 21.9%. The device exhibits excellent power stability better than 0.19% rms over 30 minutes, which is related to the reduced intracavity residual reflections and thermal self-locking effect.

Key words: continuous-wave, singly resonant optical parametric oscillator (OPO), angle-polished, stable

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基于角度切割 MgO:PPLN 晶体的高平均功率、稳定的连续波单振荡光学参量振荡器

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摘要:报道了一台稳定的、高平均功率连续波光学参量振荡器,该振荡器为单谐振环形腔结构,参量晶体为角度切割的掺氧化镁周期性极化铌酸锂(MgO:PPLN),由一台波长为 1064 nm 的 Nd:YVO_4 固态激光器泵浦.在 9.8 W 的泵浦功率下,可得到波长 3 069.1 nm 的闲频光功率 2.15 W,其泵浦-闲频光转换效率达 21.9%.得益于腔内寄生振荡的减弱以及热自稳效应,振荡器的输出功率在 30 min 内的稳定性优于 0.19% 均方根偏差(rms).

关 键 词:连续波;单谐振光学参量振荡器;角度切割;稳定

中图分类号:TN248.1;O437.4 **文献标识码**:A

Introduction

High power, stable laser sources with broadband tunability in the near- to mid-infrared (mid-IR) region are of great interest in many applications, such as trace gas detection[1-2], high-resolution molecular spectroscopy[3-4], free-space communication[5], and so on. Among available sources, singly resonant optical parametric oscillators (SROs) have emerged as attractive mid-IR

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sources for their well-known advantageous conversion efficiency and stability. In cw SROs, only one parametric light is resonating inside the cavity to avoid mode competition with the idler. In this way stable operation can be easily obtained, making them well suited for applications mentioned above. The first cw SRO was demonstrated by Yang et al. in 1993, based on $KTiOPO_4$ and pumped by a custom-built, resonantly doubled, single-frequency Nd:YAG laser[6-7]. In 1996, 93% pump depletion, 3.5 W mid-IR laser output was performed from PPLN-SRO by Bosenberg *et al.*, using both a four-mirror linear and ring cavity[8]. Henceforward four-mirror ring cavity has become a common choice when pursuing stable cw OPOs due to its less insensitive to mechanical perturbations, with a single selected wave resonating unidirectionally.

However, a crystal without angle-polishing, namely a non-angle-polished crystal, with imperfect coatings can be detrimental to the stability due to the residual reflections at the faces of the nonlinear crystals in high power OPOs. Utilizing a non-angle-polished PPLN, Gross *et al.* achieved a power stability of 1% rms over 1 hour at a power level of 1.8 W from 7.3 W pump power[9]. The residual reflection between two faces of the crystal may even lead to an undesirable high intensity inside the cavity, resulting in Raman lasing[10] or cascaded optical parametric oscillations[11]. Although the frequency and power stability optimizing is possible with an intracavity etalon or particular mechanical stabilization, it was a tradeoff at the expense of complexity or supplementary losses. On the contrary, when an angle-polished (1°) MgO:PPLN was employed as the nonlinear crystal, with a Teflon cover for air currents protection and thermal isolation, excellent power stability can be achieved even in a linear cavity[12]. It is well believed that angle-polishing of crystals which reduces residual reflections and etalon effects at the faces of the nonlinear crystal does matter in stability of high power OPOs.

In this paper, we present a cw SRO based on an angle-polished MgO:PPLN in a four-mirror ring cavity. The angle-polished crystal together with the unidirectional ring cavity contribute to achieving superior stability as well as high conversion efficiency. The cw SRO is pumped by a Nd:YVO_4 solid-state laser at 1064 nm. Maximum idler power up to 2.15 W is achieved at 3069.1 nm for 9.8 W of pump power, indicating a conversion efficiency of 21.9% from pump to idler. Moreover, the cw SRO exhibits power stability of better than 0.19% over 30 minutes even no particular stabilizing measures are applied. We also compared the different performance of the angle-polished PPLN with another one that is not angle-polished in the identical configuration, revealing the vital role of the angle-polishing issue in a stable, high-power OPO.

1 Experimental design

The schematic of our experimental setup is depicted in Fig. 1. The pump source is a cw Nd:YVO_4-laser, delivering up to 9.8 W at 1 064 nm with a 0.8 mm diameter in TEM_{00} spatial mode ($M^2 < 1.2$). The optical cavity is a four-mirror bow-tie ring, essentially identical to that used in the early work of Bosenberg *et al.*[8], comprising two concave mirrors, M_1 and M_2 ($r = 100$ mm), and two plane mirrors, M_3 and M_4. The total cavity length is 460 mm. All mirrors are highly reflective at the signal wavelength ($R > 99.9\%$) and highly transparent for the pump ($R < 2\%$) and idler ($R < 5\%$), ensuring the purely singly resonance. The nonlinear crystal is a 5% doped MgO:PPLN (HC Photonics, Taiwan) with a dimension of $50 \times 8.6 \times 1$ mm^3, containing 7 separate gratings with poling periods from $\Lambda = 28.5$ μm to 31.5 μm in a step of 0.5 μm. In our experiment, the OPO is operating at $\Lambda = 31$ μm, $T = 90$ ℃, with an idler wavelength of 3069.1 nm. To avoid residual etalons, both end faces are broadband antireflection coated for wavelengths at pump ($R < 2\%$), signal ($R < 1.5\%$), and idler ($R < 5\%$), and one of the end faces is angle (0.7°) polished. The crystal is housed in an oven of which the temperature can be stabilized within ±0.1 ℃ anywhere from room temperature to 200 ℃.

The pump beam is confocally focused to yield a beam waist of ~50 μm inside the crystal by a single lens ($f = 75$ mm), while the resonant signal inside the cavity has a beam radius of 71 μm at the center of the crystal, estimated by the ABCD matrix formalism. Focusing parameters of the pump (ξ_p) and signal (ξ_s) beam are 1.6 and 1.2, respectively. A dichroic mirror, M, separates the generated idler output from the residual pump and signal radiation.

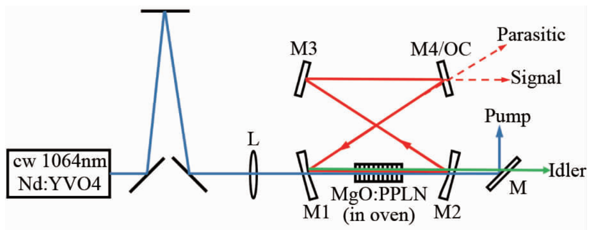

Fig. 1 Schematic of the cw SRO based on MgO:PPLN in a bow-tie ring cavity. L: lens, M: dichronic mirror
图 1 基 MgO:PPLN 晶体的四镜环形腔结构的单谐振光学参量振荡器示意图. L :透镜,M:分光镜

2 Results and discussions

The idler output power generated from the SRO at 3 069.1 nm ($\Lambda = 31$ μm, $T = 90$ ℃) versus pump is shown in Fig. 2, indicating a threshold of ~2.4 W. With the maximum pump power of 9.8 W, idler power up to 2.15 W can be obtained. Note that no realignment of the cavity is made during the pump power scaling. A distinct kink in the input-versus-output curve separates the curve into two region. Below this kink the slope efficiency is ~40% while above that it reduces to ~20%, which is believed to be mainly resulted from saturation of the pump depletion[8]. This occurs at ~2.3 times the threshold, in good agreement with earlier theoretical study, where the optimal conversion efficiency and pump depletion of SRO is predicted for pumping at $(\pi/2)^2$ the oscillation threshold in the plane-wave approximation[13]. Compared with a previous study with similar configuration[8], our OPO has a lower threshold together with a slightly poorer slope efficiency. This can be ascribed to the smaller pump bean waist in our experiment. The smaller beam waist can provide a higher intensity as well as a smaller pump mode volume, which, however, prevent from making full use of the crystal. Moreover, the pump and signal focusing parameters in our experiment are not equal to each other within the range $1 < \xi < 7$, slightly deviating from the theoretical optimal condition[14-15].

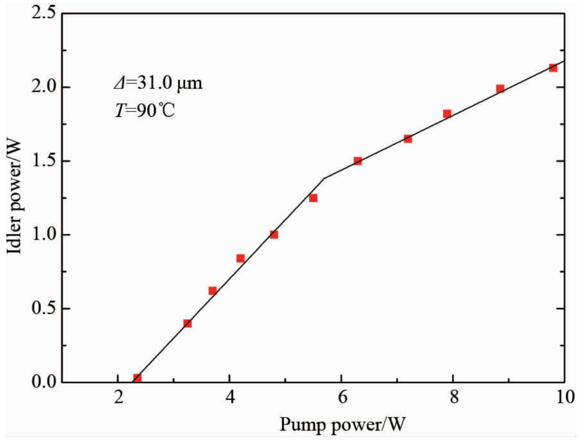

Fig. 2 Idler output versus pump power for the SRO at an idler wavelength of 3 069. 1 nm (Λ = 31 μm, T = 90℃ for MgO:PPLN)
图 2 单谐振振荡器输出的波长 3 069. 1 nm 的闲频光随泵浦功率变化规律. MgO:PPLN 晶体周期为 31 μm,工作温度为 90℃

The idler power stability of the MgO:PPLN cw SRO at maximum output power of 2. 15 W was detected by a power meter (Spectra-Physics, 407A), with the result shown in Fig. 3. The corresponding signal spectrum recorded with a spectrometer (Zolix, DEC-M204) is shown as the inset of Fig. 3. The idler exhibits a power stability better than 0. 19% rms over 30 minutes, better than the 0. 5% one of another PPLN cw SRO, which is among the best stabilities in the similar power level and without special stabilizing measures[16]. There are at least three effects that may account for the observed superior stability of the cw SRO. First, the SRO ring cavity operates unidirectionally, since all mirrors are specially coated and the crystal is angle-polished to avoid residual etalon effect or reflections. Second, although there is a high intensity inside the cavity due to the resonating signal, other complex nonlinear processes are ignorable compared with the primary parametric process. In these ways, the signal is singly and unidirectionally resonant inside the cavity without mode competition with other wavelength components. Third, a strong thermal self-locking related to absorption in the nonlinear crystal is suggested, which attempts to minimize frequency drift between the signal and parametric gain maximum[17-18]. Small frequency fluctuations can be compensated by the thermal self-locking, which relaxes the requirements for thermal and mechanical stability of the crystal and cavity, hence trying to maintain a constant output power. The fact that our cw OPO operates stably with a temperature control precision of only ±0. 1 K and without particular protection from air currents or other disturbances, shows approval to this explanation.

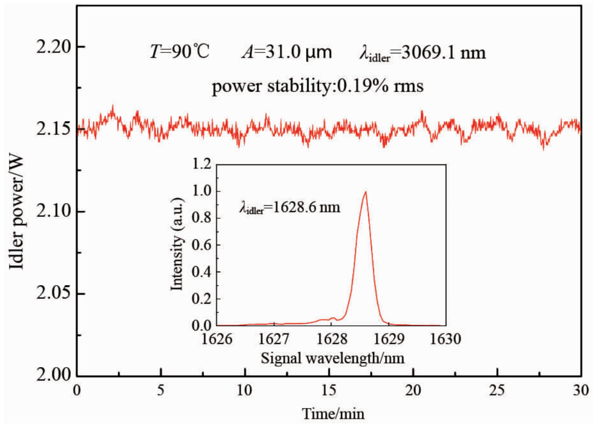

Fig. 3 Idler power stability over 30 minutes at pump power of 9. 8 W
图 3 在 9. 8 W 泵浦光功率下,闲频光功率. 在 30 分钟内的稳定性

To further study the high performance of the OPO on stability, we replace the angle-polished PPLN with another one, which is non-angle-polished. It is interesting to note that, although there is only one difference that whether the crystal is angle polished or not, between these two experiments, the results just come out quite differently. When operating with a non-angle-polished PPLN, the OPO is flickering with the visible radiations generated from complex nonlinear processes. The idler output is observably unstable, with a power fluctuation of ~5% in less than 30 seconds. It is believed that a higher intracavity intensity results in the difference performance. When the OPO operates with a non-angle-polished crystal, residual reflection is brought in by both of the crystal end faces. The residual reflection can be even significant to induce a parasitic oscillation in an opposite direction to the primary oscillation, hence leading to a higher intracavity intensity, particularly inside the crystal. Consequently, apart from the primary optical parametric process, complex nonlinear processes including sum frequency generation (SFG), second or even third harmonic generation (SHG/THG) arise inside the cavity, generating radiations in visible wavelength range. Moreover, by measuring the spectrum of signal leaked out from the OPO, additional spectral component together with the peak at the expected signal wavelength was observed, usually red-shifted towards the longer wavelength by ~12 nm (shown in Fig. 4). This is believed to arise from the cascaded optical parametric oscillations[11] induced by the extremely intensive power of the signal inside the cavity. With a partly transmitting output coupler (T ~1. 5%, depending on the signal wavelength) instead of a plane mirror M_4 that is highly reflective (R >99. 9%), the signal is coupled out in two directions as shown in Fig. 1, confirming a parasitic oscillation inside the cavity. The beam power of the signal and parasitic one are measured to be ~2 W and ~0. 5 W, respectively. By angle-tilting the crystal, the parasitic reduce to 0.2 W but cannot be completely eliminated. Since both crystals are from the same manufacturer with the same coating specification, the difference in quality is believed to be small, hence confirms the effect of angle-polishing.

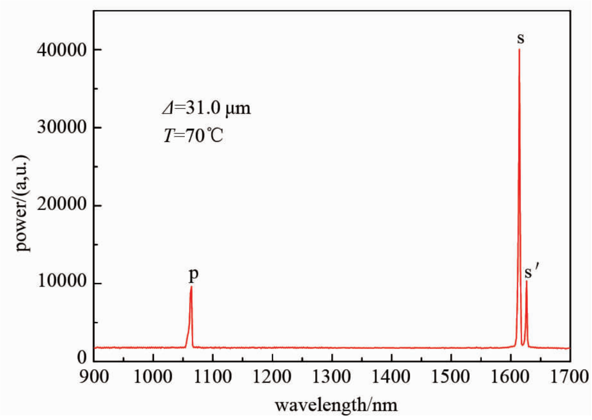

Fig. 4 Spectrum of the pump (p), signal (s) and the additional component (s') caused by the cascaded OPO in a SRO based on a non-angle-polished PPLN

图4 泵浦光、信号光以及因基于无切角 PPLN 晶体单谐振振荡器内级联 OPO 效应产生附加光谱成分的光谱图

3 Conclusion

To date, most of the cw SROs reported are based on the ring cavity, which is commonly considered to have superior stability properties compared with the linear cavity. Enhanced efficiency as well as stability can be obtained by taking advantage of the fact that ring cavity can be designed with more degrees of freedom and is unidirectional in operation. However, a non-angle-polished crystal with imperfect coating can be detrimental to the stable operation by bringing in residual reflections, which has been experimentally confirmed in our study by using a partly transmitting output coupler instead of a highly reflective plane mirror. Without particular stabilization, we have achieved a stable, high-power cw SRO with high conversion efficiency, utilizing an angle-polished MgO:PPLN as the nonlinear crystal. The maximum output power is up to 2.15 W at 3069.1 nm, corresponding to a 21.9% conversion efficiency. In addition, an outstanding power stability of 0.19% rms over 30 minutes was observed, revealing the vital role of the angle-polishing issue when pursuing a stable, high-power OPO. Future research will be directed at operating at a higher level of power, by optimizing the conversion efficiency and introducing an output coupler or a volume Bragg grating. The spectral and tuning properties of the output will be studied in order to achieve mode-hop-free tuning.

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