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A 1908 nm Internal-Cavity Tm-Doped Fiber Laser Pumped by a 1570 nm Er/Yb Fiber Laser

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Abstract

An internal-cavity Tm-doped all-fiber laser at 1908 nm in-band-pumped by a 1570 nm Er/Yb co-doped fiber laser is proposed. An external-cavity fiber oscillator composed of a pair of high-reflectivity (HR) fiber Bragg gratings (FBGs) at 1570 nm pumped by 915 nm laser diodes (LDs) serves as the bidirectional pumping source for the 1908 nm internal-cavity fiber oscillator to achieve high-efficiency laser output. Firstly, a maximum output power of 10 W is realized at a 915 nm pump power of 36.8 W in the single 1570 nm Er/Yb fiber oscillator, with a corresponding slope efficiency and a signal-to-noise ratio (SNR) of 28.1% and 62 dB, respectively. The beam quality factor M^2 of the single 1570 nm Er/Yb fiber oscillator is about 1.2. In the 1908 nm internal-cavity Tm-doped all-fiber laser, the maximum output power is 482 mW when the pump power at 915 nm reaches 12.6 W, with a corresponding slope efficiency of 8.1%. Under the same 915 nm pump power, the slope efficiency of the 1908 nm Tm-doped fiber laser with an external-cavity pump is 5.3%.

Keywords: all-fiber laser; cavity-pumped; Tm-doped fiber; Er/Yb co-doped fiber

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1. Introduction

It is known that 2 μm waveband fiber lasers have a strong absorption peak for water and plastic materials and have low absorption coefficients in nonlinear crystals such as $ZnGeP_2$ (ZGP) [1,2], which have important applications in the fields of laser medicine, laser processing, and nonlinear frequency conversion [3–6]. Tm-doped gain fibers are commonly used in high-power lasers operating in the 2 μm waveband, because Tm^{3+} ions have a rich energy level structure and Tm-doped gain fibers with a large mode field have become very mature. Currently, Tm-doped fiber lasers are pumped by 793 nm laser diodes (LDs) and 1570 nm fiber lasers. However, the conventional 793 nm pumping scheme requires multi-step energy transfer characterized by low efficiency and significant thermal effects, which restricts the enhancement of 2 μm laser power and beam quality [7,8]. Compared with the Tm-doped fiber lasers pumped by 793 nm LDs, the 1570 nm pumping method operates on the principle of in-band pumping, where the small difference in photon energy between the pump light and the output laser at ~2 μm results in an extremely low quantum defect. Consequently, the majority of pump energy is converted into laser output rather than heat, leading to a low proportion of waste heat [9]. On the other hand, the 1570 nm fiber laser operates within the $^3F_4 \rightarrow {}^3H_6$ absorption band of Tm^{3+} ions. Although its absorption cross-section is lower than that of 793 nm pumping, the pump light propagates through

the fiber core, enabling high single-pass absorption efficiency. This allows for shorter gain fiber lengths, thereby mitigating the risk of nonlinear effects [10,11].

To date, some researchers have investigated fiber oscillators near the 1570 nm waveband. In 2015, Leonid et al. used a pair of fiber Bragg gratings with a bandwidth of 0.5 nm and a wavelength of 1560 nm, an Er-doped fiber as the gain medium, and a 980 nm semiconductor laser as the pumping source, to achieve a 1560 nm laser output power of 400 mW [12]. In 2020, Turghun et al. employed a 915 nm laser diode to pump an Er/Yb co-doped gain fiber, achieving laser output at 1562 nm with 1.9 W optical power and a beam quality factor (M^2) of 1.17 [13]. In 2020, Zhang et al. employed a 1570 nm laser as the pump source to excite the Tm-doped gain fiber, generating 1720 nm laser output. When the pump power of the 1570 nm laser reached 6 W, the output power of the 1720 nm laser attained 2.36 W, with an output linewidth of approximately 4 GHz [14]. In 2022, Zhang et al. used a 1570 nm fiber laser to pump a Tm-doped gain fiber and ultimately obtained a laser output with an output power of 5.92 W with a center wavelength of 1720 nm [15]. In 2016, Chen et al. used a 1570 nm fiber laser with an output power of 1.3 W for external-cavity pumping of a Tm-doped gain fiber and finally achieved a nanosecond pulsed laser output at a wavelength of 2 μm and an output energy of 78 μJ [16]. From the above reports, it can be seen that the Tm-doped fiber lasers pumped by 1570 nm fiber lasers primarily operate at the short wavelength of 1720 nm, exhibiting high quantum efficiency, which leads to superior laser output efficiency. However, in the case of 2 μm thulium fiber lasers operating at the shorter wavelength of 1908 nm, comparatively higher reabsorption occurs than at longer 2 μm wavelengths [17], limiting the effective enhancement of output power. Therefore, compact intracavity-pumped 1908 nm Tm-doped fiber lasers need to be further investigated.

In this paper, we have reported a 1908 nm Tm-doped all-fiber internal-cavity laser in-band-pumped by a 1570 nm Er/Yb co-doped fiber laser. An external-cavity fiber oscillator was constructed using a pair of 1570 nm high-reflectivity (HR) fiber Bragg gratings (FBGs) and pumped by 915 nm laser diodes (LDs); the 1570 nm laser output from the external-cavity served as a bidirectional pumping source to pump the 1908 nm internal-cavity fiber oscillator, with the objective of achieving high-efficiency laser output. For the external 1570 nm fiber oscillator, an output power of 10 W was achieved at a 915 nm pump power of 36.8 W, with a corresponding slope efficiency of 28.1%, a signal-to-noise ratio (SNR) of 62 dB, and a beam quality factor M^2 of 1.2. In the internal-cavity laser system, a maximum output power of 482 mW at 1908 nm was attained when the 915 nm pump power reached 12.6 W, corresponding to a slope efficiency of 8.1%. Additionally, under the same 915 nm pump power, the maximum output power at 1908 nm was 287 mW with an external-cavity pumping configuration, corresponding to a slope efficiency of 5.3%.

2. Experimental Setup

The experimental setup of the 1908 nm internal-cavity Tm-doped fiber laser pumped by a 1570 nm Er/Yb co-doped fiber laser is illustrated in Figure 1. Two laser diodes (LDs) emitting at 915 nm are used as the pump source of the whole internal-cavity oscillator. The two pump sources are coupled into the laser system through a (2 + 1) × 1 pump combiner featuring 10/125 μm single-mode input/output fibers. The external 1570 nm Er/Yb fiber oscillator consists of a pair of high-reflectivity (HR) fiber Bragg gratings (FBGs) with a reflectivity of >99.5% and 3 dB bandwidth of 2 nm at 1570 nm, generating bidirectional 1570 nm laser output to pump the internal Tm-doped fiber laser oscillator. The gain fiber in the external 1570 nm Er/Yb fiber oscillator is a piece of 4 m long Er/Yb co-doped fiber (CJEYDF-SM-10/125), with a cladding absorption coefficient of 1.95 dB/m. The core and cladding diameters of the Er/Yb co-doped fiber are 10 μm and 125 μm with a corresponding

core numerical aperture (NA) of 0.14. A 1908 nm HR FBG with a reflectivity of >99.5% and 3 dB bandwidth of 2 nm and a partial-reflectivity (PR) FBG with a reflectivity of ~9.8% and 3 dB bandwidth of 0.4 nm are inserted between the two 1570 nm high-reflectivity FBGs to serve as the external resonant cavity. A section of Tm-doped fiber (SM-TDF-10P/130-M) with a length of 0.2 m and cladding absorption of 9 dB/m is used as the gain medium of the 1908 nm fiber oscillator, which has a core/cladding diameter of 10/130 μm and corresponding NA of 0.15/0.46. The Tm-doped gain fiber fusion-spliced after the Er/Yb co-doped fiber is core-pumped by the bidirectional 1570 nm laser. A cladding power stripper (CPS) connected with the 1570 nm HR FBG is used to remove residual 793 nm pump light from the fiber cladding.

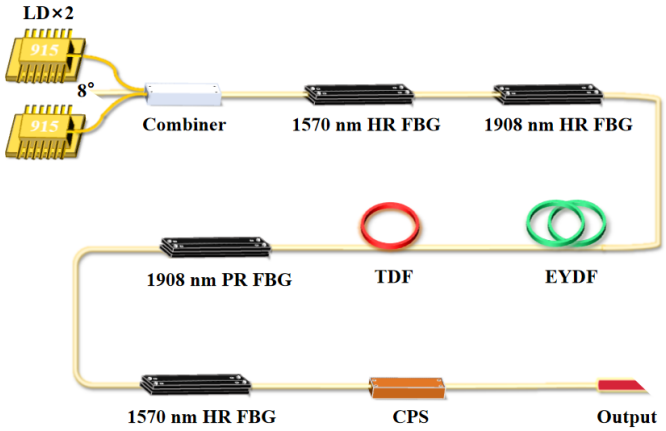


Figure 1. Experimental setup of the 1908 nm internal−cavity Tm−doped fiber laser pumped by 1570 nm Er/Yb co−doped fiber laser. EYDF: Er/Yb co−doped fiber, TDF: Tm−doped fiber, HR FBG: high−reflectivity FBG, PR FBG: partial−reflectivity FBG.

3. Experimental Results and Discussion

Firstly, a 1570 nm Er/Yb co-doped fiber oscillator formed by an HR FBG with 99.5% reflectivity and PR FBG with 10% reflectivity is constructed by using two 915 nm LDs as the forward pumping source. Meanwhile, the 1570 nm signal light is separated from a dichroic mirror coated with high transmittance at 915 nm and high reflectivity at 1570 nm. The 1570 nm output power as a function of the 915 nm pump power is shown in Figure 2. A maximum 1570 nm output power of 10 W is achieved under the launched 915 nm pump power of 36.8 W, with a slope efficiency and an optical-to-optical conversion efficiency of 28.1% and 27.2%, respectively. The output spectrum of the 1570 nm Er/Yb co-doped fiber laser is measured by a spectrometer (Yokogawa Electric Corporation (Tokyo, Japan), AQ6370D), as shown in Figure 3. The peak wavelength of the output laser is 1569.8 nm with a 3 dB bandwidth of about 0.5 nm and a signal-to-noise ratio (SNR) of 62 dB. By focusing the 1570 nm output laser through two lenses with focal lengths of 25 mm and 100 mm, a beam waist with a radius of approximately 0.2 mm is obtained. Therefore, the beam quality M^2 of the 1570 nm Er/Yb co-doped fiber laser is obtained through the 90/10 knife-edge method. The measured beam radius results at different positions are fitted by a Gauss function, as shown in Figure 4. A beam quality factor M^2 of approximately 1.2 is realized, indicating that the 1570 nm Er/Yb co-doped fiber laser is in single-mode operation.

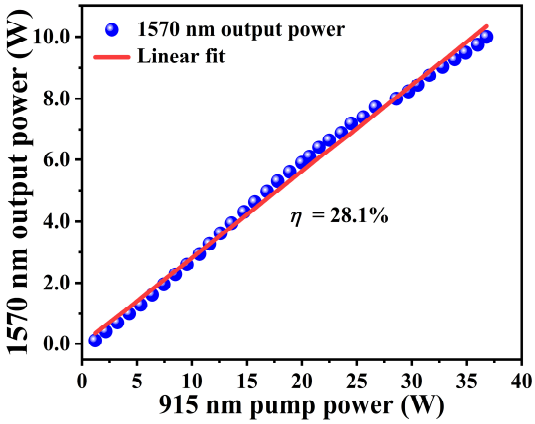


Figure 2. The 1570 nm output power in the Er/Yb co−doped fiber oscillator as a function of the 915 nm pump power.

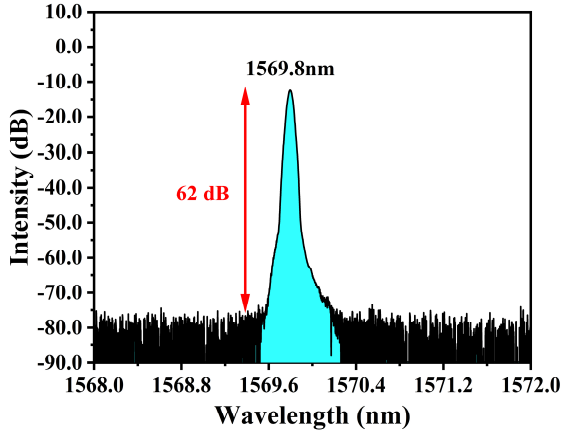


Figure 3. Output spectrum of the 1570 nm Er/Yb co-doped fiber laser at an output power of 10 W.

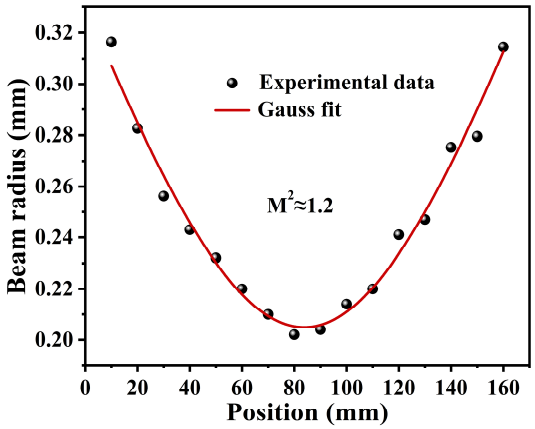


Figure 4. Beam quality factor of the 1570 nm Er/Yb co−doped fiber laser.

Then, the output characteristics of the 1908 nm internal-cavity Tm-doped fiber laser pumped by a 1570 nm Er/Yb fiber laser are investigated. The 1908 nm output power versus the 915 nm pump power is shown in Figure 5. The 1908 nm output power linearly increased with the elevation of the 915 nm pump power. A maximum 1908 nm output power of 482 mW is delivered from the internal-cavity oscillator when the 915 nm pump power reaches 12.6 W, corresponding to a slope efficiency of 8.1%. The 1570 nm and 1908 nm lasing wavelengths correspond to the spectral edges of the gain peaks in Er/Yb co-doped fiber and Tm-doped fiber, respectively, leading to lower output efficiency in internal-cavity fiber lasers. Meanwhile, the discrepancy in core numerical aperture (NA) between the

Er/Yb co-doped gain fiber and the Tm-doped gain fiber may prevent the laser from being fully confined within the fiber core. Additionally, splicing between gain fibers and between gain fibers and passive fibers may introduce additional losses. These factors are likely contributing to the reduced efficiency. The 1908 nm laser output spectrum of the 1908 nm internal-cavity Tm-doped fiber laser is shown in Figure 6. It can be seen that the main peak center wavelength is at 1908 nm with a 3 dB spectral linewidth of 0.18 nm, while the secondary peak center wavelength is at 1535 nm, with the main peak intensity being 35 dB higher than that of the secondary peak. The reason for the generation of 1535 nm parasitic lasing in internal-cavity fiber lasers is that the Er/Yb co-doped fiber exhibits a larger emission cross-section at 1535 nm. Consequently, the pump power required for 1535 nm to reach the laser oscillation threshold is significantly lower than that for 1570 nm. Furthermore, excessive fiber splicing points within the cavity create unintended end-face reflections, lowering the oscillation threshold.

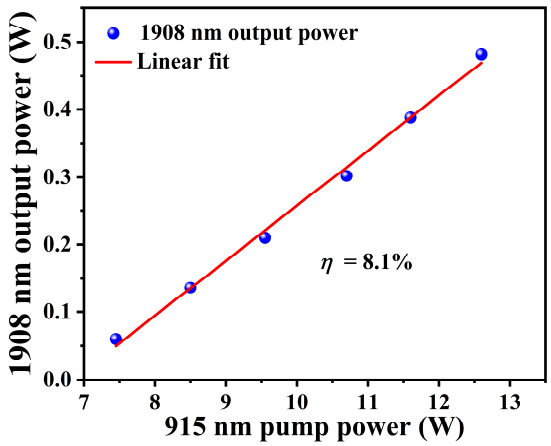


Figure 5. The 1908 nm output power in the internal−cavity Tm−doped fiber laser as a function of the 915 nm pump power.

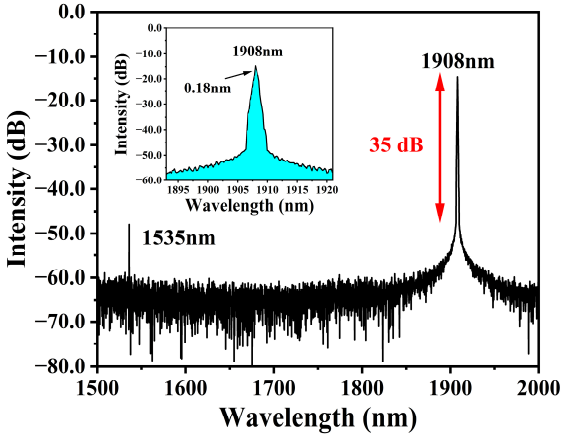


Figure 6. Output spectrum of the 1908 nm internal−cavity Tm−doped fiber laser. The inset is an enlargement of the signal peak.

To verify whether the intracavity-pumped Tm-doped fiber laser is more efficient than the externally pumped Tm-doped fiber laser, we employ a 1570 nm Er/Yb co-doped fiber oscillator to externally pump a 1908 nm Tm-doped fiber laser; the experimental setup is shown in Figure 7. The lengths of the Er/Yb co-doped fiber and Tm-doped fiber are identical to those of the intracavity laser, and the reflectivity of the 1570 nm partial-reflectivity FBG is 10%.

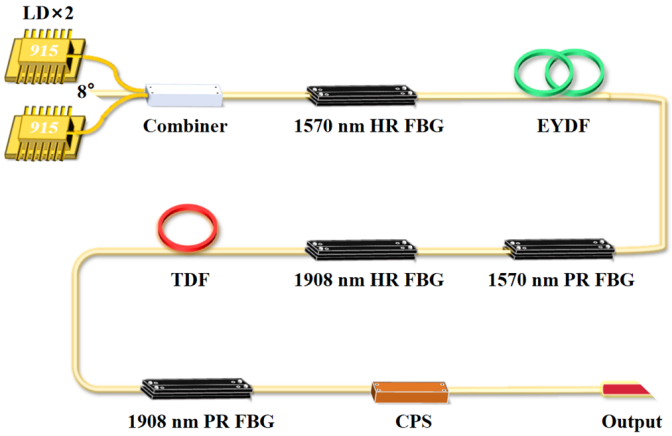


Figure 7. Experimental setup of the 1908 nm external−cavity Tm−doped fiber laser pumped by 1570 nm Er/Yb co−doped fiber laser.

The 1908 nm output power as a function of the 915 nm pump power is shown in Figure 8. At a 915 nm pump power of 12.6 W, the 1908 nm output laser power achieves 287 mW, with a slope efficiency of 5.3%. The 1908 nm laser output spectrum of the 1908 nm external-cavity Tm-doped fiber laser is shown in Figure 9. It can be seen that the main peak center wavelength is at 1908 nm, while the secondary peak center wavelength is at 1535 nm, with the main peak intensity being 27 dB higher than that of the secondary peak. Under the same 915 nm pump power, the intracavity pumping exhibits a higher slope efficiency than the external pumping, demonstrating the advantage of the intracavity pumping configuration.

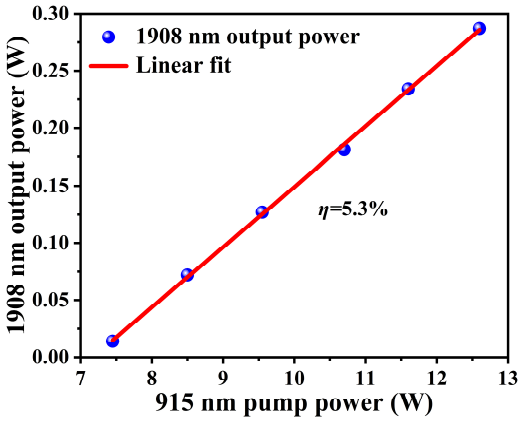


Figure 8. The 1908 nm output power in the external-cavity Tm−doped fiber laser as a function of the 915 nm pump power.

Compared to the works in references [18–21], which all achieved 2 μm laser output via external-cavity pumping of Tm-doped gain fibers, this study implements 1908 nm laser generation through bidirectional internal-cavity pumping of Tm-doped fiber, representing the primary distinction from the referenced experiments. The high pump efficiency of the reference scheme stems from the close match between the pump laser wavelength and the signal wavelength. In contrast, the substantial wavelength separation between 1570 nm and 1908 nm results in relatively lower quantum efficiency, consequently diminishing pump efficiency. However, the 1908 nm internal-cavity fiber laser offers a more compact structure. Meanwhile, the output results of the 1908 nm internal and external-cavity fiber lasers are compared, demonstrating that the internal-cavity structure achieves higher efficiency. Thus, the internal-cavity pumping method for Tm-doped fibers provides a promising experimental approach for achieving 2 μm laser output.

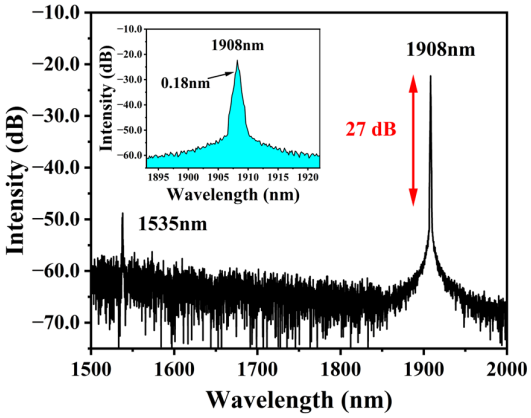


Figure 9. Output spectrum of the 1908 nm external−cavity Tm−doped fiber laser. The inset is an enlargement of the signal peak.

4. Conclusions

In conclusion, we have reported a 1908 nm Tm-doped all-fiber internal-cavity laser in-band-pumped by a 1570 nm Er/Yb co-doped fiber laser. An external-cavity fiber oscillator is formed by a pair of 1570 nm high-reflectivity (HR) fiber Bragg gratings (FBGs) and a 4 m Er/Yb co-doped gain fiber, pumped by 915 nm laser diodes (LDs). At 36.8 W of 915 nm pump power, the 1570 nm laser achieves an output power of 10 W with a slope efficiency of 28.1%, a signal-to-noise ratio (SNR) of 62 dB, and a beam quality factor M^2 of 1.2. Subsequently, the 1570 nm laser serves as a pump source to bidirectionally pump a 1908 nm internal-cavity fiber oscillator for 1908 nm laser output. The internal-cavity oscillator employs a 0.2 m Tm-doped fiber as the gain medium, achieving a maximum output power of 482 mW at 1908 nm with a slope efficiency of 8.1% when the 915 nm pump power is increased to 12.6 W. In contrast, under the same 915 nm pump power, the slope efficiency of a 1908 nm Tm-doped fiber laser externally pumped by a 1570 nm laser oscillator is 5.3%. This 1908 nm internal-cavity Tm-doped fiber laser pumped by 1570 nm Er/Yb fiber laser provides a promising approach for generating 1908 nm short-wavelength 2 μm laser output.

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