

# Study on forward stimulated Brillouin scattering in a backward pumped fiber Raman amplifier

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Strong multi-order forward stimulated Brillouin scattering (SBS) has been observed in the backward pumped S-band distributed fiber Raman amplifier (FRA) with tunable narrow signal source (less than 100 MHz) when the pump power of FRA reached the SBS threshold. This does not obey the theory that only weak backward SBS lines exist according to the conservation of energy and momentum and the wave vector selected rule. This is because the sound waveguide characteristic weakens the wave vector rule, and the forward transmitted sound waveguide Brillouin scattering lines are generated and amplified in FRA. When the pump power is further increased, 11 orders of SBS lines and comb-like profile are observed. For the excited line, the frequency is 197.2296 THz and the power is 0 dBm. The even order SBS lines are stronger than odd order SBS lines, the power of the 2nd and 4th order SBS lines is 1.75 dBm, which is 16 dB higher than that of the 1st and 3rd order SBS lines. The odd order SBS lines are named Brillouin-Rayleigh scattering lines.

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Recently, with the development of extra-capacity of fiber telecommunication experimental systems, dense wavelength division multiplexing (DWDM) technology is widely used. Now 1300- and 1550-nm bands have been connected with each other to be a broad band with the development of fiber technology. We have to resolve the problems of laser source, modulator, and amplifier if we want to realize long-distance and extra-capacity telecommunication. Erbium-doped fiber amplifiers (EDFAs) cannot satisfy for the demand, so the recent research has been focused on fiber Raman amplifiers (FRAs)<sup>[1-4]</sup>.

In this study, a tunable narrow spectral bandwidth (<100 MHz) laser diode (LD) is used as the signal source. Strong multi-order forward stimulated Brillouin scattering (SBS) is observed in backward pumped Raman amplifier, which seems to not obey the theory that only weak backward-SBS exists according to conservation of energy and momentum and wave vector rule<sup>[5]</sup>. In our experiment, strong forward SBS is observed when the pump power of FRA is increased and the amplified signal reaches the threshold value of SBS. This is because the sound waveguide characteristic weakens the wave vector selected rule and forward sound waveguide Brillouin scattering is generated<sup>[6]</sup>. When the pump power is further increased, 11th order SBS lines and comb-like profile are observed. In this paper the phenomenon of forward multi-order SBS in the S-band backward distributed FRA is discussed.

The experimental setup is shown in Fig. 1. The signal source consists of an external-cavity tunable semiconductor laser (ECL), whose wavelength is 1520 nm, the tunable range is 100 nm, the range of tunable spectral is 1470–1570 nm, the range of tunable output power is –10–3 dBm, the bandwidth of signal spectrum <100

MHz, the signal-to-noise ratio (SNR) is better than 45 dB. The pump-signal coupler is a 1427/1520 nm coarse wavelength division multiplexer (CWDM). The pump source is a fiber Raman laser, whose wavelength is 1427.2 nm with the bandwidth of 0.67 nm. The output power is tunable between 0–1200 mW. The optical spectrum analyser (OSA) is with the spectrum range between 600–1700 nm, resolution of 10 pm, and dynamic range of 50 dB. 25-km G652 single mode fiber with the loss coefficient of 0.2 dB/km (1550 nm) is used.

When the pump power of FRA is lower than 800 mW, weak spontaneous Brillouin scattering has been observed in backward-pumped distributed FRA. When the pump power is 880 mW, the frequency relative to the signal wavelength of 1520 nm is 197.2299 THz, the power of amplified incident signal is 3.08 dBm, which is near the threshold value of SBS, two orders of SBS appear, as shown in Fig. 2. The frequency of the 1st order SBS is 197.2189 THz and the power is –15 dBm, and those of the 2nd order SBS are 197.2080 THz and –20 dBm, respectively. The frequency shift of SBS lines is 11 GHz.

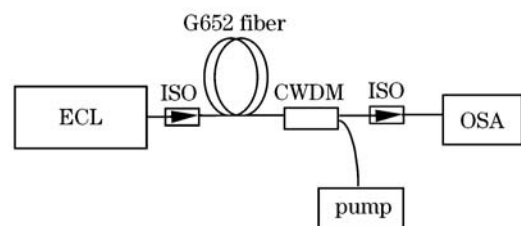


Fig. 1. Backward-pumped distributed FRA setup. ISO: isolator.

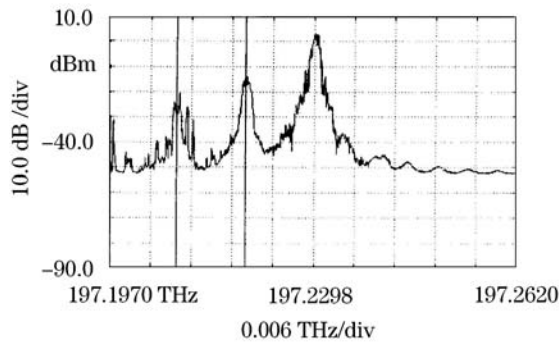


Fig. 2. The two orders of SBS under the pump power of 880 mW.

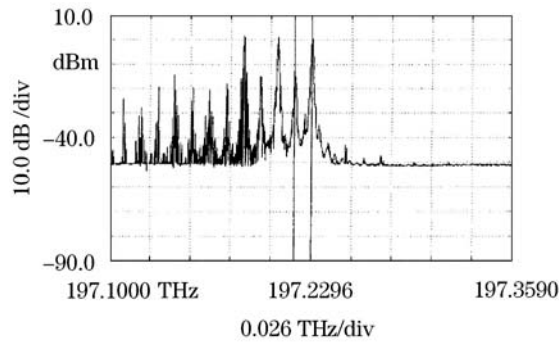


Fig. 3. 11 orders of SBS in a backward pumped FRA.

When the pump power of FRA is increased to 960 mW, 11 orders of SBS have been observed in backward pumped distributed FRA. The frequency shift of SBS lines is 11 GHz. All these led to a comb-like configuration spectrum, the gain of signal line descends, power shifts from signal to SBS, as shown in Fig. 3. The frequency of SBS signal is 197.2296 THz and the power is 0 dBm. The even orders SBS relate to high intensity SBS line, the intensity of the 2nd and 4th order is 1.75 dBm, higher than that of the amplified signal. The intensity of the 1st and the 3rd order SBS, which are named Brillouin-Rayleigh scattering, is 16 dB lower than that of the 2nd and 4th order SBS.

The process of SBS can be described as the nonlinear interaction between pump wave and Stokes wave. The pump wave generates sound wave due to electro-induced extension, then phonon induces regular modulation of refraction index<sup>[5]</sup> and 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 a grating moving with sound wave velocity  $v_A$ . This process can be described as a pump photon annihilates, timely a Stokes photon and an audio phonon generate. The process of scattering must obey conservation of energy and momentum. Frequency and wave vector have the relations of

$$\Omega_B = \omega_p - \omega_s, \quad k_A = k_p - k_s, \quad (1)$$

where,  $\omega_p$  and  $\omega_s$  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,  $\Omega_B$  and  $k_A$  are the frequency and wave vector of acoustic wave. Then we can get

$$\Omega_B = v_A |k_A| \approx 2v_A |k_p| \sin(\theta/2), \quad (2)$$

where  $\theta$  is the angle between pump wave and Stokes wave. Because there are only two directions (forward and backward) in optical fiber, there should be only backward scattering in optical fiber. But spontaneous Brillouin scattering generates in forward direction in optical fiber, this is because the sound waveguide characteristic weakens the wave vector selected rule, resulting in less Stokes Brillouin scattering generating in forward direction. This phenomenon is called sound waveguide forward Brillouin scattering<sup>[6]</sup>.

Sound waveguide forward Brillouin scattering is amplified and enhanced in backward-pumped FRA. But we find from the experiment that when the pump power of FRA is lower than 800 mW, only weak spontaneous Brillouin scattering can be observed. There is a threshold in forward SBS. When the pump power is 880 mW, two orders of SBS are generated. When the pump power of FRA is further increased, cascaded multi-order SBS appears, the frequency shift of SBS lines is 11 GHz, comb-like profile is observed and the intensity of amplified signal is lower than that of the 2nd and 4th order SBS lines, this is because power shifting from pump to SBS counteracts the gain of signal line. The intensity of the 2nd and the 4th order forward SBS lines is 16 dB higher than that of 1st and 3rd order lines in the experiment. The reason is that when the pump power of RFA in fiber is higher than the threshold value of SBS, there are strong backward SBS lines generated, leading to reversed Rayleigh scattering, called Brillouin-Rayleigh scattering lines<sup>[7-11]</sup>, but as the conversion efficiency of the Rayleigh scattering is low, the odd order Brillouin scattering is far less than the even order SBS lines.

In conclusion, we get the following results. 1) Forward SBS is observed when the pump power is higher than the SBS threshold value in a backward pumped distributed FRA. Theoretically there only exists very weak backward SBS according to wave vector principle, which provided that SBS should obey energy and momentum conservation law. However, not only backward spontaneous Brillouin scattering but also strong forward SBS were observed in our experiments. The reason is that the sound waveguide characteristic weakens the wave vector selected rule in backward-pumped FRA, the sound waveguide forward Brillouin scattering is amplified<sup>[6]</sup>. 2) When the pump power of FRA is further increased, 11 orders of SBS have been observed in backward pumped FRA. The frequency shift of SBS lines is 11 GHz. A comb-like configuration spectrum<sup>[7]</sup> was also observed. The phenomenon of strong forward SBS in a backward-pumped distributed FRA can lead to the crosstalk in DWDM transmission system, but it also can be used as a testing comb source.

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