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High efficiency continuous-wave Ho: LSO laser wing-pumped by the laser diode at 1.91 μm

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We present a high-efficiency continuous-wave Ho: LSO laser wing-pumped by a 1.91 μm laser diode. The impact of different output transmittances on the laser output power is compared and analyzed. The optimal result was achieved with a −500-mm radius curvature and a 6% transmission output coupler. The maximum output power of the Ho: LSO laser is 7.81 W, with a slope efficiency of 44.7%, a center wavelength of 2,106.6 nm, and beam quality factors of 1.4 in the *x*-direction and 1.3 in the *y*-direction.

KEYWORDS

solid-state laser, wing-pumped, laser diode, Ho: LSO, continuous-wave laser

1 Introduction

The 2 μm wavelength range falls within the atmospheric safety window, the human eye safety band, and encompasses the absorption peaks of many atoms and molecules, making 2 μm lasers versatile in environmental monitoring, laser medical treatments, laser radar, and other applications [1–3]. Of particular importance is the ability of 2 μm lasers with high peak power to serve as pump sources for optical parametric oscillators (OPO) and optical parametric amplifiers (OPA) to generate mid-infrared (3–12 μm) laser outputs [4, 5], which hold significant value in the field of laser infrared directional interference [6].

2 μm solid-state lasers utilize Tm^{3+}/Ho^{3+}-doped matrix materials as the laser gain medium, harnessing energy transitions from these rare earth elements to directly produce 2 μm laser output [7–11]. The choice of matrix material significantly influences the thermal and mechanical properties of the laser gain medium. While oxide (such as YAP, YAG) and fluoride (such as YLF, LLF) matrix materials are well-established for 2 μm solid-state lasers, there is a growing interest in tunable lasers with wide spectral ranges to meet the demands of ultrafast pulse laser technology. The non-uniform broadening of the output spectrum in solid-state lasers using silicate crystals as laser gain media can be attributed to the low symmetry and multiple substitution of active ions within the silicate crystal structure [12].

The LSO (Lu_2SiO_5) matrix is a common silicate material, belonging to the monoclinic crystal system with space group C^6_{2h} [13]. The lattice constants are as follows: a = 12.36 Å, b = 6.66 Å, c = 10.25 Å. The thermal conductivity, refractive index, and density of the LSO matrix are 5.3 $Wm^{-1}k^{-1}$, 1.82, 7.41 g/cm^3, respectively. The LSO matrix is not easily delixified [14]. In 2008, Yao et al. first reported the output characteristics of a 2 μm laser using the Tm: LSO crystal as the gain medium, emitting at a central wavelength of 2,058.4 nm with a bandwidth of approximately 13.6 nm [14]. Subsequently, in 2009, Yao et al. investigated the output characteristics of the Tm, Ho: LSO and the Ho: LSO continuous-wave (CW) lasers [15]. Corresponding pump sources were laser diode at 786 nm and Tm:YLF laser at 1.91 μm, respectively. Different central wavelengths of 2,089 nm, 2,071 nm, and 2,062 nm were achieved for the Tm, Ho: LSO laser by

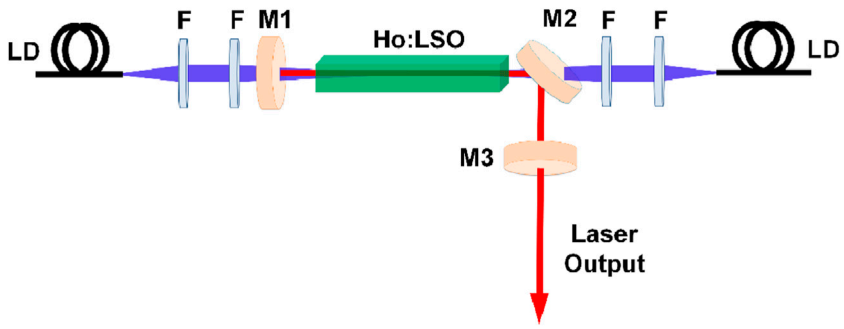

FIGURE 1
The Experiment setup of LD-wing-pumped CW Ho: LSO laser.

adjusting the transmittance of the output coupling mirror. Additionally, the Ho: LSO (Holmium-doped lutetium oxyorthosilicate) CW laser with a central wavelength of 2,106 nm was demonstrated [15]. For the $^5I_7 \rightarrow ^5I_8$ energy level transition of the Ho: LSO crystals, there are multiple absorption peaks at 1,908 nm and 1,944 nm. The emission spectrum of the Ho: LSO crystal is broad near 2 μm, with strong emission peaks in the range of 2,031 nm–2,137 nm. The upper energy lifetime of the Ho: LSO crystal is relatively long at 3.3 ms [15]. In 2012, Yao et al. further explored the output characteristics of the Tm, Ho: LSO and the Ho: LSO active Q-switched lasers [16]. Following this, in 2013, Feng et al. reported the output characteristics of the Tm: LSO passive Q-switched laser utilizing a graphene-based saturable absorber, operating at a central wavelength of 2,030.8 nm with a pulse duration of 7.8 μs [17]. Finally, in 2014, Feng et al. presented the output characteristics of the Tm: LSO wavelength-tunable active Q-switched laser based on acousto-optic Q-switching, demonstrating a wavelength tuning range from 1,959 nm to 2,070 nm with a pulse duration of 345 ns [18].

Our study presents the output characteristics of the Ho: LSO lasers pumped by a 1.91 μm fiber-coupled laser diode (LD) for the first time. The Ho: LSO laser achieves a maximum output power of 7.81 W, an optical conversion efficiency of 31.6%, and a center wavelength of 2,106.6 nm, with beam quality factors of $M_x^2 = 1.4$ in the *x*-direction and $M_y^2 = 1.3$ in the *y*-direction. Ho: LSO laser can be used as a light source for welding and cutting plastic materials, and can also be used as a pump source for mid-infrared laser.

2 Experimental setup

The experimental setup of the wing-pumped CW Ho: LSO laser is shown in Figure 1. The laser gain medium is the a-cut Ho: LSO crystal. The crystal has a doping concentration of 1 at% Ho^{3+} ion, a length of 20 mm, and a cross-sectional area of 4 mm^2. The two end faces of the crystal are coated with an anti-reflection (AR) film with a thickness of 1.9–2.1 μm. The Ho: LSO crystal is enclosed in indium foil and attached to a copper heat-sink, which is cooled by thermoelectric cooler (TEC). The operating temperature of the Ho: LSO crystal is set at 15°C.

Two 1.91 μm fiber-coupled output LD (QPC Lasers Inc.) are used as the pump source. The output fiber has a core diameter of

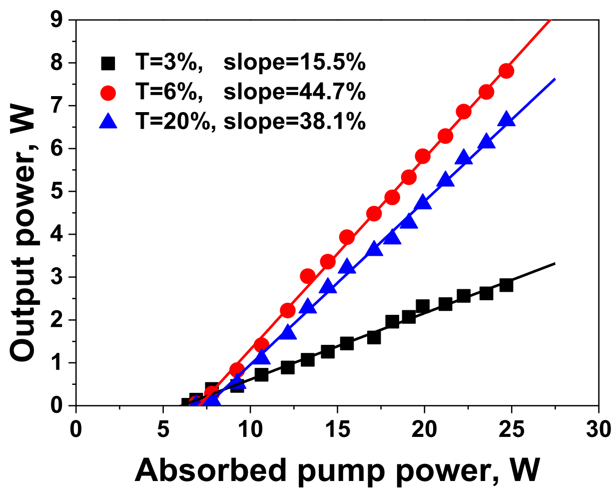

FIGURE 2
The output characteristics of wing-pumped Ho: LSO laser.

600 μm. When the operating temperature is set at 15°C and the output power is 30 W, the measured LD output center wavelength is approximately 1,910.5 nm, with a half-height line width of less than 2 nm. Each pump beam is collimated using the F lens with a focal length of 30 mm and then focused using another the F lens with the same focal length. The two pump beams pass through the M1 mirror and the M2 mirror, respectively, before being focused into the crystal with a spot diameter of 600 μm. In the non-laser output state, the measured absorption rate of the Ho: LSO crystal is approximately 50%.

The resonator consists of a 0° dichroic mirror M1, a 45° dichroic mirror M2, and a coupled output mirror M3 with a radius of curvature of −500 mm. The M1 and M2 mirrors are flat and coated with a high transmittance (HT) film at the pumping wavelength and a high reflectance (HR) film at the laser wavelength. The physical length of the resonator is approximately 42 mm. The distance between the face of the crystal near the M1 face and the M1 mirror is 5 mm. Without considering the focal length of the thermal lens of the crystal, the beam diameter of the resonator at the two end faces and the center of the crystal is approximately 0.56 mm.

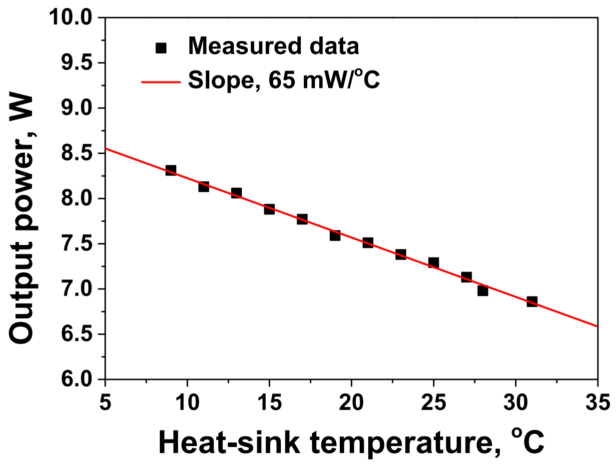

FIGURE 3
The output power versus the heat-sink temperature.

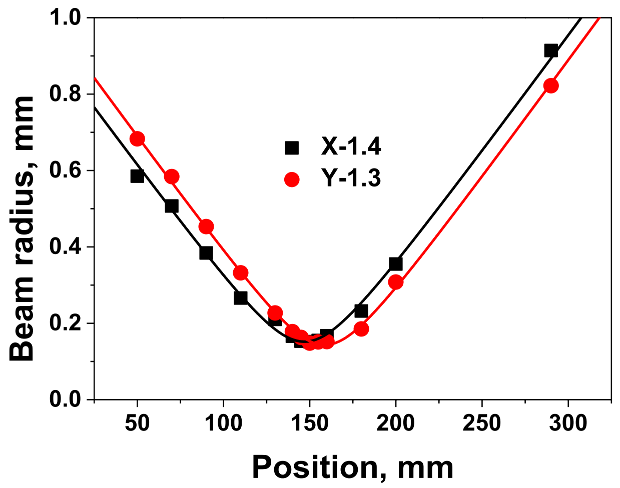

FIGURE 5
The beam quality factor of wing-pumped Ho: LSO laser at maximum output power.

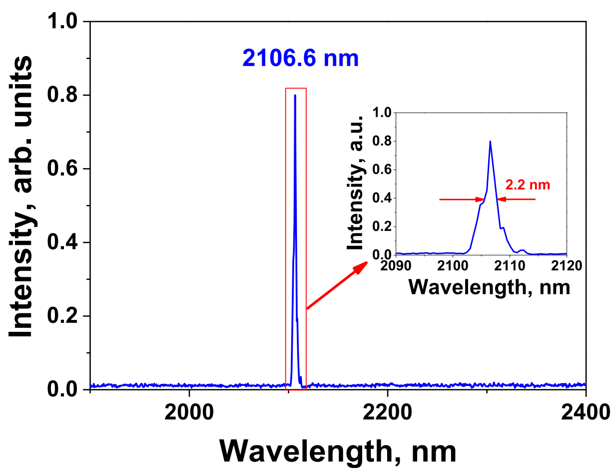

FIGURE 4
The output spectrum of wing-pumped Ho: LSO laser.

3 Experimental results

The output characteristics of the wing-pumped the Ho: LSO laser are shown in Figure 2. When the selected transmittance of the coupled output mirror is set at T = 3%, 6%, and 20%, the output power of the Ho: LSO laser increases approximately linearly with the absorbed pump power. The slope efficiency of the Ho: LSO laser is 15.5%, 44.7%, and 38.1%, respectively. At an absorbed pump power of 24.7 W, the maximum output power of the Ho: LSO laser is 2.81 W, 7.81 W, and 6.65 W, respectively. The corresponding optical conversion efficiencies are 11.4%, 31.6%, and 26.9%, respectively. The output power of the laser in the experiment was measured using a Coherent PM50 power meter.

We have measured output power of Ho: LSO laser under different crystal heat-sink temperature. Experimental results indicated that the output power decreases with increase of crystal heat-sink temperature. The slope is about 65 mW/°C. The output power versus the heat-sink temperature are shown in Figure 3.

The output spectrum of the Ho: LSO laser was measured using Bristol Instruments' Model 721 spectral analyzer, and the results are shown in Figure 4. For the coupled output mirror with a transmittance of T = 6% and an absorbed pump power of 24.7 W, the center wavelength of the output laser from the Ho: LSO laser is 2,106.6 nm, with a half-height line width of approximately 2.2 nm. The output central wavelength of the Ho: LSO laser aligns with the weak absorption peak of the excited emission cross section of the Ho: LSO crystal [15]. This is mainly due to the reduced reabsorption of the Ho: LSO crystal when the transmittance of the coupled output mirror is low.

The beam quality of the Ho: LSO laser was measured using the 90/10 knife-edge method with a coupled output mirror transmittance of T = 6% and an absorbed pump power of 24.7 W [19]. A lens with a focal length of 100 mm was used to transform the continuous output laser beam, and the spot sizes at different positions after the lens transformation were measured in both the x (horizontal) and y (vertical) directions. The measurement results are shown in Figure 5. After Gaussian beam fitting, the beam quality factors in the *x* and *y* directions, calculated based on the fitting parameters, were found to be M_x^2 = 1.4 and M_y^2 = 1.3, respectively.

4 Conclusion

In this study, we present a resonance-pumped CW Ho: LSO laser by a 1.91 μm fiber-coupled LD for the first time. The performance of the laser *i*th different transmittances for the coupled output mirrors is compared and analyzed. The highest slope efficiency of the output power of the Ho: LSO laser is achieved when the transmittance is set at 6%, reaching 44.7%. At an absorbed pump power of 24.7 W, the maximum output power of the Ho: LSO laser is 7.81 W, with an optical conversion efficiency of 31.6%. The center wavelength of the laser output is 2,106.6 nm, with a half-height line width of approximately 2.2 nm. The beam quality factors in the x and y directions are $M_x^2 = 1.4$ and $M_y^2 = 1.3$, respectively.

Author contributions

ZC: Writing–original draft, Writing–review and editing. YY: Writing–review and editing. CP: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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