Stimulated Brillouin scattering effect on gain saturation of distributed fiber Raman amplifiers

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Gain saturation is a significant phenomenon of fiber Raman amplifiers (FRAs). Gain figures versus signal power are well explained. For the small signal, the coupled ordinary differential equations are used, and for the large signal, the Raman gain coefficient is modified. It is shown that the saturation power of FRAs decreases with the pump power, and gain saturation is easier to occur in the forward pump scheme than in the backward pump scheme. These phenomena are well explained by the stimulated Brillouin scattering (SBS) effect. This research provides a guide to the fabrication of practical FRAs.

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Fiber Raman amplifier (FRA) has been widely studied as one of the key technologies to realize ultra-long-haul dense wavelength division multiplexing (DWDM) systems. Compared with the traditional Er-doped fiber amplifier, it has attractive features such as broad bandwidth, small noise figure, and low nonlinear effect. In the past few years, many researches about FRAs, where gain saturation is a critical concept, have been carried out, including choice of pumping methods[1−3], realization of gain flattening[4−7], stimulated Brillouin scattering (SBS) effect in FRAs[8], etc. As the signal power increases, the gain of the amplifier keeps almost the same at first, and then begins to decrease obviously. Gain saturation plays an important role in both optical communication and sensing systems. When a signal with a new wavelength is added to the fiber of DWDM systems, the gain of FRAs will change rapidly if the signal power exceeds the saturation power, which needs to be avoided. Thus, it is crucial for us to know exactly the value of the saturation power and study what gain saturation depends on. Recently, Xin *et al.* presented the relations between the saturation power of FRAs and the optical gain[2]. However, they made no physical explanation. Chi *et al.* studied gain saturation in discrete Raman amplifiers[9], while our study refers to distributed Raman amplifiers.

In this letter, we explain the gain figure of FRAs versus signal power. Compared with discrete FRAs, the signal power of distributed FRAs varies with transmission distance. So we modify the Raman gain coefficient, ensuring that the coefficient varies with the signal power. In addition, considering both the forward and backward pump schemes, we demonstrate the relations between the saturation power of FRAs and the pump power. Also, we make an explanation to the results.

SBS is a nonlinear effect which occurs in the fiber. When the incident power reaches the threshold of SBS, most of the power is transferred to the backscattering Stokes light. The threshold of SBS can be obtained by[10]

$$P_{\mathrm{cr}} \approx \frac{21A_{\mathrm{eff}}}{g_{\mathrm{B}}L_{\mathrm{eff}}}, \tag{1}$$

where $L_{\mathrm{eff}} = \frac{1}{\alpha}[1-\exp(-\alpha L)]$, α is the attenuation coefficient of the fiber, L is the fiber length, g_{B} is the peak value of the Brillouin gain, A_{eff} is the effective area of the core of the fiber.

The coupled ordinary differential equations for single and forward pump FRAs can be expressed as[10] (for the convenience of discussion, we substitute power for intensity)

$$\frac{\mathrm{d}P_{\mathrm{s}}}{\mathrm{d}z} = \frac{g_{\mathrm{R}}}{A_{\mathrm{eff}}}P_{\mathrm{p}}P_{\mathrm{s}} - \alpha_{\mathrm{s}}P_{\mathrm{s}}, \tag{2a}$$

$$\frac{\mathrm{d}P_{\mathrm{p}}}{\mathrm{d}z} = -\frac{\omega_{\mathrm{p}}}{\omega_{\mathrm{s}}}\frac{g_{\mathrm{R}}}{A_{\mathrm{eff}}}P_{\mathrm{p}}P_{\mathrm{s}} - \alpha_{\mathrm{p}}P_{\mathrm{p}}, \tag{2b}$$

where g_{R} is the Raman gain coefficient, α_{s} and α_{p} are attenuation coefficients of the signal light and pump light, P_{s} and P_{p} denote the signal power and pump power, ω_{s} and ω_{p} denote the angular frequencies of the signal light and pump light, respectively. When P_{s} is small enough, the first term at the right side of Eq. (2b) can be ignored and we obtain

$$P_{\mathrm{s}}(L) = P_{\mathrm{s}}(0)\exp\left(g_{\mathrm{R}}\frac{P_0}{A_{\mathrm{eff}}}L_{\mathrm{eff}} - \alpha_{\mathrm{s}}L\right), \tag{3}$$

where $L_{\mathrm{eff}} = \frac{1}{\alpha_{\mathrm{p}}}[1-\exp(-\alpha_{\mathrm{p}}L)]$, P_0 is the input pump power, $P_{\mathrm{s}}(0)$ and $P_{\mathrm{s}}(L)$ denote the signal power at $z=0$ and $z=L$, respectively. If there is no pump light, it can be easily found that

$$P_{\mathrm{s}}(L) = P_{\mathrm{s}}(0)\exp(-\alpha_{\mathrm{s}}L). \tag{4}$$

So we can obtain the on-off gain of FRAs for the small signal with Eqs. (3) and (4) as

$$G = \exp\left(g_{\mathrm{R}}\frac{P_0}{A_{\mathrm{eff}}}L_{\mathrm{eff}}\right). \tag{5}$$

In other words, when P_{s} is small enough, the on-off gain of FRAs does not change with P_{s} and is close to a constant.

However, when P_{s} is large enough to become comparable to the saturation power, g_{R} is not a constant any more. Once P_{s} reaches the threshold obtained by Eq. (1), SBS occurs, leading to the decrease of the gain.

So the gain decreases with the increasing signal power. Under this condition, $g_{\rm R}$ can be expressed as

$$g_{\rm R}=\frac{g_0}{1+P_{\rm s}/P_{\rm sat}},\tag{6}$$

where g_0 is the maximum gain coefficient and $P_{\rm sat}$ is the saturation power. Supposing that the attenuation coefficient of the fiber is included in $g_{\rm R}$, we can obtain

$$\frac{{\rm d}P_{\rm s}}{{\rm d}z}=g_{\rm R}P_{\rm s}=\frac{g_0}{1+P_{\rm s}/P_{\rm sat}}P_{\rm s},\tag{7}$$

where g_0 is concerned with the pump power. Obviously, we can make an integral to Eq. (7) along the fiber. Simultaneously, using $P_{\rm s}(L)=GP_{\rm s}(0)$, we finally obtain

$$G=G_0\exp\left[(1-G)\frac{P_{\rm s}(0)}{P_{\rm sat}}\right],\tag{8}$$

where G_0 is the gain of the small signal. Figure 1 shows the curves of G/G_0 versus $P_{\rm s}(0)/P_{\rm sat}$ when G_0 is 10, 15, and 20 dB. We can easily find that G/G_0 decreases at first and then becomes flat.

Moreover, for the forward pump scheme, the signal light and pump light are injected into the fiber from the same end, and the amplification effect is significant. However, for the backward pump scheme, the signal light and pump light enter the fiber from different ends and the signal light suffers a considerable loss before it is amplified effectively.

In order to validate the above theories, we conducted some experiments. The experimental setups are shown in Figs. 2 and 3. The setup shown in Fig. 2 is used to measure the on-off gain of the forward pump FRA, while Fig. 3 displays the backward pump scheme. A fiber laser (FL) was the signal source with the wavelength of 1550 nm and adjusted output power of 0–10 mW. 75- and 100-km single mode fibers (G652, Wuhan Research Institute of Post and Telecommunication) with the loss of 0.2 dB/km at 1550 nm were used as the gain medium. The pump light, from a 1450-nm laser diode (LD), was injected into G652 by a 1450/1550 wavelength division multiplexer (WDM). With the circulator, we could not only launch the signal power into the fiber but also examine the backscattering spectrum with the optical spectrum analyzer (OSA) (Q8384, Advantest, Japan) connected to it. The resolution of the OSA was set to 0.02 nm. Two power meters (PM1 and PM2) were used to measure the remnant pump power and output signal power, respectively.

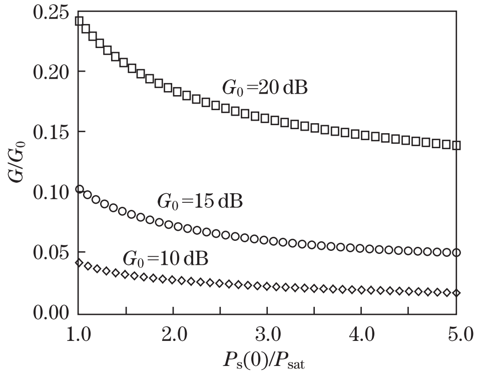

Fig. 1. G/G_0 versus $P_{\rm s}(0)/P_{\rm sat}$.

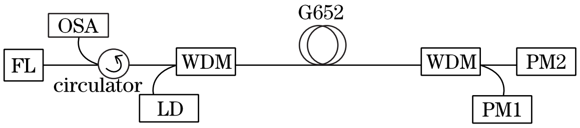

Fig. 2. Forward pump FRA setup.

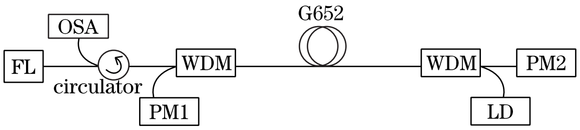

Fig. 3. Backward pump FRA setup.

The on-off gain of a 75-km FRA versus signal power in the forward pump scheme is shown in Fig. 4. It shows that, the lines marked with square, round, and triangle correspond to the LD driver circuit current of 400, 800, and 1200 mA, and the corresponding pump power is about 80, 180, and 270 mW, respectively. It is apparent that the on-off gain is without much difference when the signal power is small enough, which verifies the theory that the on-off gain is close to a constant for the small signal. However, when the signal power exceeds a critical value, the on-off gain decreases rapidly. In addition, when the signal power is large enough, the on-off gain becomes flat gradually. These results are accordant with Fig. 1. Also, we can find that gain saturation is easier to occur when the pump power is larger. We can explain this phenomenon as follows: The signal light is amplified by the pump light. When the signal power reaches the threshold of SBS, it transfers considerable power to the Stokes light with a lower frequency, leading to the decrease of the signal power. Thus, the on-off gain decreases and gain saturation appears. What is more, the larger the pump power is, the easier the SBS effect occurs. Therefore, the saturation power decreases with the pump power.

The back scattering spectra of 5-mW signals with the pump power of about 80, 180, and 270 mW are shown in Fig. 5. There are three dominant peaks whose wavelengths are about 1555.198, 1555.108, and 1555.024 nm, corresponding to the Stokes light, Rayleigh light, and anti-Stokes light, respectively. The shifts between the peaks are 0.090 and 0.084 nm, which are well in agreement with the theoretical SBS shift of 0.089 nm

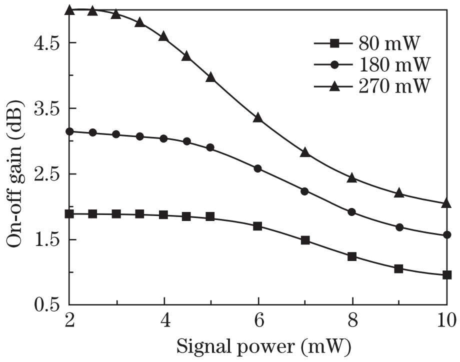

Fig. 4. On-off gain of a 75-km FRA versus signal power in the forward pump scheme.

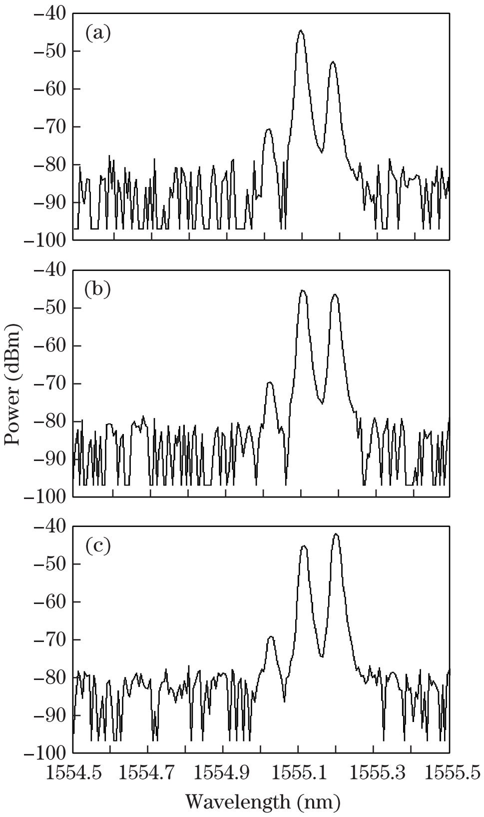

Fig. 5. Backscattering spectra of 5-mW signals with (a) 80-, (b) 180-, and (c) 270-mW pump power.

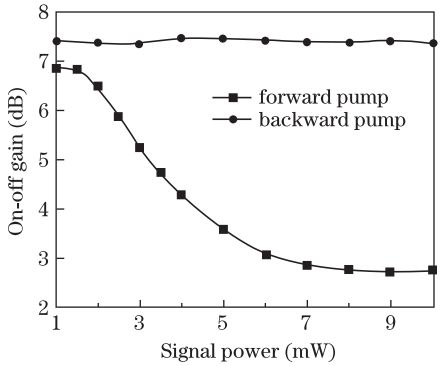

Fig. 6. On-off gain of a 100-km 230-mW FRA versus signal power.

calculated from[10]

$$\Delta\lambda_{\mathrm{B}} = \frac{2nv_{\mathrm{A}}\lambda}{c}, \tag{9}$$

where $n = 1.45$ is the refractive index, $v_{\mathrm{A}} = 5.95$ km/s is the acoustic velocity, $\lambda = 1550$ nm is the pump wavelength of SBS, and $c = 3 \times 10^8$ m/s is the light velocity. From Fig. 5, we can also find that the power of Stokes light increases with the pump power, which verifies that the larger the pump power is, the easier the SBS effect occurs.

We also compared the gain characteristic curve of FRAs in the forward pump scheme with that in the backward pump scheme. The experimental results are shown in Fig. 6, where the lines marked with square and round denote the forward and backward pump schemes, respectively. The fiber length was 100 km and the pump power was about 230 mW. Obviously, gain saturation is easier to occur in the forward pump scheme than in the backward pump scheme. We can also use the SBS effect to explain this phenomenon. For the forward pump scheme, both the signal light and the pump light are combined in the same end of the fiber, which leads to an effective amplification. However, for the backward pump scheme, the pump light becomes weak after a long-haul transmission, so that the signal light cannot be very large. Thus, it is easier to reach the SBS threshold and cause gain saturation in the forward pump scheme than in the backward pump scheme.

In conclusion, gain saturation is a significant phenomenon which should be paid much attention to when we develop a practical FRA. We explain the gain figure versus the signal power. For the small signal, the gain is almost a constant and we use the coupled ordinary differential equations; for the large signal, the gain decreases at first and then becomes flat. Under this condition, the Raman gain coefficient is modified. It is shown that the saturation power decreases with the pump power and gain saturation is easier to occur in the forward pump scheme than in the backward pump scheme. Furthermore, we explain the results using SBS effect.

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