Highly sensitive Raman gain coefficient measurement by detecting spontaneous Raman scattering power for distributed Raman amplification systems

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Abstract: We propose a highly sensitive method that can safely measure the Raman gain coefficient spectrum by detecting the spontaneous Raman scattering emitted from the transmission fiber pumped by a single-polarization laser-diode light source in distributed Raman amplification systems. With the proposed method, we have successfully obtained an accurate Raman gain coefficient spectrum with a significantly low pump power of \(\sim 0.35\) mW at a small Raman gain of 0.01 dB.

Keywords: distributed Raman amplification, gain coefficient

Classification: Fiber-Optic Transmission for Communications

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1 Introduction

Distributed Raman amplification (DRA) has been intensely studied as a powerful technique that can significantly improve the optical signal-to-noise ratios of optically amplified wavelength-division-multiplexed (WDM) transmission systems [1, 2, 3]. In recent years, DRA technology has been also applied to some multicore-fiber transmission systems [4, 5]. In a terrestrial Raman amplified WDM transmission system, which has an optical fiber transmission line installed in the field, the spectrum of the Raman gain coefficient (g) must be measured in an accurate and safe manner in order to confirm the feasibility of the system [2, 3]. In the conventional measurement methods, polarization-multiplexed laser-diode (LD) pump light sources (LSs) with optical powers greater than ~100 mW were used to obtain accurate values of g [1, 2, 3]. In this paper, we propose a novel method that can accurately and safely measure g of a field transmission line using a single-polarization LD pump with a significantly low and eye-safe power of ~0.35 mW at a Raman gain as small as 0.01 dB. In the proposed method, we have accurately obtained g by detecting the spontaneous Raman scattering (SpRS) power emitted from the transmission fiber.

2 Experimental configuration

The experimental configuration is shown in Fig. 1. Two spools of 20-km single-mode fiber (G.652.D, SMF-1 and -2) with a total length of 40 km (SMF_DUT) were pumped by a pump LS. The pump LS was a single-polarization LD module for our proposed method (called “SpRS method” in this paper) or was a polarization-multiplexed module with two LDs for the conventional pump on–off method [1, 2, 3]. Each LD had an external cavity configuration with a fiber Bragg grating (FBG) reflector; thus, the LD is called an “FBG LD.” The wavelength of the pump LS wavelength was 1455 nm. The distributed Raman gain (G) in units of dB is defined as the difference in the signal output powers with and without Raman pumping, $P_{s,\text{with}}$ and $P_{s,\text{without}}$, respectively, in units of dBm, i.e., $G = P_{s,\text{with}} - P_{s,\text{without}}$. The signal light was emitted from a tunable light source (TLS). The output signal power and SpRS power were measured by an optical spectrum analyzer (OSA, Anritsu MS9740A). A polarization scrambler (PS) was placed after the TLS to accurately measure the signal light power launched into the OSA by averaging the states of the signal polarization. The pump light emitted from the pump LS was coupled to SMF_DUT via a wavelength-selective coupler placed after the pump LS (WSC-b). Then, the pump light emitted from SMF_DUT was launched into an optical power meter (PM) via another wavelength-selective coupler placed after SMF_DUT (WSC-f). The PM was used to monitor the pump power launched into SMF_DUT ($P_{\text{pin}}$). A variable optical attenuator (VOA) was placed after the pump LS to adjust $P_{\text{pin}}$. Three optical isolators (ISOs) were placed in the experimental setup in order to
suppress the excess noise caused by some residual reflections. In the proposed SpRS method, \( G \) is numerically calculated using the measured power of the spontaneous Raman scattering emitted from SMF DUT \( (P_n) \). The values of \( G \) measured by the SpRS method and conventional method are denoted as \( G_{\text{SpRS}} \) and \( G_{\text{on-off}} \), respectively.

3 Experimental results

\( G \) is expressed as follows when the depletion in the pump power is negligible:

\[
G = (10/\ln 10)gL_{\text{eff}}P_{\text{pin}}, \tag{1}
\]

where \( L_{\text{eff}} \) is the effective length \([1, 2, 3, 6]\). \( G \) has a spectral peak at a signal wavelength \((\lambda)\) of 1554.0 nm, which was measured using the conventional pump on–off method so that \( G_{\text{on-off}} = 3.92 \text{ dB} \) at \( P_{\text{pin}} = 121 \text{ mW} \). We further measured the spectra of \( G_{\text{SpRS}} \) at several predetermined target values of \( G \) \((G_{\text{target}})\) at \( \lambda = 1554 \text{ nm} \). \( G_{\text{target}} \) was set to 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, 0.01, 0.005, 0.002, and 0.001 dB. The target value of \( P_{\text{pin}} \) at each value of \( G_{\text{target}} \) was determined by Eq. (1) using the set of measured values of \( G_{\text{on-off}} \) of 3.92 dB and \( P_{\text{pin}} \) of 121 mW.

The differential equation for the SpRS power \( P_n \) propagating in the axial z direction in SMF DUT in the case of the SpRS method is given by

\[
\frac{dP_n(z)}{dz} = -\alpha_nP_n(z) + g^s(z)P_p(z)P_n(z) + 2gP_p(z)(N_k + 1)hv_n\Delta v_n, \tag{2}
\]

where \( \alpha_n \) is the loss coefficient of the SpRS light; \( h \) is Planck’s constant; \( v_p \) and \( v_n \) are the frequencies of the pump light and SpRS light, respectively; \( \Delta v_n \) is the bandwidth of the SpRS light; \( N_k \) is the phonon occupation number: \( N_k = 1/\exp[h(v_p - v_n)/k_BT] - 1 \); \( k_B \) is Boltzmann’s constant; \( T \) is the absolute temperature; \( g \) is the Raman gain coefficient averaged over two polarization states; \( g^s(z) \) is the local Raman gain coefficient for single-polarization pumping; and \( P_p^s(z) \) is the local power of the pump light with a single polarization state. \( g^s(z) \) takes values between \( g_o \) and \( g_p \), which are the Raman gain coefficients for the orthogonal and parallel polarization configurations, respectively \([6]\). \( g \) is equal to the average of \( g_o \) and \( g_p \). We employed the following approximation for \( g^s(z) \). It is considered that the pump light and SpRS light have fairly randomized polarization states in SMF DUT. Moreover, the second term on the right-hand side of Eq. (2) has a small contribution to the calculation when \( G \) is small, as in the case of this experiment: \( g^s(z) = g \).

The SpRS power at the output of SMF DUT \( (P_{n,\text{out}}) \) was measured by the OSA. We define \( P_{n,\text{out}} \) to be the power at the point (SMF out) just inside the fusion splicing

Fig. 1. Experimental configuration.
point between SMFDUT and WSC-b (point A in Fig. 1). $G$ and $g$ were obtained by numerically solving Eq. (2) with the measured powers of $P_{n,\text{out}}$. The temperature near SMFDUT was $\sim 25 ^\circ \text{C}$ ($T = \sim 298 \text{K}$).

Let the optical power $P_{n,\text{out}}$ at a wavelength of $\lambda$ be $P_{n,\text{out}}(\lambda)$. The measured optical spectra of $P_{n,\text{out}}(\lambda)$ in dBm at the several values of $G_{\text{target}}$ from 2 to 0.001 dB are shown in Fig. 2(a). The wavelength resolution, the video bandwidth, and the number of sampling points per nanometer were 0.927 nm, 10 Hz, and 10, respectively. The ripples in $P_{n,\text{out}}(\lambda)$ in the low-power region of Fig. 2(a) were caused by the system noise of the OSA, i.e., the noise generated when no light was launched into the OSA. The depth of each spectral ripple increased as $P_{n,\text{out}}(\lambda)$ decreased.

The Raman gain spectra obtained by the SpRS method ($G_{\text{SpRS}}(\lambda)$) that were obtained from the measured $P_{n,\text{out}}(\lambda)$ spectra are shown in Fig. 2(b) at the same values of $G_{\text{target}}$ from 2 to 0.001 dB. The ripples in $G_{\text{SpRS}}(\lambda)$ in the low-gain region are straightforwardly attributed to the ripples in $P_{n,\text{out}}(\lambda)$ (Fig. 2(a)).

Fig. 3 shows characteristics of $G$ and $g$. We obtained the spectral peak gain ($G_{\text{SpRS, peak}}$) as the average value from 1553.5 to 1554.5 nm. Let the relative gain accuracy at $\lambda = 1554.0 \text{ nm}$ at each target gain $G_{\text{target}}$ in percent be $\Delta G_{\text{rel}} = ((G_{\text{SpRS, peak}}/G_{\text{target}}) - 1) \times 100$. Moreover, let the maximum and minimum gains in the wavelength range from 1553.5 to 1554.5 nm be $G_{\text{max}}$ and $G_{\text{min}}$, respectively. Let the relative spectral gain variation at $\lambda = 1554.0 \text{ nm}$ at each target gain $G_{\text{target}}$ in percent be $\Delta G_{\text{spec}} = (G_{\text{max}} - G_{\text{min}})/G_{\text{SpRS, peak}} \times 100$. $\Delta G_{\text{rel}}$ and $\Delta G_{\text{spec}}$ are plotted as a function of $G_{\text{target}}$ in Fig. 3(a). As shown in the figure, the absolute value of $\Delta G_{\text{rel}}$ increased as $G_{\text{target}}$ decreased. Moreover, $\Delta G_{\text{spec}}$ increased as $G_{\text{target}}$ decreased. This is because the depths of the ripples in the $P_{n,\text{out}}(\lambda)$ spectra (Fig. 2(a)) increased as $G_{\text{target}}$ decreased. The absolute values of both $\Delta G_{\text{rel}}$ and $\Delta G_{\text{spec}}$ increased as $G_{\text{target}}$ decreased and were as small as less than 5% in the $G_{\text{target}}$ range from 2 to 0.001 dB. Moreover, the relative accuracy of and the spectral variation in $g$ ($\Delta g_{\text{rel}}$ and $\Delta g_{\text{spec}}$) at $\lambda = 1554.0 \text{ nm}$ in percent are equal to those of $G$, respectively.

![Fig. 2. Spectral characteristics of (a) the spontaneous Raman scattering power and (b) the Raman gain measured using the SpRS method for target gain values from 2 to 0.001 dB.](image-url)
Δ\(G_{rel}\) and \(ΔG_{spec}\), as shown in Fig. 3(a), because of the relation between \(G\) and \(g\) in Eq. (1).

\(G_{SpRS}\) and \(G_{on-off}\) as a function of the measured pump power (\(P_{pin0}\)) are shown in Fig. 3(b) for \(G_{target}\) from 2 to 0.001 dB. \(P_{pin0}\) was measured at the optical-connector splicing point between the VOA and WSC-b (point B in Fig. 1). \(G_{on-off}\) was measured for \(G_{target}\) from 2 to 0.5 dB, whereas \(G_{SpRS}\) was measured for \(G_{target}\) from 2 to 0.001 dB. The Raman gains calculated using Eq. (1) (\(G_c\)) are also shown in Fig. 3(b). As shown in Fig. 3(b), the three gains, \(G_{on-off}\), \(G_{SpRS}\), and \(G_c\), show good coincidence.

The spectra of \(g\) were calculated by Eq. (1) using the measured Raman gains \(G_{SpRS}\) shown in Fig. 2(b) and \(P_{pin}\) and are shown in Fig. 3(c) for typical values of \(G_{target}\) of 0.1, 0.01, 0.005, 0.002, and 0.001 dB. The spectral peak value of \(g\) at each value of \(G_{target}\) (\(g(G_{target})\)) was normalized by that of \(g(0.1\ \text{dB})\) and added to the shifts of 0.4, 0.3, 0.2, 0.1, and 0 (without a shift) for \(G_{target} = 0.1, 0.01, 0.005, 0.002,\) and 0.001 dB, respectively. The spectral peak value of \(g(0.1\ \text{dB})\) was 0.44 \(\text{km}^{-1}\cdot\text{W}^{-1}\). The values of \(P_{pin0}\) from the pump LS launched into WSC-b were 3.5, 0.35, and 0.035 mW at \(G_{target} = 0.1, 0.01,\) and 0.001 dB, respectively. Therefore, we can obtain the \(g\) spectra at significantly lower pump powers using the proposed SpRS method compared with the conventional method, which requires pump powers greater than \(\sim 100\ \text{mW}\). When \(G_{SpRS}\) ranged from 0.1 to 0.001 dB (from 2.3\% to 0.023\% on a linear scale), \(G_{SpRS}\) was so small that the amplification of the SpRS light was negligible. As for the typical performance of the proposed SpRS method, we obtained an accurate \(g\) spectrum at a small value of \(P_{pin0}\) of

![Fig. 3](image-url)
0.35 mW with $G_{SpRS} = 0.01$ dB, which is more than $\sim 100$ times smaller than that needed for the conventional method (more than $\sim 100$ mW), with $\Delta g_{spec} = 0.7\%$ and $\Delta g_{rel} = 2.9\%$ (Fig. 3(a)).

4 Conclusion

We have proposed a novel method that can accurately and safely measure the Raman gain coefficient spectrum by detecting the spontaneous Raman scattering power emitted from a transmission fiber. With the proposed method, we have successfully obtained an accurate Raman gain coefficient spectrum using a single-polarization LD pump LS with a significantly low and eye-safe power of $\sim 0.35$ mW at a Raman gain as low as 0.01 dB.

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