Self-seeded multiwavelength Brillouin–erbium fiber laser

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We propose and demonstrate a self-seeded multiwavelength Brillouin-erbium fiber laser with an internally self-excited Brillouin pump, which is achieved by incorporation of a length of single-mode fiber together with a Sagnac loop mirror into a fiber ring cavity. In this simple scheme the Brillouin pump is self-excited in the fiber ring cavity and then used to seed the Brillouin multiwavelength comb in the single-mode fiber. Stable generation of more than 120 Brillouin Stokes wavelengths with relatively uniform amplitudes is demonstrated with this scheme. It is also shown that such a self-seeded Brillouin laser has good stability and repeatability.

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Multiwavelength laser combs are of great interest for many applications, such as precise spectroscopy, optical sensing, characterization of photonic components, and large-capacity wavelength-division-multiplexing optical communication. There are a number of methods for generating multiwavelength combs, including cooling the erbium-doped fiber (EDF) in liquid nitrogen to reduce the homogeneous broadening,[1,2] slicing the supercontinuum longitudinal mode,[3,4] frequency shifting feedback inside the ring cavity to prevent single-mode oscillation,[5,6] and using a multiwavelength Brillouin–erbium fiber laser[7–11] (BEFL). Among these methods, the BEFL is the most attractive for generating combs because of its simple configuration and its intrinsic properties of rigid frequency spacing and extremely narrow linewidths.

The hybrid BEFL was first proposed by Cowle and Stepanov.[7] It took advantage of the combined linear gain from EDF and the nonlinear gain of stimulated Brillouin scattering (SBS) from the nonlinear fiber. The narrow-bandwidth nonlinear gain from SBS determines the operating wavelengths, and the gain in EDF improves the output power. Through the cascading approach, Brillouin multiorder Stokes wavelengths with rigid wavelength spacing were achieved.[8–10] A further improvement over the cascading approach is the generation of Brillouin gain and amplification of Stokes wavelengths in both directions without excess loss, which provides a higher efficiency in producing the multiwavelength comb. With this method the generation of a 30-channel 10-GHz laser comb was demonstrated.[9] Also, through use of four-wave mixing along with SBS, more Stokes and anti-Stokes multiwavelength combs can be obtained.[11] In addition, a tunable BEFL with a high-birefringence fiber Sagnac loop filter is also proposed to broaden the wavelength range of Brillouin multi-Stokes generation.[12] All these approaches require use of a Brillouin pump, although it can be injected from the external cavity or directly generated within the intracavity. On the other hand, the wavelength number of the Brillouin comb is limited to a few tens, and the power distribution is uneven among these Brillouin wavelengths. Typically, most power is concentrated on a few low-order Stokes wavelengths. In this Letter we propose and demonstrate a new self-seeded multiwavelength BEFL with an internally self-excited Brillouin pump instead of an external Brillouin pump. We achieve this by incorporating a length of single-mode fiber (SMF) as the Brillouin gain medium in the fiber ring cavity. By using such a simple scheme, we generate more than 120 Brillouin wavelengths with relatively uniform amplitudes, which is the largest wavelength number achieved in BEFLs to the best of our knowledge.

Figure 1 shows the experimental schematic of the self-seeded BEFL, which is similar to the one in Ref. 9 except that there is no external Brillouin pump and the reflector is replaced with a Sagnac loop mirror. In the schematic the fiber ring cavity consists of a 16-m EDF to provide the linear gain, a 1550/980-nm wavelength-division multiplexer to couple the 980-nm laser as the copropagating pump into the EDF, an optical circulator to form a unidirectional ring, a 5-km SMF as the SBS gain medium, and a high-birefringence fiber Sagnac loop mirror. Port 2 of the optical circulator is spliced to one end of the SMF. The other end of the SMF is connected to the Sagnac loop mirror. The high-birefringence fiber Sagnac loop mirror is composed of a 3-dB coupler, a length of polarization-maintaining fiber (PMF), and two polarization controllers (PCs), and its reflection profile can be modified through adjustments to the PCs.[13] The Brillouin signals are amplified in the EDF and are then injected into the 5-km SMF. Because of the

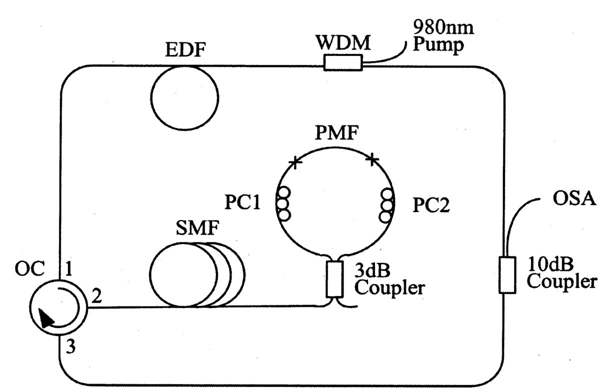

Fig. 1. Schematic of the self-seeded multiwavelength BEFL: WDM, 980/1550 wavelength-division multiplexer; OSA, optical spectrum analyzer; OC, optical circulator.

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reflection of the Sagnac loop mirror, the Brillouin signals pass the long SMF two times in a round. The signal passing through the SMF results in Brillouin gain, which generates the next-order Brillouin Stokes wavelength. Finally, an optical spectrum analyzer with a spectral resolution of 0.065 nm is used to measure the output signals through a 10-dB coupler.

In our first experiment the 980-nm pump is fixed at 140 mW, and the length of the PMF is 16 cm. A stable Brillouin multiwavelength comb can be generated under the arbitrary polarization states of two PCs. Adjusting the PCs in the Sagnac loop mirror produces more than 120 Brillouin wavelengths, which cover from ~1564 to ~1576 nm, as shown in Fig. 2(a). The spacing between adjacent wavelengths is ~0.088 nm, i.e., ~11 GHz. There are ~90 Brillouin wavelengths within a 5-dB bandwidth and ~70 wavelengths within a 3-dB bandwidth. For most of the wavelengths the output powers are higher than −20 dBm. Compared with the reported results,[7–11] the uniformity of the multiwavelength output power is greatly improved. By further careful adjustments to the PCs, more uniform Brillouin multiwavelength signals with minimized power variation are generated. As shown in Fig. 2(b), there are 71 Brillouin wavelengths within a 3-dB bandwidth, which covers the spectral range from ~1568 to ~1574 nm. Particularly in the range from ~1570 to ~1574 nm the output power variation among 45 Brillouin wavelengths is less than 0.4 dB.

To study the stability of this self-seeded BEFL, we repeated the output spectrum measurements each hour under the condition that more than 120 Brillouin wavelengths were generated. Figure 3 presents five enlarged pictures of the measured spectra of the sampled wave band bounded by the solid rectangle in Fig. 2(a). Figure 3 indicates that this self-seeded BEFL has excellent stability in both the wavelengths and the output powers on a long time scale, even without the use of an external Brillouin pump. Moreover, the repeatability was further proved when the measurement was reperformed after a few days. This shows that such a self-seeded Brillouin laser has good reliability and repeatability.

The operation mechanism of this self-seeded BEFL without an external Brillouin pump is described as follows. The oscillating mode is first established in the fiber ring cavity; then the dynamic distributed feedback of its Rayleigh scattering in the SMF results in the linewidth narrowing of the oscillating mode.[14] This in turn creates the conditions for SBS in the SMF. When a narrowed oscillating wavelength is excited in the cavity, this wavelength serves as the Brillouin pump ω_P. Meanwhile, Brillouin wavelengths $\omega_B = \omega_P \pm \Delta\omega$ with narrowed linewidths are generated simultaneously through a cooperative SBS and Rayleigh backscattering process, in which $\Delta\omega$ is the Brillouin frequency shift. Through the cascading process within the ring configuration, the growth of SBS then causes an avalanche process to seed the multiwavelength comb. As shown in Fig. 4, each Brillouin Stokes wavelength ω_B will experience two different gains in each round trip: One is the linear gain from the EDF, and the other is the Brillouin nonlinear gain from the SMF. Because of the intrinsic narrowband property of the Brillouin gain, the total gain exhibits a comblike property. When the Brillouin gain is high enough, the total gain therefore shows an inhomogeneous broadening mechanism. The balance between the loss and the total gain determines the Brillouin pump wavelength. Usually, the self-excited Brillouin pump wavelength takes place at the peak of the gain. Since the reflection profile of the Sagnac loop mirror can be changed by adjusting the PC, the wavelength of the Brillouin pump can therefore be modified to set the desired wavelength band. When the lasing threshold condition is satisfied, i.e., the total gain is equal to the round-trip loss, the wavelength and power of each signal in the Brillouin

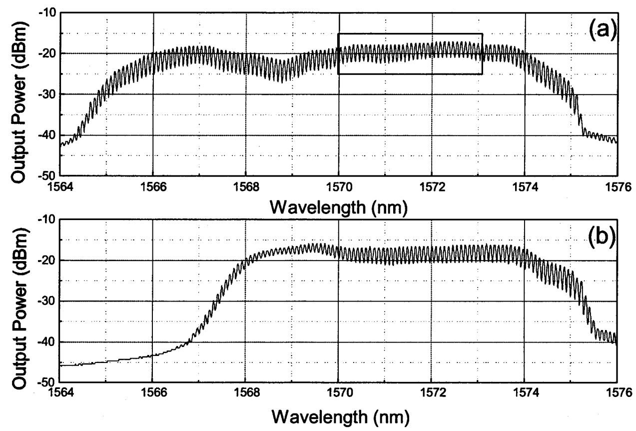

Fig. 2. Spectra of the generated Brillouin multiwavelength combs (a) when more than 120 Brillouin wavelengths are generated and (b) with uniform Brillouin wavelength generation.

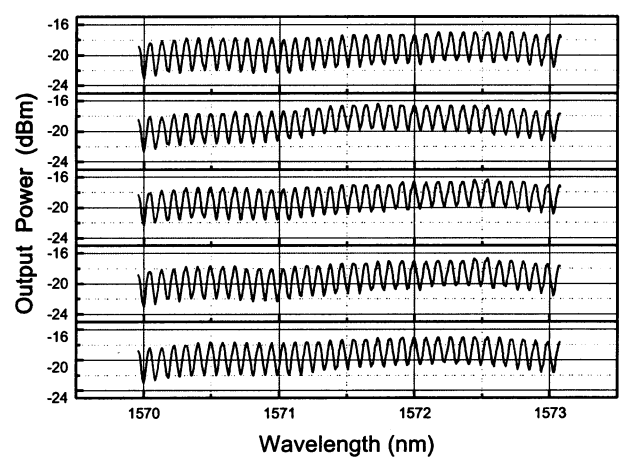

Fig. 3. Five measured spectra of the sampled wave band in the solid box in Fig. 2(a).

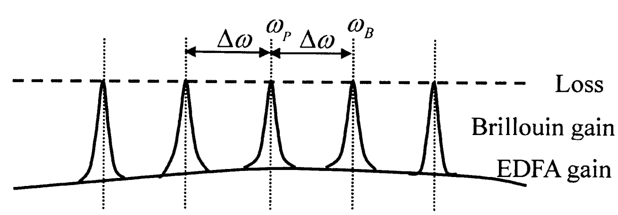

Fig. 4. Gain profile of each roundup trip for the self-seeded BEFL. EDFA, erbium-doped fiber amplifier.

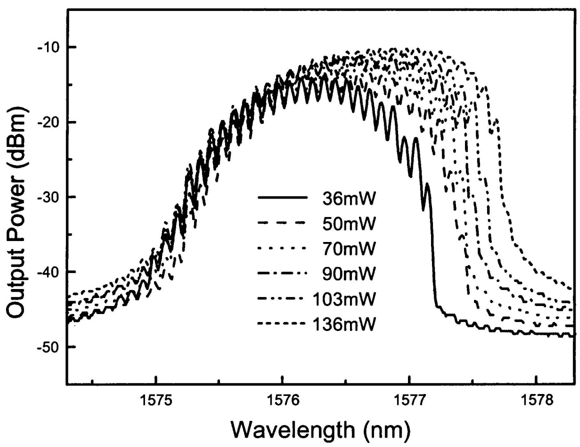

Fig. 5. Multiwavelength spectra with different powers of the 980-nm pump.

multiwavelength comb are determined and a stable self-seeded BEFL is achieved. It is clearly seen that the Brillouin pump is self-excited in the fiber ring cavity and then used to seed the Brillouin multiwavelength comb generation in the SMF.

In our specific scheme the EDF provides the linear gain for the signal, and 5 km of SMF is chosen to provide the nonlinear gain for each Brillouin Stokes signal. Because of the reflection of the Sagnac loop mirror, each wavelength signal serving as the Brillouin pump ω_P will pass the SMF twice, and therefore the Brillouin signals are generated in both directions. The Brillouin signal circulates in the ring on the reflection of the Sagnac loop mirror and through the circulator. Using this configuration, the effect of the SMF on generating SBS is significantly enhanced and the threshold of SBS is lowered. This provides a more efficient way to generate the Brillouin multiwavelength, both for the wavelength number and power uniformity.

In addition, we study the effect of a 980-nm pump on the performance of this self-seeded BEFL. During the measurements we fixed the two PCs and set the lasing wavelength to be ~1576 nm, then gradually increased the 980-nm pump power. The output spectra with different pump powers are shown in Fig. 5. It is observed that both the number and the power of Brillouin multiwavelength signals become larger with an increase in the 980-nm pump power. When the pump power increases from 36 to 136 mW, the wavelength number increases from 24 to 36. Meanwhile, the powers of the Brillouin signals also increase with the pump power, particularly for the high-order Brillouin Stokes wavelengths. When the pump power exceeds 70 mW, the first ~10 orders of Stokes wavelength signals become saturated and the increased power is almost transferred to the longer wavelengths. This observation is in accordance with Stepanov and Cowle's theory.[15] It should be noted that Brillouin multiwavelength generation is not stable when the 980-nm pump power is below 36 mW, indicating that the threshold of this self-seeded BEFL is ~36 mW.

By adjusting the PCs, we can modify the reflection profile of the Sagnac loop mirror and generate the multiwavelength combs in a broader wavelength range.[12] In our experiment the wavelength range of Brillouin multichannel comb generation is ~30 nm when a 16-cm PMF is incorporated into the Sagnac loop mirror. The stable self-seeded BEFL would still be achieved if the Sagnac loop mirror in the scheme were replaced by any other kind of broadband mirror.

In conclusion, we have proposed and demonstrated, for the first time to the best of our knowledge, a stable self-seeded BEFL without an external Brillouin pump. This was realized by incorporating a long SMF and a Sagnac loop mirror into the fiber ring cavity. With such a simple configuration, more than 120 Brillouin Stokes wavelengths were generated with uniform powers. Furthermore, we studied the dependence of the Brillouin multiwavelength signals on the power of the 980-nm pump. By adjusting PCs in the Sagnac loop, we were able to produce the Brillouin multiwavelength comb in an ~30-nm wavelength range.

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