Amplification effect on SBS and Rayleigh scattering in the backward pumped distributed fiber Raman amplifier

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Received August 28, 2008

The amplification effect on stimulated Brillouin scattering (SBS) and Rayleigh scattering in the backward pumped G652 fiber Raman amplifier (FRA) is studied. The pump source is a 1427.2-nm fiber Raman laser whose power is tunable between $0-1200$ mW, and the signal source is a tunable narrow spectral bandwidth (< 10 MHz) external cavity laser (ECL). The Rayleigh scattering lines are amplified by the FRA and Stokes SBS lines are amplified by the FRA and the fiber Brillouin amplifier. The total gain of SBS lines is the production of the gain of Raman amplifier and that of Brillouin amplifier. In experiment, the SBS gain is about 42 dB and the saturation gain of 25-km G652 backward FRA is about 25 dB, so the gain of fiber Brillouin amplifier is about 17 dB.

OCIS codes: 060.0060, 060.4370, 060.2320.

doi: 10.3788/COL20090705.0393.

The main scattering mechanisms exploited for distributed optical fiber sensor (DOFS) are Rayleigh, Raman, and Brillouin scattering. In contrast to Rayleigh scattering, there is a difference in frequency between the incident light and the scattered Raman and Brillouin light. Components which get energy in the scattering process and therefore have a higher frequency are referred to as anti-Stokes ones, and those which lose energy and have lower frequency are referred to as Stokes components. Recently, the dependence of Brillouin power and frequency on temperature/strain has been used as the basis for distributed temperature and strain optical sensors. The main regimes that are used to measure distributed temperature and strain are spontaneous Brillouin scattering and stimulated Brillouin scattering (SBS). Brillouin optical time domain reflectometry (BOTDR)[1], which in principle is similar to conventional Rayleigh optical time domain reflectometry (OTDR), exploits spontaneous Brillouin scattering and requires access to only one end of the sensing fiber. The position of measurands in the fiber is determined by using the time interval between launching the pulsed light and observing the backscattered light. The spatial resolution is determined by the pulse width and detection bandwidth. Other techniques, such as Brillouin optical time domain analysis (BOTDA) and Brillouin optical correlation domain analysis (BOCDA), exploit SBS and generally rely on access to both ends of the sensing fiber. Distributed sensors based on BOTDA were described by Horiguchi *et al.*[2]. Recently, Raman amplification and Brillouin amplification are used to make a comb fiber laser[3]. In this letter, we discuss the Raman amplification effect on Rayleigh and Brillouin scattering, which is utilized to compensate signal loss to extend sensing range. It is a basic research of DOFS.

In classical theory of Brillouin scattering, the process of SBS can be described as the nonlinear effect between light and hypersonic acoustic wave[4]. In a simple quantum-mechanical picture, a photon of the incident field (called the pump) is annihilated to create a photon at a lower frequency (belonging to the Stokes wave) and a phonon with the right energy and momentum to conserve the energy and the momentum. The frequencies and wave vectors of the three waves follow

$$\Omega_{\mathrm{B}} = \omega_{\mathrm{p}} - \omega_{\mathrm{s}}, \quad (1)$$

$$k_{\mathrm{b}} = k_{\mathrm{p}} - k_{\mathrm{s}}, \quad (2)$$

where ω_{p} and ω_{s} are the frequencies of pump wave and Stokes Brillouin scattering wave, k_{p} and k_{s} are the wave vectors of pump wave and Stokes Brillouin scattering wave, Ω_{B} and k_{b} are the frequency and wave vector of the acoustic wave, respectively. Then we can get

$$\Omega_{\mathrm{B}} = \nu_{\mathrm{b}}\,|k_{\mathrm{b}}|\sin(\theta/2) \quad (3)$$

where ν_{b} is the frequency of Stokes Brillouin scattering wave, θ is the angle between pump wave and Stokes Brillouin scattering wave. Because there are only forward and backward directions in optical fiber, there should be only backward scattering in optical fiber[5].

If the decay of acoustic wave is $\exp(-\Gamma_{\mathrm{B}}t)$, where Γ_{B} is the decay factor, and then the Brillouin scattering gain coefficient has a Lorentzian profile

$$g_{\mathrm{B}}(\Omega) = g_{\mathrm{p}}\frac{(\Gamma_{\mathrm{B}}/2)^2}{(\Omega-\Omega_{\mathrm{B}})^2+(\Gamma_{\mathrm{B}}/2)^2}. \quad (4)$$

The peak value of Brillouin gain coefficient is

$$g_{\mathrm{p}} = \frac{2\pi^2 n^7 p_{12}^2}{c\lambda_{\mathrm{p}}^2\rho_0\nu_{\mathrm{b}}\Gamma_{\mathrm{B}}}, \quad (5)$$

where p_{12} is the longitudinal stretch-optics coefficient, ρ_0 is the material density, λ_{p} is the pump wavelength, n is the refraction index. In the continuity condition, the Brillouin coupling equation reads[4]

$$\frac{\mathrm{d}I_{\mathrm{s}}}{\mathrm{d}z} = g_{\mathrm{B}}I_{\mathrm{p}}I_{\mathrm{s}} - \alpha_{\mathrm{s}}I_{\mathrm{s}},$$
$$\frac{dI_{\mathrm{p}}}{\mathrm{d}z} = -\frac{\omega_{\mathrm{p}}}{\omega_{\mathrm{s}}}g_{\mathrm{B}}I_{\mathrm{p}}I_{\mathrm{s}} - \alpha_{\mathrm{p}}I_{\mathrm{p}}, \quad (6)$$

where I_{p} and I_{s} are intensities of pump and signal waves, α_{s} and α_{p} are fiber loss coefficients at the pump and

1671-7694/2009/050393-03

signal wavelengths, ω_p and ω_s are angular frequencies of pump and signal waves, z is the length of optical fiber.

If the fiber loss α is neglected, then

$$I_s(0) = I_s(L)\exp(g_B P_0 L_{eff}/A_{eff} - \alpha L), \quad (7)$$

where $I_s(L), I_s(0)$ represent the intensities of signal light at z=0 and $z = L, P_0 = I_p(0)A_{eff}$ is the pump power when z=0, A_{eff} is the effective section, and the effective fiber length is

$$L_{eff} = [1 - \exp(-\alpha L)]/\alpha. \quad (8)$$

The threshold power P_{th} of Brillouin scattering can be obtained from[6]

$$g_B P_{th} L_{eff}/A_{eff} \approx 21. \quad (9)$$

The gain of Brillouin scattering, determined by the ratio of output power to input power, $G = P_{out}/P_{in}$, is given as

$$G_B = \exp(g_p P_0 L_{eff}/A_{eff}). \quad (10)$$

In the continuity condition, the Raman coupling equation reads[4]

$$\frac{dI_s}{dz} = g_R I_p I_s - \alpha_s I_s$$
$$\frac{dI_p}{dz} = -\frac{\omega_p}{\omega_s} g_R I_p I_s - \alpha_p I_p \quad (11)$$

where g_R is the Raman gain coefficient.

When the signal and pump waves propagate at the same time in the single mode fiber and the time-shift frequency is in the bandwidth of Raman gain spectrum of pump light, the signal light is amplified during propagating in the fiber because the pump light generates stimulated Raman scattering (SRS). It is called as Raman amplifying effect. In the Raman amplifier, the signal intensity is

$$I_s(L) = I_s(0)\exp(g_R I_0 L_{eff} - \alpha_s L). \quad (12)$$

Because of the fiber absorbing attenuation of pump light, the effective fiber length L_{eff} becomes

$$L_{eff} = [1 - \exp(-\alpha_p L)]/\alpha_p. \quad (13)$$

If there is no pumping, $I_s(L) = I_0 \exp(-\alpha_s L)$, so the amplifier gain is

$$G_R = \exp(g_R P_0 L_{eff}/A_{eff}), \quad (14)$$

where $P_0 = I_0 A_{eff}$ is the power of pump source.

In the experiment, the amplifier gain $G = P_{out}/P_{in}$. The noise figure of amplifier is

$$F = P_{ASE}/h\nu B_0 + 1/G, \quad (15)$$

where P_{ASE} is the power of amplified spontaneous emission (ASE), B_0 is the bandwidth, ν is the frequency of signal light.

The measuring experimental setup[5] of Brillouin scattering effect is shown in Fig. 1. It consists of signal source, isolator, 1×2 bi-directional coupler (BDC), optical spectrum analyzer (OSA), and backward pumped S-band fiber amplifier (25-km G652 single mode fiber, pump-signal coupler, and pumping fiber laser). The signal source is a tunable semiconductor external cavity laser (ECL). Its 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 less than 10 MHz, and the signal-to-noise ratio (SNR) is better than 45 dB. The isolator prevents 1550-nm light from returning into the ECL. The loss coefficient of the single mode fiber is 0.22 dB/km. The pump-signal coupler is a 1427/1520 nm coarse wavelength division multiplexer (CWDM). The pump source is a fiber Raman laser with the wavelength of 1427.2 nm, bandwidth of 0.067 nm, and output power tunable between 0 − 1200 mW. The OSA has a spectrum range of 600 − 1700 nm, a resolution of 1 pm, and a dynamic range of 60 dB.

Figure 2 shows the amplification Rayleigh scattering spectrum when the backward pump power is 600 mW. The Raman gain is 20.05 dB. Figure 3 shows the amplification Rayleigh and Brillouin scattering spectra when the backward pump power is 1100 mW. The first and second order Stokes Brillouin scattering lines and the first anti-Stokes Brillouin line have been observed. The central wavelength of backward Rayleigh line is 1520.028 nm and the shift of the first Brillouin scattering line is 85 pm (10.6 GHz). The Raman gain of Rayleigh line is 25.6 dB and the total gain of the first Stokes Brillouin line is 37 dB.

The power and gain of Rayleigh scattering and Stokes Brillouin scattering in the backward distributed fiber Raman amplifier (FRA) under different pump powers are shown in Table 1 and Fig. 4. The gain of Rayleigh scattering is nonlinearly dependent on the pump power of the FRA. The gain saturation phenomenon of Rayleigh scattering is present and the power is transmitted to Brillouin scattering, as

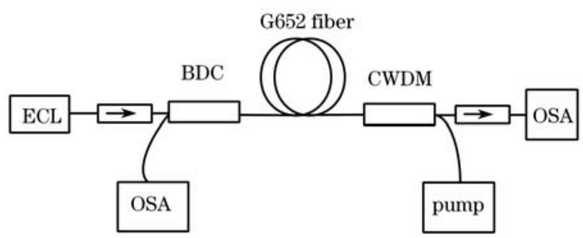

Fig. 1. Experimental setup of SBS in the FRA.

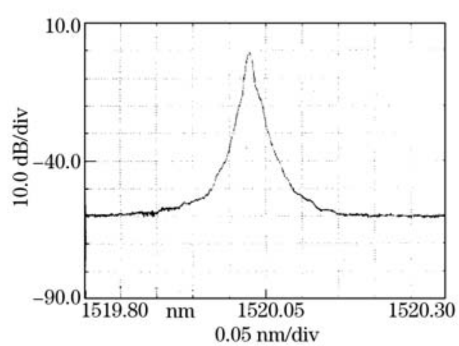

Fig. 2. Amplification Rayleigh scattering spectrum.

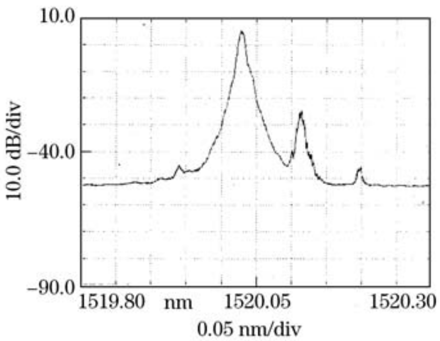

Fig. 3. Amplification Rayleigh and Brillouin scattering spectra.

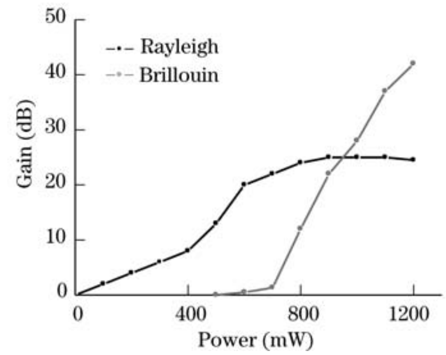

Fig. 4. Gain of Rayleigh scattering and Stokes Brillouin scattering of FRA under different pump powers.

Table 1. Power and Gain of Rayleigh Scattering and Stokes Brillouin Scattering of FRA under Different Pump Powers

P_0 (mW)	0	500	600	700	800	900	1000	1100	1200
P_R (dBm)	−21	−7.9	−0.95	1.24	2.97	4.54	4.62	4.6	3.86
G_R (dB)	0	13.1	20.05	22.24	23.97	25.54	25.62	25.6	24.86
P_B (dBm)		−54	−53	−50	−46	−36	−25	−17	−12
G_B (dB)		0	1	2	12	22	29	37	42

shown in Fig. 4. The total gain of SBS is about 42 dB, which is much larger than the Rayleigh gain. The Rayleigh scattering line is amplified by the FRA.

Practically, the Stokes SBS lines are amplified by the FRA and fiber Brillouin amplifier[7−10]. The total gain G_{Total} is the production of the Raman gain G_{R} and the Brillouin amplifier gain G_{B},

$$G_{\text{Total}} = G_{\text{R}} \cdot G_{\text{B}}. \quad (16)$$

In experiment, the saturation gain of SBS is about 42 dB and the saturation gain of 25-km G652 backward FRA is about 25 dB, so the gain of Brillouin amplifier is about 17 dB.

In conclusion, the amplification effect on backward SBS in the backward pumped S-band distributed G652 FRA at 1520 nm pumped by the power-tunable fiber laser has been observed. In experiment, the Stokes SBS lines are amplified by the FRA and fiber Brillouin amplifier. The total gain is the production of the Raman gain and the gain of Brillouin amplifier. The gain of the first order Stokes SBS line is about 42 dB and the saturation gain of 25-km G652 backward FRA is about 25 dB, so the gain of Brillouin amplifier is about 17 dB.

This work was supported by the Great Scientific Research Project of Zhejiang Province under Grant No. 021101558.

References

1. K. Shimizu, T. Horiguchi, Y. Koyamada, and T. Kurashima, Opt. Lett. **18,** 185 (1993).
2. T. Horiguchi and M. Tateda, J. Lightwave Technol. **7,** 1170 (1989).
3. A. K. Zamzuri, M. A. Mahdi, A. Ahmad, M. I. Md Ali, and M. H. Al-Mansoori, Opt. Express **15,** 3000 (2007).
4. G. P. Agrawal, *Nonlinear Fiber Optics and Applications of Nonlinear Fiber Optics* (Elsevier, New York, 2001), Chap. 8, 9.
5. Z. Zhang, B. Dai, L. Li, H. Xu, D. Geng, H. Liu, J. Wang, C. Li, T. Liu, and I. S. Kim, Proc. SPIE **6027,** 602742 (2006).
6. Y. Shen, M. Song, X. Zhang, and K. Chen, Chinese J. Lasers (in Chinese) **32,** 497 (2005).
7. Z. Zhang, B. Dai, L. Li, H. Xu, H. Liu, J. Wang, C. Li, and I. S. Kim, Chin. Opt. Lett. **3,** 629 (2005).
8. Z. Zhang, L. Li, D. Geng, B. Dai, Y. Jin, H. Liu, I. S. Kim, J. Wang, X. Wu, D. Fang, and S. Zhuang, Chin. Opt. Lett. **2,** 627 (2004).
9. Z. Zhang, L. Li, D. Geng, H. Liu, Y. Jin, I. S. Kim, J. Wang, X. Wu, D. Fang, and S. Zhuang, Proc. SPIE **5633,** 110 (2005).
10. Z. Zhang, J. Wang, C. Li, T. Liu, L. Li, D. Geng, H. Liu, I. S. Kim, Y. Jin, D. Fang, and S. Zhuang, Acta Opt. Sin. (in Chinese) **24,** 1673 (2004).