Amplification effect on stimulated Brillouin scattering in the S-band forward G652 fiber Raman amplifier

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The amplification effects on forward and backward stimulated Brillouin scattering (SBS) lines in the forward pumped S-band distributed G652 fiber Raman amplifier (FRA) have been studied. There is a pump threshold power of Stokes backward stimulated Brillouin scattering (B-SBS) line in the forward pumped G652 FRA, it is about 1 mW. The Stokes B-SBS lines are amplified by FRA and fiber Brillouin amplifier (FBA). The gain of amplification is given as $G_a = G_R \cdot G_B$ where G_R is Raman gain and G_B is Brillouin gain. In experimental work, the saturation gain of the first order Stokes backward SBS line is about 58 dB and the saturation gain of 25-km G652 forward FRA is about 25 dB, so the gain of FBA is about 33 dB. The forward stimulated Brillouin scattering (F-SBS) is generated and amplified in S-band G652 FRA. The stimulated threshold powers of the forward first order Stokes SBS (SB_1^-), second order Stokes SBS (SB_2^-), and third order SBS (SB_3^-) in the forward pumped FRA are 2.3, 1.6, and 1.6 mW, respectively. In experimental work, the saturation gains of SB_1^-, SB_2^-, and SB_3^- are about 38, 62, and 60 dB, respectively. The saturation Raman gain of 25-km G652 forward FRA is about 8.8 dB, so the Brillouin gains of SB_1^-, SB_2^-, and SB_3^- are about 29.2, 53.2, and 51.2 dB, respectively. The forward and backward cascaded SBS lines have been observed.

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Recently, with fast developing of extra-capacity of fiber communication systems, the dense wavelength division multiplexing (DWDM) technology is applied. The erbium-doped fiber amplifiers (EDFAs) cannot be satisfying for the user, so recently most research works have been focused on the fiber Raman amplifier (FRA)[1−4]. Stimulated Brillouin scattering (SBS) effect is a noise source for FRA, but the amplification SBS is a good comb source for DWDM fiber communication system[5].

During the process of manufacturing and testing S-band distributed FRA, with tunable narrow signal source (less than 100 MHz), strong high-order forward and backward SBS lines are observed in forward pumped FRA. The forward propagating acoustic waveguide SBS lines are generated and amplified in S-band FRA, because the waveguide characteristics weaken the wave vector rule[6,7]. Multi-order and cascaded SBS lines have been observed in FRA[8−11]. In this paper the amplified phenomenon of SBS lines in the S-band forward distributed FRA is discussed.

Process of SBS can be described as the nonlinear interaction between pump wave and Stokes wave. The pump wave generates acoustic wave due to electro-induced extension, then phonon induces regular modulation of refraction index[6], forming grating of refraction index, and it scatters pump light with Bragg diffraction. Scattering light generates frequency shift-down because Doppler shift is related to grating moving with sound wave velocity v_a. This process can be described as a pump photon annihilation, timely a Stokes photon and acoustic phonon generation. The process of scattering must obey conservation of energy and momentum. Frequency and wave vector have the relation as

$$\Omega_B = \omega_p - \omega_S, \quad k_a = k_p - k_S, \tag{1}$$

where ω_p and ω_S are the frequencies of pump wave and Stokes wave respectively, k_p and k_S are the wave vectors of pump wave and Stokes wave, Ω_B and k_a are the frequency and wave vector of acoustic wave.

Then we can get

$$\Omega_B = v_a|k_a| \approx 2v_a|k_p|\sin(\theta/2), \tag{2}$$

where θ is the angle between pump wave and Stokes wave. Because of two directions of forward and backward propagating in optical fiber, there should be only backward scattering in optical fiber. Forward SBS exists and it does not obey the common theory, because the waveguide characteristics weaken the wave vector rule. The forward propagating waveguide Brillouin scattering lines are generated and amplified in S-band FRA.

The Raman gain G_R is defined as

$$G_R = \exp(g_R P_0 L_{eff}/A_{eff}), \tag{3}$$

and the Brillouin gain G_B is defined as

$$G_B = \exp(g_B P_0 L_{eff}/A_{eff}), \tag{4}$$

where g_R and g_B are the Raman gain coefficient and the Brillouin scattering; P_0 is pump power; L_{eff} and A_{eff} are the effective length and the effective area.

Figure 1 is our experimental setup to measure amplification effect on forward and backward SBS in the forward pumped S-band distributed G652 fiber Raman amplifier. It consists of signal source, isolators (ISOs), bi-directional coupler (BDC), optical spectrum analyzers
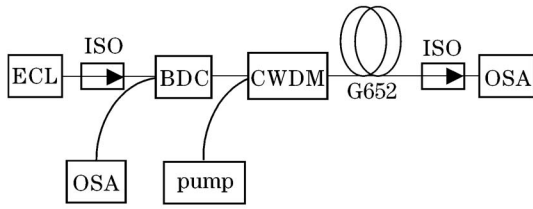
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Fig. 1. Experimental setup.

(OSAs) and forward pumped S-band fiber amplifier. Brillouin pump (BP) source consists of tunable external cavity laser (ECL), of which wavelength is 1520 nm, the tunable range is 80 nm, the range of tunable output power is from −7 to 3 dBm, the bandwidth of signal spectrum is < 100 MHz, and signal-to-noise ratio is better than 45 dB. The BDC is a 1 × 2 one. The fiber loss coefficient of G652 single mode fiber is 0.2 dB/km at 1520 nm. Pump-signal coupler is 1427/1520 coarse wavelength division multiplexer (CWDM). Pump source is a fiber Raman laser, of which wavelength is 1427.2 nm, bandwidth is 0.67 nm, and tunable power is 0—1200 mW. The spectrum range, resolution and dynamic range of OSA are 600—1700 nm, 10 pm, and 60 dB, respectively.

In the Stokes region, second order Stokes backward stimulated Brillouin scattering (B-SBS) is observed when the pump power for forward pumped FRA is 850 mW. The spectrum of BP, second order 1st SB⁻, 2nd SB⁻ and anti-Stokes Brillouin scattering (SB⁺) lines are shown in Fig. 2. The frequency shift of SBS is 10.7 GHz. Stokes backward Brillouin scattering line 1st SB⁻, 2nd SB⁻ and SB⁺ are dependent on the Raman pump (RP) power of S-band forward FRA.

The intensity of SB⁺ is 25 dB less than BP and the intensity of SB⁻ is 20 dB large than BP, as shown in Fig. 3. FRA pump threshold power of Stokes backward stimulated Brillouin scattering line (SB⁻) is about 500 mW. According to the theory, the threshold power entering in
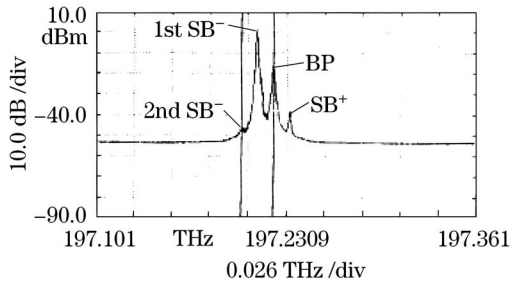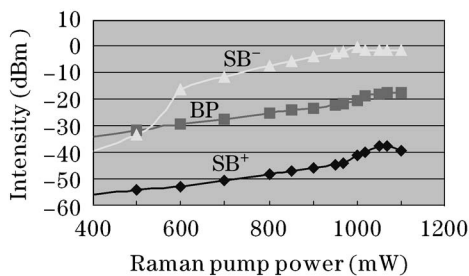

Fig. 2. Spectrum of Brillouin scattering.

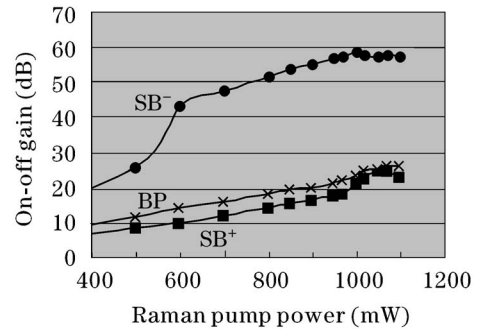Fig. 3. SB⁺, BP and SB⁻ intensities as functions of Raman pump power.

Fig. 4. Gains of SB⁺, BP and SB⁻ as functions of Raman pump power.

the fiber is about 1 mW.

The on-off gain of Brillouin scattering pump line BP is nonlinearly dependent on FRA pump power and no related to fiber length, as shown in Fig. 4. BP's Rayleigh scattering line is amplified by FRA and BP's gain is Raman gain. In practice, the Stokes B-SBS lines are amplified by FRA and FBA.

The gain of amplification is given as

$$G_a = G_R \cdot G_B, \qquad (5)$$

The FRA is a wideband amplifier, but FBA is a narrow band amplifier. In experiment, the saturation gain of SB_1^- is about 58 dB and the saturation gain of 25-km G652 backward FRA is about 25 dB, so the Brillouin gain of SB_1^- is about 33 dB.

The first order forward Brillouin scattering line has been observed when the pump power of FRA is 850 mW.

The spectrum of BP and SB⁻ is shown in Fig. 5.

The intensity of multi-order forward SBS (F-SBS) is dependent on the pump power of forward FRA, as shown in Fig. 6. The stimulated threshold powers for the forward first order Stokes SBS (SB_1^-), second order Stokes SBS (SB_2^-) and third order SBS (SB_3^-) in the forward pumped FRA are 2.3, 1.6, and 1.6 mW, respectively.

The gain of BP line is nonlinearly dependent on the pump power of 25-km G652 forward FRA, the gain saturation phenomenon of BP line occurs and the power is transferred to Brillouin scattering, as shown in Fig. 7. In experimental work, the saturation gains of SB_1^-, SB_2^-, and SB_3^- are about 38, 62, and 60 dB, respectively. The saturation gain of 25-km G652 forward FRA is about
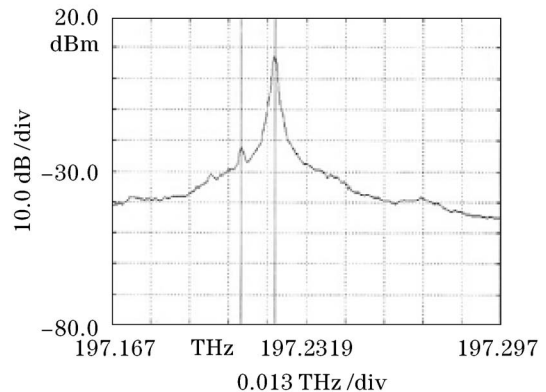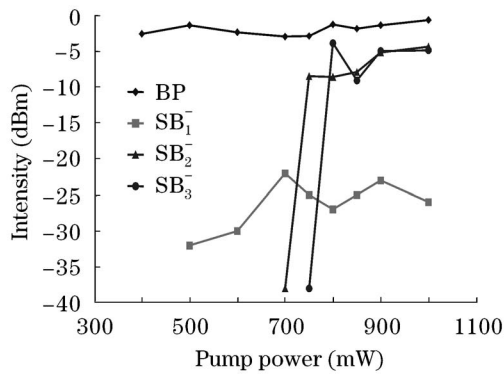

Fig. 5. Spectrum of forward SBS.

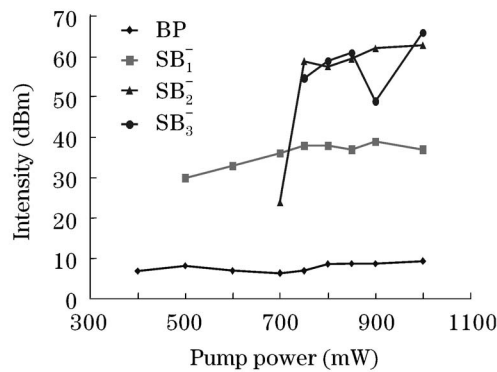Fig. 6. Intensity of F-SBS as a function of pump power.

Fig. 7. Gain of F-SBS as a function of pump power.

8.8 dB, so the gains of SB_1^-, SB_2^- and SB_3^-, in the forward fiber Brillouin amplifier are about 29.2, 53.2, and 51.2 dB, respectively.

In Stokes area, multiple orders of forward and backward SBS lines have been observed when the pumped power is higher than the SBS threshold power. Cascaded forward and backward SBS in forward pumped S-band FRA can be observed when the pump power is further increased. It is important to note that part of the signal power transfers to SBS power, the gain decreases and noise increases to generate a crosstalk, and the cascaded SBS that generates the comb spectrum can be used as comb source. There is cascade backward SBS in the S-band forward pumped distributed G652 Raman amplifier for no pump power and 1200-mW pump power, as shown in Fig. 8.
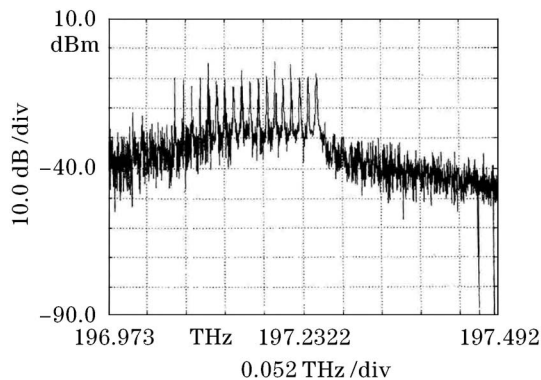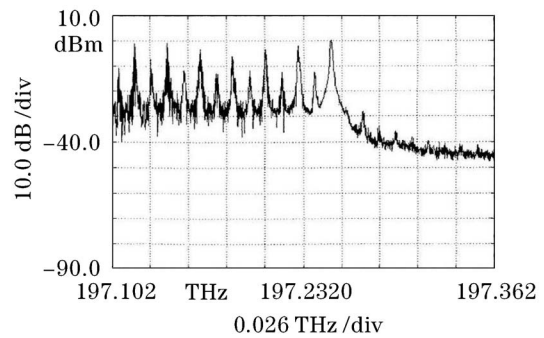

Fig. 8. Cascade B-SBS lines spectrum.

Fig. 9. Spectrum of cascade F-SBS in the S-band FRA.

Table 1. Threshold and Gain on Stokes SBS

	B-SBS	F-SBS		
	SB^-	SB_1^-	SB_2^-	SB_3^-
Threshold (mW)	1	2.3	1.6	1.6
Total Gain (dB)	58	38	62	60
Raman Gain (dB)	25	8.8	8.8	8.8
Brillouin Gain (dB)	33	29.2	53.2	51.2

Cascaded F-SBS in the forward pumped S-band FRA has been observed when the pump power is 1200 mW, as shown in Fig. 9. The frequency of SBS signal is 197.2506 THz and the power is 0.31 dBm. The even-order intensity SBS line is 12 dB higher than odd-order SBS. The reason is that when the pump power of FRA is higher than the threshold power, there are strong backward SBS lines generated, leading to reversed Rayleigh scattering, called Brillouin-Rayleigh scattering lines[7−11], but as the conversion efficiency of the Rayleigh scattering is low, the odd-order Brillouin scattering is lower than the even-order SBS lines.

The threshold power and Raman gain and Brillouin gain on backward and forward SBS in the S-band forward distributed FRA are listed in Table 1.

In conclusion, we have gotten the following results. 1) The effect of Raman amplification on forward and backward SBS in the forward pumped S-band distributed G652 fiber Raman amplifier at 1520 nm, forward pumped by the tunable power fiber laser, have been observed. 2) Cascaded backward and forward SBS lines have been observed in the S-band forward pumped distributed FRA. It is important to note that part of the signal power transfers to SBS power, the gain is decreased and noise is increased to generate a crosstalk, and the cascaded SBS that generates the comb spectrum can be used as comb source. 3) The threshold power and gain on Stokes SBS in the S-band forward distributed FRA are obtained.

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