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Optimal pump beam profile in an optical parametric oscillator with the walk-off effect

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Abstract: In this paper, we present the optimal elliptical pump beam profile for a walk-off-affected optical parametric oscillator (OPO) that minimizes the averaged pump power at the oscillation threshold. The optimal waist is derived analytically by balancing the improvement in walk-off compensation against the reduction in peak pump intensity as the beam size increases. In our experiment, the measured optimal pump waist in the walk-off direction is 1.03 mm, which is in good agreement with the theoretical prediction of 1.10 mm. Based on the optimal elliptical pump beam profile, an efficient type-II phase-matched β-BaB_2O_4 (BBO) OPO is demonstrated, which is pumped by a homemade 355 nm ultraviolet (UV) laser at 10 kHz repetition rate. In this situation, a maximal signal beam output power of 3.50 W is achieved under an incident pump power of 19.20 W, corresponding to a conversion efficiency of 18.23%. These results indicate that optimizing the pump beam profile contributes to building efficient OPOs.

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1. Introduction

Ultraviolet (UV) laser-pumped nanosecond (ns) pulsed optical parametric oscillators (OPOs) have been the attractive sources in many fields including quantum physics, atomic physics, laser ionization spectroscopy and spectroscopy analysis, etc. [1–4], owing to their exceptional features like broadband tunability covering the visible and near-infrared wavelength ranges. In UV laser-pumped OPOs, efficient utilization of the pump energy is crucial for achieving high conversion efficiency and reducing the oscillation threshold under limited pump power conditions. Compared to LiB_3O_5 (LBO) and $CsLiB_6O_{10}$ (CLBO) nonlinear crystals [5,6], the angle-matched β-BaB_2O_4 (BBO) crystal is a popular candidate to act as the nonlinear gain crystal because it has a relatively higher nonlinear coefficient, damage threshold and moisture resistance. However, the intrinsic walk-off effect of BBO crystal can severely limit the effective gain length and further raises the oscillation threshold as well as reduces the conversion efficiency of the built OPO. As early as 1989, Bosenberg et al. [7] inserted two identical type-I BBO crystals in opposite directions into an OPO resonator to compensate for their walk-off effect mutually, which led to a reduced oscillation threshold from 3.5 mJ to 1.7 mJ. But the two-crystal scheme was difficult to align in the experiment. Later, S. Wu [8] further lowered the threshold pump power of the type-I phase-matched BBO OPO to 0.4 mJ in 1998 by employing an elliptical shaped pump laser beam, which simultaneously mitigated the influence of the walk-off effect along the long axis and increased the beam intensity along the short axis. In 2008, R. C. Bapna et al. [9] demonstrated that the oscillation threshold of a UV-pumped BBO OPO can be reduced by a factor of 16 using an elliptically shaped pump beam compared with spherical focusing. Similar engineering

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implementations using elliptical shaped pump beam were also reported in UV-pumped BBO OPOs in 2018 [10]. In 2025, our group [11] presented a high-power type-II BBO OPO by decreasing the color center absorption loss in the nonlinear crystal, which was realized by heating the crystal to accelerate the recombination process of the color centers. Previous studies have demonstrated the effectiveness of elliptical pumping experimentally; however, an explicit analytical design rule for determining the optimum pump waist has not been reported.

In this paper, we derive an analytical condition for the optimal pump waist that balances walk-off compensation against pump intensity reduction, thereby minimizing the oscillation threshold. The validity of the result is experimentally verified in a type-II phase-matched BBO OPO pumped by a homemade 355 nm UV laser. Based on the optimized pump beam profile, an output power of 3.5 W at 460 nm is realized under an incident pump power of 19.20 W. Furthermore, the wavelength tuning range of the system covered from 409.62 nm to 614.12 nm by rotating the BBO crystal to change the phase-matching angle, and the corresponding tuning range of the idler beam was 839.72 nm to 2645.97 nm. Our results confirmed that this optimization effectively reduces the oscillation threshold and improves the conversion efficiency, providing a practical design guideline for high-efficiency OPOs.

2. Theoretical analysis

When the type-II phase-matched BBO nonlinear crystal is employed as the frequency conversion medium of the double-pass-pumping OPO, the inherent spatial walk-off effect can induce the separation between the interacting pump (e-ray) and signal (o-ray) beams. In this case, the oscillation threshold pump power P_{th} of an OPO is given by [9,12],

$$P_{\mathrm{th}} = \frac{f_{\mathrm{rep}}\tau\pi r_{\mathrm{px}} r_{\mathrm{py}}}{2kg_s l_{\mathrm{eff}}^2(1+\gamma)^2}\left(\frac{33L}{2\tau c} + 2\alpha l + \ln\frac{1}{\sqrt{R}} + \ln 2\right)^2 = k_{\mathrm{a}}\frac{r_{\mathrm{px}} r_{\mathrm{py}}}{l_{\mathrm{eff}}^2}, \tag{1}$$

where f_{rep} and τ are the repetition rate and pulse-width of the pump laser, respectively. k, g_s, α, l, L and c are the gain coefficient, mode-coupling coefficient, absorption coefficient, length of the crystal, cavity length and speed of the light, respectively. γ is the ratio of the backward to forward pump amplitudes when the double-pass-pumping scheme is utilized. r_{px} and r_{py} are the waist radii of the pump laser beam in the walk-off and non-walk-off directions, respectively. and k_a is a constant that is independent of the pump beam size. In Eq. (1), l_{eff} is the effective parametric gain length [12] and can be expressed as,

$$l_{\mathrm{eff}} = l_{\mathrm{w}} \cdot \mathrm{erf}\left(\frac{l\sqrt{\pi}}{2l_{\mathrm{w}}}\right), \tag{2}$$

in which $l_w = \sqrt{\pi} k_b r_{px}/2$ is the effective gain length for an infinitely long crystal, where $k_b = \sqrt{(1+a)/(1+a/2)}/\rho$. ρ and $a = (r_{sx} r_{sy})/(r_{px} r_{py})$ are the walk-off angle and mode size ratio between the signal and pump lasers, respectively. The physical meaning of a can be understood as the ratio of the signal beam area to the pump beam area, when both the numerator and denominator of this expression can be multiplied by π. r_{sx} and r_{sy} are the waist radii of the signal beam in walk-off and non-walk-off directions, respectively. By substituting Eq. (2) into Eq. (1), and applying an approximation $\mathrm{erf}(x) \approx \tanh(1.2\,x)$, the dependence of P_{th} on the size of the pump laser can be simplified as:

$$P_{\mathrm{th}} = k_{\mathrm{a}}\frac{r_{\mathrm{py}}}{r_{\mathrm{px}}}\tanh^{-2}\left(\frac{1.2l}{k_{\mathrm{b}} r_{\mathrm{px}}}\right). \tag{3}$$

As a result, the optimal size of the pump beam in the walk-off direction r_{px} can be derived by finding the minimum of P_{th} with respect to r_{px}, which is given by,

$$r_{\mathrm{px}}^{\mathrm{opt}} \approx l \cdot \rho\sqrt{\frac{1+a/2}{1+a}}. \tag{4}$$

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According to Eq. (4), the optimal pump waist in the walk-off direction is proportional to the length and the walk-off angle of the nonlinear crystal, and is also related to the mode size ratio between the signal and pump lasers. In the non-walk-off direction, the size of the pump laser beam was expected to be small to intensify the pump laser. However, the divergence of the pump beam should not exceed the acceptance angle of the BBO crystal, and the intensity of the pump laser should not exceed the damage threshold of the BBO crystal. The derivation of this criterion is based entirely on previously published theoretical models by Brosnan et al. in 1979 [12] and verifiable mathematical analysis, the criterion in this work may provide simple, useful and quantitative reference for determining the optimal pump beam profile. This includes OPOs operated with burst-mode laser systems, such as the burst-mode KTP OPO reported in Ref. [13].

3. Experimental setup

To experimentally verify the derived optimal pump waist, an OPO pumped by a homemade 355 nm UV pulsed laser [14] was designed and constructed, as shown in Fig. 1. The repetition rate, the pulse width, the central wavelength, and the linewidth of the UV pump laser were 10 kHz, 8.18 ns, 354.71 nm, and 22.4 pm, respectively. The maximal average output power and M^2 value were 19.20 W and 1.67, respectively. After being guided by two flat mirrors M_1 and M_2, which were coated with high-reflective (HR) films at 355 nm, the pump beam was directed into the OPO resonator. The resonator of the OPO adopted a classical plano-plano structure consisting of M_3 and M_5. The input coupler M_3 was coated with anti-reflective (AR) film at 355 nm and HR film at 400-700 nm. The output coupler M_5 was coated with a partly reflective (PR) film of 70% at 400-700 nm to balance the gain and loss. The nonlinear gain medium BBO (Castech) with the size of $12 \times 6 \times 18$ mm^3 (walk-off direction × non-walk-off direction × propagation direction) was cut at $\theta = 37°$, $\phi = 30°$ for type-II critical phase-matching. The crystal was wrapped in the tin foil and mounted in a copper oven whose temperature was precisely controlled to 185°C to decrease the color center loss. The pump reflector M_4 was coated with HR film at 355 nm and AR film at 400-2000 nm and inserted between the BBO crystal and M_5 to achieve the double-pass-pumping scheme and protect the output coupler. To prevent the damage of the pump source from the back-reflection of M_4, a suitable aperture (A) was inserted along the pump beam path. The generated parametric beams were separated by a dichroic mirror M_6 coated with HR film at 400-700 nm and high-transmission (HT) film at 800-900 nm at 45°. To experimentally maximize the conversion efficiency by balancing the walk-off compensation and the pump laser intensity, a pump shaping system consisting of two pairs of cylindrical lenses was employed to adjust the pump size. Before entering the OPO, the pump beam had already been shaped into a nearly collimated circular beam with a diameter of 2.5 mm. The first pair of cylindrical lenses including $f_1 = 150$ mm and $f_3 = 100$ mm was used to adjust the pump laser size of the vertical direction, while the second pair of cylindrical lenses including $f_2 = 150$ mm and $f_4 = 100$ mm was used to adjust the beam size of the horizontal direction. To circularize the generated signal beam, a cylindrical lens $f_5 = 100$ mm was inserted in the output arm of the OPO.

In the experiment, the optimal waist radius of the pump laser in the walk-off direction was calculated to be 1.10 mm according to Eq. (4), where the length of the BBO crystal was 18 mm, the walk-off angle was 71.92 mrad. Since the waist of the pulsed pump laser was focused on the center of the BBO crystal in a plano-plano resonator, so we assumed that the signal beam shared the identical confocal parameter [15] with the pump beam, which generated a parameter a of 1.212. Consequently, the value of r_{px} in the experimental verification stage was varied from 0.75 mm to 1.22 mm. At the same time, the radius of the pump beam in the non-walk-off direction r_{py} was fixed at 0.11 mm, according to the M^2 factor of the pump laser and the acceptance angle of the BBO crystal from SNLO.

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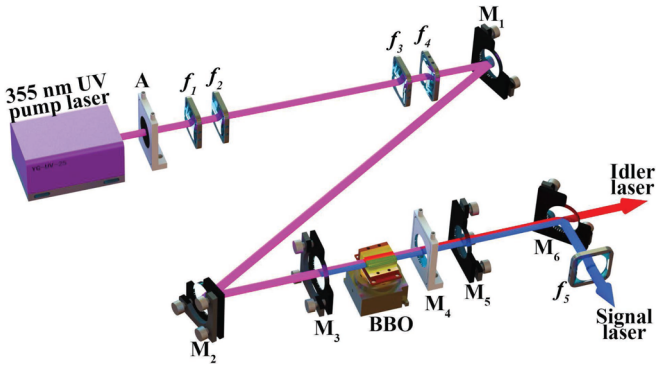

Fig. 1. Schematic diagram of designed OPO. A: protective aperture, f_1-f_5: cylindrical lenses for beam shaping, M_1 and M_2: pump guiding flat mirrors, M_3: input coupler, BBO: BBO crystal, M_4: pump reflector, M_5: output coupler, M_6: dichroic mirror

4. Results and discussion

4.1. Experimental verification

Based on Eq. (3), the influence of the waist radii of the pump laser on P_{th} can be calculated and illustrated in Fig. 2. From Fig. 2, it is seen from curve (a) that the calculated threshold pump power P_{th} is as high as 45 W for a circular pumping light spot with the waist radius smaller than 0.6 mm, which is far larger than the affordable power of 19.20 W of the employed pump source in experiment. And it can further increase with the expansion of the pump laser beam. This result shows that it is not possible to obtain the required signal light and idler light output if we employ a circular pumping light spot to pump the built OPO. Meanwhile, the calculated threshold pump power P_{th} can significantly decrease with the expansion of r_{px} for the fixed r_{py}=0.11 mm from the curve (b) in Fig. 2. Especially, when the r_{px} is enlarged to 1.10 mm, the threshold pump power is decreased to near 6.5 W, which is smaller than the power of 19.20 W of the employed pump source. The calculated results mean that the elliptical-shaped pump laser can effectively decrease the threshold pump power of the type-II phase-matched BBO OPO.

In the experiment, the signal wavelength was tuned to 460 nm by precisely controlling the crystal temperature and phase-matching angle to 185 °C and 31.6°, respectively after all of the optical elements were well aligned. And the waist radius of the pump laser in the non-walk-off direction r_{py} was shaped to 0.11 mm according to the previous calculation. In this case, the output power trends of the OPO were firstly measured with the variation of the pump power for different r_{px} values, which was illustrated as the dots in Fig. 3. It was seen that the output power increased monotonically with the incident pump power and no obvious saturation was observed under the maximal incident pump power of 12.25 W for all the tested r_{px} values. The increased variance observed in the 11-12 W range cannot be reliably attributed to a specific physical mechanism based on the available experimental evidence. We therefore attribute it primarily to experimental fluctuations and measurement uncertainty rather than to a systematic dependence on the pump-beam radius.

To minimize the error in determining the oscillation threshold of OPO, the measured power data were fitted by using the theoretical model by Granot et al. in Ref. [16], which described how the conversion efficiency of the OPO varied with the threshold pump power and the incident pump power. The least-squares fitted curves are shown as dashed lines in Fig. 3, while the fitted threshold values and their corresponding uncertainties are presented in Fig. 5(a).

The beam profile of the pump laser was measured and illustrated in Fig. 4 for different r_{px} values, which were 0.75 mm, 0.86 mm, 1.03 mm, 1.12 mm and 1.22 mm, respectively. The

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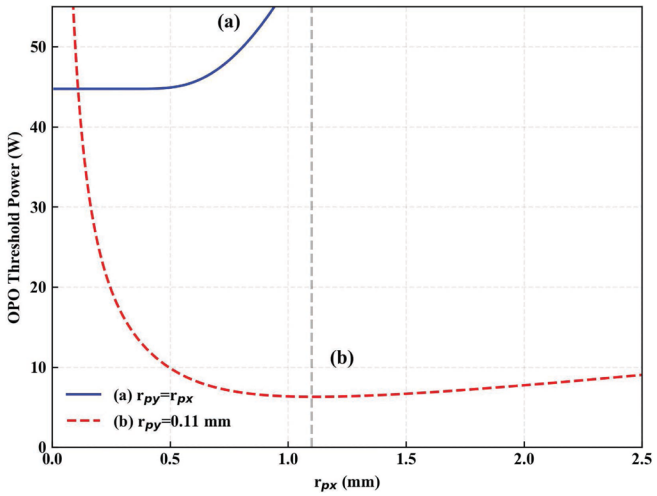

Fig. 2. Relationship between P_{th} and r_{px} when using a round-shaped pump laser (blue solid line) and an elliptical-shaped pump laser (red dashed line)

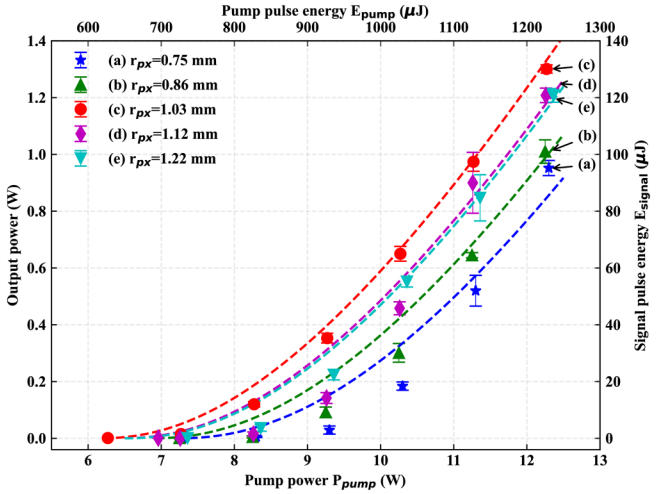

Fig. 3. Measured output power trends of the OPO for various r_{px} and the dashed lines are the corresponding fits based on Ref. [16] to determine the oscillation threshold.

corresponding oscillation threshold power was varied from 7.02 W to 6.85 W, 6.13 W, 6.43 W and 6.48 W, respectively. To further facilitate the comparison of the impact of r_{px} on the OPO threshold pump power and conversion efficiency, the fitted threshold pump power and the conversion efficiency for the maximal incident pump power of 12.25 W were extracted and compared to the theoretical calculations, as shown in Fig. 5(a). According to Fig. 5, with the increase of r_{px}, P_{th} shows a trend of first decreasing and then increasing, and it was found that the minimal threshold pump power of 6.13 W and the maximal output power 1.30 W as well as conversion efficiency of 10.62% can be simultaneously achieved only if r_{px} was optimized to the value of 1.03 mm, which was in reasonable agreement with the previous theoretical calculation of 1.10 mm according to Eq. (4). The error may originate from the approximations made in the theoretical analysis and fluctuations in the value of r_{py} during the experiment.

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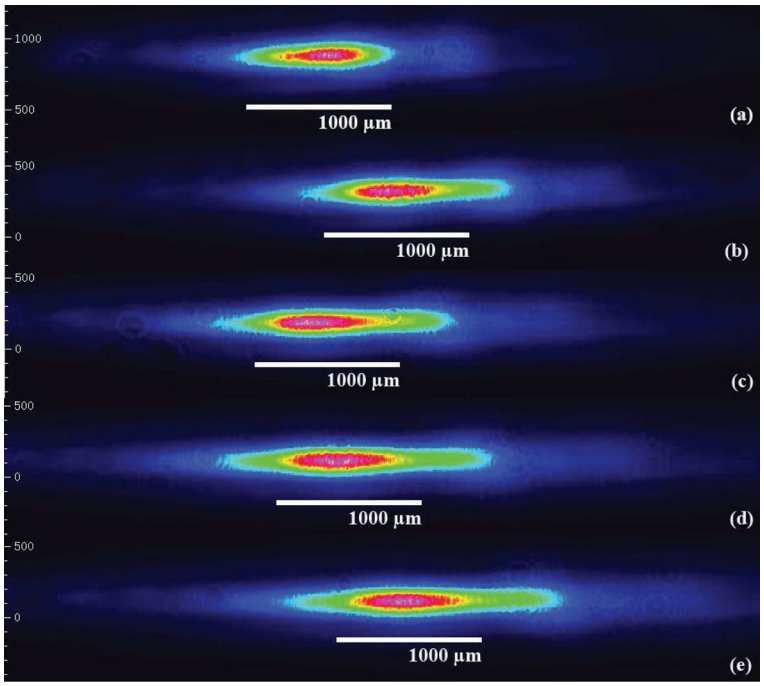

Fig. 4. Measured 2D spatial intensity profiles of the pump beam at the focal plane. The waist radii in the non-walk-off direction were approximately 0.11 mm, while the waist radii in the walk-off direction were varied from (a) 0.75 mm, (b) 0.86 mm, (c) 1.03 mm, (d) 1.12 mm and (e) 1.22 mm, respectively.

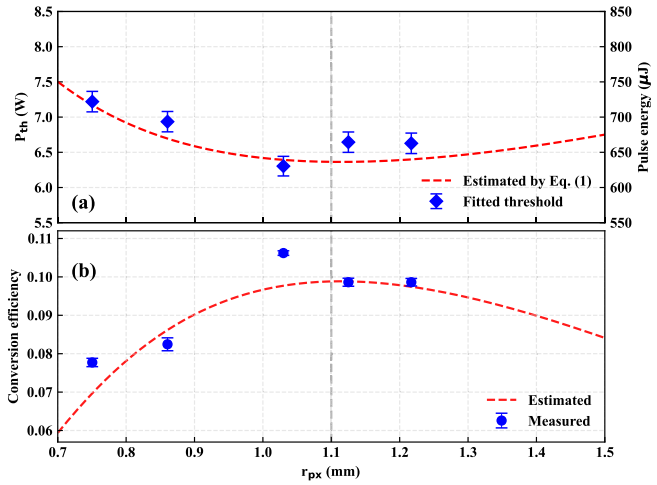

Fig. 5. (a) oscillation threshold power of the OPO and (b) conversion efficiency under different r_{px}, when r_{py} and P_{pump} were 0.11 mm and 12.25 W, respectively

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4.2. OPO characterization

Finally, an OPO with high output power and broadband tunable range covering visible and infrared spectral regions was realized by optimizing the waist radii of pump laser beam in walk-off and non-walk-off directions to 1.03 mm and 0.11 mm, respectively. At the same time, the pump power was increased to its maximum of 19.20 W. By rotating the phase-matching angle of the BBO crystal, the wavelength and corresponding output power of the generated parametric beams were recorded and illustrated in Fig. 6. It was clear that the signal light of the built OPO was tuned from 409.6 nm to 614.1 nm by using a spectrometer (AMOS-UVNIR, LBTEC), and the corresponding tuning range of the idler beam covered from 839.72 nm to 2645.97 nm. Among the available wavelength range, the peak power of 3.25 W occurred at 463.3 nm. Based on this result, a detailed power curve was subsequently measured at 460 nm under the same pump power, where the signal power reached 3.5 W, as shown in the inset of Fig. 6. It showed that the signal power increased monotonically to 3.5 W with the increase of the incident pump power and the obvious saturation was not observed when the pump power was increased to maximal pump power of 19.20 W. The slight variation between the two measurements is attributable to the day-to-day reproducibility of the OPO system. The corresponding conversion efficiency reached up to 18.23%.

As shown in Fig. 7 (a) and (b), the repetition rate and the pulse width of the measured signal beam were 10 kHz and 5.15 ns, respectively, which were measured by using a detector (DET10A2, Thorlabs) and an oscilloscope (MSO64B, Tektronix). Then the spectral width of 20 pm was measured at 460.31 nm by using a spectrometer (LSA2R, HighFinesse), as shown in Fig. 7(c). Lastly, the M^2 value was determined by measuring the beam size at different locations by using a CCD camera (BC106N-VIS/NIR, Thorlabs) and fitting the data using the standard Gaussian beam propagation model. The measured M^2 values of the signal beam in horizontal and vertical directions were 1.48 and 1.84, respectively, as illustrated in Fig. 8. The typical shape of the circularized signal beam was illustrated in the inset of Fig. 8.

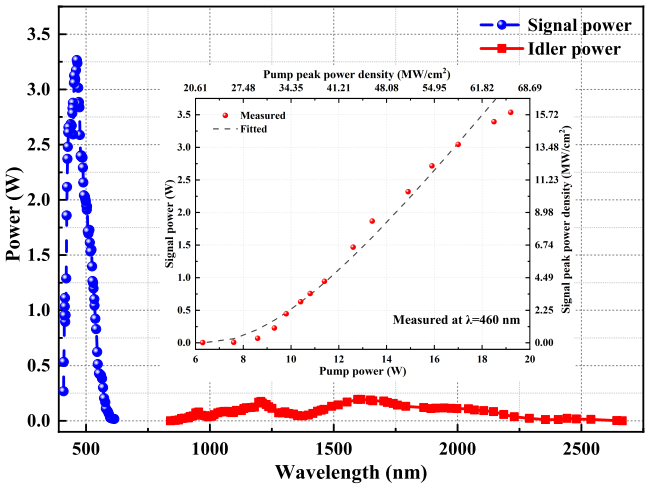

Fig. 6. Measured wavelength tuning range of signal beam and idler beam. Inset: measured power curve, when signal wavelength is tuned to 460 nm

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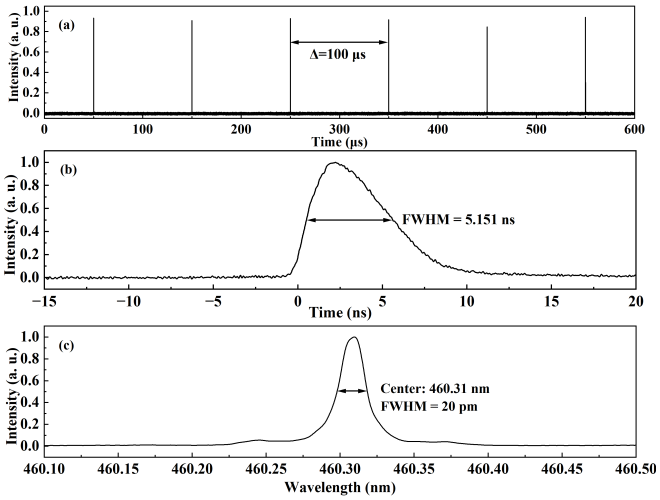

Fig. 7. Temporal and spectral characteristics of signal beam. (a) Measured pulse train showing a repetition interval of 100 μs. (b) Single-shot temporal profile of signal beam with a FWHM of 5.15 ns. (c) Measured spectrum of signal beam centered at 460.31 nm and FWHM of 20 pm

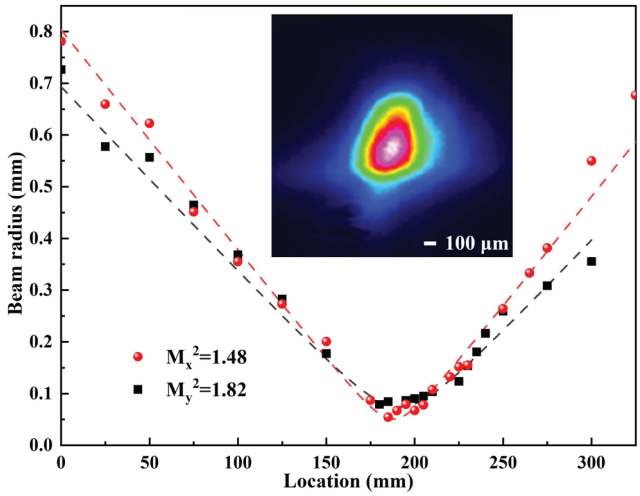

Fig. 8. Measured M^2 value of signal beam and beam shape at 460 nm.

5. Conclusion

In conclusion, we have derived an analytical condition for the optimal pump waist in walk-off-affected OPOs, which provides a quantitative design rule for minimizing the oscillation threshold. The predicted optimal condition is experimentally verified in a type-II phase-matched BBO OPO, showing good agreement between theory and measurement. On the basis of the optimized pump beam profile, a high-efficiency OPO is realized, achieving a maximal signal output power of 3.50 W at 460 nm under an incident pump power of 19.20 W, corresponding to a conversion efficiency of 18.23%. This work establishes a practical guideline for pump beam optimization in high-efficiency UV laser-pumped OPO systems.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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