Uniform amplitude multi-wavelength single-longitudinal-mode Brillouin–erbium fiber lasers

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A multi-wavelength single-longitudinal-mode (SLM) Brillouin–erbium fiber laser has been proposed and demonstrated by using the broadband linear gain and the narrow band gain of stimulated Brillouin scattering both in Er-doped fiber. Eight orders of lased Stokes have been observed with relatively uniform amplitudes and rigid spacing of 11 GHz. Each Stokes frequency works on SLM operation owing to very short oscillating cavity. The output signal-to-noise ratio is as high as 50 dB. The hybrid gain of two mechanisms in Er-doped fiber is helpful to improve the flatness of the multi-wavelength combs.

Keywords: Multi-wavelength; single-longitudinal-mode; fiber laser; Brillouin–erbium fiber laser; stimulated Brillouin scattering

1. Introduction

Multi-wavelength fiber laser sources have been attracted great interests for their applications in many fields, such as precise spectroscopy, optical sensing, and wavelength-division-multiplexing optical communications [1]. There are a number of methods for generating multi-wavelength combs, including cooling the erbium-doped fiber (EDF) in liquid nitrogen to reduce the homogeneous broadening [2], inducing birefringence mechanism in fiber cavity [3], inserting a frequency shifter or a phase modulator into the laser cavity [4], and using a multi-wavelength Brillouin–erbium fiber laser (BEFL) [5–9]. Among these methods, the BEFL is the most attractive for generating combs. It took advantage of the high gain from Erbium ions and the narrowband nonlinear gain of stimulated Brillouin scattering (SBS) in optical fibers [10]. However, these Brillouin fiber lasers usually have long cavity, and thus the single-longitudinal-mode (SLM) operation is difficult to be realized, which limits their applications due to multimode oscillation, mode hopping, and relatively large linewidth. Furthermore, the power distribution is uneven among these Brillouin lasers. Typically, most power is concentrated on a few low-order Stokes [5,6].

Brillouin fiber lasers have linewidth narrowing effect and can guarantee the SLM operation if the cavity length is enough short [11–13]. Several techniques have been proposed to achieve SLM operation, such as using a 2.15 m long bismuth-based EDF [14] and a 12-m-long hybrid Brillouin/ytterbium fiber [15]. In BEFL cavity, we can simultaneously amplifying the Brillouin pump (BP) and Brillouin signal. This allows a shorter length of active fiber to be used for the BEFL generation, which in turn reduces a total cavity loss and increases the output power.

In this paper, we present a multi-wavelength SLM BEFL by utilizing a simple configuration and its intrinsic properties of rigid frequency spacing around 11 GHz and extremely narrow linewidth. More than eight orders of Stokes have been observed with similar output power, and each order of Stokes has only one longitudinal mode and relatively uniform amplitudes. The output signal-to-noise ratio (SNR) is as high as 50 dB.

2. Experimental setup and principle

Figure 1 shows the experimental setup for generating the multi-wavelength SLM BEFL. The 1566.40 nm laser light from a tunable laser source (TLS) travels through a 50:50 coupler-1, and then is amplified by the erbium-doped fiber (EDFA) as the BP. After the optical circulator (OC), the BP is injected into the active ring cavity clockwise. The cavity consists of a 5.5-m EDF and the total length of the cavity is 11 m. Thus, its free spectral range (FSR) is 18.8 MHz that is comparable to the 20 MHz SBS gain bandwidth. So the BEFL can operate in the stable single-frequency lasing [11–13].

This configuration can shorten the cavity length, which can guarantee the SLM operation and reduce the SBS threshold. A 1550/980-nm wavelength-division-multiplexer to couple the 980-nm pump into the EDF. A

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SBS Stokes wave was generated in balancing the mode competition between the Brillouin Stokes lines and self-lasing cavity modes. As Stokes passing through coupler-2, 95% of Stokes is feedback to the cavity and 5% of Stokes is back to coupler-1. Then, Stokes is re-amplified by EDFA as the pump of the next order of Stokes.

3. Experimental results and discussion

Pumping the EDF with the 980-nm pump will also produce gain, which can be used to overcome the resonator losses. If the wavelength of the BP is close to that at which maximum gain is produced in the EDF, lasing will occur at the Stokes-shifted wavelength [16]. In our experiment, the laser cavity peak gain occur at around 1565–1568 nm, so the BP wavelength is set at 1566.40 nm. The requirement of higher BP power to suppress the mode competition from the self-lasing cavity modes is critically important. The injected BP is amplified by the EDFA before entering the single-mode fiber and the self-lasing cavity modes are suppressed and a laser oscillates in the ring cavity in the counter clockwise. This lower-order BS line can be utilized as the BP for a cascading generation of additional higher-order BS lines.

Figure 2(a) shows the output spectra of the BEFL with different EDFA power at 980 nm pump power of 177 mW. The resolution of the Optical Spectrum Analyzer is set at 0.015 nm. The pump wavelength is 1566.40 nm. When the EDFA power is set at 149 mw, the BP power is not enough to fully saturate the cavity modes competition. There exist cavity modes together with Brillouin Stokes. Therefore, this causes instability on the Stokes signals. As the BP power increases, this higher intensity of Stokes lines suppresses the energy extraction by the self-lasing cavity modes. When the BP power is higher enough to suppress the cavity modes competition, the output spectrum is clean from any spurious self-lasing cavity modes, and stable multi-wavelength lines can be generated. Here, because the SBS threshold in a pumped EDF is much less than in standard SMFs, the SBS effect is generated from the EDF but not from the pigtails. Eight orders of Stokes lines are generated with rigidly ~0.09 nm wavelength spacing when EDFA power was set at 607 mw, as shown in Figure 2(b).
The output spectra measured as a function of 980 nm pump power at fixed EDFA power of 607 mW are shown in Figure 3. Here, EDFA power is bigger enough than the cavity power, so the stable multi-wavelength can be ensured. The two orders Stokes lines are clearly measured at the 980-nm pump power of 130 mW. Due to the noise reduction process of SBS in SMF [17], the SNR is as high as 50 dB. As the 980 nm pump power increases, the number of Stokes lines also increases, but the SNR decreases. This observation is in accordance with Cowle and Stepanov’s theory [10]. Furthermore, the EDF with the 980-nm pump in the cavity produce sufficient gain to ensure the generated Stokes. Thus, the multi-wavelength comb is flattened.

The output power feature of port 1 and port 2 is investigated by increasing the 980 nm pump power. The output power from TLS is fixed at 1 mw. Laser of port1 consists of generated BS. Port 2 consists of the signals of TLS and BS amplified by EDFA which act as the original Brillouin seed. As shown in Figure 4, emitted power from port 1 increases almost linearly after the threshold. With the power of BS increasing, the power of port 2 decreases. In addition, we find that increasing the input power from TLS prevents the generation of high orders of BS which coincidence with Ref. [18]. The reason could be explained that the laser input to EDFA is linearly amplified. The more power from TLS, the less chance for 1st or higher order of BS will be amplified larger enough to exceed the threshold of next order of BS.

Now, we investigate the longitudinal characteristics of the multi-wavelength BEFL. The BEFL can operate in the stable single-frequency lasing when the fiber length is short enough [11–13]. The cavity consists of a 5.5-m EDF and the total length of the cavity is less than 10-m. Thus, its FSR is less than 20 MHz that is comparable to the 20 MHz SBS gain bandwidth. So SLM operation is secured. The generated multi-wavelength BEFL has rigid frequency difference about \( j \times 11 \) GHz in the 1566.40 nm pump wave. Two of the Stokes’ signals should be selected by using a narrow bandwidth filter. The generated microwave signal frequencies of \( \sim 11 \) GHz can be detected by a photodetector and observed by an electrical spectrum analyzer. The electrical spectrum of the generated microwave signal is shown in Figure 5.

In the previous ring or linear configurations, the cavity is very longer than 10 m and SLM operation cannot be realized, which limits their applications due to multimode oscillation and mode hopping. Furthermore, the power distribution is uneven among these Brillouin wavelengths. The hybrid gain of both EDF and SBS is helpful to improve the flatness of the multi-wavelength combs. Typically, most power is concentrated on a few low-order Stokes wavelengths [5,6] and some outputs SNR are as low as 20 dB [7,8]. Here, the generated BEFL has more than eight orders of Stokes outputs and
similar outputs power. The output SNR is as high as 50 dB and each order of Stokes operates on SLM status with rigid wavelength spacing.

4. Conclusions

In conclusion, a multi-wavelength SLM BEFL is successfully demonstrated utilizing a very short EDF as both the linear and nonlinear gains medium. More than eight orders of Stokes are obtained at a wavelength of 1566.40 nm. Each order of lased Stokes works on SLM operation with relatively uniform amplitudes. The frequency spacing of the generated comb is around 11 GHz, and the output SNR is as high as 50 dB.

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