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Beam quality improvement of the high-energy KTA-OPO based on a confocal unstable cavity with Gaussian reflectivity mirror

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A high-energy 100-Hz optical parametric oscillator (OPO) based on a confocal unstable resonator with a Gaussian reflectivity mirror was demonstrated. A KTA-based OPO with a good beam quality was obtained when the magnification factor was 1.5, corresponding to the maximum signal (1.53 μm) energy of 56 mJ and idler (3.47 μm) energy of 20 mJ, respectively. The beam quality factors (M^2) were measured to be $M_x^2 = 5.7$, $M_y^2 = 5.9$ for signal and $M_x^2 = 8.4$, $M_y^2 = 8.1$ for idler accordingly. The experimental results indicated that the beam quality positively changed with the increase of magnification factors, accompanied by an acceptable loss of pulse energy.

Keywords: optical parametric oscillators; confocal unstable resonator; beam quality.

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1. Introduction

Optical parametric oscillators (OPOs) with high energy and good beam quality have important applications in laser guidance, laser ranging, and optoelectronic countermeasures, benefiting more from the excellent spectral extending ability than conventional resonant cavities[1–3]. In the conventional structure of OPOs, simultaneously achieving high energy and good beam quality remains challenging. The OPO based on a confocal unstable cavity has attracted a great deal of research because of its excellent performance in solving the conflicting requirements of high energy and good beam quality.

In order to achieve an efficient output from nonlinear crystals and maintain good beam quality, the main implementation difficulty in the design of a high-energy OPO is figuring how to obtain a large mode volume and efficient transverse mode discrimination. The stable resonators with a short cavity length are widely used in OPOs, but at the expense of beam profile deterioration[4–8]. Therefore, a stable cavity is not suitable for high-energy OPOs with high-beam quality.

The optimized confocal unstable resonator can meet the requirements of good beam quality and high energy at the same time[9–11]. A confocal unstable cavity exhibits many excellent properties compared to a stable cavity[12]. First, the confocal unstable resonator has a large mode volume even at short cavity length, which is suitable for high-energy OPOs. Second, the confocal unstable cavity has a controllable diffraction loss by selecting an appropriate magnification (m). Third, owing to the diffraction loss, the transverse mode of a confocal unstable cavity is more efficiently managed. Moreover, the structure of a confocal unstable cavity is simple and compact, which is an excellent choice in high-brightness OPO applications[13–15]. In 1999, Farmer *et al.* obtained a pulse energy of 20 mJ at 1.5 μm using an unstable cavity with an m of 1.2, whose beam quality was measured to be around 4.4 times the diffraction limit[16]. In 2002, Raevsky *et al.* reported a KTP-based OPO based on an unstable resonator, with a pulse repetition frequency (PRF) of 30 Hz and a beam divergence of about 2.8 mrad, which was 2.5 times less than that of the stable cavity[17].

Besides the cavity structure, the oscillator mirror type is another important factor for the performance of OPOs. For example, adopting a Gaussian reflectivity mirror (GRM) as the output coupler could optimize the loss distribution and provide an additional loss for the high-order modes, thus contributing to the improvement of beam quality[18–21]. Compared with the common confocal unstable cavity, adopting GRM can eliminate the central black spot of the beam, meanwhile reducing the beam quality degradation caused by diffraction effects of the hard-edge (output coupler). Various theoretical studies of the GRM-based OPO have been reported to date. In 2005, Zou *et al.* did relevant theoretical research and established theoretical models to describe the characteristics of confocal unstable cavities, such as the threshold, pulse setting time, gain width, and pulse rising time[22,23]. However, their main works were focused on the theoretical analysis.

The output energy and PRF of above research were limited. While high-energy OPOs are the desired laser sources for many fields, especially in the military field, the high-energy nanosecond pulsed laser is an important solution for long-range optoelectronic countermeasures system. To the best of our knowledge, GRM-based confocal unstable cavities have rarely been experimentally demonstrated for high-energy OPOs. In previous work, we have demonstrated a high-energy $KTiOAsO_4$ (KTA)-based OPO with a nonconfocal unstable cavity instead of a plane-parallel one, realizing good beam qualities of signal and idler beams; however, the brightness needs to be further improved by a confocal unstable cavity with better performance to meet more demanding applications[24].

In this study, we demonstrate a high-beam quality and high-energy KTA-based OPO by adopting a confocal unstable resonator with a GRM output coupler. Especially, the influence of the magnification factor (m) on the beam quality was investigated theoretically and experimentally. A series of OPOs with different m (1.15, 1.2, 1.33, and 1.5) were compared. The experimental results indicated the confocal unstable cavity with m of 1.5 has the highest brightness output, corresponding to a total output energy of 76 mJ with a PRF of 100 Hz. The beam quality factors (M^2) were measured to be $M_x^2 = 5.7$, $M_y^2 = 5.9$ for signal and $M_x^2 = 8.4$, $M_y^2 = 8.1$ for idler, respectively.

2. Experimental Setup

The schematic diagram of the KTA-OPO with a GRM confocal unstable cavity is shown in Fig. 1. The singly-signal-resonant OPO was pumped by a high-energy Nd:YAG master oscillator power amplifier (MOPA) system with a PRF of 100 Hz, which was described in detail in Ref. [24]. A pump laser delivered a 1064 nm pulse train with a pulse energy of 480 mJ, a pulse duration of 18 ns, and beam quality factors of $M_x^2 = 4.9$ and $M_y^2 = 3.6$.

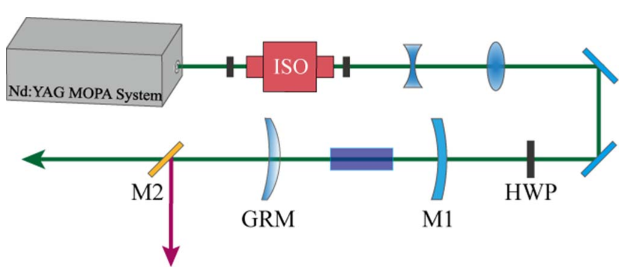

Fig. 1. Schematic diagram of KTA-based OPO. ISO, isolator; HWP, half-wave plate; M1, mirror 1; GRM, Gaussian-reflectivity mirror; M2, 45° beam splitter.

A convex lens and a concave lens were used to expand the pump beam diameter from 4 to 7 mm for aligning with the aperture (10 mm × 10 mm × 33 mm) of the KTA crystal, which was cut for the noncritical phase matching (NCPM). A confocal positive-branch unstable resonator consisted of two meniscus mirrors, whose physical length is defined as

$$L = \frac{R_1 + R_2}{2} + L_c\left(1 - \frac{1}{n}\right). \tag{1}$$

The R_1 and R_2 were curvature radii of input mirrors M1 and GRM, respectively. The n was the refractive index of the nonlinear crystal, and the crystal length was denoted by L_c. The resonator magnification factor was defined as $m = -R_1/R_2$. M1 was a concave mirror with the high-reflection (HR) coating for the signal and idler. The unstable cavity where L, R_1, and R_2 do not satisfy Eq. (1) is the nonconfocal unstable cavity, as described in Ref. [24]. The main reason for adopting a confocal unstable cavity instead of a nonconfocal unstable cavity is the advantage of being able to produce an automatically collimated output laser, which can benefit the beam quality.

A 45° beam splitter (M2) was placed behind the resonator to filter the residual pump laser, while the signal and idler were reflected out. Then, four kinds of unstable cavities with different m (1.15, 1.2, 1.33, and 1.5) were studied with the same transmittance of output couplers.

3. Results and Discussion

We experimentally investigated the relationship between OPO performance and cavity configuration. The GRM was a convex mirror with a high-transmission (HT) coating for idler and Gaussian-reflectivity coating (reflectance of 70%) for signal. The reflectivity distribution of a GRM was expressed as

$$R(r) = R_{max} \exp\left[-2\left(\frac{r}{w}\right)^k\right]. \tag{2}$$

The R_{max} was 70%, which was the maximum reflectivity at the center of the mirror, and the w was the $1/e^2$ radius. k was the order of the Gaussian profile.

M1 with 1500 mm radius-of-curvature and GRM with 1300 mm radius-of-curvature formed a confocal unstable resonator with an m of 1.15 and an optical cavity length of 100 mm. The total output energy was 85 mJ when the pump energy was 300 mJ. The beam quality factors (M^2) were measured to be $M_x^2 = 9.4$, $M_y^2 = 9.5$ for signal and $M_x^2 = 10.4$, $M_y^2 = 10.3$ for idler accordingly. To further improve the beam quality, we increased the value of the m, and the output characteristics of confocal unstable resonators with different m were compared by setting the same cavity length and pump beam size. It can be observed from Fig. 2(a) that the value of the threshold gradually increases, followed by a gradual decrease of the maximum output energy at the same pumping energy. The reason is that the resonator losses of confocal unstable cavities will increase with m. The total

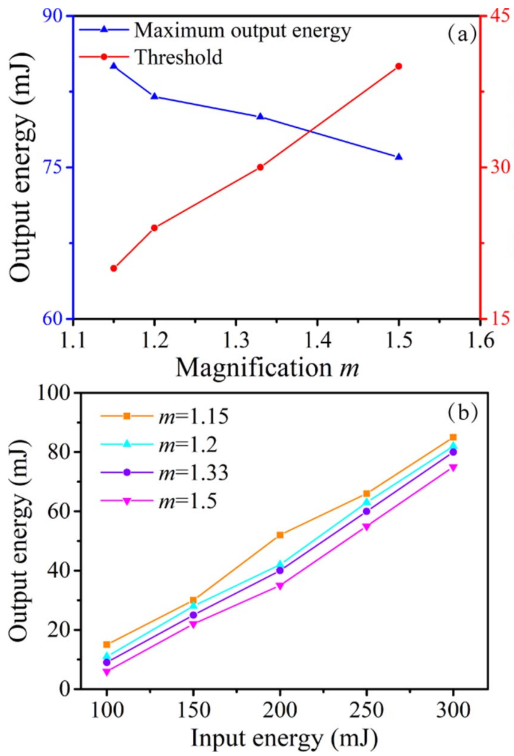

Fig. 2. (a) Threshold and maximum output energy versus magnification factors; (b) output energies (signal + idler) with different magnification factors (m) versus input energy.

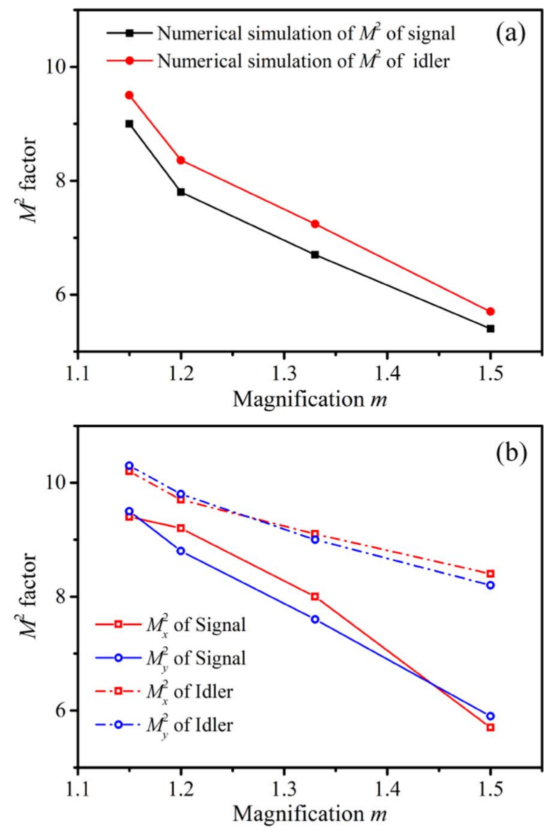

Fig. 3. The M^2 factors versus magnification factor (m). (a) Numerical simulation; (b) experimental results.

output energies (signal + idler) with various m versus pump energy are shown in Fig. 2(b). The maximum output energies of 85 and 76 mJ were obtained, corresponding to m of 1.15 and 1.5, respectively. The conversion efficiency was gradually reduced with the increase of round-trip loss, which was caused by the change of m.

The beam quality properties with different magnification factors were investigated based on the numerical model from Ref. [24]. In this model, the parameters of simulation contained diffraction, cavity loss, and magnification factors. According to the theory, the divergence angle of a backpropagated signal was positively changed with the m; thus, the high-order transverse modes were filtered out. From the simulated results, the M^2 of signal was improved from 9 to 5.4 as the m was increased from 1.15 to 1.5, and the corresponding M^2 of idler was optimized from 9.5 to 5.7, as shown in Fig. 3(a). Two types of commercial CCDs (Ophir, SP620U-MIR; Data Ray, WinCamD-IR-BB) for signal and idler were used to analyze the beam profiles. Figure 3(b) illustrates the relationship between beam quality and magnification factor of the confocal unstable resonator from the experimental data. As the m increases, the value of M^2 decreases. As illustrated in Fig. 4, the best beam quality was finally obtained with an m of 1.5, which was measured to be $M_x^2 = 5.7$, $M_y^2 = 5.9$ for signal and $M_x^2 = 8.4$, $M_y^2 = 8.1$ for idler accordingly. Table 1 summarizes the M^2 factors and the output brightness with different m.

As discussed above, the larger m corresponds to a smaller output efficiency, but with a better beam quality. Thus, both conversion efficiency and beam quality should be taken into consideration simultaneously while selecting an appropriate m.

As summarized in Table 1, the brightness of the signal was increased more significantly compared to the idler. The reason is that the OPO used in our experiment was a singly resonant oscillator (SRO), which was a signal-resonant OPO. For this OPO, the nonresonant wave (idler) was output directly, while the signal was limited in output due to its oscillation. This limitation led to the loss of higher-order modes through diffraction, thus resulting in a signal with better beam quality.

Besides the structure of unstable cavity, there were other aspects to optimize beam quality. The divergence of the parametric light has a dependence on pulse duration of pump light, and the transmittance of the output mirror also affects the loss of the cavity. Therefore, our following work will be focused on the improvement of the pump light output characteristics and the optimization of other parameters of the confocal unstable cavity, which are beneficial for improving conversion efficiency and maintaining a better beam quality at the same time.

The spectrum of pump light at 1064 nm is shown in Fig. 5(a). The 1535 nm signal was measured with a spectral bandwidth (FWHM) of 0.26 nm, as shown in Fig. 5(b). According to the theory of nonlinear frequency conservation, the corresponding wavelength of the idler was 3475 nm. We also observed the

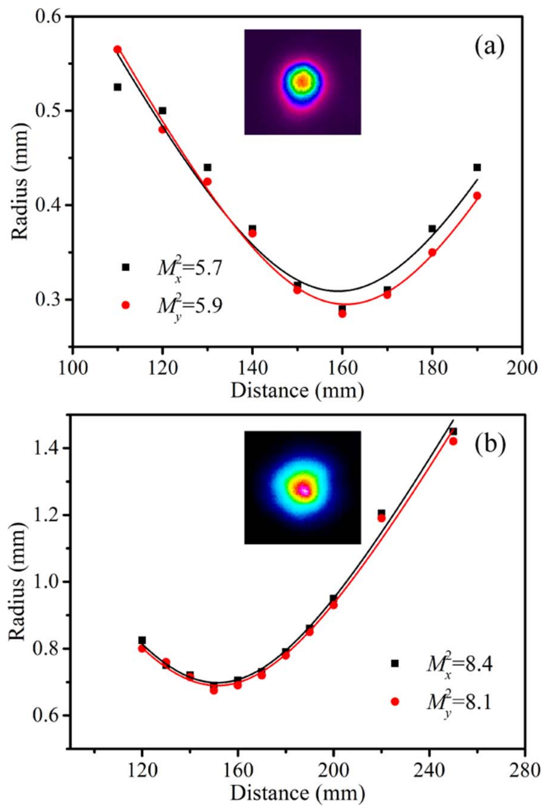

Fig. 4. The M^2 factors of signal and idler with magnification factor (m) of 1.5. (a) M^2 factors of signal; (b) M^2 factors of idler; insets show the beam profiles of signal and idler.

Table 1. Summary of M^2 and Brightness (B) with Different Magnification Factors (m).

	m	1.15	1.2	1.33	1.5
Signal	M_x^2/M_y^2	9.4/9.5	9.2/8.8	8.1/7.6	5.7/5.9
	B [GW/(sr·mm^2)]	18.1	19.3	25.2	43.3
Idler	M_x^2/M_y^2	10.2/10.3	9.7/9.8	9.1/9.0	8.4/8.1
	B [GW/(sr·mm^2)]	1.21	1.28	1.41	1.6

spectrum of confocal cavities with different m, but they had hardly any significant differences.

The pulse profiles of signal and idler were recorded by an oscilloscope (LeCroy, Wavesurfer 3034). Figure 6 depicts the pulse durations of signal (16.5 ns) and idler (15.2 ns). In Fig. 6, we can see that the pulse width of the idler was shorter than that of the signal. In the SRO, the idler was driven completely by the pump and signal rather than oscillating in the cavity, which means it only generated an idler pulse when the pump and signal pulses overlapped[25]. This phenomenon was consistent with the simulation results in our previous study[24].

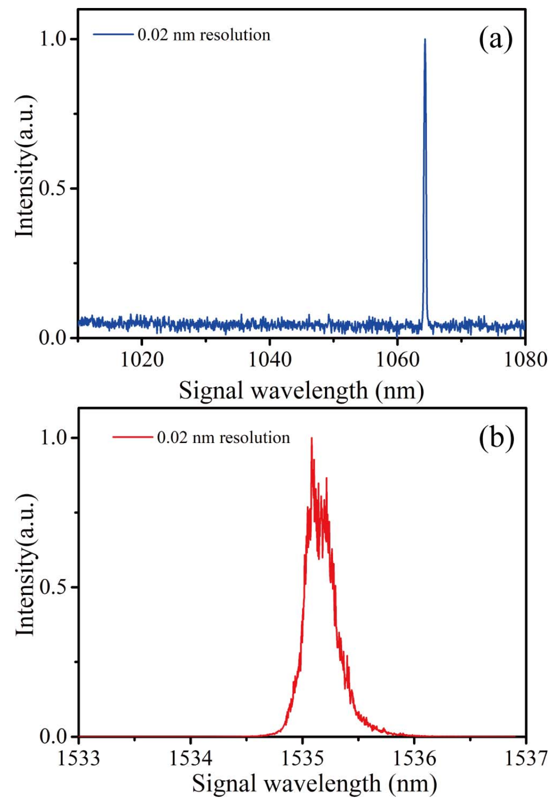

Fig. 5. Spectrum with 0.02-nm resolution. (a) Spectrum of pump light; (b) signal spectrum of OPO.

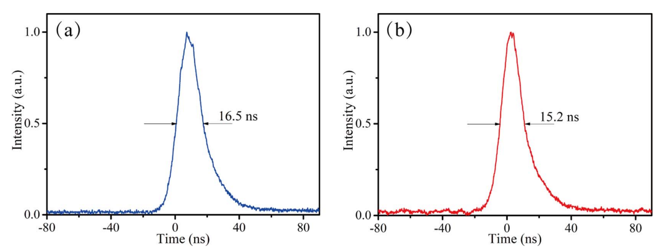

Fig. 6. (a) Pulse duration of signal; (b) pulse duration of idler.

4. Conclusion

In this work, a high-energy KTA-based OPO adopting a GRM confocal unstable cavity was achieved. In order to obtain better beam quality, the m of the unstable cavity was comparatively investigated in detail. By increasing the m from 1.15 to 1.5, the beam quality of KTA-OPO has been optimized, and laser brightness was effectively improved. The highest pulse energy of 76 mJ was obtained with m of 1.5. The M^2 factors were measured to be $M_x^2 = 5.7$ and $M_y^2 = 5.9$ for signal, and $M_x^2 = 8.4$ and $M_y^2 = 8.1$ for idler accordingly. The brightness was greatly improved by using a confocal unstable resonator compared to the previous work with a nonconfocal resonator. It was demonstrated simultaneously by simulation and experiments that the confocal unstable cavity with large m can obtain a better beam quality while maintaining an acceptable energy loss.

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