High-efficiency hybrid brillouin/ytterbium fiber laser

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A high-efficiency hybrid Brillouin/ytterbium fiber laser (BYFL) is demonstrated using a 41.5-cm-long highly ytterbium-doped fiber and a 10-m-long single-mode optical fiber. The BYFL operates at 1 052.92 nm, and the difference between it and the Brillouin pump (BP) wavelength matches the expected stimulated Brillouin scattering (SBS) Stokes shift. Its output power reaches 70.1 mW, which is more than seven times higher than the seeded BP power. The BYFL has an optical signal-to-noise ratio that is greater than 65 dB and has many potential applications, such as in controllable optical delay lines, sensing, and RF photonics.

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Stimulated Brillouin scattering (SBS) is one of the most important nonlinear effects in optical fibers. Although SBS is detrimental for coherent optical communication systems, this disadvantage does not prohibit the exploitation of SBS in distributed strain and temperature sensing[1], microwave generation[2], optical carrier amplitude control[3], gyroscopes[4], and lasers[5].

Brillouin fiber lasers (BFLs) have attracted significant interest for decades due to their linewidth narrowing effect. The free-running spectral linewidth of the single-frequency Brillouin ring fiber laser has been reported to be only a few hertz[6], which can be several orders of magnitude narrower than that of their single-frequency pump beams. Moreover, the BFL exhibits low relative intensity and frequency noises. All these advantages make the BFL applicable in controllable optical delay lines, sensing[7], and radio frequency (RF) photonics[8].

For a conventional ring-cavity Brillouin laser, the pump-coupling ratio depends on the cavity loss and the round-trip phase shift in the cavity, which must be an integer number of 2π to achieve the intensity enhancement. Although the conventional BFL exhibits useful characteristics, it has disadvantages such as the small output power, the requirement of cavity matching to the pump signal, and the difficulty in incorporating intracavity elements because of their associated loss. The hybrid Brillouin/ytterbium fiber laser (BYFL) can overcome these disadvantages by using an ytterbium-doped fiber amplifier to compensate for the resonator losses while still commencing a lasing action from the Brillouin gain.

A high-efficiency BYFL based on Ref. [9] is demonstrated in this letter. When the Brillouin pump (BP) power is 9.68 mW, the laser output power reaches 70.1 mW at a 980-nm pump power of 383 mW, compared with that of Guan's work, which obtains only 40 mW of laser output. This BYFL has an optical signal-to-noise ratio (OSNR) that is greater than 65 dB.

Figure 1 shows the BYFL configuration. The BP, a distributed feedback laser diode with a linewidth of less than 70 kHz at 1 052.86 nm, was amplified by a fiber amplifier and then seeded into the laser cavity through a circulator and a 70/30 coupler. The BP was first amplified by a 41.5-cm-long highly ytterbium-doped fiber (HYDF) with a pump absorption rate of 975 dB/m. Then, the BP entered into a 10-m-long single-mode fiber (SMF), which functions as the Brillouin gain medium. The Stokes wave was generated in the SMF and circulated clockwise, and a 1 053-nm isolator was inserted in the cavity to prevent the laser from injection locking to the BP. The 70/30 coupler coupled the laser out of the cavity through the 70% port, whereas 30% of the laser light remained in the cavity. A 1-nm band-pass filter was used to suppress the 1 030-nm gain peak, which made the free-running laser operate around 1 053 nm.

The laser operation could be viewed as a form of intracavity injection locking. The laser is a traveling-wave ytterbium-doped fiber laser (YDFL) when no BP is injected into the cavity[10]. However, the mode of operation in this study is different because of the injected BP. When a BP with a narrow linewidth is injected into the cavity, a Stokes wave propagating clockwise is generated at a frequency shifted from the BP frequency by the Stokes shift in the SMF. The Brillouin gain is insufficient for commencing a laser action for the BFL with this lossy resonator. Therefore, a 980-nm pump light is used to pump the YDF and produce additional gain, which can be used to compensate the resonator losses. If the wavelength of the BP is close to the wavelength at which maximum gain is obtained in the YDF, lasing will operate at the Stokes-shifted wavelength.

Figure 2 demonstrates the maximum broad-band gain of the YDF at wavelength a. b is the wavelength of the Stokes wave, at which the light obtains a combined gain from both the YDF and Brillouin gain medium. If the total gain at wavelength b is greater than that at a and is equal to the required gain for the threshold, as shown in Fig. 2(a), lasing will occur at b with the combined gain from the two media and the peak of the YDF gain will be suppressed. If Stokes wavelength b is very far from wavelength a such that the total gain at wavelength b is smaller than that at a, as shown in Fig. 2(b), lasing will occur at wavelength a with only the YDF gain. Considering that the Brillouin gain is relatively small, the BYFL must operate at a wavelength close to the wavelength at which the YDFL will operate without BP. Therefore, the wavelength of the BP must be carefully tuned.

The BYFL in the current study had a maximum broadband gain around a wavelength of 1 052.92 nm when no BP was injected. Moreover, the BP's wavelength was tuned to 1 052.86 nm. When the BP was seeded into the cavity, the 1 052.92-nm Stokes wave was generated. Moreover, no light was observed at the other wavelength when the BP power was larger than 9.68 mW and when the 980-nm pump power reached the BYFL threshold.

The BEFL considered in this study utilizes the BP preamplification technique[11]. The BP was first seeded into an active fiber instead of a long passive fiber, which preamplified the BP using the YDF with a 980 nm pump and thus reduced the required BP power for generating the Stokes wave.

The output power characteristic of the BYFL is illustrated in Fig. 3 for three different BP powers. The best efficiency of the BP in BYFL signal conversion occurs for lower levels of injected BP powers. As the BP power was increased from 9.68 to 18.4 mW, the laser threshold increased and the output power decreased from 70.1 to 62.8 mW. This result was due to the gain saturation of the BP in the YDF, which leads to less available gain for the amplification of the Stokes light and thus lower BYFL output power[9]. When BP power was 9.68 mW, the laser threshold was 110 mW. Moreover, the maximum laser output was 70.1 mW when the 980-nm pump power was 383 mW, which is more than seven times as high as the BP power, while in Ref. [9], only 40 mW of the laser output was obtained under the same conditions. This is due to the use of a 1-nm band-pass filter at 1 053 nm instead of a 1 030 nm/1 053 nm WDM to suppress the 1 030 nm gain peak and make the free-running laser operate around 1 053 nm. Here, the filter has two functions. Aside from that aforementioned, it can also decrease the amplified spontaneous emission (ASE) in the cavity, which improves the OSNR of the Stokes wave before entering the YDF. Each time the Stokes wave is amplified by the YDF, ASE occurs. Before the Stokes wave enters the YDF, the 1-nm band-pass filter decreases the noise generated by the ASE, which eventually allows the Stokes wave to obtain more energy from the YDF. This approach might also be used to improve the output power of the high-power single-frequency hybrid BYFL[12].

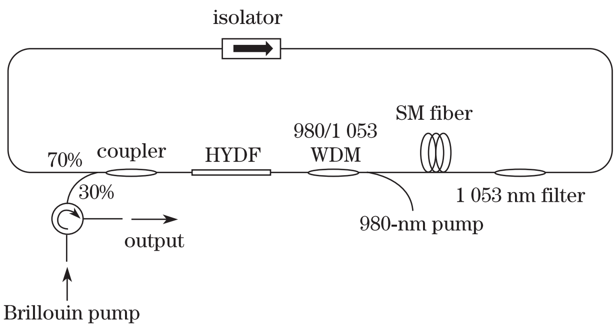

Fig. 1. BYFL configuration.

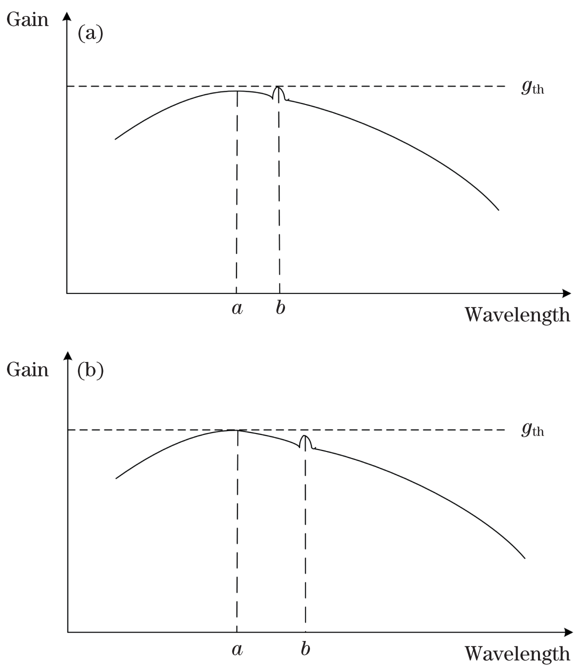

Fig. 2. Schematic of the BYFL wavelength.

The OSNR of the BYFL and BP were measured using an optical spectrum analyzer (OSA) set to 0.02-nm resolution. As shown in Fig. 4, the OSNR of the laser operating at 70.1 mW was greater than 65 dB, whereas the OSNR of the 9.68-mW BP was 55 dB, showing that the OSNR of the BYFL can be 10 dB higher than the seed source. This result is due to the intensity and phase-noise reduction in the SBS process. The noise of the BP mainly came from the ASE in the fiber amplifier. Additionally, the BP wavelength was 1 052.86 nm and the BYFL wavelength was 1 052.92 nm. The frequency difference between the BP and laser output corresponded to the Stokes shift of the SBS at the working wavelength.

The single-frequency output was verified using a scanning Fabry-Perot (FP) spectrometer. The FP cavity was 5-cm long, which corresponds to a free spectral range of 1.5 GHz. With a finesse of 200, this FP spectrometer obtained a resolution of about 7.5 MHz. The laser cavity length was 12.685 m, which corresponds to a 16.3-MHz mode spacing. Therefore, the cavity modes of the BYFL could be resolved using the FP spectrometer. The measurement shown in Fig. 5 demonstrates its single-frequency operation. Although two cavity modes can, in principle, coexist in the 20-MHz gain bandwidth, the SBS line shape provides enough discrimination to allow the laser to operate in the single-frequency regime.

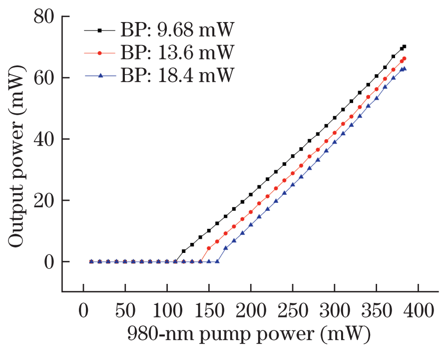

Fig. 3. BYFL output with 980-nm pump power for three different BP powers.

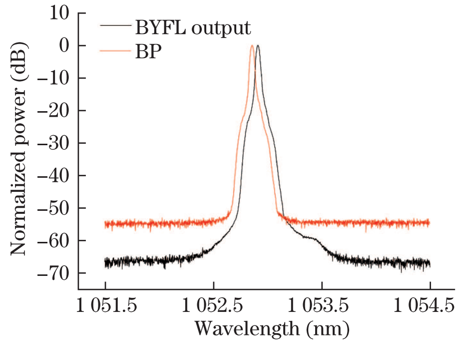

Fig. 4. Normalized OSA spectral of the BP and BYFL output with an output power of 70.1 mW. The OSA resolution is 0.02 nm.

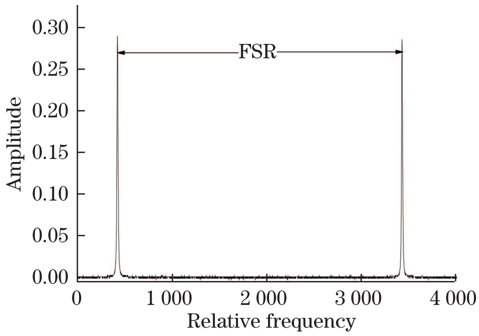

Fig. 5. Laser output spectrum on the scanning FP spectrometer with an output power of 70.1 mW.

In conclusion, a high-efficiency hybrid BYFL utilizing a BP pre-amplification technique is built using a 41.5-cm-long HYDF and a 10-m-long single-mode optical fiber. This BYFL exhibits 70.1 mW of maximum output power when the 980-nm pump power is 383 mW, which is more than seven times higher than the input BP power. The output power increases by 75% compared with the result of Ref. [9]. The OSNR of the BYFL is more than 65 dB, which is 10 dB higher than the seed source.

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