Raman-Based Distributed Temperature Sensor With Simplex Coding and Link Optimization

Jonghan Park, Gabriele Bolognini, Duckey Lee, Pilhan Kim, Pilki Cho, Fabrizio Di Pasquale, and Namkyoo Park, *Member, IEEE*

***Abstract*—In this letter, a coded, Raman-based distributed temperature sensor system using 255-bit Simplex coded optical time domain reflectometry (OTDR) and optimized sensing link composed of cascaded fibers with different Raman coefficients, is proposed. This system is compared to a system with an uncoded OTDR on standard single-mode fiber, demonstrating significant enhancement in the interrogation distance (19.5 km from coding gain, and 9.6 km from link optimization). Total sensing range of 37 km at 17-m/3-K spatial/temperature resolution were achieved, while employing conventional low power (80 mW) laser diodes.**

***Index Terms*—Distributed temperature sensor, optical time domain reflectometry (OTDR), spontaneous Raman scattering (SRS).**

I. Introduction

DISTRIBUTED temperature sensors (DTS) based on spontaneous Raman scattering (SRS) in single-mode fibers (SMFs) have been intensively studied in previously published research [1], [2]. In the majority of the proposed schemes, an optical time domain reflectometer (OTDR) is used to monitor the temperature-dependent backscattered light, for assessment of temperature variation along the sensing link. Measurements of temperature variations as small as 4 K, with a spatial resolution of 10 m, over a 10-km SMF have been reported [3]. However, with the use of high peak power ($\sim$1 W) OTDR pulses for the excitation of spontaneous Raman process in the fiber, the associated onset of other detrimental nonlinear propagation effects—such as stimulated Raman scattering—hindered the further increase in the pulse power and extension of the measurement range [4].

Taking a different approach, a notable step forward has recently been achieved by applying a coded OTDR [5] to SRS-based DTS systems, extending the sensing range up to 17 km (15 m/5 K resolution) [6], while using commercially available low-power (80 mW) laser diodes (LDs).

Extending our previous work, here a DTS system with improved sensing range (up to 37 km) and better resolution (17 m/3 K) is demonstrated, based on off-shelf, conventional OTDR hardware. With the use of longer code words (255 bit) and a sensing fiber cascade arranged in terms of their figure of merit, 2.2 and 1.7 times improvement in the interrogation range and the temperature resolution, respectively, were obtained when compared to previous work [6].

Manuscript received March 2, 2006; revised June 15, 2006.

J. Park, D. Lee, P. Kim, P. Cho, and N. Park are with the Optical Communication Systems Laboratory, School of Electrical Engineering and Computer Science, Seoul National University, Seoul, Korea (e-mail: jonghan@stargate.snu.ac.kr; duckey@stargate.snu.ac.kr; phkim@stargate.snu.ac.kr; pkcho@stargate.snu.ac.kr; nkpark@plaza.snu.ac.kr).

G. Bolognini and F. Di Pasquale are with the Scuola Superiore Sant'Anna, CNR Research Area,1 56124 Pisa, Italy (e-mail: gabriele.bolognini@cnit.it; fabrizio.dipasquale@cnit.it).

Digital Object Identifier 10.1109/LPT.2006.881239

II. Theory

Analysis on Raman Stokes lines with an OTDR allows the assessment of distributed temperature sensing in a fiber, since Stokes intensities are dependent on the fiber temperature T, due to the change in phonon distribution.

Considering a short pump light pulse (peak power P_{in} and pulsewidth W) launched into the fiber at $z = 0$, the backward-propagating Rayleigh-scattered pump power (P_{RS}) and Raman anti-Stokes (AS) power (P_{AS}) generated at position z and received at fiber input (at different times) can be written as

$$P_{\mathrm{RS}}(z) \approx \frac{W}{2} P_{\mathrm{in}} R_S(z) \exp\left[-2\int_0^z \alpha_{\mathrm{RS}}(z_1) dz_1\right] \quad (1)$$

$$P_{\mathrm{AS}}(z) \approx \frac{W}{2} P_{\mathrm{in}} g_R(z) F_T(z) \times \exp\left\{\int_0^z -\left[\alpha_{\mathrm{RS}}(z_1) + \alpha_{\mathrm{AS}}(z_1)\right] dz_1\right\} \quad (2)$$

where R_S and g_R are the Rayleigh back-scattering and peak Raman gain coefficients, respectively, and α_{RS} and α_{AS} are absorption coefficients at pump and AS wavelengths, respectively. It is important to note that $F_T(z)$ in (2), is a temperature-dependent function, related to the Bose–Einstein thermal population and spectral cross section (σ_R, which is normalized by g_R) of spontaneous AS scattering [7]. In mathematical form, it can be written as

$$F_T \propto \int_{v_1 - v_p}^{v_2 - v_p} \sigma_R(v_R) \left[\exp\left(\frac{h v_R}{k_B T}\right) - 1\right]^{-1} dv_R \quad (3)$$

where v_R is the optical frequency shift of Raman scattering, v_1 and v_2 are low- and high-frequency corners of the ideal optical bandpass filter at the receiver-end, v_p is the pump frequency, and h, k_B are Planck's and Boltzman's constants, respectively. In order to compensate for the possible change in fiber loss, the ratio between P_{RS} and P_{AS} is typically used [3]

$$\frac{P_{\mathrm{RS}}(z)}{P_{\mathrm{AS}}(z)} = \frac{1}{F_T(z)} \frac{R_S(z)}{g_R(z)} \exp\left(\int_0^z -(\alpha_{\mathrm{RS}}(z_1) - \alpha_{\mathrm{AS}}(z_1)) dz_1\right) \quad (4)$$

from which the final information on the temperature distribution $F_T(z)$ can be derived.

Aknowledging that the signal-to-noise ratio (at the receiver) determines the maximum interrogation distance, and as it is ultimately set by the AS power P_{AS} (since $P_{\mathrm{AS}} \ll P_{\mathrm{RS}}$), we here write an expression for the amount of normalized, backscattered

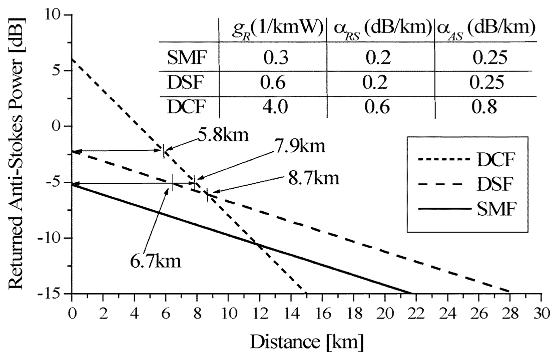

Fig. 1. Normalized backward-propagating received anti-Stokes power as a function of distance z for three different types of SMFs (inset: specifications of used fiber parameters).

AS power generated at position z and measured at $z = 0$, as follows [see (2)]:

$$\overline{P}_{\mathrm{AS}}(z) = g_R \exp\left[-\left(\alpha_{\mathrm{RS}} + \alpha_{\mathrm{AS}}\right) z\right]. \tag{5}$$

Fig. 1 presents the calculated $\overline{P}_{\mathrm{AS}}(z)$ values for different types of commercial fibers: standard SMF, dispersion-shifted fiber (DSF), and dispersion-compensating fiber (DCF). As can be seen in the figure, the AS power $\overline{P}_{\mathrm{AS}}(z)$ exhibited strong dependency on fiber types (with different Raman efficiency and fiber loss), resulting in different achievable sensing ranges for the different fibers.

In particular with the specific set of fiber parameters (inset of Fig. 1), the received backscattered AS power generated at $z = \zeta, \overline{P}_{\mathrm{AS}}(\zeta)$, was always greater in DSF than in SMF. In case of DCF, $\overline{P}_{\mathrm{AS}}(\zeta)$ was greater than that of DSF for all distances $\zeta < 8.7$ km (the cross-over point in Fig. 1).

From this comparison, it can be concluded that it is always convenient to use DSF instead of the SMF as the sensing fiber for DTS system (with the exception when nonlinearity have to be avoided). Use of DCF is found to be convenient for: 1) short-range DTS systems (of less than several kilometers) and 2) extending the sensing range by cascading DCF *at the end* of SMF- or DSF-based SRS-DTS systems, thus fully exploiting the benefits of higher Raman efficiency provided by DCF. This last feature can be easily quantified if the z-distance in the curves of Fig. 1 is considered to be taken from the end of an SMF or DSF spool. For example (see Fig. 1), considering an SRS-DTS based on an SMF link, it is possible to extend the sensing range by 6.7 or 7.9 km, by cascading DSF or DCF at the end of the SMF link. For a DSF (or SMF-DSF cascade) link, a 5.8-km increase in measurement range can also be achieved by cascading DCF. In addition to link optimization, it is possible to further extend the sensing range by applying coding techniques [6].

For Simplex coding, the coding gain achieved with a code length of L is given by $G_{\mathrm{cod}} = (L+1)/2\sqrt{L}$ [5]; expressing the achieved enhancement in terms of measurement range increase Δz_{cod}, we write

$$\Delta z_{\mathrm{cod}} = \frac{1}{\alpha_{\mathrm{RS}} + \alpha_{\mathrm{AS}}} \ln \frac{L+1}{2\sqrt{L}}. \tag{6}$$

III. Experiment

In Fig. 2, we illustrate the experimental setup. An in-house-built PC-controlled OTDR board with a digital signal processor,

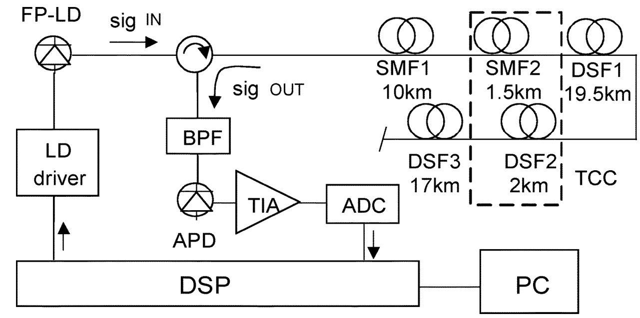

Fig. 2. Experimental setup for Raman-DTS with Simplex coding.

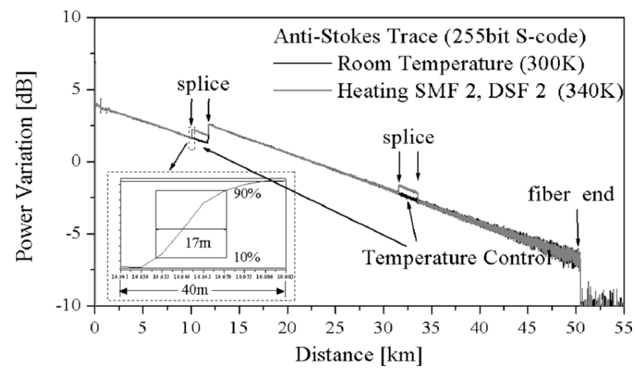

Fig. 3. Decoded traces of anti-Stokes power (with 255-bit Simplex codes. Black line: room temperature. Gray line: SMF2 and DSF2 at 340 K).

was used to modulate the laser diode in the board, according to the Simplex code pulse patterns [5], with 100-ns single bit pulsewidth. The light source consisted of a conventional multimode Fabry–Pérot LD, with peak power of 80 mW at 1550 nm (FWHM $=$ 10 nm). The input pulses were injected into the sensing fiber through an optical circulator. The backscattered signals were then coupled to the receiver (InGaAs APD with 0.7 excess noise factor and high-gain trans-impedance amplifier (TIA) with 3-MHz bandwidth), after a bandpass filter (1400 $\sim$ 1510 nm for the AS, 1520 $\sim$ 1600 nm for the Rayleigh scattered pump light). The calculated temperature sensitivity with this setup was 0.65%/K (at $T = 300$ K) for this AS optical filter bandwidth.

After the receiver, an analog-to-digital converter was used to sample the incoming trace data at 20 MHz. The code-imprinted traces were then transmitted to the PC, where the decoding process was achieved. The spatial resolution (defined from the 10%–90% OTDR response time suitably converted into corresponding distance) for the current DTS system was measured to be 17 m (inset in Fig. 3) for all distances. Five spools of fibers (SMF1, 2 and DSF1, 2, 3) were used (10, 1.5, 19.5, 2, and 17 km, respectively), spliced together to compose a 50-km sensing link. SMF2 and DSF2 were placed inside a temperature-controlled chamber, while the other spools were maintained at room temperature (300 K).

Fig. 3 shows the experimentally obtained AS traces with the sensing link at 300 K (black line) and at 340 K (for SMF2 and DSF2 only gray line), *decoded* from the 255 coded traces (706 averages are taken for each single-codeword trace) [5]. Increases in AS power in heated fiber sections are evident. It is also possible to see the expected enhancement of sensing range with the use of higher Raman gain fiber (DSF) after the

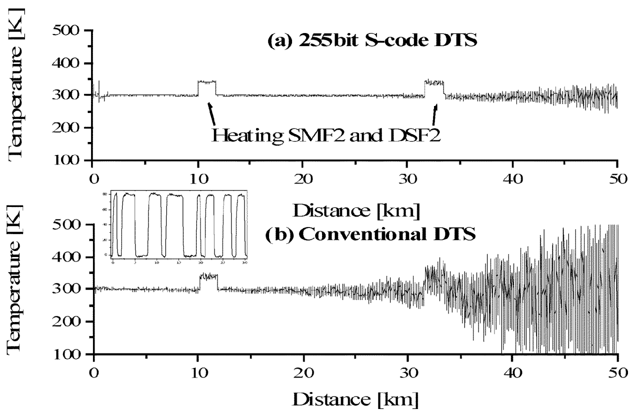

Fig. 4. Measured temperature with (a) 255 bit coded and (b) conventional DTS. Inset: LD output (first 30 bits of 255 code pattern).

TABLE I
MEASURED FIBER PARAMETERS (* NORMALIZED WITH SMF 1).

	SMF1	SMF2	DSF1	DSF2	DSF3
$\alpha_{AS}-\alpha_{RS}$ [dB/km]	0.056	0.075	0.063	0.047	0.047
R_s/g_R *	1	1.033	0.995	0.995	0.995

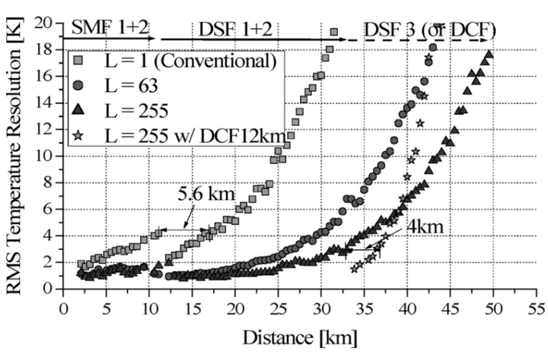

Fig. 5. Temperature resolution versus distance for different code length (the spatial resolution is 17 m).

SMF ($z = 11.5$ km), in the same figure. Fig. 4(a) shows the corresponding temperature distribution, obtained from the ratio $P_{\rm AS}/P_{\rm RS}$ (using (4) with parameters in Table I). To compare, the temperature measured with the *simple average* of 180 000 single-pulse traces (same measurement number as that of coded OTDR) are shown in Fig. 4(b).

The root-mean-square (rms) temperature resolution (derived from rms noise of the OTDR AS trace), plotted as a function of distance is shown in Fig. 5, for different code lengths ($L = 1,\ 63,\ 255$ bit) and fiber types (SMF, DSF, DCF). With a target temperature resolution of 3 K, the sensing range was limited to 7.5 km for the conventional OTDR ($L = 1$) with an SMF link. In contrast, it can clearly be seen, with 255-bit code, that it was possible to monitor the same temperature variation up to 33 km (SMF + DSF link). Fig. 6 summarizes the measured enhancement for the sensing range at different code lengths. An even greater increase in the sensing range (4 km) was also possible, by replacing the DSF3 with a connectorized DCF (12 km, see

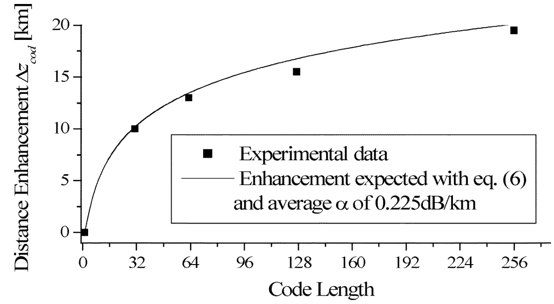

Fig. 6. Increase in measurement range as a function of code length.

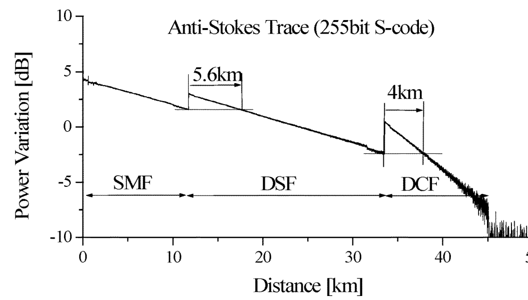

Fig. 7. Measured anti-Stokes trace (with DSF3 replaced to DCF).

Fig. 7), showing again good agreement with the theory (5.8 km, for which the connector loss was ignored).

IV. CONCLUSION

Improved performance for Raman-based DTS systems is demonstrated, based on Simplex coding and link optimization techniques. An increase in the interrogation range (19.5 km from the 255 bit coding, and 9.6 km from link optimization) was measured with respect to conventional OTDR. At 3-K/17-m temperature/spatial resolution, a total sensing range of 37 km was obtained using conventional single-mode transmission fibers and low-power laser diode.

REFERENCES

[1] J. P. Dakin *et al.*, "Distributed optical fiber temperature sensor using a semiconductor light source and detector," *Electron. Lett.*, vol. 21, pp. 569–570, 1985.

[2] M. A. Farahani and T. Gogolla, "Spontaneous Raman scattering in optical fibers with modulated probe light for distributed temperature Raman remote sensing," *J. Lightw. Technol.*, vol. 17, no. 8, pp. 1379–1391, Aug. 1999.

[3] H. H. Kee *et al.*, "1.65 mm Raman-based distributed temperature sensor," *Electron. Lett.*, vol. 35, pp. 1869–1870, 1999.

[4] P. C. Wait *et al.*, "A theoretical comparison of stimulated Raman and Brillouin based fibre optic distributed temperature sensors," *Opt. Commun.*, vol. 144, pp. 17–23, 1997.

[5] D. Lee, H. Yoon, N. Y. Kim, H. Lee, and N. Park, "Analysis and experimental demonstration of simplex coding technique for SNR enhancement of OTDR," in *Proc. IEEE LTIMC*, New York, Oct. 2004, Paper LTIMC-15.

[6] G. Bolognini *et al.*, "Performance enhancement of Raman-based distributed temperature sensors using simplex codes," in *OFC 2006 Tech. Dig.*, Mar. 2006, Text OTuL1.

[7] M. N. Islam, *Raman Amplifiers for Telecommunications*. New York: Springer, 2004, vol. 1.