High-Performance Raman-Based Distributed Fiber-Optic Sensing Under a Loop Scheme Using Anti-Stokes Light Only

Marcelo A. Soto, Alessandro Signorini, Tiziano Nannipieri, Stefano Faralli, and Gabriele Bolognini, *Member, IEEE*

***Abstract*—A distributed fiber-optic temperature sensor technique inherently allowing for system calibration, compensating time-dependent variations of the fiber losses as well as local external perturbations, is proposed using a loop-scheme together with Raman anti-Stokes-only measurement. A temperature resolution enhancement with respect to a standard loop configuration is shown by experiments, providing a robust and reliable high-performance sensing technique for long sensing ranges.**

***Index Terms*—Optical fiber measurements, optical time-domain reflectometry, Raman scattering.**

I. INTRODUCTION

DISTRIBUTED optical fiber sensors for temperature monitoring have been subject of an intense research activity throughout many years [1], [2] and have been employed in a large variety of application areas (such as fire detection, power cable monitoring and leakage detection) thanks to their unique sensing capabilities. The most common sensing schemes employ spontaneous Raman backscattering through simultaneous measurements of the backscattered Raman anti-Stokes (AS) and Stokes (S) (or AS and Rayleigh) components in a single-ended fiber configuration [2], [3]. Sensor schemes based on single-ended configuration, although representing the common solution in long range applications due to their extended distance, suffer however from the impact of fiber wavelength-dependent losses (WDL) [4]. In order to make the Raman-based distributed temperature sensor (RDTS) suitable for practical applications, the effects due to WDL and local loss variations must be cancelled out; this is achieved by employing a loop scheme, with double-end fiber interrogation, where AS and S traces are acquired in both forward and backward directions and then properly averaged [4]. For single-ended schemes, the use of AS light only has been proposed in [5] in conjunction with a specific reflective mirror at the far fiber-end, resulting in a four-fold optical path length for light pulses and scattering, and hence increased losses, making this technique more suitable for short-range applications, rather than for long-range sensing; moreover, due to the reflective mirror at the far fiber-end, the system can be more sensitive to multiple optical reflections (ghosts) with unknown connector conditions in real applications.

In this letter we propose a loop measurement technique using only the AS backscattered light and a single channel receiver, leading to a simpler, reliable and cost-effective system for long sensing ranges with inherent differential loss correction. In addition, we experimentally show that such a simplified AS-only loop-RDTS provides enhanced temperature resolution with respect to standard loop schemes.

II. THEORY

In RDTS an optical fiber is used as a distributed sensing medium, exploiting the temperature dependence of the spontaneous Raman backscattered light and the well-known optical time-domain reflectometry (OTDR) technique [1], [3]. In such systems, a short pulse of light, at a frequency ν_0, is launched into the optical fiber, generating two Raman backscattered components (at frequencies $\nu_0 \pm \Delta\nu$), which are measured as a function of time at the receiver side. While the intensity of the Raman down-shifted frequency component (S light) is only slightly temperature-dependent, the intensity of the up-shifted frequency component (AS light) strongly depends on the local fiber temperature [3]. However, usually the AS signal alone is not employed for absolute temperature measurements, due to its dependence on fiber attenuation and local losses, which can affect the temperature measurement. Actually, such a dependence must be cancelled out by normalizing the AS OTDR traces with a temperature-independent signal such as the Stokes [1] or Rayleigh intensity [3]. Thus (after taking into account differential group velocity impact), the temperature (T) dependence of the ratio $R(z,T)$ of anti-Stokes (I_{AS}) over Stokes (I_S) intensity can be expressed as:

$$R(z,T) = \left(\frac{\lambda_S}{\lambda_{AS}}\right)^4 \exp\left(\frac{-h\Delta\nu}{kT(z)} - \int_0^z \left[\alpha_{AS}(\xi) - \alpha_S(\xi)\right] d\xi\right), \tag{1}$$

with λ_S and λ_{AS} representing the Stokes and anti-Stokes wavelengths respectively; α_S and α_{AS} are the respective fiber attenuation coefficients; $\Delta\nu$ is the frequency separation between AS and pump signal, h is the Planck constant and k is the Boltzmann constant [4]. If the differential loss ($\alpha_{AS} - \alpha_S$) is characterized as a function of the distance, the exponential factor of (1) can be corrected. However, in real applications, such a factor is not constant in time since the optical fiber may be exposed to environmental conditions that spectrally change the fiber attenuation during the sensor lifetime [4]. Hence, significant errors in temperature measurements can be induced when no further

---

Manuscript received November 12, 2010; revised December 29, 2010; accepted February 02, 2011. Date of publication February 10, 2011; date of current version April 01, 2011.

The authors are with Scuola Superiore Sant'Anna, CEIICP, Pisa 56124, Italy (e-mail: gabriele.bolognini@sssup.it).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2011.2113174

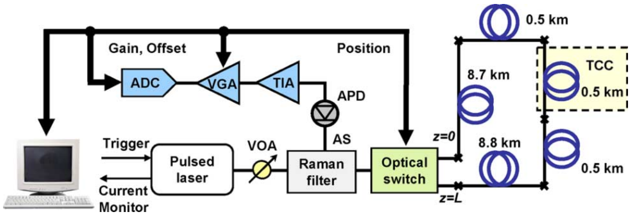

Fig. 1. Experimental setup.

calibration is performed. However, when pump pulses are alternatively sent into the sensing fiber from both fiber ends in a loop configuration, then the differential WDL can be compensated without any further calibration. In such a scheme, the ratio between AS and S signals is obtained in both forward and backward directions, and the geometric average of these two ratios is calculated. Such a procedure cancels out all loss factors depending on the fiber position, leading to self-calibrated temperature measurements that do not depend on the optical loss variations during the sensor lifetime, as demonstrated in [4]. Some auto-correction methods have been recently proposed and shown to compensate differential WDL using for instance the anti-Stokes signal reflected from a mirror [5] or using two light sources at different wavelength [6]. The first technique actually provides a cost-effective solution for real applications; however, the maximum sensing distance in that case is limited by the mirror reflectivity, which moreover, due to pulse reflection by the mirror, generates a two-fold increase in two-way optical path (and corresponding loss) compared to standard schemes, finally allowing only for short-to-medium sensing ranges [5]. Our proposed loop-RDTS uses AS traces measured in forward and backward directions, with the advantage of standard loop configuration. A self-calibrated sensor for long sensing ranges can be then implemented using only AS traces, avoiding the use of S signal (and double receiver) for trace normalization. The AS traces in both forward and backward directions can then be written as:

$$I_{AS}^{For}(z) = C_{AS\_For} N_{\Omega} \exp\left[-J(0,z)\right], \tag{2}$$
$$I_{AS}^{Back}(z) = C_{AS\_Back} N_{\Omega} \exp\left[-J(z,L)\right], \tag{3}$$

where α_P is the fiber attenuation at the pump wavelength, C_{AS_For} (forward direction) and C_{AS_Back} (backward direction) are constant parameters accounting for the Raman cross-section at λ_{AS} and the input optical power, $J(a,b)$ and N_{Ω} are the loss integral and the Bose-Einstein population factor respectively given by:

$$\begin{aligned} J(a,b) &= \int_a^b \left[\alpha_{AS}(\xi) + \alpha_P(\xi)\right] d\xi, \\ N_{\Omega} &= \left[\exp\left(\frac{h\Delta\nu}{kT(z)}\right) - 1\right]^{-1}. \end{aligned} \tag{4}$$

The main issue arising when implementing the proposed technique is due to typical laser power fluctuations. While this issue is inherently solved in standard RDTS by taking the AS/S ratio (see (1)), this correction is not straightforward when using AS traces only [5]. An effective normalization in our AS-only loop-scheme can be simply performed: *i)* by using a temperature-controlled reference fiber [4], *ii)* by measuring the launched optical pulse power through an optical tap coupler or, *iii)* by using a laser current monitor proportional to the real-time pulse power fluctuations for each trace. In our experiments we used a built-in laser current monitor for AS trace normalization with pulse peak power, providing a cost-effective alternative for a single-receiver RDTS.

The AS intensity in loop configuration $I_{AS\_Loop}(z)$ can then be obtained from the geometric mean of the normalized single-ended AS traces $I_{AS\_n}(z)$ in both forward and backward directions according to:

$$\begin{aligned} I_{AS\_Loop}(z) &= \left[I_{AS\_n}^{For}(z) \cdot I_{AS\_n}^{Back}(z)\right]^{1/2} \\ &= C_{AS\_Loop} N_{\Omega} \exp\left[-\frac{1}{2}J(0,L)\right], \end{aligned} \tag{5}$$

where $C_{AS\_Loop} \propto \left[C_{AS\_For} \cdot C_{AS\_Back}\right]^{1/2}$ includes the normalization accounting for the laser power fluctuations. Note that the exponential factor in (5), including effect of WDL, is a constant factor that does not depend on the fiber position z, contrarily to the z-dependent exponential term in (1). Finally, considering that the averaged AS trace depends on the unknown constant parameter C_{AS_Loop}, a single calibration procedure for each fiber is needed by employing a reference trace at a known temperature (T_{ref}), as in standard RDTS [4], [5]. Thus, the self-calibrated temperature profile $T(z)$ can then be easily obtained as follows:

$$\begin{aligned} &T(z) \\ &= \left\{\frac{k}{h\Delta\nu} \ln\left[\frac{I_{AS\_Loop}(z,T_{ref})}{I_{AS\_Loop}(z,T)}\left[\exp\left(\frac{h\Delta\nu}{kT_{ref}}\right) - 1\right] + 1\right]\right\}^{-1}. \end{aligned} \tag{6}$$

Cancelation of WDL effects and time-dependent local loss perturbations can be inferred from the above-reported equation, and is inherent of the AS-only technique as also shown in [5], when combined with bidirectional OTDR measurements, as in the case of loop-scheme acquisitions [4].

III. EXPERIMENTAL SETUP

The experimental setup shown in Fig. 1 has been used to validate the proposed technique for long-range RDTS based on a single channel receiver. A low-spontaneous-emission EDFA-based pulsed laser operating at 1550 nm has been used with a maximum peak power of 50 W, 10 ns pulse width (allowing for meter-scale spatial resolution) and 5 kHz repetition rate. In order to avoid fiber nonlinearities, the average optical power at the fiber input has been lowered to 1.5 mW by using a variable optical attenuator (VOA). An optical filter is employed to extract the backscattered AS Raman signal, which is then measured by a single high-sensitivity receiver consisting in a low-noise avalanche photodiode (APD), a trans-impedance amplifier (TIA), a variable gain amplifier (VGA) operating with optimal gain for dynamic range maximimization, and an analog-to-digital converter (ADC, 14 bit, 200 MS/s). In order to achieve long sensing distances, five spools of graded-index 50/125 multimode fiber have been used, allowing for a total of 19-km range. One fiber section (~ 500 m) at ~ 9-km distance has been placed in a temperature-controlled chamber (TCC), allowing for a validation of the proposed technique. Both fiber ends have been connected to the sensor through a 1×2 optical switch, allowing pulses to be alternately sent in both forward and backward directions.

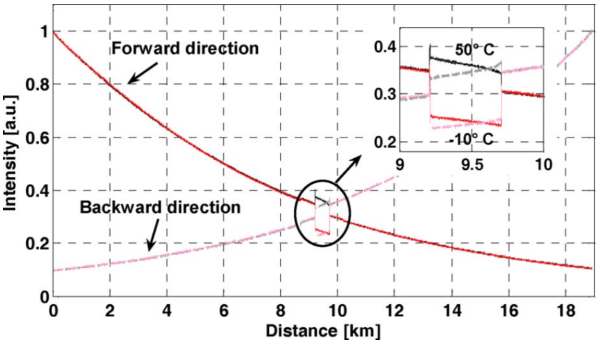

Fig. 2. Single-ended AS traces in both forward and backward directions for different TCC temperatures. Inset: fiber spool inside TCC.

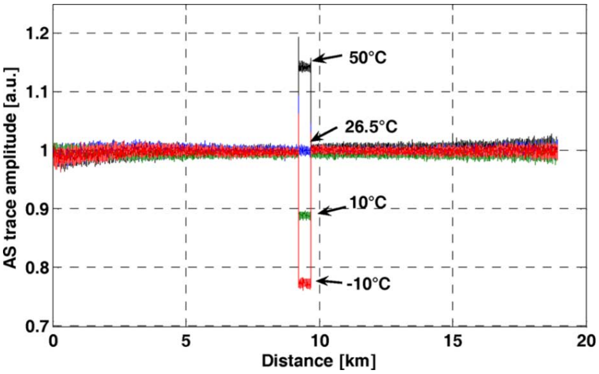

Fig. 3. Normalized loop-AS traces for different TCC temperatures.

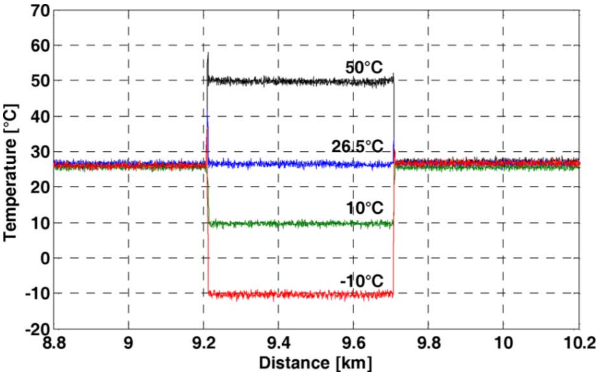

Fig. 4. Temperature profile obtained using only AS traces in loop configuration for different TCC temperatures.

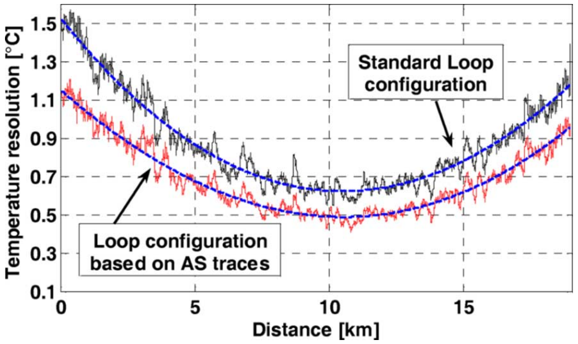

Fig. 5. Temperature resolution in AS-only- and standard-loop.

IV. RESULTS

Anti-Stokes traces have been measured (with 100 k time-averaged traces) and then normalized in both directions with a total measurement time of $\sim$ 40 s; they are shown in Fig. 2 for two different TCC temperatures (-10°C and 50°C) while keeping the rest of the sensing fiber at room temperature (26.5°C). The geometric averages of the normalized AS traces are then calculated and shown in Fig. 3, with TCC from -10°C up to 50°C. We can notice from Fig. 3 that the AS-only loop-RDTS cancels out issues from local losses (such as splices), WDL and attenuation, and moreover does not require correction for differential group velocity effects (required in AS/S schemes). The temperature profile along the 19 km of fiber is then calculated according to (6); results are shown in Fig. 4, reporting the temperature profile in proximity of the third fiber spool (inside the TCC). The corresponding temperature resolution has been calculated from the standard deviation of the measured temperature and is shown in Fig. 5. Since the signal-to-noise ratio (SNR) of single-ended traces decreases along the sensing fiber, measurements exhibit a worse temperature resolution in proximity of both fiber ends compared to the midway fiber regions. Fig. 5 also compares the temperature resolution achieved with AS-only measurements to the one obtained with a standard RDTS in loop configuration (involving additional optical filtering in Fig. 1 for Stokes light and the related receiver stage, see e.g., [4]). We can see that, likely due to different insertion loss in optical switch ports, the worst temperature resolution occurs at the fiber input ($z = 0$), giving rise to a slightly asymmetric resolution behavior along the fiber. Note that our proposed AS-only loop-scheme provides an enhanced temperature resolution (~ 1.4 times better) with respect to a standard loop configuration. This is because AS-only loop-schemes are not affected, in $T(z)$ calculation, by the additional noise introduced in Stokes-line measurements. Thus, a temperature resolution of $\sim 1.5^{\circ}$C (obtained using S and AS traces) at fiber input is improved down to $\sim 1.1^{\circ}$C with the use of AS-only scheme.

In conclusion, we have proposed a scheme for long-range RDTS based on loop configuration employing Raman AS measurements only. Such a scheme allows for the cancellation of spurious WDL-related issues together with an improved resolution over long fiber lengths, exhibiting in our experiment a ~ 1.4 times improved temperature resolution compared to standard loop-RDTS, thus providing a cost-effective, reliable and high-performance system using a single receiver only.

REFERENCES

[1] B. Culshaw and A. Kersey, "Fiber-optic sensing: A historical perspective," *J. Lightw. Technol.*, vol. 26, no. 9, pp. 1064–1078, May 1, 2008.

[2] J. P. Dakin and D. J. Pratt, "Distributed optical fibre Raman temperature sensor using a semiconductor light source and detector," *Electron. Lett.*, vol. 21, no. 13, pp. 569–570, 1985.

[3] G. Bolognini, J. Park, M. A. Soto, N. Park, and F. Di Pasquale, "Analysis of distributed temperature sensing based on Raman scattering using OTDR coding and discrete Raman amplification," *Meas. Sci. Technol.*, vol. 18, pp. 3211–3218, 2007.

[4] A. F. Fernandez *et al.*, "Radiation-tolerant Raman distributed temperature monitoring system for large nuclear infrastructures," *IEEE Trans. Nucl. Sci.*, vol. 52, no. 6, pt. 1, pp. 2689–291, Dec. 2005.

[5] D. Hwang, D.-J. Yoon, I.-B. Kwon, D.-C. Seo, and Y. Chung, "Novel auto-correction method in a fiber-optic distributed-temperature sensor using reflected anti-Stokes Raman scattering," *Opt. Express*, vol. 18, no. 10, pp. 9747–9754, 2010.

[6] K. Suh and C. Lee, "Auto-correction method for differential attenuation in a fiber-optic distributed-temperature sensor," *Opt. Lett.*, vol. 33, no. 16, pp. 1845–1847, 2008.