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Single-frequency hybrid Brillouin-thulium fiber laser with kilohertz linewidth

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ABSTRACT

Stimulated Brillouin scattering (SBS) is a well established method to narrow the laser linewidth to kilohertz level, which however suffers high threshold due to the low SBS gain at the region of 2 μm. The hybrid Brillouin/thulium fiber laser (BTFL) is such an approach which could suppress the laser linewidth with low threshold and high efficiency. In this paper, an ultra-narrow linewidth hybrid Brillouin/thulium fiber laser (BTFL) was demonstrated. Through experimentally optimizing the output coupling, pump scheme, Brillouin pump power and cavity length of the laser, 344-mW laser output with a narrow linewidth of 0.93 kHz was obtained, in which the linewidth of Stokes light was suppressed more than 43 times compared with the 40 kHz linewidth of the Brillouin pump. Besides, the influences of output coupling and pump scheme on the power and linewidth behavior of a single-frequency BTFL were also experimentally investigated, and there exists a performance balance among linewidth narrowing, output power and SBS threshold. The BTFL output power was further boosted to 5.5 W by a one-stage cladding-pumped fiber amplifier, and the corresponding spectral linewidth was broadened to 1.93 kHz. The output coupling exerted a significant influence on the BTFL performance.

Keywords: Stimulated Brillouin scattering, single frequency, narrow linewidth, thulium-doped

1. INTRODUCTION

Stimulated Brillouin scattering (SBS) has long been used to narrow the linewidth of fiber lasers, and narrow-linewidth Brillouin fiber lasers with strong linewidth suppression have been demonstrated in1 μm, 1.5 μm and 2 μm region [1–6]. This is significant in various scientific applications such as coherent LIDAR, high-resolution spectroscopy, and free-space optical communication [7–11]. However, one drawback of this Brillouin laser type is that Watt-level single-frequency pump power is typically required to reach the SBS threshold, which makes the device's operation inefficient for low-to-moderate power applications. A solution to the abovementioned problems is to incorporate the gain from the population inversion of the active fiber inside the Brillouin Stokes cavity. as was first demonstrated in 1996 by Gregory et al. with a hybrid Brillouin/Erbium fiber laser (BEFL) system [12]. The SBS threshold was below 10 mW in terms of the 980-nm laser diode (LD) power, and 10 mW of output power were generated with 50 mW generated by a LD pump. Hybrid Brillouin/ytterbium lasers (BYFLs) at the 1-μm region and hybrid Brillouin/thulium fiber lasers (BTFLs) at the 2-μm region have also been demonstrated with promising power and linewidth behavior [13-15]. In 2017, Fu *et al.* investigated a hybrid Brillouin/thulium fiber laser, a piece of thulium-doped fiber was insert into the ring cavity to provide gain for both Brillouin pump and Stokes light [3]. Though a low Brillouin laser threshold of 200 mW could be achieved, the spontaneous emission induced by active fiber influenced the linewidth-narrowed effect.

The linewidth broadening of Brillouin fiber lasers is mainly caused by phase fluctuation. Because the circulating Stokes field in the cavity and the phonon field can influence the phase noise induced by spontaneous emission [16,17], the output coupling can be an effective method of optimizing the spectral linewidth of the BTFLs. For single-frequency fiber lasers, the linewidth is also sensitive to the noise of the pump source, which can conduct the signal, and the length of the fiber

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can affect the narrowing effect of SBS. In this study, the influences of the output coupling, fiber length, and pump source on the spectral linewidth and power behavior of the BTFL were experimentally investigated. A Stokes output of 344 mW with a narrow linewidth of 0.93 kHz was obtained by optimizing the abovementioned parameters, and was further amplified to 5.5 W with a linewidth of 1.93 kHz. The results revealed that the BTFLs are promising for a sub-kHz single-frequency source at 2 μm, and that the trade-off between the output power and the spectral linewidth can actively be optimized by choosing a suitable output coupling.

2. EXPERIMENTAL ARRANGEMENT

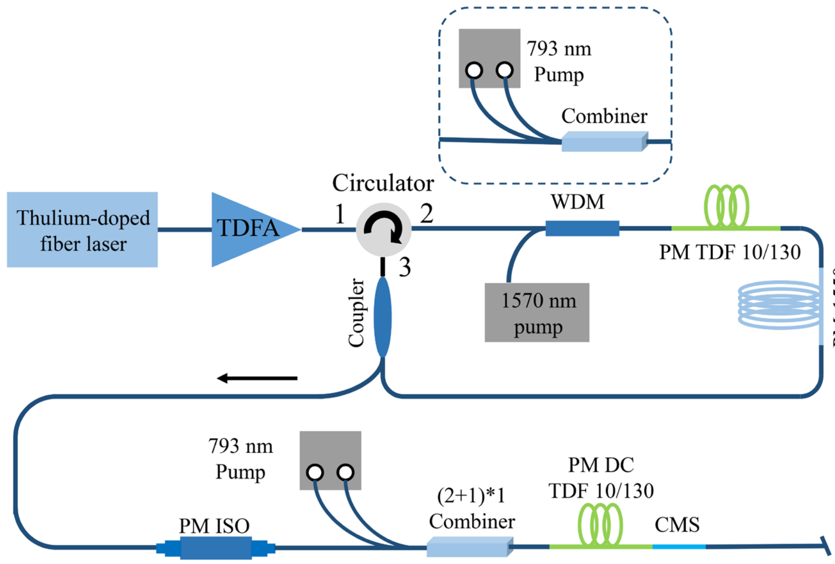

Figure 1. Schematic of hybrid Brillouin/thulium fiber laser.

Fig. 1 shows the experimental arrangement of the narrow-linewidth BTFL, along with the power amplifier. A single-frequency thulium-doped fiber MOPA at 1,956.49 nm with a linear-polarized output power of 300 mW, and a spectral linewidth of 40 kHz serving as the Brillouin pump, was coupled into the ring Stokes cavity through a circulator. A piece of 0.5-m long double-clad thulium-doped active fiber (Nufern PM-TDF-10/130-2000-HE) was inserted into the cavity to provide gain for both the clockwise propagating Brillouin pump and the anticlockwise propagating Brillouin Stokes. A piece of polarization-maintaining (PM) single-mode fiber (Corning PM1550) was spliced into the cavity for extra Brillouin gain. Part of the anticlockwise propagating Stokes was coupled out of the cavity through a coupler. Different output couplings of 10%, 30%, 50%, 70%, and 90%, and different PM1550 fiber lengths of 5 m and 8 m (total cavity length of 11 m and 14 m) were used in the experiment. We also tested the pump schemes of both the cladding pump at 793 nm and the core pump at 1,570 nm, wherein the pump light was coupled into the active fiber using wavelength-division multiplexing (WDM) and a combiner, respectively. The measured absorption coefficient of the 1,550-nm core pump and 793-nm cladding pump were 250 dB/m and 4.7 dB/m, respectively.

Subsequently, the BTFL output was coupled into the stage of a power amplifier, which consisted of a piece of a 2-m-long single-mode thulium-doped active fiber (Nufern PM-TDF-10/130-HE) cladding pumped at 793 nm through a (2+1)×1 combiner, within a co-propagating pumping scheme. An isolator was used between the BTFL output coupler and the signal port of the amplifier's pump combiner. To strip off the residual 793-nm pump power with a high refractive index gel, the output end of the thulium-doped fiber was spliced into a 30-cm long matched passive fiber (Nufern PM-GDF-10/130-2000-M). The output passive fiber was angle-cleaved (approximately 8°) to eliminate the Fresnel reflection on the facet. All the fiber and devices employed in the experiment were PM.

3. POWER PERFORMANCE AND SPECTRAL LINEWIDTH

First, we characterized the power performance of the BTFL with the 5-m-long PM1550 fiber. With a fixed incident Brillouin pump power of 250 mW (measured at port 2 of the circulator), the SBS threshold gradually increased from 0.35 W to 1.0 W in terms of pump power coupled into the thulium-doped fiber. The output coupling increased from 10% to 70%

when using the 1,570-nm core pump scheme, as shown in Fig. 2(a). For the highest output coupling of 90% in the experiment, the SBS was not observed under the maximum available pump power of 1.43 W. Although the lower output coupling helped reduce the SBS threshold to only 0.35 W, the maximum single frequency output power was only 26 mW before the occurrence of high-order Stokes under a 1,570-nm power of 620 mW, and was accompanied by a sharp drop of output power. For the output coupling of 30% and 50%, the maximum Stokes output power under the fixed 1,570-nm pump power of 1.43 W and Brillouin pump of 250 mW increased to 316 mW and 397 mW, respectively, with a corresponding slope efficiency of 46.5% and 62.0%. The slope efficiency and maximum output power substantially benefited from the higher output coupling compared with the slope efficiency of 9.6% with an output coupling of 10%. With an output coupling of 70%, although the slope efficiency of 69.3% was higher than that with lower output couplings, the relatively high SBS threshold of 1 W limited the maximum Stokes output power, which decreased to 277 mW under the same condition. Therefore, the trade-off between the SBS threshold, slope efficiency, and output power should be considered when optimizing the power performance of the BTFL.

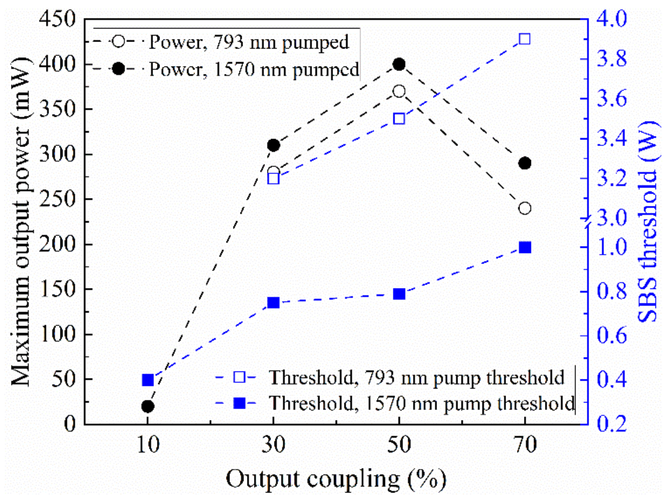

Figure 2. SBS threshold and Stokes output power with different output coupling under fixed Brillouin pump of 250 mW

The laser performance under a 793-nm cladding pump was also investigated using a combiner to couple the LD pump into the thulium-doped fiber. The SBS threshold and Stokes output power under the maximum pump are plotted in Fig. 2(a). With the incident Brillouin pump of 250 mW, the maximum Stokes output of 370 mW under a pump power of 6.2 W LD was also obtained with an output coupling of 50%, SBS threshold of 3.5 W, and slope efficiency of 13.7%. The insufficient pump absorption of the 2-m thulium doped fiber limited the efficiency under the cladding pump scheme. As will be described below, we used the cladding pump scheme to investigate the linewidth under a different pump scheme. Therefore, the fiber length was not optimized for output power. With the output couplings of 30% and 70%, the maximum output power was 280 mW and 240 mW, respectively, while the SBS threshold was 3.2 W and 3.9 W, respectively. Considering the high-order Stokes and high SBS threshold, the output couplings of 10% and 90% were not used with the 793-nm cladding pump scheme. Fig. 2(b) shows the power transfer of the BTFL under a 1,570-nm core pump and 793-nm cladding with an output coupling of 50%, with which the maximum output power was obtained.

The spectral linewidth of the Stokes output was measured using a delayed self-heterodyne system, and is plotted in Fig. 4. As can be seen, when the 1,570-nm core pumping was adopted, the spectrum linewidth gradually broadened from 1.7 kHz to 3.5 kHz as the output coupling increased from 30% to 70%. A similar trend was also observed with the 793-nm cladding pump. With a lower output coupling ratio, more power was reserved in the ring cavity for the Stokes light. In this case, the lower pump power threshold can be achieved to generate the SBS effect, which was verified as shown in Fig. 2(a). Moreover, because the linewidth narrowing effect of the Brillouin laser was caused by the combined influence of the acoustic damping and cavity feedback, the linewidth narrowing ratio between the Brillouin pump and the Stokes signal was larger. In other words, the narrower Stokes linewidth could be derived by decreasing the output coupling ratio [23]. Because the hybrid gain scheme was adopted in our Brillouin-thulium fiber laser, the system noise resulting from the spontaneous emission of the thulium-doped fiber is considered as another issue related to the narrowing of the laser linewidth. Enhanced cavity feedback with a lower output coupling could alleviate the effect of spontaneous emission noise and increase the monochromaticity degree of the Stokes light, respectively. Moreover, the output power of the linewidth-narrowed Stokes light significantly decreased as the output coupling ratio reduced. As demonstrated by the experiment, the Stokes power decreased from 400 to 26 mW when the output coupling ratio changed from 50% to 10%. Therefore, for an optimized hybrid Brillouin-thulium fiber laser, an appropriate output coupling ratio should be carefully chosen to ensure performance balance between the linewidth narrowing effect and laser power.

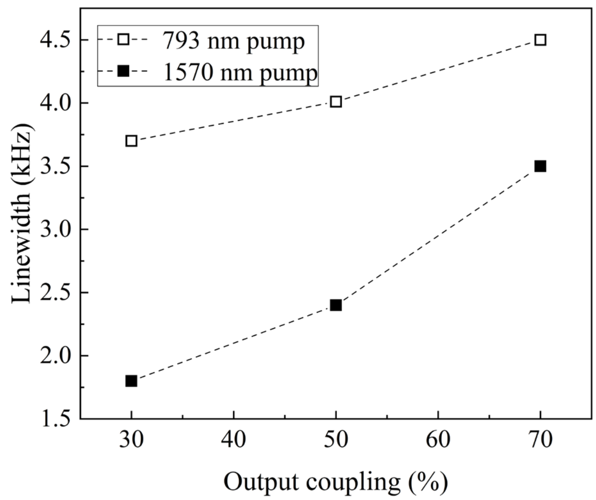

Figure 3. Stokes BTFL linewidths measured with different coupling and pump schemes. The dashed lines serve as a visual guide.

4. FURTHER LINEWIDTH NARROWING

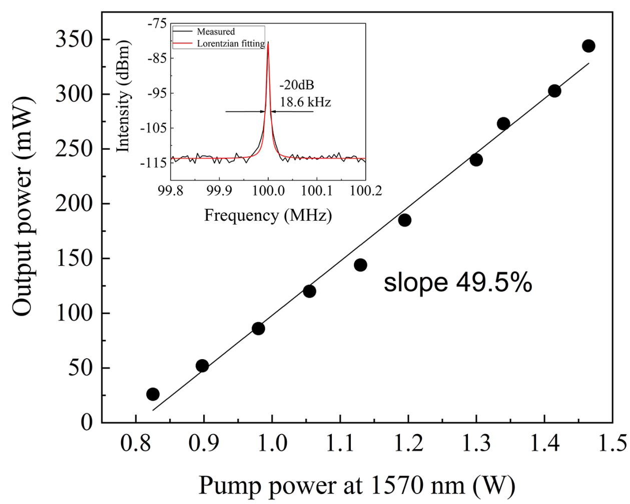

Figure 4. Power transfer of BTFL with 14-m-long cavity; inset: Stokes linewidth was measured at maximum output power of 344 mW. The dashed lines serve as a visual guide.

To further narrow the laser linewidth, we increased the length of the PM1550 fiber to 8 m (total cavity length of 14 m) and used the output coupling of 30%, with which the high-order SBS was not observed. The output power did not decrease substantially compared with its maximum value with an output coupling of 50%. With regard to the 1,570-nm pump power, the SBS threshold was 700 mW with a fixed Brillouin pump of 250 mW, which is lower than that observed with a 5-m-long PM1500 fiber (total cavity length of 11 m). Additionally, the maximum Stokes output power under 1.43 W with 1,570 nm of pump power was 344 mW, as shown in Fig. 5. The inset of Fig. 5 shows the spectral linewidth recorded using the delayed self-heterodyne system. The 20-dB linewidth of 18.6 kHz indicates a 3-dB linewidth of 0.93 kHz and a 43-fold linewidth reduction. The longer fiber length helped narrow the Stokes linewidth, in addition to providing a higher Brillouin gain [16]. However, the single-frequency operation of the BTFL became unstable when the fiber length increased further. The minimum Brillouin pump power required for a stable Stoke output was 210 mW; that is, with a Brillouin pump below

210 mW, SBS was not observed under the maximum 1,570-nm pump power of 1.43 W. Considering the parameters in our demonstration, the Brillouin fiber laser has a theoretical linewidth reduction ratio of approximately 110 [23], and was much larger than 43 in our experiment.

Subsequently, the BTFL output was coupled into the amplifier, which was cladding-pumped at 793 nm. Fig. 6(a) and (b) shows the plot of the power transfer and linewidth evolution of the amplifier, respectively. A maximum power of 5.5 W was obtained under the launched pump power of 17 W, with a slope efficiency of 34.9 %. As can be seen in the inset of Fig. 6(a), the signal-to-noise ratio (SNR) at the maximum power was approximately 65 dB, and there was no obvious evidence of ASE at a longer wavelength. The spectral linewidth of the amplifier output exhibited a broadening as the power increased, owing to the phase noise induced by the stronger ASE [25]. The 20-dB linewidth at the maximum output power of 5.5 W was measured as 38.6 kHz, as shown in Fig. 6(b), which corresponds to a 3 dB linewidth of 1.93 kHz.

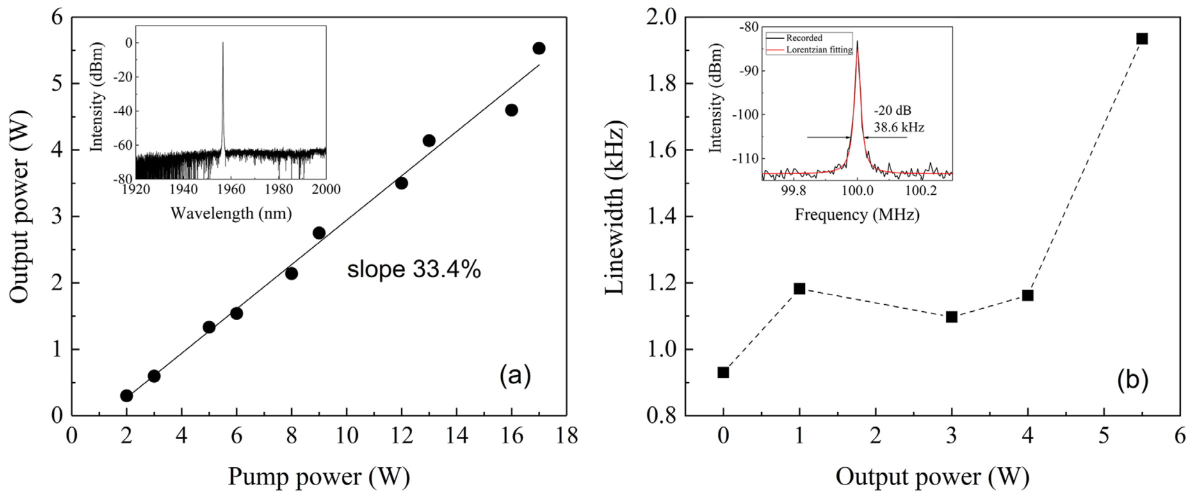

Figure 5. (a) Power transfer of amplifier; inset: spectrum recorded by the OSA Yokogawa 6375 at maximum power of 5.5 W. (b) Linewidth evolution of amplifier; inset linewidth measurement at maximum power of 5.5 W. The dashed lines serve as a visual guide.

5. SUMMARY

This paper experimentally investigated the influence of output coupling on the power and linewidth behavior of a narrow-linewidth BTFL. The experimental results revealed that there exists a trade-off between the SBS threshold, output power, and spectral linewidth of the BTFL. Thus, the laser performance can be optimized by choosing an appropriate output coupling. A Stokes output of 344 mW at 1,956.61 nm with a narrow-linewidth of 0.93 kHz was obtained by optimizing the output coupling and cavity length of the BTFL. The laser power was further boosted to 5.5 W by a one-stage cladding-pumped amplifier and the linewidth was broadened to 1.93 kHz.

6. ACKNOWLEDGEMENTS

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