CHINESE OPTICS LETTERS

Vol. 20, No. 12 | December 2022

Continuous-wave π-polarized 1084 nm laser based on $Nd:MgO:LiNbO_3$ under 888 nm thermally boosted pumping

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Received May 31, 2022 | Accepted June 17, 2022 | Posted Online September 23, 2022

A continuous-wave (CW) π-polarized 1084 nm laser based on $Nd:MgO:LiNbO_3$ under 888 nm thermally boosted pumping is reported. According to the absorption spectrum and energy level structure of $Nd:MgO:LiNbO_3$, the 888 nm laser diode (LD) is used for thermally boosted pumping. This pumping method eliminates the quantum defect caused by the nonradiative transition in $Nd:MgO:LiNbO_3$ under the traditional 813 nm pumping and effectively improves the serious thermal effect of the crystal. The unmatched polarized 1093 nm laser is completely suppressed, and the π-polarized laser output of 1084 nm in the whole pump range is realized by the 888 nm thermally boosted pumping. In the present work, we achieved the CW π-polarized 1084 nm laser with a maximum output power of 7.53 W and a slope efficiency of about 46.1%.

Keywords: continuous-wave laser; π-polarization; $Nd:MgO:LiNbO_3$; thermally boosted pumping.

DOI: 10.3788/COL202220.121401

1. Introduction

The quasi-phase matching optical parametric oscillator (QPM-OPO) based on the superlattice material is an effective technique to obtain near and mid-infrared bands of 1.5–5 μm[1–4]. The typical wavelength laser in these bands has an irreplaceably important role in the fields of precision measurement, remote sensing detection, and optoelectronic countermeasures. Compared with the traditional superlattice material MgO-doped periodically poled $LiNbO_3$ (PPLN), the Nd:MgO:PPLN is formed by further polarization treatment with Nd^{3+}-doped $MgO:LiNbO_3$ as the substrate. This crystal can complete the two processes of fundamental frequency optical gain and optical parametric frequency conversion in this single medium, which is called optical parametric oscillation self-frequency conversion[5–8]. This feature provides a new way to realize the small-scale integration of such lasers, which has been of wide concern and studied in recent years.

The key to achieving high-efficiency self-frequency conversion based on Nd:MgO:PPLN is to obtain high-quality fundamental light. In 2016, the Li research group of Shandong University took the lead in studying the fundamental light properties of *a*-cut $Nd:MgO:LiNbO_3$. They obtained the alternating output of a dual-wavelength laser at 1085 nm and 1093 nm through the internal passive *Q*-switching and analyzed the principle of dual-wavelength laser generation from the energy levels and thermal effect[9]. In the previous study, our research group obtained continuous-wave (CW) fundamental light at 1084 nm and 1093 nm by an 813 nm laser diode (LD) end-pumped $Nd:MgO:LiNbO_3$ with output power of 2.2 W and 6.5 W, respectively, which further verified the orthogonal polarization characteristics of the dual-wavelength laser[10]. Since the cascade frequency conversion process requires severe polarization matching ($e + e \rightarrow e$) after $Nd:MgO:LiNbO_3$ is polarized, the σ-polarized 1093 nm fundamental light produced under serious thermal effect is not favorable for the subsequent optical parametric frequency conversion, despite the higher output power. Therefore, it is particularly important to suppress the oscillation of the unmatched polarized 1093 nm fundamental light. Based on it, our research group got the controllable output of π-polarized 1084 nm CW laser output by optimizing the cavity structure of the 813 nm LD dual-end-pumped resonant cavity using the thermal lens effect of $Nd:MgO:LiNbO_3$ and the stable interval of the resonator cavity[11]. However, due to the heat generation problem under high pump power, the π-polarized wavelength in the whole pump interval cannot be controlled.

Compared with traditional 813 nm pumping, direct pumping and thermally boosted pumping with low quantum defect are effective methods to reduce heat generation and increase conversion efficiency. This method has been widely used in pumped $Nd:Y_3Al_5O_{12}$ (Nd:YAG), $Nd:YVO_4$, and other gain crystals, but there are few reports on the application of this method to pump Nd-ion-doped $LiNbO_3$ as heretofore[12–15]. In this paper, based on the absorption properties and energy level structure of Nd:MgO:LiNbO$_3$, under the 888 nm thermally boosted pumping for the first time, to the best of our knowledge, the CW π-polarized 1084 nm laser output of the whole pump range is realized. As to the 1084 nm CW laser near-base mode output, the maximum power is 7.53 W, and the slope efficiency reaches 46.1%, which lays a foundation for further application of self-frequency conversion.

2. Experimental Details

The Nd:MgO:LiNbO$_3$ crystal is an anisotropic crystal. If it is used as a gain medium, it is necessary to select the appropriate pump wavelength according to the spectral characteristics of the crystal. The absorption spectrum of Nd:MgO:LiNbO$_3$ with 0.8% (atomic fraction) Nd^{3+}-doped was measured using a spectrophotometer (Jasco V-570 UV VIS-NIR), as shown in Fig. 1. In addition to the main absorption peak at 813 nm, Nd:MgO:LiNbO$_3$ also has an intense absorption peak at 888 nm. Therefore, the band centered at 888 nm is another preferable absorption peak for thermally boosted pumping Nd:MgO:LiNbO$_3$.

The energy level structure diagram of Nd:MgO:LiNbO$_3$ is shown in Fig. 2[16–19]. Process A indicates the traditional 813 nm pumping. The laser-active ions are pumped from sublevel Z$_1$ of ground-state level $^4I_{9/2}$ to level $^4F_{5/2}$ and then thermally relaxed to the upper lasing level $^4F_{3/2}$ with heat generation. Process C indicates the 888 nm thermally boosted pumping, which is to pump laser-active ions from sublevel Z$_3$ of ground-state level $^4I_{9/2}$ directly to sublevel R$_2$ of level $^4F_{3/2}$ without a relaxation process, which reduces heat generation. Compared to traditional pumping, the output performance of 888 nm thermally boosted pumping has numerous superiorities, such as lower thermal effects and better beam quality. For the 1084 nm emission with a pumping wavelength of 813 nm or 888 nm, the quantum defect is 25% and 18.1%, respectively, and the thermal load is reduced by 27.6%.

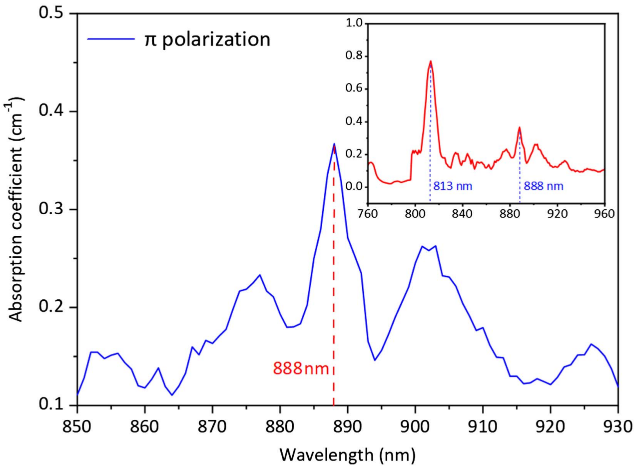

Fig. 1. Absorption spectrum of Nd:MgO:LiNbO$_3$.

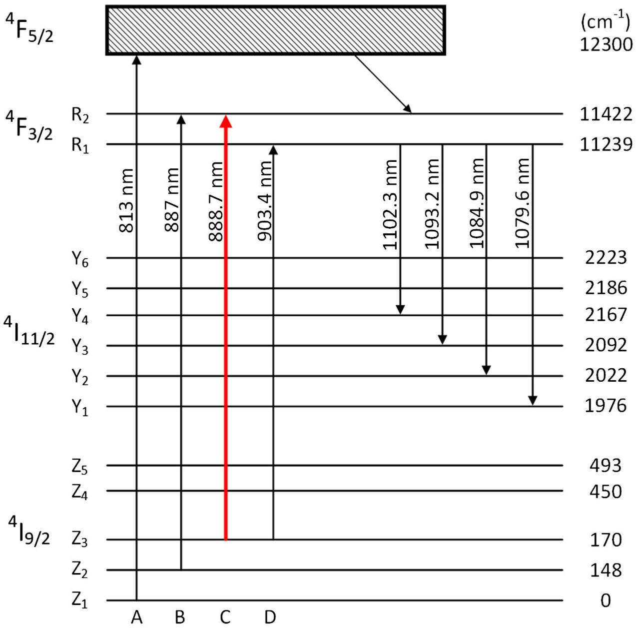

Fig. 2. Energy level structure diagram of Nd:MgO:LiNbO$_3$.

Figure 3 shows a schematic diagram of the Nd:MgO:LiNbO$_3$ laser under 888 nm thermally boosted pumping. The pump source was an 888 nm fiber-coupled continuous LD produced by nLIGHT with a core diameter of 400 μm and a numerical aperture of 0.22. The pump light was transmitted through the 1:2 coupling mirror group (transmission coupling efficiency reached 97%) and focused on the Nd:MgO:LiNbO$_3$ crystal center. The gain medium was an *a*-cut Nd:MgO:LiNbO$_3$ crystal, the size of the crystal was $6\,\text{mm} \times 2\,\text{mm} \times 30\,\text{mm}$ with 0.8% Nd^{3+}-doped, and 800–900 nm and 1060–1090 nm wave antireflection films were coated on both ends of the crystal. The laser crystal was wrapped in an indium foil, mounted in a zinc-plated copper water-cooled copper holder, and controlled by a thermoelectric cooler (TEC) temperature control device. The temperature control accuracy reached ±0.01°C, and the temperature was maintained at 20°C in the experiment. For the Nd:MgO:LiNbO$_3$ crystal, the absorption efficiencies at 813 nm and 888 nm are 84.5% and 68.1%, respectively.

The stable length of the resonator cavity was 60 mm. A flat mirror M$_1$ as an input mirror was coated for high transmittance at 888 nm and high reflection at 1084 nm. The output coupler (OC) M$_2$ was plane-concave (radius of curvature $R = 150\,\text{mm}$) with high transmittance at 1084 nm and 1093 nm ($T = 6\%, 10\%, 15\%, 20\%$). The P was a 45° polarizer coated with 1060–1100 nm 45° polarization film to distinguish the two orthogonally polarized output lasers.

3. Results and Discussion

The outputs at 1084 nm and 1093 nm under 813 nm and 888 nm pumping as a function of absorbed pump power were measured with a laser power meter (Ophir F150A BB SH 26), respectively,

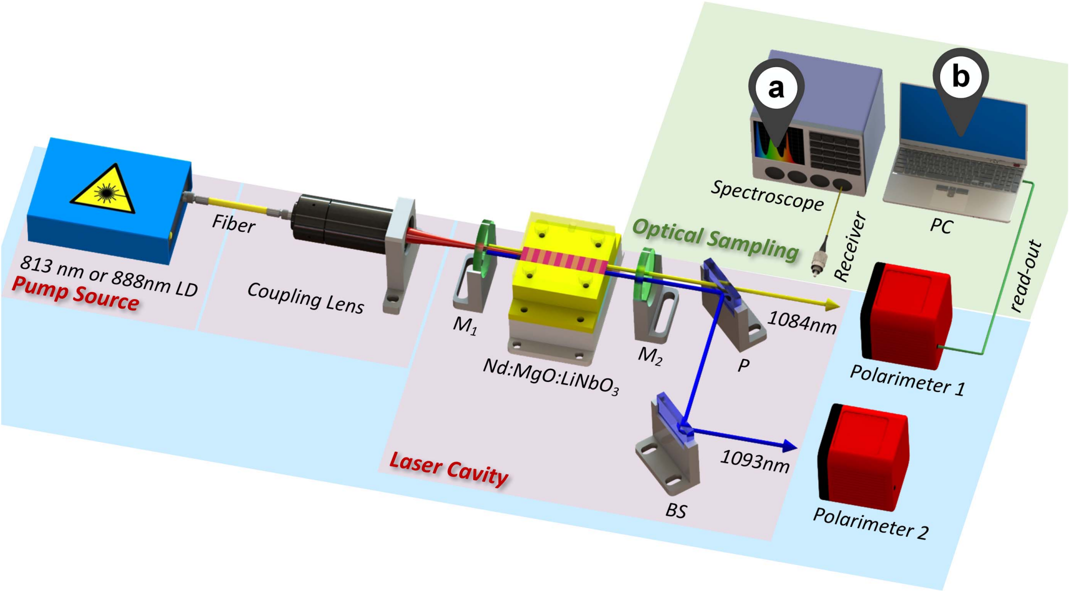

Fig. 3. Schematic diagram of the thermally boosted pumped Nd:MgO:LiNbO$_3$ laser.

as shown in Fig. 4. The wavelength variation of Nd:MgO:LiNbO$_3$ crystal was measured with a spectrum (ARCoptix FT-NIR), as shown in Fig. 5. The polarization state and Stokes parameters of output wavelengths as the polarization angle switched were measured by the polarization measuring instrument (Thorlabs PAX1000IR2), as shown in Fig. 6. At 1084 nm, the relative intensity in the 0° direction was always stronger than that in the 90° direction, indicating the π polarization. However, at 1093 nm, the trend was quite the opposite, indicating the σ polarization. The polar coordinates exhibited the shape of two leaves, indicating the linearly polarized light. Compared to the measurement findings under the outputs of the 1084 nm and 1093 nm laser, it can be obviously seen that the two-leaf model is rotated exactly 90°.

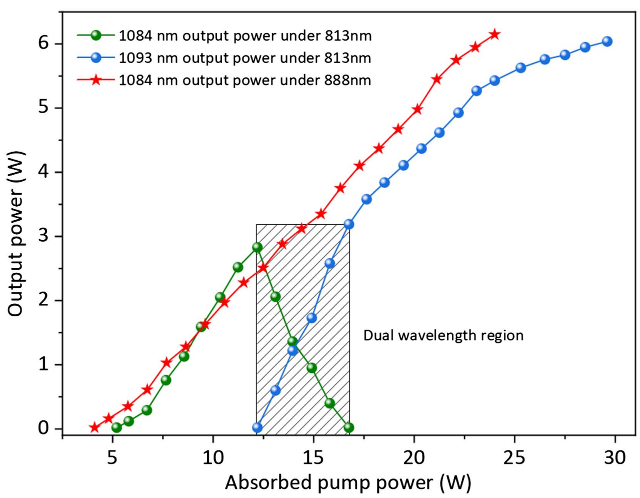

Fig. 4. Output power with respect to absorbed pump power.

In our experiment, the pump power for 813 nm and 888 nm pumping was 35 W. The maximum absorbed pump power for 813 nm and 888 nm pumping was 29.6 W and 24 W, respectively. Firstly, the Nd:MgO:LiNbO$_3$ was pumped by the traditional 813 nm LD at the OC of $T = 6\%$. When the absorbed pump power was 5.8 W, the 1084 nm emission reached the threshold, and the gain at 1084 nm was greater than 1093 nm. When the absorbed pump power was in the dual-wavelength region from 12.2 W to 16.75 W, the output power of the 1084 nm emission decreased rapidly until it disappeared, and the 1093 nm emission appeared and increased gradually. When the absorption pump power was greater than 16.75 W, with only 1093 nm emission output, the gain at 1093 nm was greater than at 1084 nm. Finally, under the traditional 813 nm pumping, the output power was 2.83 W at 1084 nm when the absorbed pump power was 12.2 W, and the maximum output power was 6.04 W at 1093 nm when the absorbed pump power was 29.6 W. The thermal effect of the crystal became serious with the increase of the pump power. The polarization state of output wavelengths changed from π polarization to σ polarization. The output wavelengths are 1084 nm in π polarization and 1093 nm in σ polarization, respectively, which are orthogonal to each other.

For the 888 nm thermally boosted pumping operation, the 1084 nm laser reached the threshold, while the absorbed pump power was 4.8 W. The maximum output power at 1084 nm was 6.15 W, while the absorbed pump power was 24 W, with a slope efficiency of about 32%. The output power was 5.43 W at 1093 nm when the absorbed pump power was 24 W under 813 nm pumping. Compared with the 813 nm pumping at the OC of $T = 6\%$, the 888 nm thermally boosted pumping can reduce the threshold by 17.2% and increase the output power by 0.72 W.

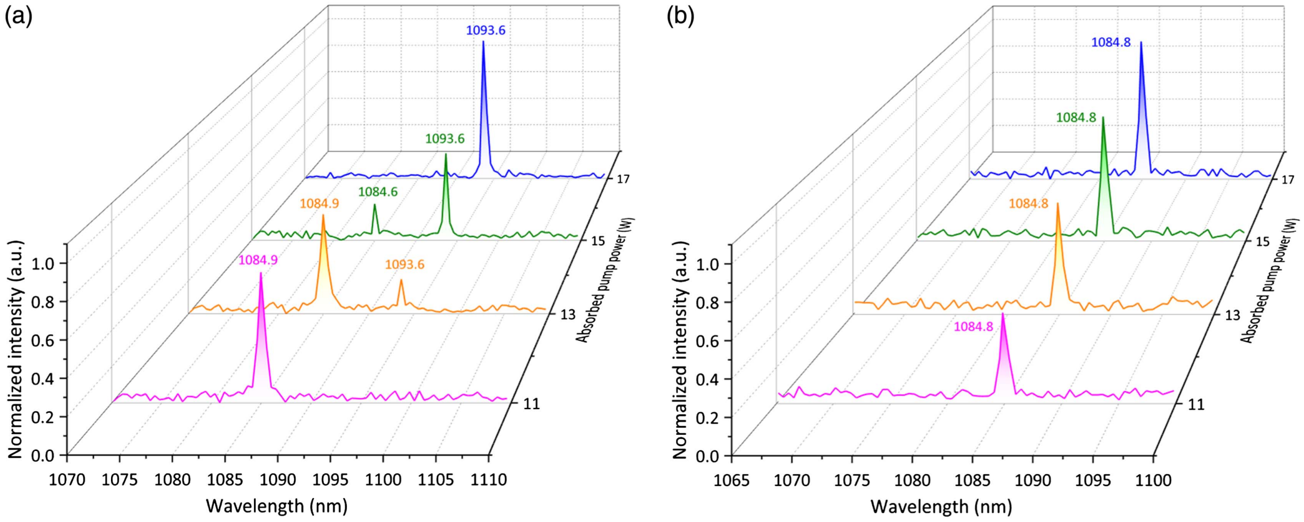

Fig. 5. Change process of laser wavelength with the absorbed pump power: (a) 813 nm pumping, (b) 888 nm pumping.

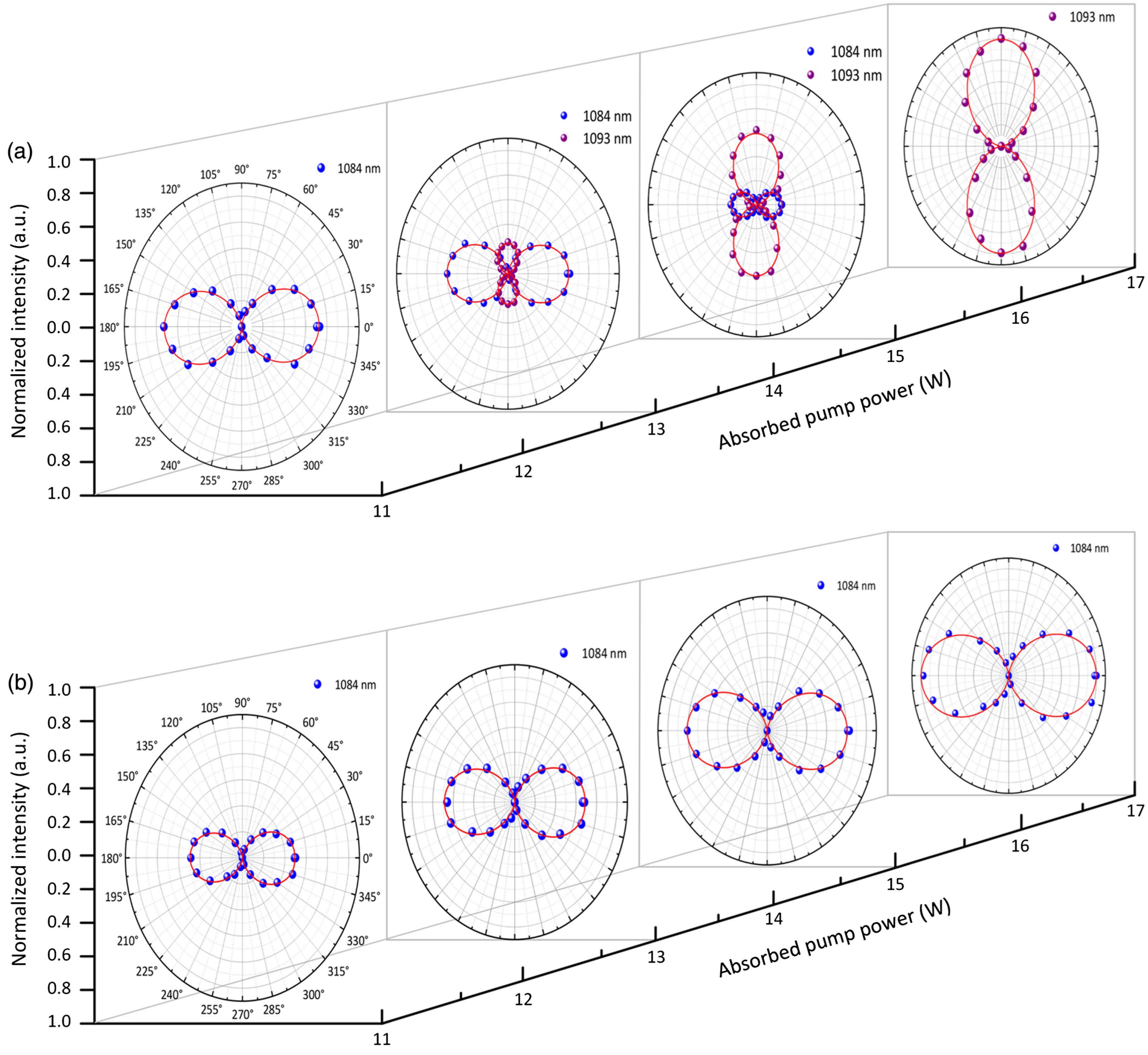

Fig. 6. Variation trend of the polarization state with the absorbed pump power: (a) 813 nm pumping, (b) 888 nm pumping.

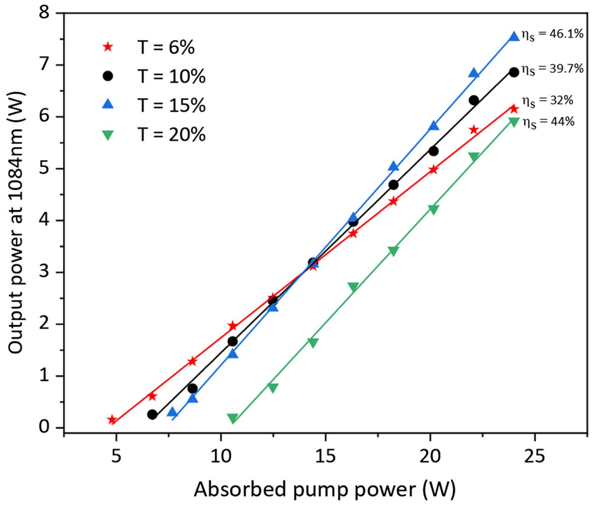

Fig. 7. Output power with respect to the absorbed pump power at 888 nm.

For determining the optimal OC, we further tried the OCs of 10%, 15%, and 20% transmission. The maximum output power at 1084 nm reached 6.86 W, 7.53 W, and 5.92 W, respectively, as shown in Fig. 7. The corresponding slope efficiencies increased to 39.7%, 46.1%, and 44%, respectively. The measured output wavelength was always 1084 nm in π polarization. With the increase of the output mirror transmittance, the threshold of the 1084 nm laser also increased accordingly. The maximum output power of the 1084 nm laser was obtained at $T_{\text{oc}} = 15\%$.

In this research, although the crystal has a higher absorption efficiency of 813 nm pump light, more heat in the unit volume is generated, and there is a large temperature gradient inside, which has a great impact on the output wavelength and polarization state. According to the experimental results, due to 888 nm being closer to 1084 nm, the quantum efficiency is larger, and the thermal saturation is less prone to occur. Therefore, the stimulated emission cross section of π polarization is always larger than that of σ polarization, which makes the gain of 1084 nm always greater than that of 1093 nm.

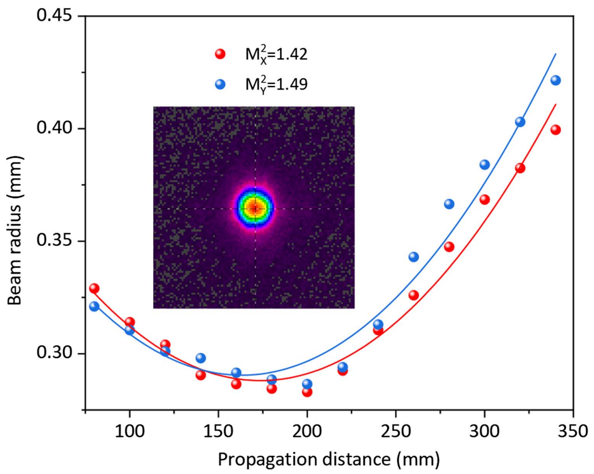

Fig. 8. 1084 nm spots and the beam quality obtained by fitting.

The oscillation of 1093 nm fundamental light is suppressed, and the polarization state is not changed, which ensures the stable output of π-polarized 1084 nm fundamental light. Thus, the thermal effect of the Nd:MgO:LiNbO$_3$ crystal is effectively alleviated by 888 nm thermally boosted pumping in the absorbed pump power range from 4.8 W to 24 W.

A focusing lens ($f = 200$ mm) and a pyroelectric array camera (Spiricon Pyrocam III) were used behind M_2 ($T = 6\%$), and the spot size of the 1084 nm laser at the output power of 6.15 W was measured along the propagation direction after splitting by the knife-edge method. The evolution of the focused beam occurred at different positions from the lens. Beam profile curves were fitted according to the Gaussian beam propagation expression, and the quality factor M^2 of the beam was calculated as $M_X^2 = 1.42$ and $M_Y^2 = 1.49$, as shown in Fig. 8. Under the 813 nm pumping, the beam quality is $M^2 > 1.7$. The beam quality is improved by using thermally boosted pumping at 888 nm.

4. Conclusion

In summary, based on the absorption spectrum and energy level structure of Nd:MgO:LiNbO$_3$, the CW π-polarized 1084 nm laser of the *a*-cut Nd:MgO:LiNbO$_3$ with 0.8% Nd^{3+}-doped under thermally boosted pumping at 888 nm was experimentally realized for the first time, to the best of our knowledge. When the absorbed power pump is 24 W, the maximum 7.53 W π-polarized 1084 nm laser output is obtained. The beam quality is $M^2 < 1.5$. It is proved that the thermal effect of the Nd-ion-doped LiNbO$_3$ crystal can be effectively alleviated by thermally boosted pumping at a certain absorbed pump power. In addition, the output power and slope efficiency can be further improved by increasing the absorbed pump power and optimizing the cavity design of the resonant cavity. The above results confirm that it is a method to obtain high-quality fundamental light, which provides a possibility to further realize high-efficiency self-frequency conversion based on periodic polarization of the Nd:MgO:PPLN crystal.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (Nos. U20A20214 and 11974060) and the Natural Science Foundation of Jilin Province (No. 20210101154JC).

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