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A novel tunable multi-wavelength Brillouin fiber laser with switchable frequency spacing

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ABSTRACT

We propose and experimentally demonstrate a novel wavelength tunable and frequency spacing switchable multi-wavelength Brillouin fiber laser by employing optical gain and absorption during the Stimulated Brillouin scattering process. The frequency spacing can be switched by only varying the Brillouin pump power. Up to 16 Stokes lines with single Brillouin frequency spacing are observed under the lower Brillouin pump power, and 7 Stokes lines with double Brillouin frequency spacing are realized under the high Brillouin pump power by exploiting the Brillouin pump absorption. The proposed multi-wavelength laser can also be tuned from 1547 to 1569 nm and has the potential applications in the areas of optical communications and sensing.

1. Introduction

Over the past decades, multi-wavelength fiber lasers have aroused great interest due to their potential applications in wavelength division multiplexing (WDM) systems and fiber optic sensing networks, coherent optical communication and testing, optical storage and other fields [1–5]. At room temperature, multi-wavelength fiber lasers can be achieved by using nonlinear optical effects such as Stimulated Brillouin scattering (SBS) [6], four-wave mixing (FWM) [7] and nonlinear polarization rotation (NPR) [8]. The requirements for developing multi-wavelength light sources include spacing tunable multi-wavelength lasing lines and stabilized flattened peak powers. In the reported schemes, additional auxiliary devices are commonly required for the frequency spacing tunable multi-wavelength fiber laser. A tunable Mach–Zehnder interferometer (MZI) [9], chirped-fiber Bragg gratings (CFBG) [10], an array waveguide grating (AWG) [7] have been employed as filters to realize the tunable frequency spacing. Those approaches greatly increase not only the cavity loss but also the cost of the fiber laser.

Multi-wavelength Brillouin erbium fiber laser (MBEFL), which exploits SBS in the optical fiber, has become a research hot spot in recent years due to the advantages of ultra-narrow linewidth [11], low threshold power [12], low noise intensity [13], and wide tunable range [14]. SBS effect results from an interaction between the intense pump light and acoustic waves in a nonlinear medium with a constant Brillouin frequency shift [15]. And in the standard silica based fibers the Brillouin frequency shift is approximately 10 GHz. Various efforts have been made to increase the frequency spacing or realize the spacing tunable to make demultiplexing process easily. Wang-Yuhl Oh et al. has realized 10 and 20 GHz optical combs generation in MBEFL by the adjustment of polarization controllers in the Sagnac reflector [16]. The optical comb generation with 20 GHz spacing in their work is demonstrated by discrimination of the even-order and the odd-order Stokes waves. But the signal-to-noise ratio (OSNR) of the multi-wavelength operation of 10 GHz spacing is very small. The output spectrum is not stable. The generation of switchable dual-wavelength Brillouin ring-cavity fiber laser is described in Ref. [17]. Incorporating the FBG filter only realizes that the spacing of dual-wavelength can be tuned at an interval of about $0.084 \times N$ nm ($N = 1, 2, \ldots, 13$).

In this paper, we experimentally demonstrate a novel wavelength tunable and frequency spacing switchable MBEFL by utilizing optical gain and absorption during the SBS process. The frequency spacing of the laser can be easily switched between 10 GHz and 20 GHz by just changing the Brillouin pump (BP) power. Compared with [16], the generation of doubled frequency spacing in our proposed scheme is not based on the discrimination of the even-order and odd-order Stokes waves. The influences of pump powers, BP wavelength, and fiber length on the performance of the proposed MBEFL are investigated experimentally. By the experimental result of triple Brillouin frequency spacing, the hypothesis of switchable frequency spacing at an interval of about $10 \times N$ GHz ($N = 1, 2, 3, \ldots$) at the expense of the optical fibers and

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power is confirmed indirectly.

2. Experimental setup

Fig. 1(a) illustrates the schematic diagram of the proposed MBEFL. Two feedback branches and a ring cavity are connected by a four-port circulator. Two feedback branches consist of 9.4 km and 25.2 km single mode fiber (SMF), a four-port circulator (cir1) and the loop-back three-port optical circulator (cir2 and cir3), respectively. Erbium doped optical fiber amplifier (EDFA) is composed of a 980 nm pump laser, 10 m EDF, an isolator (ISO) and two wavelength selective couplers (WSCs). The 980 nm pump laser is divided into two parts by a 3 dB optical coupler to improve the performance of the EDFA. Two WSCs are used to couple the pump and the generated Stokes lines. Cir1 can ensure the unidirectional oscillation of the optical laser to increase the OSNR and decrease the reverse Rayleigh scattering.

Cir2 and cir3 at the end of the feedback branches serve as the total reflection mirror to reflect the residual BP and the generated Stokes lines. They perform as the quasi-ring cavity which may help to partially reduce the mutual injection noise for obtaining the stable lasing power and decrease the SBS threshold [18]. Two SMFs act as the nonlinear Brillouin gain medium, which have nonlinear coefficient of 1.1 $W^{-1}\,km^{-1}$, effective area of 83.97 μm² and attenuation of 0.23 dB/km. A tunable laser source (TLS) with a 3 MHz linewidth and 13 dBm maximum output power, acts as the BP signal and is injected into the ring cavity via the 3 dB coupler in the clockwise direction. The laser output optical spectrum is monitored by an optical spectrum analyzer (OSA) with a resolution of 0.02 nm.

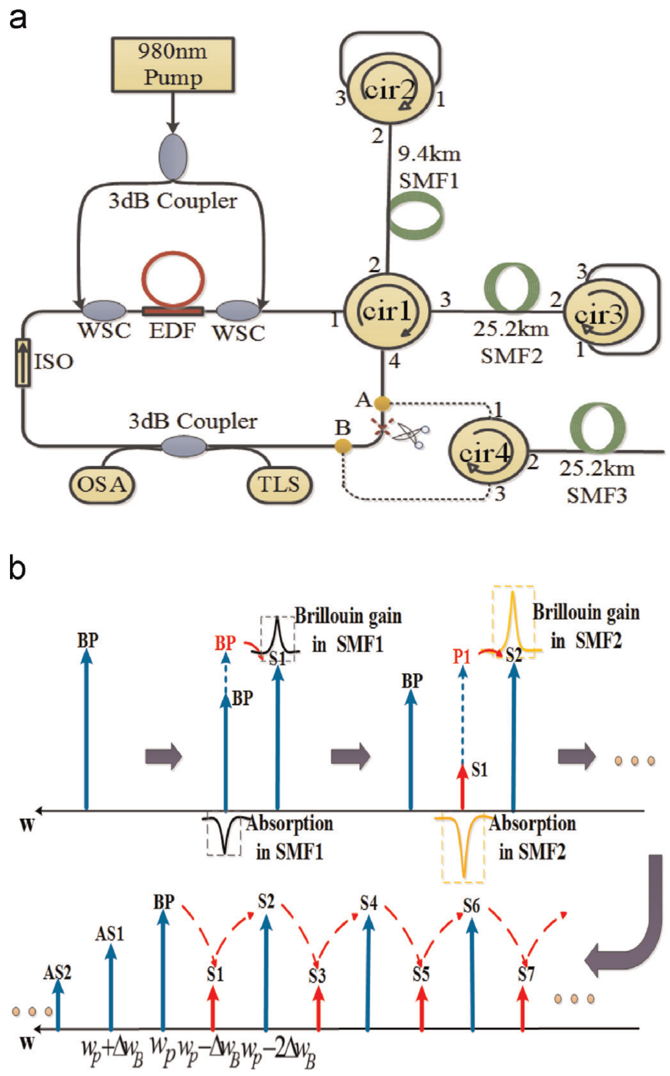

Fig. 1. (a) Experimental setup of the multi-wavelength BEFL, and (b) the diagram of the generation of double Brillouin frequency spacing spectrum.

The high power (~5 dBm) BP light is fed into the fiber ring through the 3 dB coupler and amplified by EDFA. Then it enters SMF1 via cir1. After entering SMF1, once the pre-amplified BP power exceeds the Brillouin threshold of SMF1, the first-order Brillouin Stokes (BS1) light will be generated and propagates in the backward direction. The BS1 with a frequency ω_{Bs1} is downshifted by $\Delta\omega_B$ from the BP optical frequency ω_P. Meanwhile, BP signal and BS1 experience pump depletion and Brillouin amplification in the SMF1, respectively. It matches with the diagram which is illustrated in Fig. 1(b). Then the generated backward BS1 light propagates towards port 2 to port 3. It enters SMF2, acting as the pump to stimulate second-order Brillouin Stokes $\left(\mathrm{BS2}, \omega_{Bs2} = \left(\omega_p - \Delta\omega_B\right) - \Delta\omega_B\right)$ light. Thus, the generated BS2 light has double Brillouin frequency shift related to the BP light. As shown in Fig. 1(b), due to the large absorption during the SBS process, BS1 is depleted after passing twice through SMF2. Therefore, the frequency spacing between two peak Stokes lights is approximately 20 GHz. Under this situation, the generated BS2 is transmitted from port 3 to port 4 by cir1 and guided into the ring cavity. This process will be repeated and high-order BS waves will be generated in succession. The cascaded SBS continues to take place until the power of the next high-order BS wave will not be high enough to exceed the threshold power of the SBS, and hence the generation of the next high-order BS wave will cease.

When the injected BP power is low (≤ -12 dBm), the SBS process is different from what described above. In this case the multi-wavelength laser will generate the lasing lines with single Brillouin frequency spacing. This behavior can be ascribed to the high Brillouin threshold of the SMF1. According to the threshold condition [19], the shorter SMF is, the higher threshold will be. Though the weak BP cannot meet the condition in SMF1, it exceeds the Brillouin threshold of SMF2. Thus, the laser behaves similarly as the common Brillouin fiber laser. Therefore, the Brillouin frequency spacing is about 10 GHz.

3. Results and discussion

As the TLS is turned off, the unstable self-lasing cavity modes are intrinsically generated and dominate the laser oscillation around 1557–1563 nm owing to the mode competition in EDFL. The mode competition limits the tuning wavelength range and impacts the power stability of the suggested BEFL. In order to suppress the free-running cavity modes, BP wavelength is required to match with the self-lasing modes wavelength to improve the performance of the laser. Hence, we set BP at a wavelength of 1557 nm.

Fig. 2(a) reveals the output spectrum with 0.172 nm wavelength spacing under 5 dBm BP power with 980 nm pump power of 90 mW. A total of 17 lasing lines including 14 Stokes (7 odd-orders and 7 even-orders) and 3 anti-Stokes lasing lines are obtained. The intra-cavity BP pre-amplification technique in the proposed configuration provides an efficient method to suppress the free-running cavity modes by injecting sufficient BP signal. As shown in Fig. 2(a), the weak odd-order Stokes lines appear, which experience the power depletion during SBS process in SMF2. Contrarily, the intense even-order Stokes lasing lines are generated owing to the Brillouin amplification in SMF2. The measured OSNR is more than 28 dB, and the peak power is about −3.5 dBm.