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Compact efficient optical parametric generator internal to a Q-switched Nd : YVO_4 laser with periodically poled MgO:$LiNbO_3$*

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This paper demonstrates a compact efficient optical parametric generator internal to a Q-switched diode-end-pumped Nd:YVO_4 laser with periodically poled MgO:$LiNbO_3$(PPMgLN). With the Q-switch set at a repetition rate of 25 kHz and the PPMgLN crystal operated at room temperature (25°C), the intracavity optical parametric generator threshold was reached as a diode pump power of 0.9 W. A maximum signal output power of 0.34 W with a pulse width of 25 ns and a beam quality factor of 1.4 was obtained at an incident diode power of 3.4 W, leading to a conversion efficiency of 10% with a slope efficiency of 14.4%. By varying the crystal temperature from 25 to 200°C, the output signal wavelengths were tuned in range of 1506–1565 nm. Over a 30-minutes interval, the instability of the signal power was measured to be less than 1%. In addition, the threshold pump intensity for the intracavity optical parametric generator is theoretically investigated, and the obtained result is in good agreement with the experimental results.

Keywords: quasi-phase-matching, intracavity optical parametric generator, periodically poled MgO-doped lithium niobate (PPMgLN)

PACC: 4265K, 4260F, 4270

1. Introduction

Compact tunable optical sources have gained much attention in applications involving ranging, remote sensing, optical tomography and spectroscopy. Optical parametric generators (OPGs) are regarded as attractive devices with relatively simple configuration of tunable coherent radiation.[1−7] Currently, the most widespread scheme for constructing an OPG is the extracavity OPGs, in which the pump laser and the OPG are separate elements. Since a macroscopic power is directly amplified from quantum fluctuations through a single-pass or multiple-pass configuration, the threshold of an extracavity OPG is high and OPG is not easy to achieve. In order to overcome this disadvantage, the nonlinear crystal can be located directly within the pump laser cavity to exploit high circulating power levels and use multiple round trips of the pump laser to increase the effective interaction length, which is referred to as intracavity optical parametric generators (IOPGs). Therefore, the IOPGs can give a much lower threshold and higher conversion efficiency.

Although the successful poling of periodically poled lithium niobate (PPLN) has significantly promoted the development of the quasi-phase-matching (QPM) as a practical technique in nonlinear optics, the material itself is limited to certain important limitations.[8] The high coercive field required to invert the crystal domain polarity usually indicates a relatively thin poled thickness and the elimination of the photorefractive damage needs to be operated at an elevated crystal temperature. As a much more promising candidate for PPLN, $LiNbO_3$ doped with MgO is characterized to have a higher resistance to the photorefractive damage so that it can be operated at room temperature. Meanwhile, a much lower coercive field means that it's much easier to fabricate a thicker QPM device for high energy conversion efficiency.[9−11]

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In our previous works, we have demonstrated an IOPG based on PPLN with a conversion efficiency of 5.6%, in which the PPLN crystal was heated to a very high temperature in order to avoid photorefractive damage.[12] In this paper we report a more efficient IOPG with PPMgLN that was operated at room temperature (25°C). A maximum signal output power of 0.34 W with a repetition rate of 25 kHz, a pulse width of 25 ns, a beam quality factor of 1.4 and an instability of 1% was obtained, leading to 10% conversion efficiency. Moreover, the theoretical values of the threshold pump intensity for the IOPG were calculated, which show good agreement with the experimental results.

2. Experimental setup

The PPMgLN IOPG setup is illustrated in Fig.1. The IOPG employed an a-cut 0.4-at% doped, 8-mm-long Nd:YVO_4 crystal as the laser material and a QPM PPMgLN crystal as the nonlinear material. The pump source was a water-cooled, fibre coupled diode laser emitting at 808 nm with a core diameter of 400 μm and a numerical aperture of 0.22. A coupling lens with $> 90\%$ coupling efficiency was used to focus the pump radiation into gain medium to a circular spot of 300 μm diameter. Such a selection of the crystal length and doping concentration was to avoid thermally induced fracture and to absorb a significant portion of the pump energy.[13] The laser crystal was wrapped with indium foil and mounted in water-cooled copper blocks. The water temperature was maintained at 18°C. The input facet of the crystal was coated to transmit the diode laser at 808 nm and to have a high reflectivity (HR) at 1064 nm to serve as one of the cavity mirrors. The other facet was antireflection (AR) coated at 1064 nm. M1 was a concave mirror with 200 nm radius of curvature to provide a focus of the cavity mode at the location of the PPMgLN crystal and M2 was a concave mirror with 100 nm radius of curvature. Both of the mirrors were HR-coated at 1064 nm ($R > 99.8\%$) without any special transmission coatings within the signal wavelength range of 1500–1600 nm. The measured transmission curves of M1 and M2 in the signal wavelength are nearly flat and the transmission was approximately 80%. To reduce the pump beam astigmatism induced by the folded configuration, the incident angle on M1 was set as small as 9°. Since mirror substrates were made of K9 glass, most of the idler generated by the IOPG was absorbed into the substrates. The feedbacks at the idler and signal wavelengths were $< 1\%$, which satisfied the operation condition for the IOPG and permitted the signal output to be extracted in two directions. The repetition rate of the acousto-optic Q-switch used in the experiment could be continuously varied from 1 kHz to 50 kHz. The PPMgLN crystal was periodically poled along the crystal z-axis with a grating period of 30 μm and a length of 50 nm, supplied by HC Photonics, Taiwan.[14] Both facets of the crystal were AR coated with reflections of less than 1%, 1% and 3% for the pump, the signal and the idler wavelengths, respectively. The PPMgLN crystal was mounted in an oven which allowed variation of the temperature in the range 25–200°C with a stability of ±0.1°C. The three-mirror cavity consisted of a slightly focused region formed by mirrors M1 and M2, yielding a waist size of 135 μm for the 1064 nm pump laser. The PPMgLN crystal was located at the intracavity focus location. The polarization of the 1064 nm pump laser was set parallel to the z-axis of the PPMgLN crystal to access the largest nonlinear tensor coefficient of d_{33}.

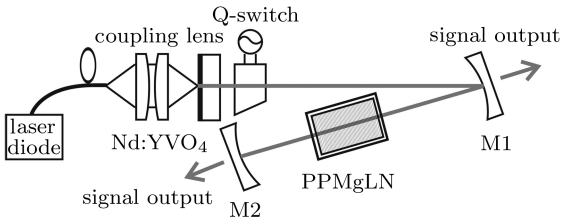


Fig.1. Experimental setup for the IOPG with PPMgLN internal to a Q-switched diode-end-pumped Nd:YVO_4 laser.

3. Results and discussion

During the experiments, the PPMgLN crystal was first kept at room temperature (25°C). A maximum average signal output power of 0.34 W was generated for an incident diode power of 3.4 W at a Q-switch repetition rate of 25 kHz, leading to a conversion efficiency of 10% from the diode input power to the signal output power. The output power was limited due to partial extraction at the uncoated cavity mirrors, so higher signal output power could be expected if the mirrors could be AR coated in the signal wavelengths. Figure 2 depicts the average signal power as a function of the Q-switch repletion rate for an input diode

power of 3.4 W. To avoid damage to intracavity optical components, the Q-switch was operated at repetition rates above 10 kHz.

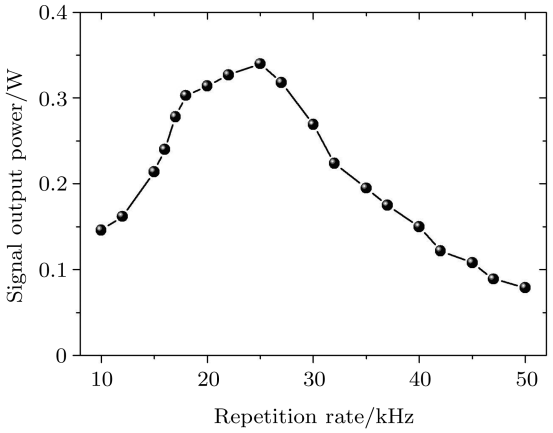


Fig.2. The signal output power as a function of the Q-switch repetition rate for an incident diode power of 3.4 W.

Figure 3 depicts a typical plot of the measured average power of the signal radiation at the repetition rate of 25 kHz. The measurements show that the average signal powers vary almost linearly with the input diode power above threshold. The slope efficiency from the diode input power to the signal output power was 14.4%. With further increasing the diode power, the signal output was saturated and increased very slowly. We attributed this degradation of the IOPG laser to the significant thermal effects in the Nd:YVO_4 and PPMgLN, which degraded the pump field's mode quality at the higher intracavity fields. Because the substrates of the cavity mirrors absorbed most of the idler waves in the range of 3–4 μm, only the signal output was extracted and measured. At the maximum output power, the beam quality M^2 factor was measured to be 1.4. The amplitude instability of the signal wave was less than 1% (rms) during half an hour.

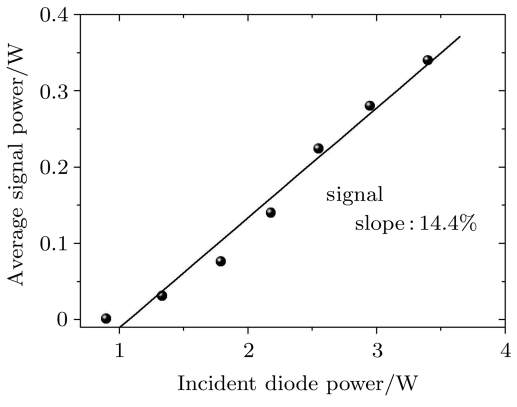


Fig.3. The average signal output power as a function of the incident diode power at a Q-switch repetition rate of 25 kHz.

For the OPG, the signal is assumed to be amplified from one photon parametric noise. Thus the threshold of the pump intensity I_p can be expressed as [15]

$$KI_\mathrm{p} = \left[\frac{1}{2l}\ln\left(\frac{4\lambda_\mathrm{s}E_\mathrm{s}}{hc}\right)\right]^2, \qquad (1)$$

where $K = \dfrac{8\pi^2 d_\mathrm{eff}^2}{\varepsilon_0 c\lambda_\mathrm{s}\lambda_\mathrm{i}n_\mathrm{s}n_\mathrm{i}n_\mathrm{p}}$, h is Planck's constant, c is the speed of light, ε_0 is the dielectric constant of the free space, d_eff is the effective nonlinear coefficient, l is the nonlinear crystal length, λ is the wavelength, n is the refractive index, the subscript s, i and p denote signal, idler, and pump frequency, respectively, E_s is the signal pulse energy when the OPG reaches the threshold. Here, the IOPG threshold is determined by measuring the diode-pump power when an average signal output power of 1 mW is achieved, in agreement with Ref.[2]. The measured IOPG threshold was 0.9 W at 25 kHz repetition rate.

For the above experiment, $\lambda_\mathrm{s} = 1.506\,\mu$m, $\lambda_\mathrm{i} = 3.629\,\mu$m, $\lambda_\mathrm{p} = 1.064\,\mu$m, $n_\mathrm{s} = 2.14$, $n_\mathrm{i} = 2.07$, $n_\mathrm{p} = 2.16$, $E_\mathrm{s} = 40$ nJ. The nonlinear coefficient d_{33} of the 5% MgO:$LiNbO_3$ at 1.064 μm is 25 pm/V.[16] For perfect poling of the quasi-phase-matched MgO:$LiNbO_3$, $d_\mathrm{eff} = 2d_{33}/\pi = 15.9$ pm/V. Using Eq.(1), we find that the calculated threshold intensity I_p is 50 MW/cm^2.

In order to obtain the intracavity peak power intensity of the 1.064-μm laser at the threshold, the rate equation model for the four-level Q-switched laser is employed. In the small signal approximation, we neglect the nonlinear loss for the 1.064-μm laser induced by the optical parametric process. By using the typical four-level Q-switched rate equation in Ref.[17], we can calculate the intracavity peak pump intensity of the 1.064-μm laser at a certain input power of the diode laser. In the experiments the Q-switch was set at a repetition rate of 25 kHz and the close time was 3 μs. The diffraction loss for the Q-switch was 85%. The round-trip cavity loss for the 1.064-μm pump laser was 3%. With an assumption of the step change for the Q-switch, the 1064-nm peak power intensity is calculated to be 60 MW/cm^2 at an incident diode power of 0.9 W. Considering that the beam size of the 1.064-μm pump laser at the nonlinear crystal (135 μm, radius) is different from the beam size in the laser medium (150 μm, radius), we find that the power

intensity in the nonlinear crystal is 74 MW/cm^2, 1.5 times above the theoretical threshold of OPG. Taking the ideal assumption for the Q-switch and the perfect poling of the MgO:$LiNbO_3$ into account, we find that the theoretical predictions are in good agreement with the experimental results.

The signal pulse temporal behaviour at 1506 nm was recorded by using a digital oscilloscope (Tektronix TDS 620B) with a fast InGaAs photodiode, as shown in Fig.4. The full width at half maximum (FWHM) of the signal pulse was measured to be 25 ns. The multi-pulse phenomenon usually observed in the intracavity optical parametric oscillators (IOPO) was eliminated in the IOPG configuration due to the much higher threshold of IOPG compared to the IOPO.[18–20] So after generating the first signal pulse, the remaining energy could not reach the OPG threshold during the open state of the Q-switch.

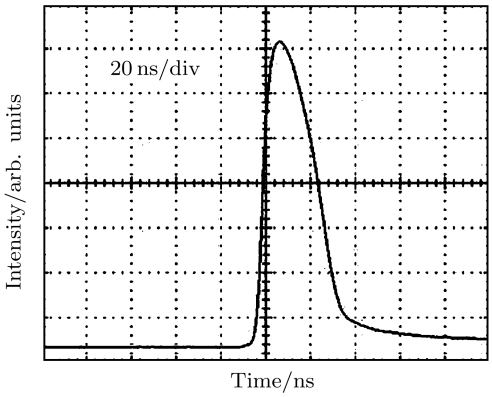


Fig.4. The signal temporal shape at 1506 nm.

The temperature tuning characteristics have also been investigated with an Agilent 86142B optical spectrum analyser. The use of PPMgLN as the parametric crystal indicates that the OPG can be operated over a wide temperature range starting near room temperature due to the absence of the photorefractive damage. A continuously tunable signal output from 1506 nm to 1565 nm (measured by the optical spectrum analyser) and the idler from 3.629–3.327 μm (calculated by energy conservation condition) were achieved by varying the crystal temperature from 25°C to 200°C. Figure 5 shows the theoretical temperature tuning curve (solid curve) calculated by using the phase matching condition and the experimental results (circle dot). The temperature dependent Sellmeier equation for the refractive indices n_e of the extraordinary wave and the thermal expansion equation is provided by HC Photonics, Taiwan. It can be seen that the experimental results are in good agreement with theoretical predictions.

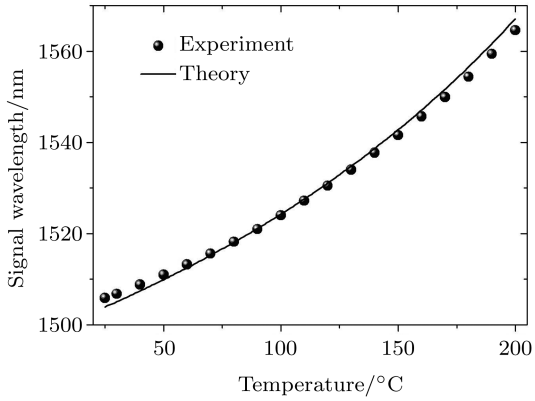


Fig.5. The signal output wavelengths as a function of the PPMgLN crystal temperature.

4. Conclusions

In conclusion, we have demonstrated a compact efficient IOPG internal to a Q-switched diode-end-pumped Nd:YVO_4 laser with PPMgLN. The PPMgLN, which had a grating period of 30 μm, was kept at room temperature, and the repetition rate of the Q-switch was set at 25 kHz. A maximum average signal output power of 0.34 W with an amplitude instability of 1%, a pulse duration of 25 ns and a beam quality factor of 1.4 was achieved, leading to a conversion efficiency of 10% with a slope efficiency of 14.4%. No multi-pulse phenomenon was observed in the IOPG experiments. The wavelengths of the signal output could be tuned in the range of 1506–1565 nm and the idler of 3.629–3.327 μm by varying the crystal temperature from 25 to 200°C. The theoretical analysis of the IOPG threshold showed good agreement with the experimental results.

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