



## OPEN 915 nm pumping kilowatt fiber oscillator with high optical-to-optical efficiency

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We demonstrate an all-fiber oscillator with high optical-to-optical efficiency using laser diodes working at 915nm as the pump sources to reduce the demand for thermal management. When the output power of the bidirectional pumped oscillator is 1.16kW, the optical-to-optical efficiency is as high as 75.4%. In this working state, the output characteristics of the oscillator are observed. The Raman suppression ratio is 41.23dB and the beam quality factor  $M_x^2 = 1.14$ ,  $M_y^2 = 1.29$ . Analyzing the time trajectory of the highest power output, there are no significant characteristic peaks in the time domain signal and the frequency domain signal, which indicates that the oscillator has good stability. Improving the output characteristics of the 915nm pumping lasers has a positive significance for the application of non-strict ambient temperature control.

Fiber lasers are widely used in industrial fields such as laser cutting, laser welding, and laser drilling due to their advantages of compact structure, high efficiency, and high stability<sup>1,2</sup>. Since the output power of ytterbium-doped (Yb-doped) fiber lasers exceeded the kilowatt for the first time in 2004<sup>3</sup>, the single fiber output power of Yb-doped fiber lasers has continuously increased to tens of kilowatts<sup>4–10</sup>. The research on 1-kilowatt fiber lasers is mainly focused on the early stages, usually using pump sources working at 975nm and active fibers with large core diameters. In 2004, Jeong et al. reported a 1.36kW fiber laser using large core diameter fibers and 975nm pumping<sup>4</sup>. In 2011, Yan et al. reported 1.1kW of output power based on monolithic fiber laser with MOPA structure. The pump wavelength is 975nm and the optical-to-optical efficiency is surround 66.5%<sup>11</sup>. In 2012, Xiao et al. present a 1kW output power single mode fiber oscillator operating at a wavelength of 915nm, utilizing Yb-doped large mode area double-clad fiber with core and inner cladding diameters of 20/400μm. Notably, the pump sources in this study exhibits a typical power conversion efficiency of 30% and the slope efficiency of the output laser is 71%<sup>12</sup>. In the same year, Yu et al. achieved a 1.2kW single-mode laser output with an optical-to-optical efficiency of 60%. The laser diodes (LDs) as pump sources operate at 915 ± 10nm and electro-to-optical efficiency less than 54%<sup>13</sup>. In 2010, the concept of mode instability threshold was proposed<sup>14</sup>. And since then, there has been an increasing amount of research on mode stability<sup>15–19</sup>. When the output power in the fiber laser system reaches a certain threshold, mode coupling or mode competition will occur between different modes in the fiber, leading to the deterioration of beam quality, usually resulting in a decrease in output efficiency. In recent years, research on fiber lasers has mainly focused on achieving high-power fiber lasers, pursuing breakthrough power, better beam quality, and longer-term reliable operation<sup>20</sup>. For industrial processing fields with kilowatt power requirements, higher brightness, higher optical-to-optical efficiency, and lower cost are also important.

Unlike most previous studies on 1-kilowatt fiber lasers, we selected laser diodes with a working wavelength of 915nm as the pump sources and provided energy to the Yb-doped fiber in a bidirectional pumping manner. The Yb-doped fiber with core/cladding diameters of 14/250μm, which reduces the number of transmission modes that can be supported within the core. Studies has shown that the bidirectional pumping method can provide higher mode instability threshold for fiber amplifiers<sup>21</sup>. It is worth mentioning that according to the absorption characteristics of Yb-doped fiber, the absorption cross section at the wavelength of 915 nm is smaller and wider. The smaller absorption cross section reduces the thermal load in the gain fiber, also bringing about strong gain saturation, thereby improving the mode instability threshold<sup>22–24</sup>. In addition, according to the temperature drift characteristics of the laser diode, the output wavelength of diodes will change with the temperature, and when the output wavelength changes in a range near 915nm, the laser can still maintain a good working condition. This has a very positive significance for industrial applications. Therefore, it is meaningful to study the output characteristics of fiber lasers pumped at 915nm. Generally, in order to obtain laser output with good mode stability, the winding radius of the Yb-doped fiber can be appropriately adjusted to increase the loss of the higher-order modes and increase the threshold of mode instability<sup>25,26</sup>. However, the loss of higher-order modes

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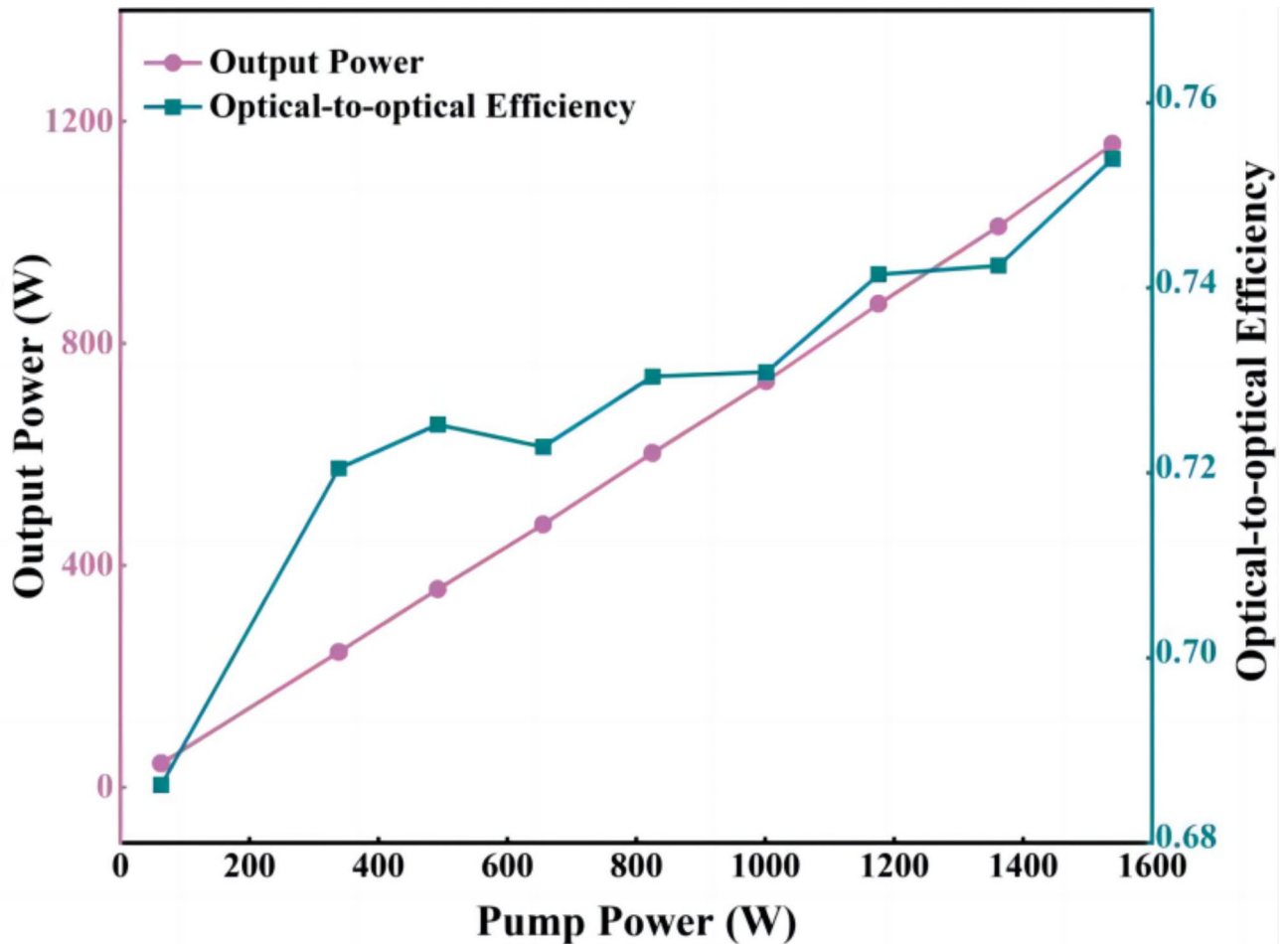


Fig. 2. Output power evolution and optical-to-optical efficiency.

effects can lead to changes in spectral linewidths. When reaching the output power of 1011W, weak Raman spectrum can be observed around wavelength 1135nm. At this point, the Raman suppression ratio is 47.39dB. There is a threshold for stimulated Raman scattering, which is related to the pump light intensity. When the pump power reaches the threshold of stimulated Raman scattering, the light field transfers part of the energy to the nonlinear medium to generate stimulated Raman scattering<sup>30</sup>. When the output power reaches 1160W, the Raman suppression ratio is 41.23dB.

To further observe the output spectral characteristics, Fig. 4 shows the center wavelengths of the output spectra at different powers, as well as the spectral linewidths of 3dB, 10dB, and 20dB. It can be observed that as the output power gradually increases, the center wavelengths of the oscillator's output spectra remain within the range of 1079.9–1080.3nm. Observing the linewidth changes of 3dB, 10dB, and 20dB, we found that the overall linewidths increase linearly with the increase of output power. It is worth mentioning that after the output power increased to 732W, the phenomenon of spectral linewidths broadening at 3dB and 10dB become slow. After the output power reaches 1011W, the spectral linewidths tends to narrow.

To verify the mode stability of the system, the beam quality factor measured at the highest output power in the experiment is  $M_x^2 = 1.14$ ,  $M_y^2 = 1.29$ , which means a good single-mode output characteristic. Figure 5 shows the beam quality factors  $M_x^2$  and  $M_y^2$  of the oscillator at different output powers, as well as the energy distribution of its laser spot. When the maximum output power is reached, the value of  $M_x^2$  and  $M_y^2$  actually decreases slightly. According to the shape of the laser spots, it can be observed that the spot at this time is more round than other spots at low power.

In recent years, more and more people have characterized mode stability by analyzing the time trajectory and Fourier spectrum of oscillator output<sup>31</sup>. In order to further observe the output working state of the oscillator system, we also verified the stability of the system from a time domain perspective. The time-domain spectrum of the 1160W power stable output of the oscillator was measured. Figure 6 shows the time-domain spectrum and frequency-domain spectrum under the highest power stable operating state. It can be seen that both time-domain and frequency-domain signals are very stable throughout the entire process, without generating periodic signals or other characteristic peaks. This indicates that the system is in a stable working state and has not reached the mode instability threshold at the highest power output.

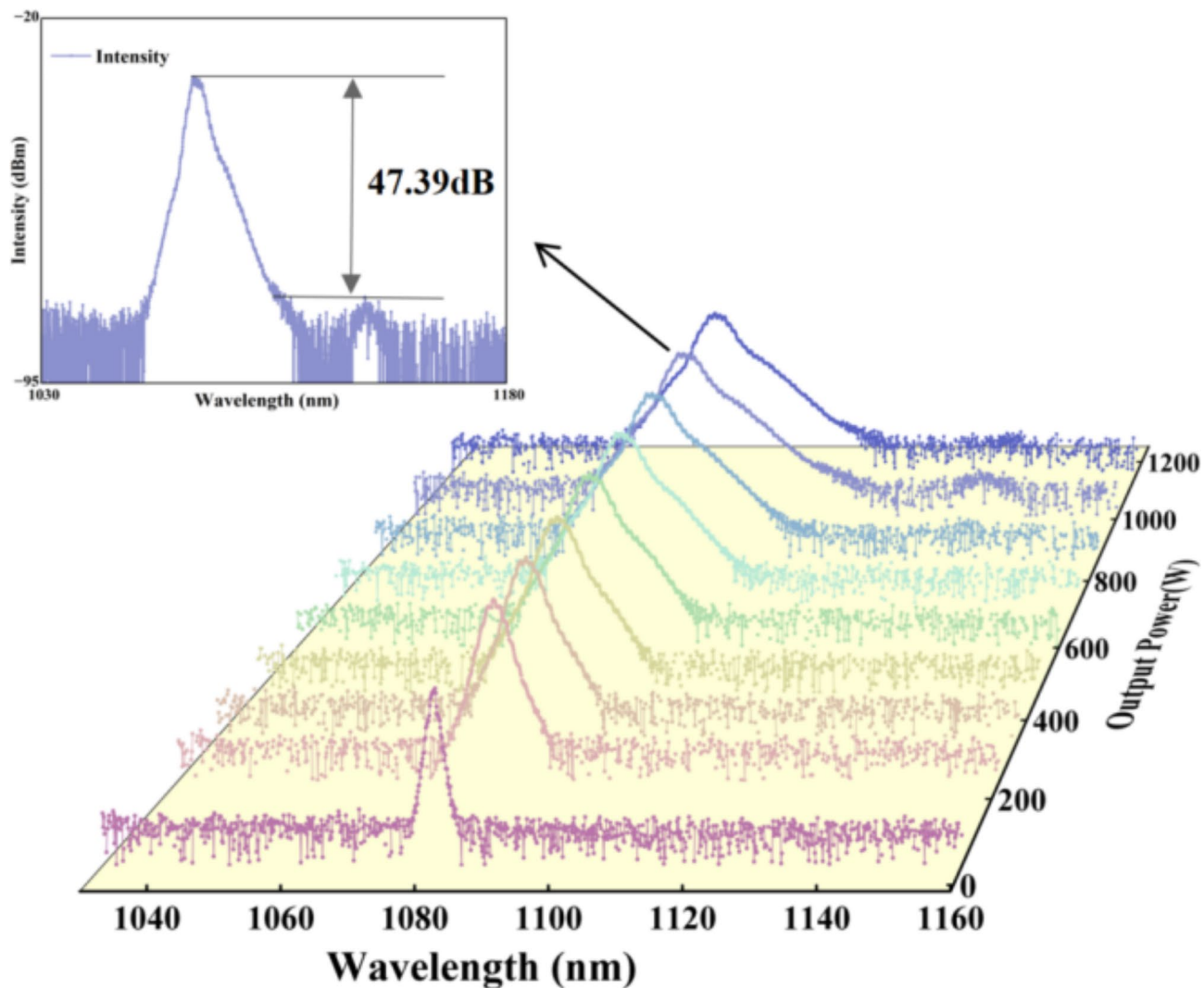


Fig. 3. Spectral evolution process and Raman threshold spectra.

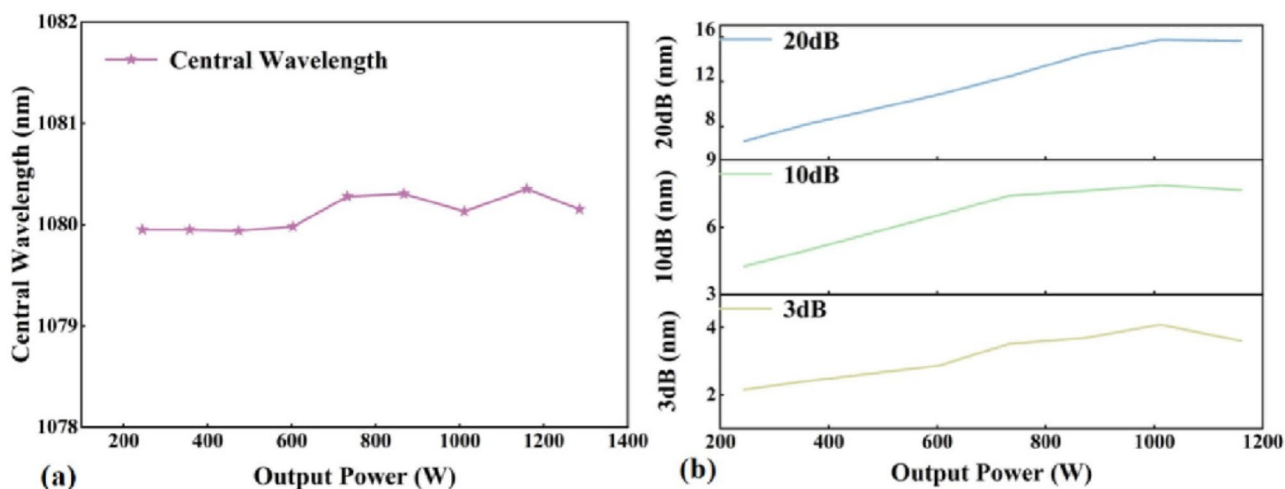


Fig. 4. (a) Spectral center wavelengths, (b) Spectral linewidths.

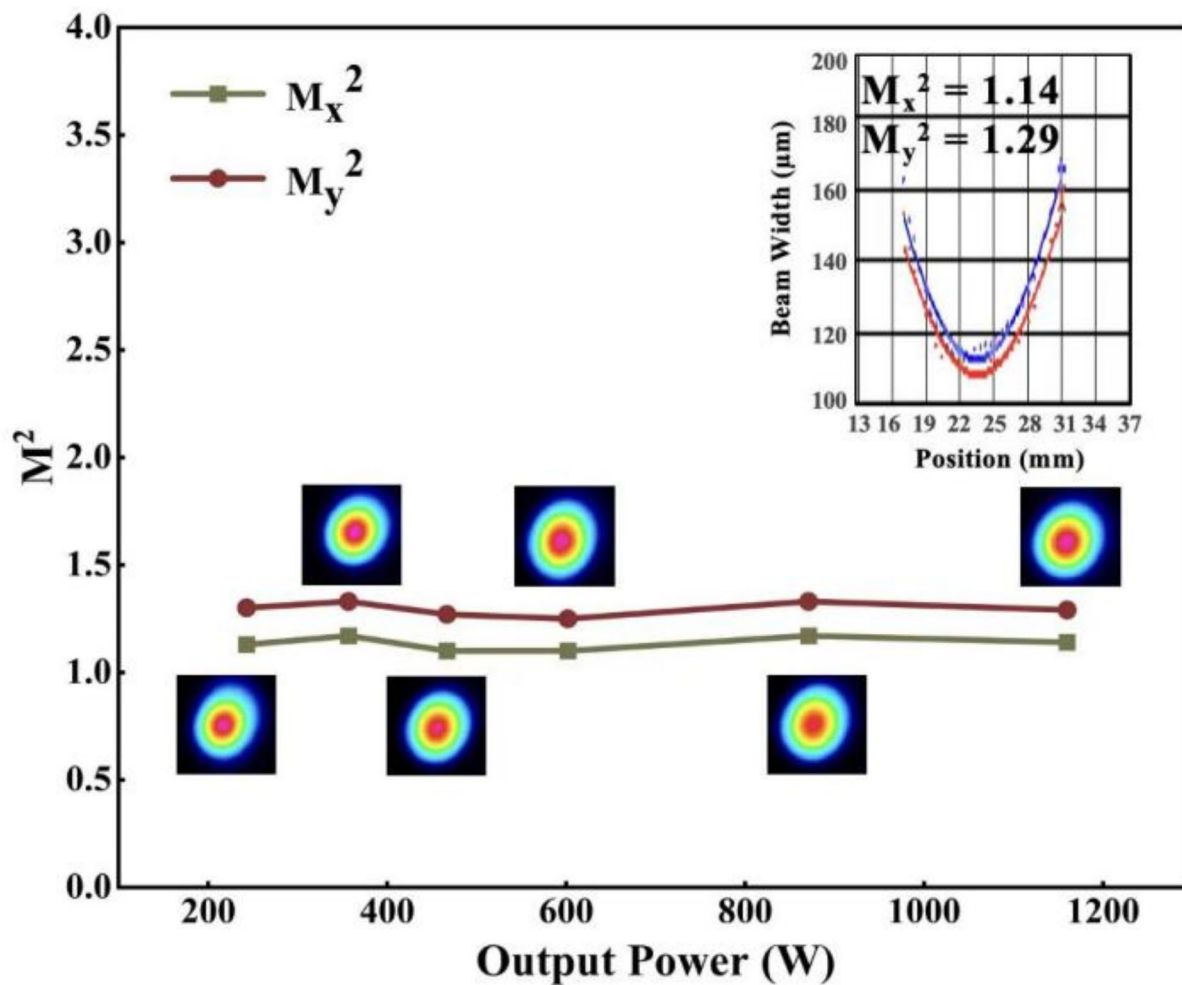


Fig. 5. Beam quality factor evolution with output power.

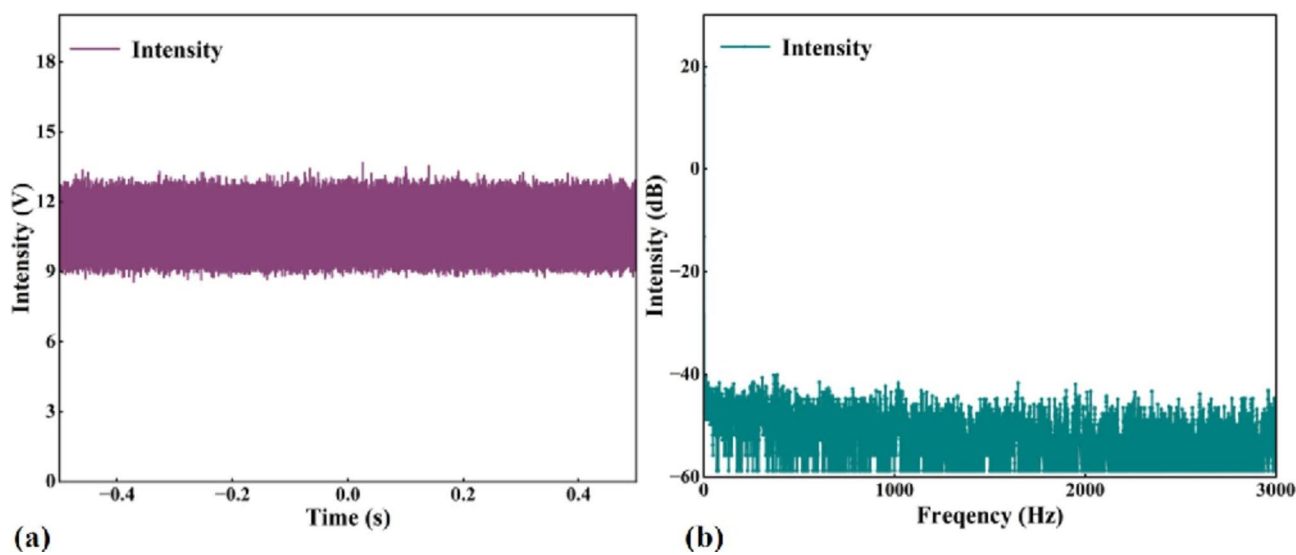


Fig. 6. (a) Frequency domain intensity, (b) Time domain intensity.

## Conclusion

In this paper, a nearly diffraction limited all-fiber oscillator with high efficiency is reported and we have fully demonstrate the advantages of 915nm laser diodes as pump sources in oscillators. By optimizing the length and winding radius of the gain fiber, the laser can achieve kilowatt-level output power with high efficiency and high beam quality nearly 1080nm, which has good time-domain characteristics. When the pump power is 1538W, the output optical power is 1160W, which the optical-to-optical efficiency can reach 75.4%. The oscillator can be widely used in the industrial field because of its good output characteristics. Overall, this study also demonstrates the potential of 915nm-pumped all-fiber oscillators for high-power, high-efficiency fiber laser systems. The advantages of 915nm pumping will give lasers the opportunity to face more diverse industrial applications. In the future, we hope to achieve further breakthroughs in output power on the basis of ensuring high optical-to-optical efficiency and high stability.

## Data availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

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## Author contributions

X.C. designed the experiments, X.C. and Y.Y. performed the experiments, X.C. analysed the results. X.C. wrote the manuscript. M.G., P.S. and J.M. revised the manuscript. All authors reviewed the manuscript.

## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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