Single-end Measurement of Raman Gain Efficiency Distribution in Concatenations of Single-mode Optical Fibers

Kunihiro Toge*[a], Kazuo Hogari*[a] and Tsuneo Horiguchi*[b]

*[a] NTT Access Network Service Systems Laboratories, NTT Corporation;
1-7-1 Hanabatake, Tsukuba, Ibaraki, Japan 305-0805;
*[b] Shibaura Institute of Technology, 3-9-14, Shibaura, Minato-ku, Tokyo, Japan 108-8548

ABSTRACT

This paper proposes a new method for measuring a longitudinal distribution of the Raman gain efficiency in concatenations of single-mode optical fibers by using a backscattering technique and a pulsed pump light. The advantage of this method is that it can provide us with an easy way of evaluating optical fiber networks because we can measure from only one end of optical fibers. We perform an experiment employing this method and confirm that it can be used to measure Raman gain efficiency distribution easily.

1. INTRODUCTION

For some years, Raman amplification technology has been applied to WDM systems [1]-[2]. Raman amplification has attractive features in that the gain wavelength region can be adjusted by changing the wavelength of the pump lights, and the use of multi-wavelength pump lights can significantly extend the gain wavelength region. In order to design WDM networks using Raman amplification, it is important to investigate the Raman gain efficiency that is given by the Raman gain coefficient per effective cross-sectional area of optical fibers.

We have recently reported a method for the distributed measurement of the Raman gain characteristics [3]. With this method, a continuous-wave (CW) signal light and a pulsed pump light are counter-propagated in optical fibers. The CW signal light amplified by the pulsed pump light is guided to a detector through an optical coupler and then averaged. We can derive the Raman gain efficiency distribution by time-domain analysis of the averaged waveform. It was confirmed that this method could be used to evaluate installed optical fiber networks [3]. However, the measurement operation is complicated because measurement instruments must be installed at both ends of optical fiber cables. This also yields a problem in that this method cannot be employed to evaluate optical fiber networks where the repeaters such as erbium-doped fiber amplifiers are installed at the midpoint in optical fiber networks. An optical time domain reflectometry (OTDR)-based set-up incorporating a CW pump source has been also reported in [4]. It is possible to evaluate only the averaged Raman gain efficiency in each fiber in concatenations of optical fibers from the Raman gain in the OTDR traces. However, this method cannot be used to evaluate the distribution in an optical fiber.

This paper proposes a single-end measurement method for determining the Raman gain efficiency distribution using a backscattering technique and a pulsed pump light to realize ease of operation and distributed measurement with a resolution that depends on the pump pulse width. We first describe the measurement principle of the proposed method. We report a measurement result of concatenated fibers obtained with this method, and compare it with a result obtained by our previous method to confirm the validity of our proposed method.

2. MEASUREMENT PRINCIPLE

The basic configuration that we used is shown in Fig. 1. It consists of an OTDR-based set-up incorporating a pulsed pump source. The squared optical pulses from the signal and pump sources are co-propagated in the optical fibers with a total length of L. The signal light is launched into the fibers at the position Z=0 and the time t=0. The pump light is delayed behind the pulsed signal light as shown in Fig.1, and launched into the fibers with a delay time T. This delay is designed to avoid forward Raman amplification when the signal and pump lights are co-propagating. When the light velocity v is assumed to be constant in the optical fibers, the backscattered signal light from the position Z=z propagates in the –Z direction, and is amplified at Z=z-vT/2 by the backward Raman amplification with the pulsed pump light that propagates in +Z direction as shown in Fig. 2. Then, the backscattered signal light propagates to the photo detector (PD)
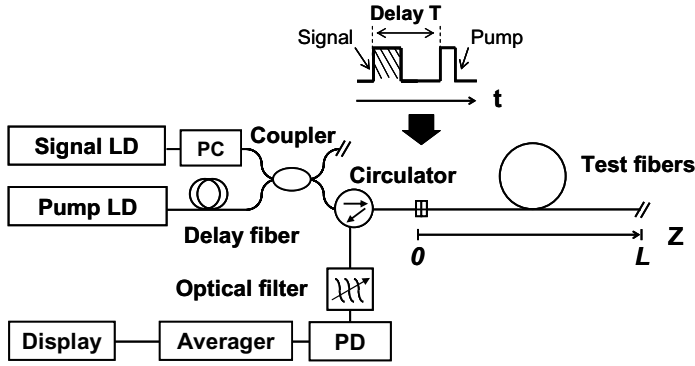
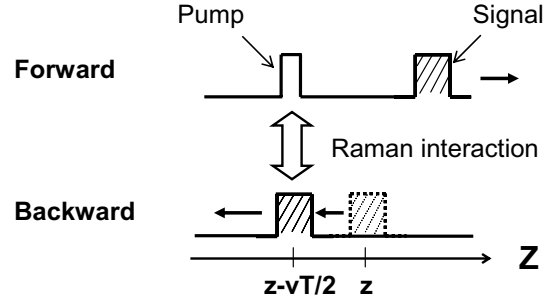Fig. 1. Basic configuration for proposed method.

Fig. 2. Schematic illustration of Raman interaction with proposed method.

with the attenuation of optical fibers through an optical filter that is used to eliminate the Rayleigh backscattering of the pulsed pump light. The OTDR traces of the backscattered signal power with and without the pulsed pump light, $P_1(z)$ and $P_2(z)$ can be given by [5]

$$P_1(z) = P(0)R(z)W_s C \exp\left[-2\int_0^z \alpha_s(x)dx\right]G(z) \tag{1}$$

$$P_2(z) = P(0)R(z)W_s C \exp\left[-2\int_0^z \alpha_s(x)dx\right] \tag{2}$$

where $P(0)$ is the launched signal power, R(z) is the backscatter coefficient, W_s is the optical pulse width of the signal light, C is the transmission loss of the optical circulator and the optical filter, $\alpha_s(z)$ is the local attenuation coefficient of optical fiber at the signal wavelength, and G(z) is the Raman gain which can be obtained from the ratio of the two OTDR traces shown in Eqs.(1) and (2). For $vT/2 \le z \le L$, The Raman gain can be expressed as

$$G(z) = \exp[k \cdot \gamma(z - vT/2)P_p(z - vT/2)] \tag{3}$$

where k is constant for z and related to the pulse width of the pump light, $\gamma(z-vT/2)$ and $P_p(z-vT/2)$ are the Raman gain efficiency and the pump power at $Z=z-vT/2$. We note that the Raman gain G(z) obtained from the ratio of two OTDR traces is based on the Raman gain efficiency and the pump power at $Z=z-vT/2$ due to the delay of the pump light. We also note that the spatial resolution of the measurement is defined by the pulse width of the pump light. The Raman gain efficiency distribution can be given as for $0 \le z \le L-vT/2$

$$\gamma(z) = \frac{\ln G(z + vT/2)}{kP_p(0)\exp\left[-\int_0^z \alpha_p(x)dx\right]} \tag{4}$$

where $P_p(0)$ is the launched pump power at $Z=0$, $\alpha_p(z)$ is the local attenuation coefficient of optical fibers at the pump wavelength. Assuming that we know the Raman gain efficiency at a given point $Z=z_0$, we can normalize Eq.(4) by the value at $Z=z_0$ as follows:

$$\gamma(z) = \frac{\ln G(z + vT/2)}{\ln G(z_0 + vT/2)} \frac{\exp\left[\int_0^z \alpha_p(x)dx\right]}{\exp\left[\int_0^{z_0} \alpha_p(x)dx\right]} \gamma(z_0). \tag{5}$$

Therefore, from Eq.(5), the normalized Raman gain efficiency distribution can be obtained by measuring the Raman gain $G(z+vT/2)$ and the local attenuation coefficient at the pump wavelength $\alpha_p(z)$ in the optical fibers. The latter can be measured easily by excluding the signal source and the optical filter. With this method, we can evaluate the Raman gain efficiency distribution from one end of an optical fiber.

3. EXPERIMENT AND RESULTS

We prepared the experimental setup shown in Fig.1. The signal and pump source were provided by a pulsed LDs operating at 1550 and 1450 nm, respectively. The pulse widths of the signal and pump lights were 4 and 2 μs, respectively. They were modulated with the same pulse period of 1.06 ms. The delay time of the pump light was set at 5 μs. In this experiment, the peak power of the pulsed pump light launched into the fibers was about 25 mW. In order to obtain the Raman gain efficiency distribution for the scrambled state of polarization (SOP) between the signal and the pump light, the SOP was scrambled using a polarization controller (PC).

We prepared a reference optical fiber (REF) with a known Raman gain efficiency of 0.73W^{-1}km^{-1} which is uniformly distributed along the fiber. We examined the Raman gain characteristics of a dispersion shifted single-mode fiber (DSF) and a dispersion compensating fiber (DCF). These fibers were concatenated, and connected to the REF. The total concatenated length L was 10.6 km. The properties of the fibers we prepared are listed in Table 1.

Figure 3 shows the Raman gain which is obtained from the ratio of the two OTDR traces. We found that the Raman gain increased due to the Raman amplification and decreased with position owing to the attenuation of the pump light. We also found that the trace of the Raman gain shifted by vT/2 ($\approx$ 500 m) due to the delay of the pump light.

Figure 4 shows normalized Raman gain efficiency distributions. The solid line shows the result obtained with the single-end method proposed in this paper, the dashed line shows the result obtained with the both-ends method reported in [3]. We confirmed that they were in good agreement. This agreement indicates that the single-end measurement we proposed can be used to determine the longitudinal distribution of the Raman gain efficiency in concatenated optical fibers. We also found a measurement dead zone above L-vT/2 ($\approx$ 10.1 km). This is due to the delay of the pulsed pump light. The dead zone can be minimized by using a signal light with a shorter pulse width in order to shorten the delay time of the pulsed pump light.

Table 1. Properties of optical fibers used in the experiment.

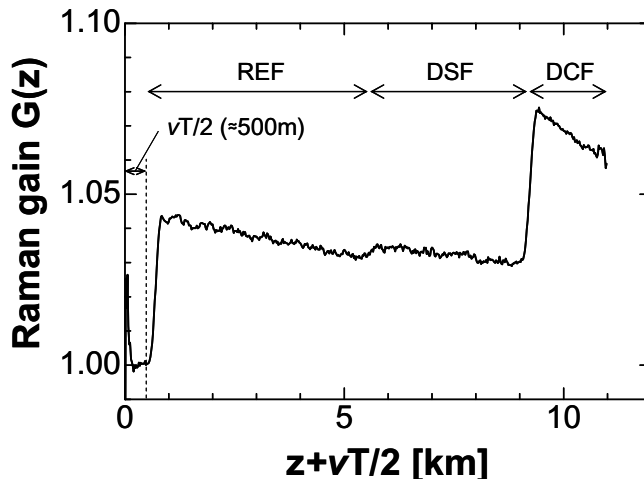| Fiber/Splice	Length	Mode field diameter	Optical attenuation at 1550 nm	Optical attenuation at 1450 nm
REF	5.0 km	8.4 μm	0.20 dB/km	0.28 dB/km
Splice	-	-	0.14 dB	0.17 dB
DSF	3.6 km	7.8 μm	0.20 dB/km	0.27 dB/km
Splice	-	-	0.14 dB	0.23 dB
DCF	2.0 km	5.5 μm	0.39 dB/km	0.63 dB/km

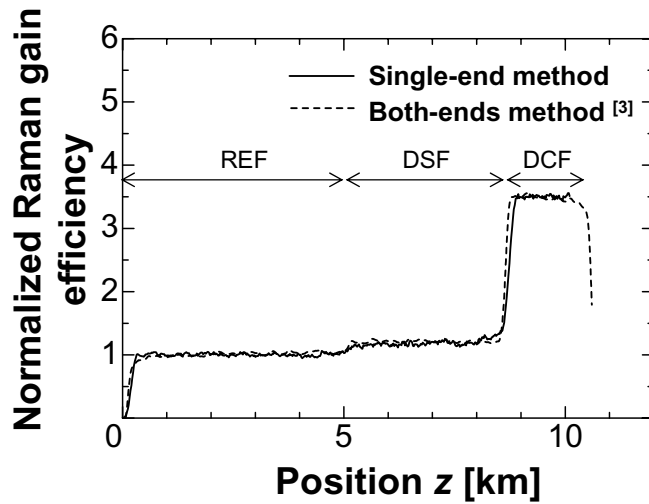Fig. 3. Measured Raman gain obtained from the ratio of two OTDR traces with and without the pulsed pump light.

Fig. 4. Normalized Raman gain efficiency distribution along test fibers.

4. CONCLUSION

We proposed a single-end measurement method for evaluating the Raman gain efficiency distribution in concatenations of optical fibers by using a backscattering technique and a pulsed pump light. We found that result obtained with this method was in good agreement with that of a previously reported method in which the signal and pump lights are launched from both ends of optical fibers. Our method can provide us with ease of operation because all the measurement instruments are installed together at one end of the optical fiber, and will be a useful tool for designing optical fiber networks that employ the Raman amplification.

REFERENCES

1. N. Takachio, H. Suzuki, H. Masuda, and M. Koga, "32×10Gb/s distributed Raman amplification transmission with 50-GHz channel spacing in the zero-dispersion region over 640 km of 1.55-µm dispersion-shifted fiber", *OFC/IOOC '99*, PD9.1 -PD9.3, 1999
2. H. Nakamoto, T. Tanaka, N. Shimojoh, T. Naito, I. Yokota, A. Sugiyama, T. Ueki, and M. Suyama, "1.05 Tbit/s WDM transmission over 8186 km using distributed Raman amplifier repeaters," *OFC '01*, Tuf6-1, 2001
3. K. Toge, K. Hogari and T. Horiguchi, "Technique for measuring longitudinal distribution of Raman gain characteristics in optical fibers", Journal of Lightwave Technology, LT-21, 12, 2003.
4. M. Wuilpart, G. Ravet, P. Mégret and M. Blondel, "Distributed measurement of Raman gain spectrum in concatenations of optical fibers with OTDR", Electronics letters, 39, 1, pp. 88-89, 2003
5. M. S. O'Sullivan and J. Ferner, "Interpretation of SM fiber OTDR signatures", *SPIE '01 Optic. Testing Metrology,* 661, pp. 171-176, 1986.

*toge@ansl.ntt.co.jp; phone 81 29 868-6367; fax 81 29 868-6142; NTT Access Service Systems Laboratories, NTT Corporation.