Measurement of Stimulated-Brillouin-Scattering Threshold for Various Types of Fibers Using Brillouin Optical-Time-Domain Reflectometer

C. C. Lee and S. Chi

***Abstract*—We have investigated the stimulated Brillouin scattering (SBS) threshold of various types of fibers both theoretically and experimentally by utilizing Brillouin optical-time-domain reflectometer. The measured deviations of SBS threshold of less than ± 0.1 dB compared with the conventional method are demonstrated for standard single-mode fiber (SMF), large-effective-area dispersion-shifted fiber (LEAF), TrueWave/Reduced Slope fiber (TWF), and conventional dispersion-shifted fiber (DSF).**

***Index Terms*—BOTDR, SBS, SBS threshold.**

I. INTRODUCTION

THE PROCESS of stimulated Brillouin scattering (SBS) can be described as a parametric interaction among the incident light, the Stokes light, and an acoustic wave [1]. SBS causes the degradation in optical signals, and thus sets a limitation on system performance. For the systems of high-power transmitters and long spans, this effect will become an important factor in the system design [2]. It is known that the SBS threshold is determined by the Brillouin gain spectrum. Therefore, the SBS thresholds for different types of fibers can be derived by measuring their Brillouin gain spectra.

The Brillouin optical-time-domain reflectometer (BOTDR) based on heterodyne detection has been used to measure the spontaneous Brillouin scattering spectra along the fiber length [3], [4]. The SBS gain spectra for fibers can be derived from the spectra of spontaneous Brillouin scattering, and thus the SBS thresholds of fibers can also be obtained.

In this letter, we propose a method to measure the SBS thresholds for various types of single-mode fibers by utilizing BOTDR. Using BOTDR method to measure the SBS threshold measurement with BOTDR method for standard single-mode fiber (SMF), large-effective-area dispersion-shifted fiber (LEAF), truewave/reduced slope fiber (TWF) and conventional dispersion-shifted fiber (DSF) has also been demonstrated and analyzed.

Manuscript received November 16, 1999; revised January 31, 2000.

C. C. Lee is with Chunghwa Telecom Labs., P.O. Box 6-1, Yang-Mei 326, Taoyuan, Taiwan (e-mail: chchl@ms.chttl.com.tw). He is also with the Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan.

S. Chi is with the Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan.

Publisher Item Identifier S 1041-1135(00)03588-6.

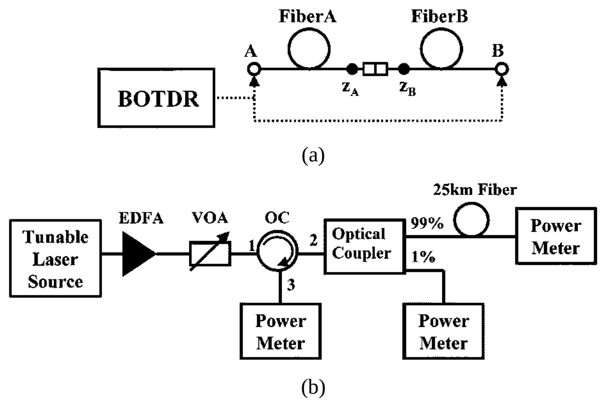

Fig. 1. Experimental setups for SBS threshold of fibers using: (a) BOTDR. (b) Conventional method.

II. ANALYSIS

A. SBS Threshold

For continuous-wave (CW) light with a laser linewidth much narrower than the Brillouin gain bandwidth of fiber, the SBS gain $G(\nu)$ with frequency shift ν can be described by [5]

$$G(\nu) = \int_0^\ell \frac{g_0}{1 + [(\nu - \nu_B(z))/(\Delta\nu_B/2)]^2} \cdot \exp(-\alpha z)\, dz \tag{1}$$

where

- ℓ total fiber length;
- ν_B Brillouin frequency shift;
- α fiber loss coefficient;
- $\Delta\nu_B$ linewidth for spontaneous Brillouin scattering;
- g_0 determined by the fiber material parameters and is given by $g_0 = (2\pi n^7 p_{12}^2 K)/(c\lambda^2 \rho V_a \Delta\nu_B)$ [6], where
- n refractive index;
- ρ material density;
- p_{12} elastooptic coefficient;
- V_a acoustic velocity and given by $V_a = (\lambda/2n) \cdot \nu_B$;
- c light velocity;
- λ light wavelength, and factor K can range from $0 < K < 1$ according to polarization mismatch between pump and Stokes waves.

If Brillouin gain is averaged along a fiber with random polarization, the K value theoretically will be observed ranging between a minimum of 1/3 and a maximum of 2/3 [7]. The SBS threshold of a fiber link is determined by the peak Brillouin gain experienced all along the fiber. This peak Brillouin gain can be

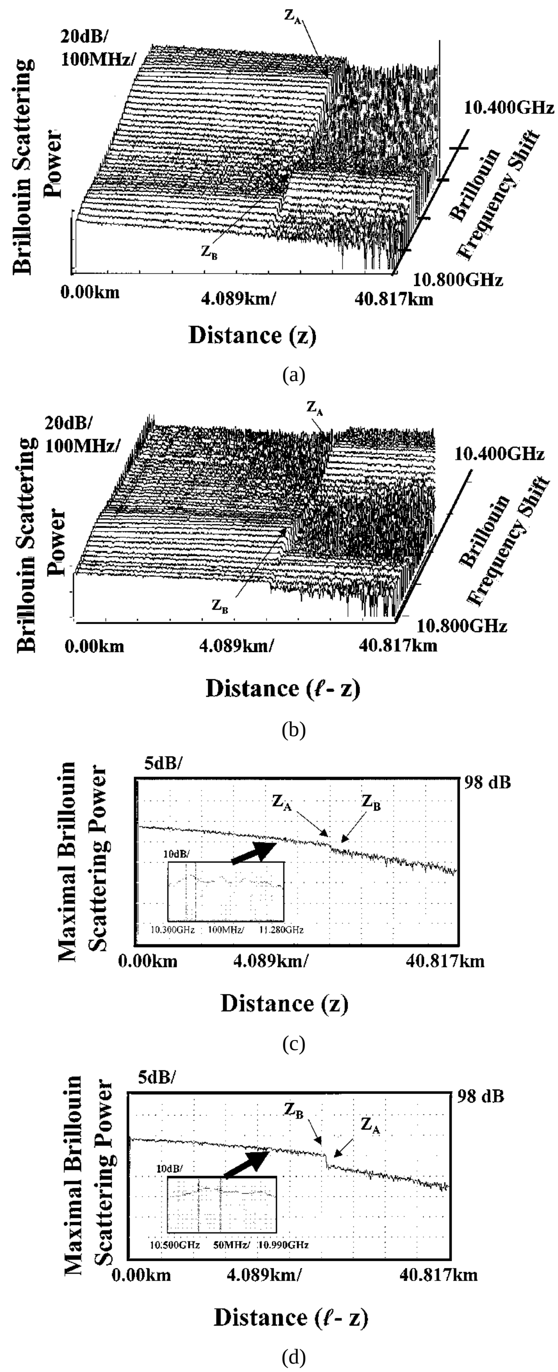

Fig. 2. The measured 3-D curves of Brillouin scattering spectra versus fiber distance from (a) DSF and (b) TWF ends, and the maximal Brillouin scattering powers versus fiber distance measured at (c) DSF and (d) TWF ends for DSF and TWF connected fibers.

derived by integrating the local Brillouin gain along the fiber link for each frequency and choosing the maximal gain. That is, SBS first occurs at frequency $\nu_{\max}$ at which $G(\nu)$ is maximized. For the fiber links with homogeneous Brillouin gain characteristics, the SBS threshold of the fiber can be obtained by utilizing Smith's expression. Smith's condition for the SBS threshold, where the Stokes light power equals the pump power for the SBS threshold, the SBS threshold power P_{th} can be approximately given by $P_{\text{th}} = 19A_{\text{eff}}/G(\nu_{\max})$ [8], where A_{eff} is the effective core area. The factor 19 is used to replace the approximated factor 21 in [8], because today's fibers have much lower loss than the fibers at that time. Therefore, the SBS threshold power for uniform fiber, $P_{\text{th}}^{\text{uni}}$, is given by $P_{\text{th}}^{\text{uni}} = 19A_{\text{eff}}/g_0L_{\text{eff}}$, where L_{eff} is the effective interaction length given by $L_{\text{eff}} = (1-\exp(-\alpha\ell))/\alpha$.

B. BOTDR Measurement

When the self-heterodyne BOTDR is used to measure the spontaneous Brillouin scattered signals for the optical fiber, the powers of the backward spontaneous Brillouin scattering, $P_{sp}^{+}(z)$ and $P_{sp}^{-}(z)$, can be obtained at Brillouin frequency shift ν_B by measuring the test fiber at $z=0$ and $z=\ell$ ends, and are expressed by [3]

$$\begin{aligned} P_{sp}^{+}(z) &= P_0\exp(-2\alpha z)\alpha_B S\cdot(c/n)\cdot W/2 \\ P_{sp}^{-}(z) &= P_0\exp(-2\alpha(\ell-z))\alpha_B S\cdot(c/n)\cdot W/2 \end{aligned} \qquad (2)$$

where

- P_0 is the input pulsed power;
- W is the pulsewidth;
- S is the backscatter capture fraction;
- S is given by $S = (\lambda/n)^2/4\pi A_{\text{eff}}$ for single-mode fibers;
- α_B is the Brillouin scattering-loss coefficient, and is given by $\alpha_B = (8/3)(\pi^3/\lambda^4)kT(p_{12}^2n^8/\rho V_a^2)$ [3], where k is Boltzmann's constant, and T is the absolute temperature.

Therefore, the SBS gain parameter g_0 can be expressed as the function of α_B, and is given by

$$g_0 = \frac{3}{8\pi^2}\cdot\frac{\nu_B\lambda^3K}{cn^2kT\Delta\nu_B}\cdot\alpha_B. \qquad (3)$$

Since the BOTDR can measure the spectral profile for spontaneous Brillouin scattering at each position of the test fiber (that is, ν_B, $\Delta\nu_B$, and α_B can be measured), from (1) and (3), the SBS gain $G(\nu)$ profile along fiber length can be derived when K (for example, $K=1/2$ is used when we utilize the polarization scrambling on pump light and average the measured gain over polarization states), n and T are known, and thus the SBS threshold of the test fiber can be derived by utilizing BOTDR.

If α_B and S are z-dependent, the loss, P_{loss}, between two adjacent positions on test fiber, z' and $z'+\Delta z$, can be derived by averaging the bi-directional measured losses between positions at z' and $z'+\Delta z$, and is given by

$$P_{\text{loss}} = \sqrt{\frac{P_{sp}^{+}(z')}{P_{sp}^{+}(z'+\Delta z)}\cdot\frac{P_{sp}^{-}(z'+\Delta z)}{P_{sp}^{-}(z')}}. \qquad (4)$$

The ratio of Brillouin scattering-loss coefficient at position z' and $z'+\Delta z$ is given by

$$\frac{\alpha_B(z'+\Delta z)}{\alpha_B(z')} = P_{\text{loss}}\cdot\frac{S(z')}{S(z'+\Delta z)}\cdot\frac{P_{sp}^{+}(z'+\Delta z)}{P_{sp}^{+}(z')}. \qquad (5)$$

Thus, the SBS gain parameter $g_0(z'+\Delta z)$ can be given by

$$g_0(z'+\Delta z) = \frac{(\nu_B'/\nu_B)}{(n'/n)^2\cdot(\Delta\nu_B'/\Delta\nu_B)}\cdot\frac{\alpha_B(z'+\Delta z)}{\alpha_B(z')}\cdot g_0(z') \qquad (6)$$

where the parameters with and without the notation "$'$" represent the parameters at $z=z'+\Delta z$ and $z=z'$, respectively. If two

TABLE I
THE MEASURED RESULTS OF SBS THRESHOLD DIFFERENCES FOR FIBERS

FIBER A / FIBER B	LEAF / SMF		SMF / DSF		DSF / TWF	
Input End	LEAF(A)	SMF(B)	SMF(A)	DSF(B)	DSF(A)	TWF(B)
Z_A / Z_B (km)	25.298	25.314	25.050	25.067	24.740	24.756
$P^+_{sp}(z_A)$ - $P^+_{sp}(z_B)$ / $P^-_{sp}(z_B)$ - $P^-_{sp}(z_A)$ (dB)	-0.50	3.61	0.10	2.30	0.60	2.78
Measured SBS Threshold difference by BOTDR (dB)	2.06		1.10		1.09	
Measured SBS Threshold difference by conventional method (dB)	2.0		1.0		1.0	

types of uniform fibers (fiber A and B) are connected, the SBS threshold difference of these two fibers can be derived by bidirectional BOTDR measurement. If $n_A \approx n_B$, $\Delta\nu_B^A/\Delta\nu_B^B \approx 1$, and $\nu_B^A/\nu_B^B \approx 1$, and $L_{\rm eff}^A \approx L_{\rm eff}^B$, the SBS threshold ratio for these two fibers can be given by

$$\frac{P_{\rm th}^A}{P_{\rm th}^B} = \frac{A_{\rm eff}^A}{A_{\rm eff}^B} \cdot \frac{g_0^B}{g_0^A} \cdot \frac{L_{\rm eff}^B}{L_{\rm eff}^A}$$

or

$$\begin{aligned} &10\,\log(P_{\rm th}^A) - 10\,\log(P_{\rm th}^B) \\ &\quad = -\,5\,\log(P_{sp}^+(z_A)) + 5\,\log(P_{sp}^+(z_B)) \\ &\qquad + 5\,\log(P_{sp}^-(z_B)) - 5\,\log(P_{sp}^-(z_A)) \end{aligned} \tag{7}$$

where z_A and z_B are the positions on fiber A and B near connection point, respectively.

III. EXPERIMENTS AND RESULTS

We use Corning LEAF, Corning SMF, Corning DSF and Lucent TWF in our experiments. The parameters of these fibers are fiber length $\approx$25 km, attenuation loss $\alpha = 0.2$ dB/km, $A_{\rm eff} = 72, 80, 50,$ and 55 μm^2, and $D = 4$, 17, 0.5, and 5.2 ps/nm·km at 1.55 μm for LEAF, SMF, DSF, and TWF, respectively. The parameters of BOTDR used in our experiments are operating wavelength =1554.1 nm, pulsewidth =100 ns, average times $=2^{15}$, sweep frequency =10 MHz, and spatial resolution =10 m. We then measure the SBS threshold differences for LEAF/SMF, SMF/DSF, and DSF/TWF by using BOTDR. Fig. 1(a) shows the experimental setup. Two different types of fibers are connected and measured bidirectionally at two ends by using BOTDR. For DSF (fiber A)/TWF (fiber B), the Brillouin scattering spectra versus fiber distance measured at two ends are shown in Fig. 2(a) and (b). The maximal Brillouin scattering powers versus fiber distance measured at two ends are also derived and shown in Fig. 2(c) and (d). From the analysis in Section II, the SBS threshold difference between DSF and TWF is 1.09 dB using (7). Similarly, the fibers of LEAF/SMF, and SMF/DSF are measured bidirectionally using BOTDR, and the SBS threshold differences are 2.06 and 1.10 dB for LEAF/SMF, and SMF/DSF. The measured results are shown in Table I. For comparison with the measurements of the conventional method, these four fibers are measured by using the configuration of Fig. 1(b). The tunable laser source with operating wavelength =1554.1 nm is connected with an erbium-doped fiber amplifier (EDFA) with 16 dBm saturated power. After passing through the variable optical attenuator (VOA), optical circulator (OC), and a 1 : 99 optical coupler for power monitoring, the optical power is injected into the under-test fiber. The backscattered power, input power (injected-into-fiber power), and transmitted power are simultaneously measured for different input power by adjusting VOA. The SBS thresholds are 11.0, 9.0, 8.0, and 7.0 dBm for LEAF, SMF, DSF, and TWF, and the SBS threshold differences are 2.0, 1.0, and 1.0 dB for LEAF/SMF, SMF/DSF, and DSF/TWF, respectively. Therefore, the measurement deviations of SBS threshold between BOTDR and the conventional method are less than $\pm$0.1 dB, which may be mainly caused by the polarization dependence of the coherent detection sensitivity for BOTDR [4] and the measurement error for the conventional method. Furthermore, by utilizing a reference fiber with known SBS gain spectrum, the distributed SBS gain profiles along fiber length and SBS thresholds of under-test fibers with nonuniform or uniform Brillouin-frequency-shift can be derived form bidirectional BOTDR measurement.

IV. CONCLUSION

The SBS thresholds of various types of fibers have been investigated both theoretically and experimentally by utilizing BOTDR. The measured deviations of SBS threshold of less than $\pm$ 0.1 dB compared with the conventional method are also demonstrated for LEAF, SMF, DSF, and TWF.

REFERENCES

[1] G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. New York: Academic, 1995, pp. 370–378.

[2] A. R. Chraplyvy, "Limitations on lightwave communications imposed by optical-fiber nonlinearities," *J. Lightwave Technol.*, vol. 8, pp. 1548–1557, 1990.

[3] T. Horiguchi and M. Tateda, "BOTDA—Nondestructive measurement of single-mode optical fiber attenuation characteristics using Brillouin interaction: Theory," *J. Lightwave Technol.*, vol. 7, pp. 1170–1176, 1989.

[4] T. Kurashima, M. Tateda, T. Horiguchi, and Y. Koyamada, "Performance improvement of a combined OTDR for distributed strain and loss measurement by randomizing the reference light polarization state," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 359–362, 1997.

[5] K. Shiraki, M. Ohashi, and M. Tateda, "SBS threshold of a fiber with a Brillouin frequency shift distribution," *J. Lightwave Technol.*, vol. 14, pp. 50–57, 1996.

[6] X. P. Mao, R. W. Tkach, A. R. Chraplyvy, R. M. Jopson, and R. M. Derosier, "Stimulated Brillouin threshold dependence on fiber type and uniformity," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 66–69, 1992.

[7] M. Oskar van Deventer and A. J. Boot, "Polarization properties of stimulated Brillouin scattering in single-mode fibers," *J. Lightwave Technol.*, vol. 12, pp. 585–590, 1994.

[8] R. G. Smith, "Optical power handling capacity of low loss optical fibers as determined by stimulated Raman and Brillouin scattering," *Appl. Opt.*, vol. 11, pp. 2489–2494, 1972.