Broadband Brillouin slow light with multiple-longitudinal-mode, tunable pump

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We propose and demonstrate broadband Brillouin slow light using a multiple-longitudinal-mode tunable fiber laser as Brillouin pump. A tunable broadband Brillouin pump with a tuning range from 1 520 to 1 555 nm is generated using a fiber ring laser with a semiconductor optical amplifier (SOA) as its gain medium. The pump spectrum consists of a large number of longitudinal modes separated by 6 MHz. The 3-dB bandwidth is about 11.5 GHz, and its fluctuation is less than 100 MHz within the tuning range. An 8-Gb/s data signal can be delayed by up to 83.0 ps (bit error rate $< 10^{-9}$) at 17-dBm pump power.

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Slow light based on stimulated Brillouin scattering (SBS) in optical fibers has attracted much interest because of its potential application in future optical communication systems. Brillouin slow light was first demonstrated in fiber[1,2], the studies have been focusing on the delay of high-speed signals with low distortion. The Brillouin gain bandwidth has to be increased to accommodate the high-speed signal. Numerous approaches have been proposed for generating a broadband Brillouin pump by indirectly modulating a laser source with an optical modulator[3−11], directly modulating a laser diode[12−19], and directly slicing the polarized amplified spontaneous emission (ASE) source[20]. Broadband SBS slow light with bandwidths up to tens of gigahertz has been demonstrated by directly modulating laser diodes[12−19], and the super-Gaussian pump waveform has been used to improve the eye opening and reduce pulse distortion[16−19]. The multiple SBS gain lines generated via the indirect modulation approach have also attracted great interest[3−11], because they not only broaden the Brillouin gain bandwidth but also achieve large fractional delays with low signal distortion. Moreover, the influence of such modified gain profiles with multiple Brillouin lines on system performance has been studied in detail[9]. However, flat gain lines with both large bandwidth and close spacing are difficult to generate by indirectly modulating the laser source using an electro-optic modulator (EOM) because of its low modulation efficiency and need for complicated driver signals[5,6]. To the best of our knowledge, the maximum gain bandwidth with this approach is only 570 MHz with 30-MHz line spacing[6], which is insufficient to slow down high-speed signals greater than the gigabit per second range. A simple, cost-effective broadband Brillouin pump with tunable wavelength must be designed to match future optical communication systems.

In this letter, we propose and demonstrate broadband Brillouin slow light using a multiple longitudinal mode (MLM) fiber laser as Brillouin pump. The tunable broadband Brillouin pump consists of a MLM fiber ring laser with a semiconductor optical amplifier (SOA) gain medium. An optical channel tunable filter (OCTF) within the ring laser cavity determines the wavelength and the spectral shape of the pump, and a tunable pump with a tuning range from 1 520 to 1 555 nm is achieved by adjusting the OCTF bias. The 3-dB bandwidth is about 11.5 GHz, and its fluctuation is less than 100 MHz within the tuning range. The broadband, closely spaced, MLM Brillouin pump is easily generated because of the inhomogeneous broadening mechanism in the SOA[21−23], and the spectrum of the pump is composed of a large number of longitudinal modes separated by 6 MHz. The delay and eye diagrams are demonstrated for an 8-Gb/s data stream using this broadband tunable MLM Brillouin pump.

The experimental setup of the broadband Brillouin slow light is shown in Fig. 1. The Brillouin pump is a SOA-based fiber ring laser, shown in the dashed box, which consists of a fiber polarization controller (PC), SOA, optical circulator (OC1), OCTF, two isolators (ISOs), variable optical attenuator (VOA1), and 80:20 optical coupler (coupler1). The SOA has a 22-dB small signal gain and 60-nm gain bandwidth, whose gain peak is about 1 530 nm. The OCTF has a wavelength from 1 510.0 to 1 570.0 nm and 3-dB bandwidth of 0.12 nm, which determines the wavelength and spectral shape of the pump. VOA1 is used to change the loss in the cavity to generate the MLM laser with different spectral

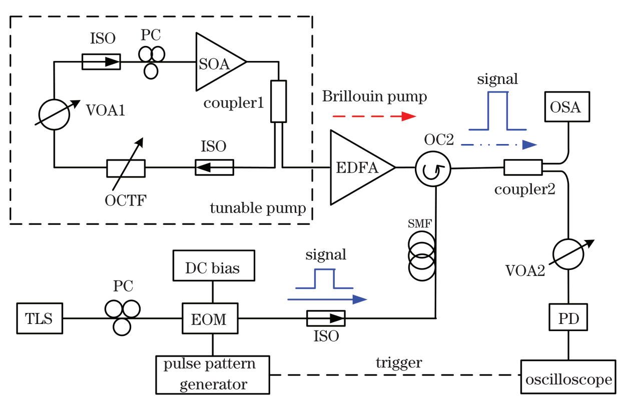

Fig. 1. Experimental setup of broadband Brillouin slow light with MLM Brillouin pump.

widths. The output of the MLM laser from the 20% port of Coupler1 is used as the broadband Brillouin pump. The pump will be injected into a 24-km single mode fiber (SMF) via another circulator (OC2) after it is amplified by a high-power erbium-doped fiber amplifier. In the SMF, the high-speed signal will be amplified and delayed while its wavelength is aligned to the pump. This signal is generated by an EOM driven by a pulse pattern generator. The power and gain of the signal is measured by an optical spectrum analyzer (OSA). Another variable optical attenuator (VOA2) is used to adjust the optical power for the bit error rate (BER) measurements. The delayed signal is also detected using a photodetector (PD), and its delay and BER are measured using a digital sampling oscilloscope and a BER tester (BERT), respectively. An isolator is used to prevent the powerful pump from traveling into the EOM and tunable laser source (TLS).

In the SBS-based slow light system, based on the resonances in a pumped optical fiber, the slow light effect can be produced from the fiber dispersion[2]. In slow light applications, real interest lies in demonstrating large relative pulse delays without substantial pulse distortion. In obtaining large relative pulse delays with minimal distortion, the uses of multiple Brillouin gain lines for SBS-based slow light in an optical fiber have been proposed and demonstrated with respect to the SBS single-resonance configuration[3−11]. The SOA-based fiber ring laser is used as the broadband Brillouin pump to obtain multiple Brillouin gain lines. The mode spacing of the fiber ring laser can be determined and modified through the cavity length. The spectral width can be adjusted by changing the OCTF bandwidth, SOA bias, or VOA1 loss. The mode spacing can be directly measured using an electrical spectrum analyzer (ESA). In our experiment, the mode spacing is approximately 6 MHz. As well known, the total Brillouin gain spectrum fluctuates in large mode spacing. This fluctuation increases with the mode spacing, resulting in large pulse distortions. A flat Brillouin gain spectrum can be achieved by overlapping multiple Brillouin gain lines when the mode spacing is less than 10 MHz in the SMF[9]. Thus, 6-MHz mode spacing can achieve a flat gain spectrum and dispersion profile[5,9]. The tunable Brillouin pump can be obtained by adjusting the OCTF bias, as shown in Fig. 2(a), when the SOA bias is 100 mA and VOA1 loss is 8 dB. The 35-nm tuning range is from 1 520 to 1 555 nm, and the power fluctuation is less than 1 dB. To further evaluate the bandwidth stability of the tunable Brillouin pump, we measured the bandwidth of the Brillouin pump by heterodyning the Brillouin pump with a narrow linewidth (∼200 kHz)

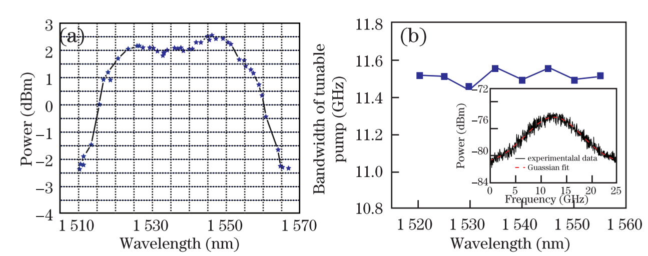

Fig. 2. (a) Ring laser power at different wavelengths; (b) 3-dB bandwidth at different wavelengths and beat spectrum.

TLS in different wavelengths. As shown in Fig. 2(b), the fluctuation of the Brillouin pump bandwidth is less than 100 MHz within the 1 520−1 555-nm tuning range. The central wavelength of the OCTF is fixed at 1550 nm. The beat spectrum of the Brillouin pump is shown in the inset of Fig. 2(b), and the pump spectrum has a Gaussian shape and 3-dB bandwidth of approximately 11.5 GHz. The SBS gain spectrum is the convolution of the intrinsic SBS gain and pump spectra. Therefore, the resultant SBS gain bandwidth is approximately equal to the pump when the pump bandwidth is much larger than the intrinsic SBS bandwidth. Moreover, a MLM pump can obtain multiple Brillouin gain lines, whose spacing is equal to the mode spacing of the pump. Hence, this MLM Brillouin pump with 11.5-GHz 3-dB bandwidth and 6-MHz mode spacing can delay high-speed signals of over 10 Gb/s with low distortion. The bandwidth of the Brillouin pump could be adjusted because it increases approximately linearly with the SOA bias or the VOA1 loss in the ring laser. Hence, a Brillouin pump with the desired bandwidth and mode spacing can be generated from this MLM, SOA-based fiber laser. Although the bandwidth of the Brillouin pump is less than those reported in Ref. [24], we mainly use multiple SBS gain lines to obtain the tunable broadband Brillouin pump, which can reduce signal distortion[3,4].

In our experiment, only 8-Gb/s non-return-to-zero signals are used to demonstrate slow light with the above broadband Brillouin pump at 1 550-nm central wavelength because of the unavailability of a higher speed PD. However, we expect that signals of 10 Gb/s or even higher at other wavelengths from 1 520 to 1 555 nm should have the similar results as that of the 8-Gb/s signal at 1 550 nm. The delay time under different gains are shown in Fig. 3. The signal delay increases with the Brillouin gain. For example, a 130.1-ps delay is obtained with 4.2-dB Brillouin gain, which corresponds to 1-bit delay. Moreover, the delay time is proportional to the Brillouin gain with a 31-ps/dB slope, which is larger than the reported values is Refs. [12,13]. The BER of the delayed signal is shown in the inset of Fig. 3. The BER decreases as the received optical power increases when no Brillouin pump is used. In addition, the measured BER of the delayed signal at 17 dBm is about 10^{-9}. Hence, the delay time with error-free operation (BER$<10^{-9}$) is only 83.0 ps. With a 20-dBm Brillouin pump, the BER decreases and then increases with received optical power, which may be mainly attributed to the serious Brillouin ASE noises at higher pump power[18,19]. The eye diagrams of signals with the different pump powers and their corresponding delay times are shown in Fig. 4. In this measurement, the temporal center of the eye diagram is used to define the pulse position. As shown, the measured delay of the eye diagram is the same as the delay of the above pulse waveform. Although the eye diagram is more delayed at higher pump powers, it is also more degraded. The eye diagram becomes coarse, and the eye opening is lowered. Moreover, the eye does not look open when no Brillouin pump is used. This degradation is due to the crosstalk noise from the Rayleigh backscattering of the broadband Brillouin pump mixed in the amplified signal at high pump powers[13,14], as indicated in the measured BER in the inset of Fig. 3. Although

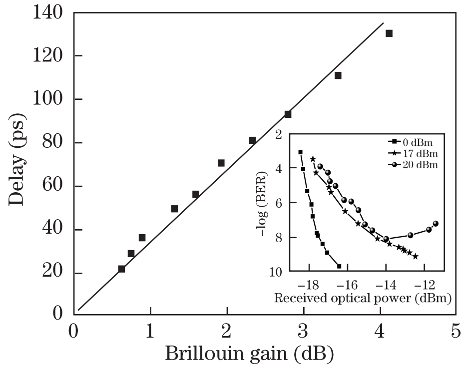

Fig. 3. Delay time under different Brillouin gains and BER under different received optical powers.

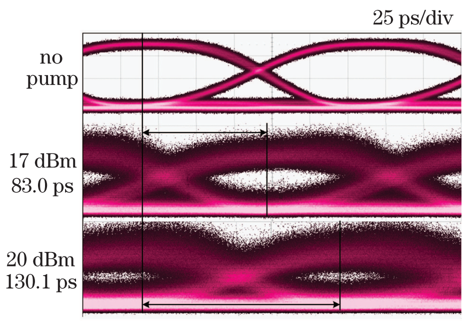

Fig. 4. Eye diagrams with delay time under different pump powers.

our experiment uses a Gaussian-shaped pump, the pulse distortion can be also reduced because the bandwidths of the Brillouin pump are significantly higher than the amplified signal[15,25]. Our experimental results verify the efficacy of the proposed technique in a single tunable broadband Brillouin slow light element.

In this letter, a tunable broadband, MLM fiber laser has been proposed as a Brillouin slow light pump to demonstrate the slow light of high-speed optical signals. This pump with a tuning range from 1 520 to 1 555 nm is achieved experimentally using SOA as gain medium, and the 3-dB bandwidth of the pump is about 11.5 GHz, which is separated by 6 MHz. Although a 130.1-ps delay of the 8-Gb/s signal can be achieved by the 20-dBm Brillouin pump, an error-free (BER$<10^{-9}$) delay of only up to 83.0 ps is achieved at 17-dBm pump power. The delayed signal can further be improved by filtering Rayleigh crosstalk noise using a narrowband optical filter. The experimental results confirm that delays can be induced at any wavelength within the telecommunication band using the proposed MLM, SOA-based fiber laser. Moreover, the method is a promising candidate in future Brillouin slow light applications.

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