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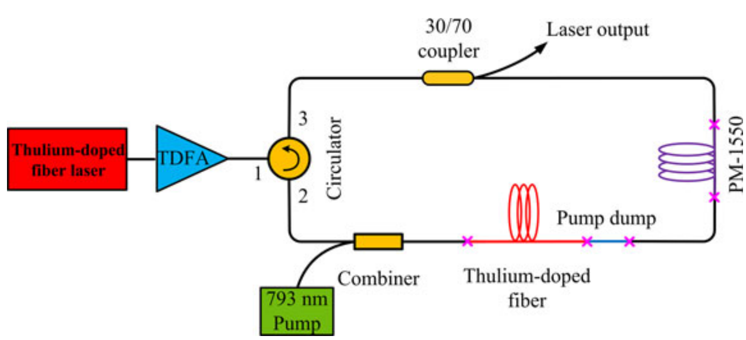
Shijie Fu
Wei Shi
Haiwei Zhang
Quan Sheng
Guannan Shi
Xiaolei Bai
Jianquan Yao



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Linewidth-Narrowed, Linear-Polarized Single-Frequency Thulium-Doped Fiber Laser Based on Stimulated Brillouin Scattering Effect

Shijie Fu,[1] Wei Shi,[1,2] Haiwei Zhang,[1] Quan Sheng,[1] Guannan Shi,[1] Xiaolei Bai,[1] and Jianquan Yao[1,2]

[1]College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China
[2]Tianjin Institute of Modern Laser & Optics Technology, Tianjin 300384, China

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Abstract: A 2-μm linear-polarized hybrid Brillouin–Thulium fiber laser (BTFL) was experimentally investigated for linewidth narrowing. The low threshold for the BTFL in terms of Brillouin pump of ~200 mW, benefits from the gain of active fiber in the ring cavity for both Brillouin pump and generated Stokes light. More than 205 mW single-frequency Stokes laser was obtained with linewidth reduction ratio of ~8 times, from 36 to 4.6 kHz. Linear-polarized output was achieved with a polarization extinction ratio of 23.8 dB.

Index Terms: Fiber laser, narrow linewidth, single frequency, stimulated Brillouin scattering.

1. Introduction

Single-Frequency fiber laser in the eye-safe wavelength regime around 2 μm has drawn intense interest recently [1]–[3], because the wavelength within the absorption bands of several chemical compounds (liquid water, greenhouse gas, ect) and the atmospheric transparency window facilitates the applications in such areas as high-resolution spectroscopy, coherent LIDAR and free-space optical communications [4]–[6]. The laser sources operating with narrow linewidth are in great demand to improve the detection ranges and resolutions for the aforementioned applications. Generally, the 2 μm single-frequency fiber laser generated with the distributed feedback (DFB) or distributed Bragg reflector (DBR) configuration exhibited a laser linewidth of tens of kilohertz [7]–[9]. Narrower laser linewidth can be achieved by active noise control of the pump and laser cavity, or applying long ring cavity associated with saturable absorber [10], [11].

Stimulated Brillouin scattering (SBS) has been extensively researched accompanied with the development of fiber laser. Although the SBS, as a kind of nonlinear effect in fibers, has been traditionally considered detrimental for high power fiber laser and amplifier [12], [13], it can be an efficient technique to achieve narrow-linewidth fiber lasers, namely Brillouin fiber laser [14], [15].

For a laser based on stimulated Brillouin scattering, an acoustic wave would be generated by the incident pump through the process of electrostriction. The acoustical modulated index grating in the fiber backscatters the pump with a Brillouin frequency down-shift. The backscattering can be amplified since the SBS gain only exists along the direction opposite that of the pump. When the SBS is generated in a fiber cavity and the round-trip gain is greater than the cavity losses, SBS lasing will occur in a direction opposite to the pump. As the phase fluctuation of the lasers causes a broadening of the laser lineshape [16], the evolution of linewidth from Brillouin pump to Stokes light is strongly connected to the condition of phase noise between pump laser and Stokes wave. For a Brillouin fiber laser, the phase noise of the pump laser is transferred to the emitted Stokes wave after being strongly reduced and smoothed under the combined influence of the acoustic damping and cavity feedback [15]. As a result, the linewidth narrowing can be achieved from Stokes light. However, due to the limited Brillouin gain coefficient, a critically pump coupled fiber resonator or very high pump threshold power is demanded [17]–[19]. In 2014, Luo *et al.* reported a 2-μm Brillouin fiber laser (BFL) with high signal-to-noise ratio of $\sim$62 dB, where a total power of 18 W from three diode pump lasers was applied to overcome the Brillouin laser threshold of up to 1.04 W [20]. In the same year, Hu *et al.* presented a low-threshold Brillouin laser at 2 μm with a piece of suspended-core chalcogenide fiber as the Brillouin gain medium [21]. By virtue of the high Brillouin gain coefficient of chalcogenide fiber, which is two orders larger than that of silica, the lasing threshold of BFL was lowered to 52 mW in the experiment. However, the output power of the BFL was limited to microwatt level resulting from the large cavity loss of 11.3 dB, including 3.3 dB of propagation loss inside the chalcogenide fiber as well as 7.4 dB of butt-coupling loss between the chalcogenide fiber and ultra-high numerical aperture (UHNA) fiber used in the demonstration.

The hybrid Brillouin-active fiber laser overcomes the problem by incorporating the active fiber gain inside the cavity to compensate for the resonator losses, which was proposed by Gregory *et al.* in 1996 and demonstrated with a hybrid Brillouin/Erbium fiber laser (BEFL) [22]. The Brillouin lasing threshold was below 10 mW in terms of launched 980 nm pump, and an output power of 10 mW from the BEFL was achieved with 50 mW launched pump power. However, for the 2 μm regime, the reduced Brillouin gain coefficient and larger transmission loss, are detrimental to the generation and subsequent power amplification of Stokes light, which means more gain from the active fiber is demanded. In this paper, a 2-μm single-frequency hybrid Brillouin-Thulium fiber laser (BTFL) was investigated, where a piece of double-cladding Thulium-doped fiber was added to the ring cavity to serve as the gain media for both the Brillouin pump and Stokes light. In the experiment, a single-frequency fiber laser with 36 kHz linewidth was pre-amplified to 250 mW to act as the Brillouin pump. Stable Brillouin laser can be built up with the Brillouin pump power of around 200 mW, which is much lower than the reported 2 μm Brillouin silica fiber laser [20]. The BTFL operated at 1925.08 nm, which is around 8.34 GHz frequency down-shift from the Brillouin pump with the lasing wavelength of 1924.98 nm. Stable single-frequency operation of the BTFL was achieved with a linewidth of 4.6 kHz, which is 8 times narrowed compared to the Brillouin pump. Furthermore, the relative intensity noise (RIN) is measured to be shot noise limited for frequency above 2 MHz. The Stokes light outputs with a polarization extinction ratio of 23.8 dB, which indicates a good linear-polarized laser operation.

2. Experimental Setup

The schematic of the hybrid Brillouin-Thulium single-frequency fiber laser is shown in Fig. 1. A Thulium-doped fiber laser (TDFL) was pre-amplified to 250 mW through a stage of Thulium-doped fiber amplifier (TDFA) to serve as the Brillouin pump. The TDFL was a short-linear-cavity single-longitudinal-mode fiber laser, operating with an output power of 25 mW and a linewidth of 36 kHz. The power amplified Brillouin pump was then inserted into a single pass ring cavity through the port 1 of an optical circulator. A piece of double-cladding Thulium-doped fiber (PM-TDF-10P/130-HE, Nufern) was employed in the ring cavity to amplify both the Brillouin pump and the generated Stokes light, which was cladding pumped with a 793-nm multimode laser diode. A $(2 + 1) \times 1$ fiber combiner was used to couple the pump power into the active fiber. Although the Thulium-doped

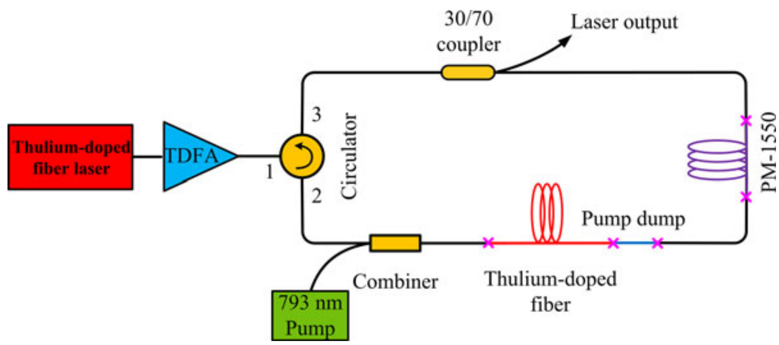

Fig. 1. Experimental setup of the hybrid Brillouin-Thulium single-frequency fiber laser. TDFA: Thulium-doped fiber amplifier.

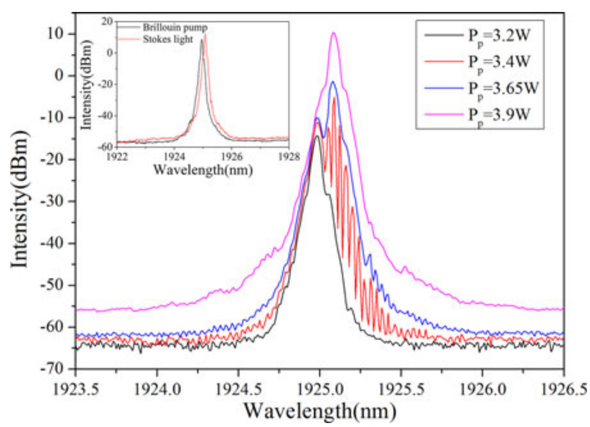

Fig. 2. Optical spectra evolution of the Brillouin-Thulium fiber laser with the increase of the pump power at 793 nm. Inset: Optical spectra comparison between the Brillouin pump and Stokes light.

fiber used here has a cladding absorption coefficient of 4.7 dB/m at 793 nm, only 1 m of active fiber was used in the experiment, because of longer fiber length resulting in the parasitic lasing at longer wavelength. The output end of the Thulium-doped fiber was fusion spliced to a 30-cm long matched passive fiber (PM-GDF-10/130-2000-M, Nufern) so as to strip off the residual 793-nm pump power with high refractive index gel. Moreover, another 10-m of polarization-maintaining fiber (PM1550, Corning) was added into the laser cavity to further decrease the Brillouin threshold of the laser. A 30/70 coupler was applied to extract 70% of the Stokes light out of the laser cavity. All the optical devices employed in the experiment were polarization maintained.

3. Experimental Results and Discussion

When the 793 nm pump power increased gradually, the injected Brillouin pump power was amplified, and thus more Stokes light would be excited and accumulate along with the propagation in the clockwise direction of ring cavity. Except for the Brillouin gain in the silica fiber, the Stokes light can be further amplified by the Thulium-doped fiber employed in the ring cavity. Therefore, the threshold of the hybrid BTFL can be greatly decreased compared with the Brillouin fiber laser, whose gain was provided only by the Brillouin gain. The process of Stokes light generation was recorded with the evolution of the optical spectra measured at the 70% port of the output coupler by an optical spectrum analyzer (OSA, AQ6375, YOKOGAWA).

The Brillouin pump we used in the experiment possessed a central wavelength of 1924.98 nm and the signal to noise ratio (SNR) of $>$65 dB, as shown in the inset of Fig. 2. When the power of

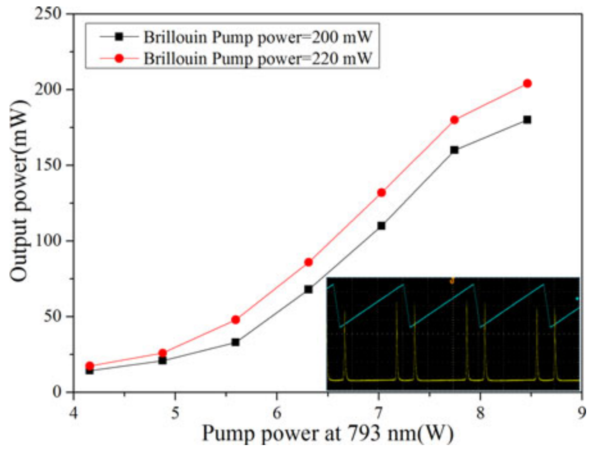

Fig. 3. The output power of the Stokes light as a function of the pump power at 793 nm under the Brillouin pump power of 200 and 220 mW. Inset: The longitudinal mode characteristics of the generated Stokes light measured with an F-P interferometer.

Brillouin pump was below 200 mW, there is no SBS observed in the whole 793-nm pump power range, except for the amplification of the Brillouin pump and the self-lasing at the wavelength around 1970 nm. As the Brillouin pump power increased to 200 mW, the SBS was gradually generated with the increase of the 793-nm pump power. Fig. 2 shows the evolution of the optical spectra with the increase of the 793-nm pump power when the Brillouin pump power was fixed to 200 mW. As shown in Fig. 2, the Stokes light was not observed until the 793-nm pump power increased to 3.4 W. However, the generated Stokes light was not stable at this power level and multi-peaks can be observed in the experiment, which was analyzed to be due to that the Stokes light was so weak that the consistent accumulation at the same frequency shift was not realized. Stable Stokes light was built up at the pump power of 3.65 W and increased rapidly with the increment of the 793-nm pump power. The optical spectrum at 3.9-W pump power in Fig. 2 reveals the central wavelength of the Stokes light at 1925.08 nm. Compared with the Brillouin pump, the Stokes light has a wavelength increase of 0.1 nm, corresponding to the frequency down-shift of around 8.34 GHz, which approaches the reported 8.36 GHz in a 2 μm Brillouin fiber laser [20]. Since the gain from 793-nm pumped Thulium-doped fiber was effectively used to amplify the Stokes light, the self-lasing at longer wavelength vanished accordingly. As shown in the inset of Fig. 2, the SNR of the Stokes light was around 70 dB, which is $\sim$3 dB higher than that of the Brillouin pump.

Since the Brillouin pump threshold for stable Stokes light operation was $\sim$200 mW, we measured the output power of Stokes light as a function of the 793-nm pump power under different power of Brillouin pump. As shown in Fig. 3, the Stokes power increases with the pump power at 793 nm. Higher Stokes power was achieved when the Brillouin pump power increased from 200 to 220 mW, owing to higher amplified Brillouin pump power used to stimulate the SBS. The maximum Stokes power of 205 mW was achieved when the 793-nm pump power was increased to 8.5 W under the Brillouin pump power of 220 mW. It can be estimated from Fig. 3 that the slope efficiency of Stokes output power would decrease gradually when the 793-nm pump power further increases. More gain in the Thulium-doped fiber is utilized to amplify the power of the Brillouin pump and thus the Stokes light would mainly be amplified by the Brillouin gain, even though much higher Brillouin pump is provided to stimulate the SBS in the ring cavity.

The longitudinal-mode characterisitics of the Stokes light was measured with a commercial scanning Fabry-Perot interferometer (SA210-12B, Thorlabs), which has a free spectral range (FSR) of 10 GHz and fineness of 150. The result is shown in the inset of Fig. 3, where single burst was observed in an FSR, indicating that single-longitudinal-mode operation was achieved for the Stokes light. In order to investigate the linewidth narrowing effect of the hybrid BTFL, a delayed self-heterodyne system was performed. As shown in Fig. 4, the 20 dB linewidth of the heterodyne signal

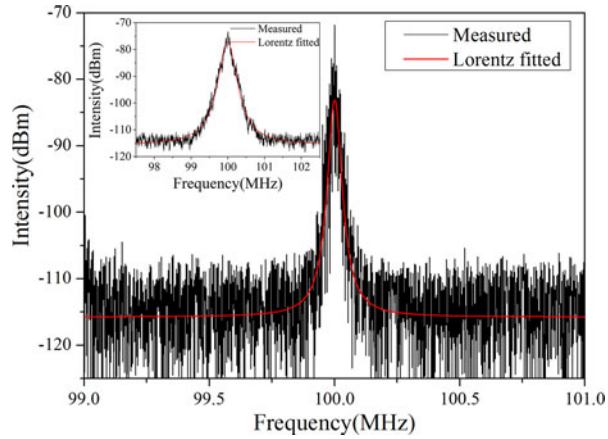

Fig. 4. Measured heterodyne signal of the Stokes light at the power of 205 mW and Lorentz fit of the lineshape. Inset: The measured linewidth of the Brillouin pump.

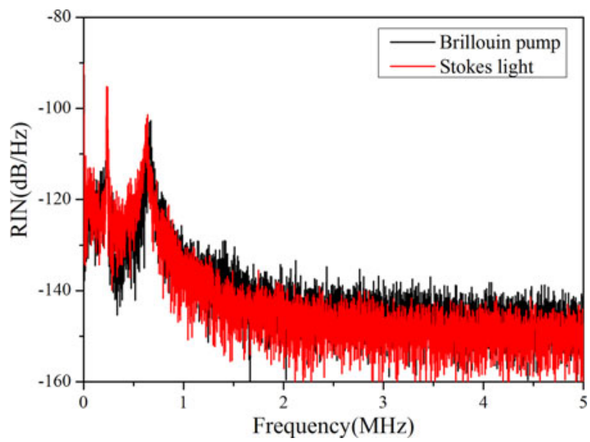

Fig. 5. Comparison of the relative intensity noise for the Brillouin pump and Stokes light.

is around 92 kHz, which means the Stokes light owns a Lorentz linewidth of 4.6 kHz. Since the seed of the Brillouin pump exhibited a Lorentz linewidth of 36 kHz and the laser linewidth did not change much after one stage of power amplification, one can conclude that the hybrid BTFL achieved a linewidth-reduction of ~8 times. For a Brillouin fiber laser, the linewidth-reduction ratio of the Brillouin pump to signal can be theoretically analyzed with the formula $\Delta \upsilon_s = \frac{\Delta \upsilon_p}{(1+\frac{\gamma_A}{\Gamma_c})^2}$, where $\gamma_A = \pi \Delta \upsilon_B$ and $\Gamma_c = -c\ln R/nL$ describe the acoustic damping ratio and the cavity loss ratio, respectively [23]. Given the parameters in our demonstration, a Brillouin fiber laser would have a linewidth-reduction ratio of around 13 in theory, which is a bit larger than in our hybrid Brillouin-Thulium fiber laser. This can be analyzed to result from the spontaneous emission, thermal fluctuation and environmental perturbations in the ring cavity [24], especially for the spontaneous emission in the cladding-pumped Thulium-doped fiber limiting further linewidth-reduction, which does not exist in a Brillouin fiber laser.

The RIN for both the Brillouin pump and the Stokes light were also measured in this demonstration. The result obtained from the electrical spectrum analyzer (ESA) is shown in Fig. 5. Both of the Brillouin pump and Stoles light exhibit a relaxation oscillation frequency peak around 640 kHz with the RIN level of −102 dB/Hz [25]. For the RIN at higher frequency, the Stokes light obtains a RIN level of −150 dB/Hz, which approaches the shot noise limit. This is around 4 dB lower than the

Brillouin pump. It should be noted that the first peak in the measured RIN in Fig. 5 originates from the pump source of the Brillouin pump, which has also been observed in [21].

Since all the fiber devices used in the laser system were polarization-maintained, the polarization characteristics of the generated Stokes light was investigated with a Glan prism and power meter. The polarization extinction ratio of around 23.8 dB was achieved with the maximum transmission power of 181.6 mW and the minimum transmission power of 0.7 mW, which indicates that the laser operated in a good linear polarization state.

4. Conclusions

In conclusion, a linewidth-narrowed, linear-polarized 2 μm single-frequency fiber laser was demonstrated through the Brillouin-Thulium fiber laser. In the experiment, a piece of Thulium-doped fiber was used in the ring cavity to serve as the gain medium for both the Brillouin pump and the generated Stokes light. The resulting threshold in terms of the Brillouin pump was lower to 200 mW and maximum Stokes laser of 205 mW was achieved in the experiment. Single-longitudinal-mode operation of the Stokes light was verified and the linewidth has been narrowed for $\sim$8 times, from 34 to 4.6 kHz. Furthermore, linear polarization output was achieved with a polarization extinction ratio of 23.8 dB. The narrow-linewidth, linear polarized 2-μm single-frequency BTFL presented here can be a good candidate for applications such as gas detection, long-range LIDAR and free-space optical communications.

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