High performance and highly reliable Raman-based distributed temperature sensors based on correlation-coded OTDR and multimode graded-index fibers

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ABSTRACT

The performance of distributed temperature sensor systems based on spontaneous Raman scattering and coded OTDR are investigated. The evaluated DTS system, which is based on correlation coding, uses graded-index multimode fibers, operates over short-to-medium distances (up to 8 km) with high spatial and temperature resolutions (better than 1 m and 0.3 K at 4 km distance with 10 min measuring time) and high repeatability even throughout a wide temperature range.

Keywords: Spontaneous Raman scattering, distributed temperature sensor, optical time domain reflectometry, fiber optics, fiber sensing, sensors, coding.

1. INTRODUCTION

Distributed temperature sensor (DTS) systems are attracting a great deal of attention for the wide range of practical applications they offer and the great advantages they can provide over conventional and fiber Bragg grating based temperature sensors in terms of cost, performance and compactness. Their main applications include monitoring of oil wells, oil/gas pipelines and power cables as well as fire detection systems especially in hazardous environments.

In DTS systems based on spontaneous Raman scattering (SRS) [1], the temperature distribution along the optical sensing fiber is usually assessed by measuring the intensity ratio of Anti-Stokes (AS) to Stokes light, or of Anti-Stokes to Rayleigh backscattered (BS) light. In both cases, this allows for temperature measurements which are independent of almost all other fiber link losses (such as splices and connectors). The sensing principle is based on the optical time domain reflectometry (OTDR) in which light pulses are sent down along the sensing fiber and the backward propagating light is detected. The pulse duration determines the minimum achievable spatial resolution; in particular, pulses as short as 10 ns are required in order to achieve spatial resolution of the order of 1 meter, as required in most practical applications. This feature, combined with the low backscattered intensity of the AS light, generally requires high peak power levels in the OTDR, as well as high sensitivity detection schemes, to make the sensor performance attractive.

In this paper we show that complementary-correlation (CC) coded OTDR techniques, combined with the use of graded-index multimode fiber (MMF), allow for enhanced performance in Raman based DTS, avoiding the use of high peak power pulses; in particular the use of low-power (< 20 mW) external cavity lasers (at ~1064 nm) maximizes the sensing performance over such MMF, providing high spatial and temperature resolution as well as high repeatability throughout a wide temperature range. Hot temperature spots can also be localized within few tens of centimeters, although with a corresponding reduction of the measured temperature level. Even though characterized by relatively high losses within the operating wavelength range, graded-index MMF are advantageous over single mode fibers (SMF) operating at around 1.5 μm for distances up to 10-15 km, due to their larger capture factor and consequent higher backscattered levels for Stokes and AS lines. Note that fiber dispersion effects (mainly modal dispersion) only slightly degrade the DTS spatial resolution for short-to-medium distance applications, thanks to use of graded-index MMF. Raman DTS systems based on SMF employing coded OTDR and laser diodes at 1.55 μm, become more attractive for longer distance applications (~ tens of km) [2].

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2. THEORY

Raman-based distributed temperature sensors are generally implemented through OTDR, propagating short laser pulses along the sensing fiber. The spontaneous Raman backscattered light contains temperature information at different points along the fiber and allows one to detect the temperature distribution with a pulse-dependent spatial resolution. In particular, Raman Stokes light has a small temperature dependence, while AS light is strongly dependent on fiber temperature. Moreover, both AS and Stokes lights are dependent on fiber loss, hence their ratio is commonly used for more reliable temperature estimation. Its temperature dependence can be written as:

$$\frac{I_{AS}}{I_S} \propto \exp\left(-\frac{h\Delta\nu_R}{kT}\right) \tag{1}$$

where h in the Planck constant, k is the Boltzmann constant, T is the absolute temperature, and $\Delta\nu_R$ is the separation between Raman AS/Stokes and probe light frequencies. To calculate the absolute temperature this equation has to be modified by the differential attenuation of the fiber and wavelength dependence of the receiver unit (in experiment, AS peak is at 1018 nm, Stokes peak is at 1112 nm). The influence of the receiver can be taken into account by performing suitable real-time fiber calibration, allowing for reliable and accurate temperature sensing.

The performance of Raman based DTS systems can be greatly enhanced by using coded OTDR [3,4]. The traditional trade-off between sensing range and resolution in OTDR also exists in DTS systems; it can be effectively overcome in DTS, by applying suitable coding techniques, as recently shown in [4]. In particular, correlation-based codes can be successfully used in direct-detection OTDR schemes, as demonstrated in [3]. The basic idea behind correlation techniques applied to OTDR and DTS is to spread the signal in time domain, and to reconstruct the fiber impulse response by correlating the detected signal with a probe; it is then possible to avoid the onset of nonlinear effects and to improve the attained SNR. Not many correlation coding schemes can be successfully employed, due to occurrence of different limiting effects. Among correlation codes, CC-Golay codes overcome all above mentioned issues [3], and have been extensively used in OTDR schemes[1]. The proposed Raman DTS system, based on CC-Golay codes, provides enhanced performance exploiting coding gain to overcome the limitation imposed by low level of Raman scattering. The enhancement in signal-to-noise ratio (SNR) provided by coding is quantified by the coding gain (G_{cod}), defined as the SNR improvement provided by coding with respect to single pulse case. In case of Golay codes, G_{cod} can be expressed as $G_{cod} = \sqrt{L}/2$ (L is the code length). Noise reduction with CC-DTS can be exploited, for a given spatial resolution, either to obtain higher temperature accuracy than in single pulse OTDR with the same averaging time, or to provide the same temperature accuracy as in standard OTDR, but within shorter measurement time, or, finally, to achieve a longer sensing range with the same temperature and measurement time. Most importantly, coding gives the opportunity to use a low-power semiconductor laser which improves the operating life when compared, e.g., to a high power YAG laser (3B laser class). This type of laser also ensures 1M laser safety class which minimizes user hazards (refer to IEC 60825-1, 2001).

3. EXPERIMENTAL SETUP

A block diagram of the experimental set-up used to implement the Raman-based DTS is shown in Fig. 1. The transmitter and receiver are inside the Agilent N4385A DTS system[1] used in our experiments. The OTDR source is provided by an external cavity laser operating at 1064 nm, characterized by extremely low average output power P_{AV}=17 mW (class 1M); Raman-backscattered light from the sensing fiber is collected into an optical receiver block. This unit is composed of wavelength selective filters (WF), mirrors (M) and an optical shutter, separating the Stokes and AS components, and a single photodiode (PD), which measures the AS and Stokes signal in series. To optimise the measurement time, two separate processors are used, one for temperature calculation, based on OTDR traces, and the other for data storage, logging, communication and control of the whole system. Compared to the well-known double receiver design, this concept has the advantage that individual offset, gain and bandwidth characteristics of each photodiode and amplifier path do not influence the temperature calculation resulting in highly stable and repeatable measurement results. The sensing fiber used in set-up 1 consists in 4430 m of graded-index MMF (50/125 μm), composed of seven different fiber spools (Fig. 1b). Each fiber section can be set to individually controlled temperatures. This allows for an accurate characterisation of the instrument under test. The sensing fiber used in set-up 2 consists of ~630 m of the same MMF type. A short fiber section with variable length has been put inside a temperature-controlled chamber (TCC) during the experiments. Set-up 3 is given by a 8500 m MMF coil kept at room temperature (25 °C), and used to obtain data on DTS temperature resolution over longer distances.

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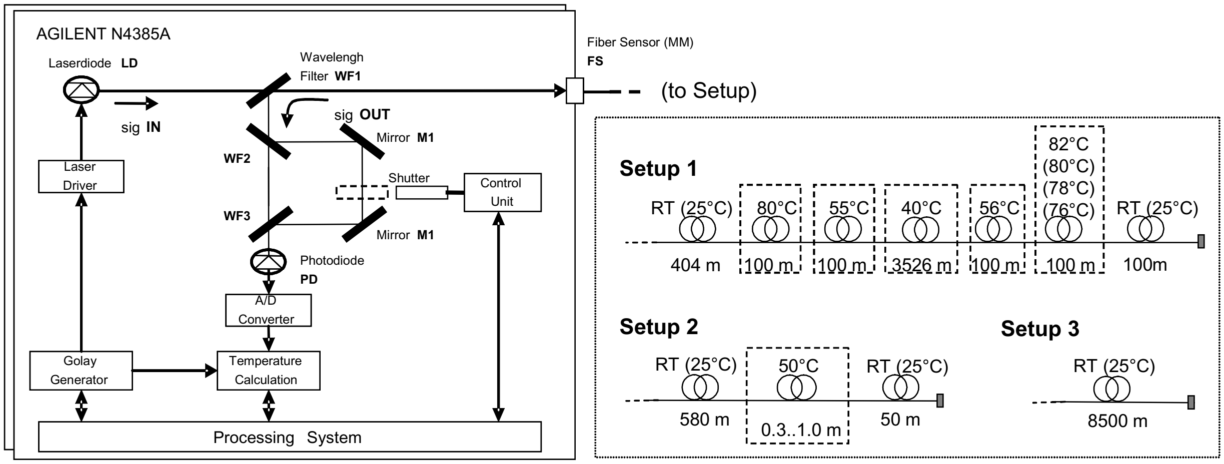
[1] Proprietary technique, Agilent Inc.



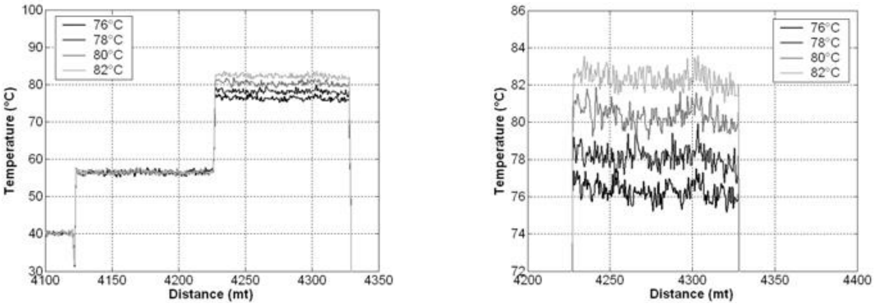
(a) (b)

Fig. 1 (a) Scheme of DTS, transmitter and single-photodiode receiver. (b) Set-up of sensing fibers used in experiments.

4. RESULTS

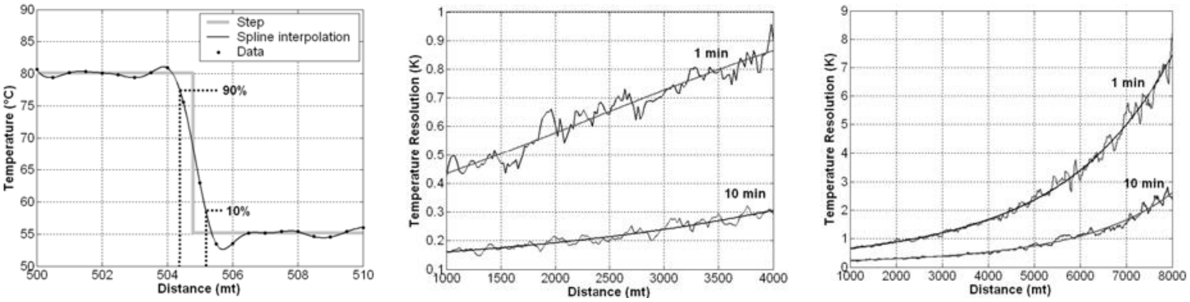
Temperature measurements using the new correlation-based DTS system have been taken under different conditions of temperature, spatial resolution and averaging time. However, before performing the actual measurement, the dependence of the AS to Stokes intensity ratio on the different fiber spools has been characterized. Due to different wavelength-dependent losses and Raman-scattering coefficients, pre-calibration of the DTS by measuring the AS to Stokes intensity ratio within each fiber spool is required for accurate temperature assessment. We have first characterized the correct operation of the DTS at medium fiber lengths (~ 4 km). Therefore we changed the temperature of 100m of fiber (coil 6) in set-up 1 in 2 K steps, in the range 76-82 °C. After 10 min measurement time, we obtained the results shown in Fig. 2. The observed temperature nonlinearity (defined as difference between set and measured temperature step) was less than 0.3 K. With the purpose of measuring the real spatial resolution, the 10% to 90% response distance has been measured with an abrupt temperature variation at around 504 m. A 25 K temperature step has been analysed (fiber coil 2 to coil 3 in set-up 1). The temperature distribution is reported in Fig. 3a, showing an achieved spatial resolution of 85 cm.

In order to estimate the temperature resolution of the N4385A DTS, the standard deviation (STD) of measured temperature distribution was calculated versus distance. Fig. 3b and Fig. 3c show the STD and temperature resolution, calculated as exponential fit of the STD, with 1.0 m spatial resolution setting and 1 and 10 min measurement time verifying the well known trade-off between these two parameters. Fig. 3b is made with setup 1 and shows a temperature resolution of 0.30 and 0.86 K at around 4 km sensing length; Fig. 3c is based on setup 3 and describes the performance up to 8 km with all sensing fibers at room temperature. The values in Fig. 3c are higher compared to Fig. 3b at the same fiber position due to a lower repetition rate of the Golay sequences in longer fibers and the not actively temperature regulated set-up. By increasing spatial resolution settings to 1.5 m and 3 m, the observed temperature resolutions at 8 km were respectively 0.65 K and 0.27 K with 10 min averaging time. As a result of the higher total fiber attenuation at longer distances, the temperature resolution changes accordingly. Similar results were obtained for fiber temperatures in the range -20 °C to 60 °C. To show high spatial resolution, we have stressed the operating conditions of the DTS system with respect to spatial resolution. In set-up 2, a short fiber section was heated to 50 °C, keeping the rest of the sensing fiber at 25 °C. Temperature traces from DTS, by heating 30 cm, 1 m and 2 m of fiber inside the TCC, at around 580 m,



(a) (b)

Fig. 2. (a) Temperature distribution with 100 m MMF placed at different temperatures. (b) Details of the measured temperatures



(a) (b) (c)

Fig. 3. (a) Spatial resolution from 25 K temperature step. (b) Standard deviations and temperature resolutions (exponential fit) of the DTS up to 4 km sensing fiber, and (c) up to 8 km sensing fiber, with 1 min and 10 min measurement time.

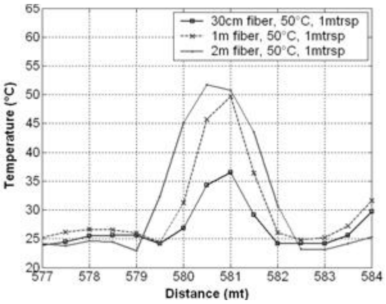


Fig. 4. Measured temperature values (setup 2), heating a MMF section (30 cm, 1 m and 2 m) at a sensing distance of ~ 580 m.

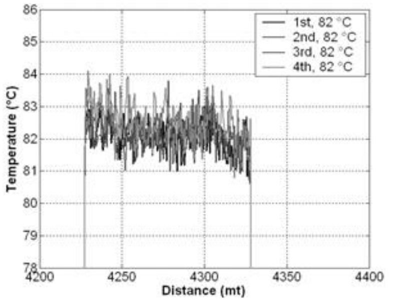


Fig. 5. Repeatability of four temperature measurements with the N4385A DTS.

are shown in Fig. 4. Note that accurate detection of the temperature variation can only be achieved when 1 m or 2 m of fiber are heated. In fact, by heating 30 cm spool (TCC at 50 °C), DTS could detect a lower temperature value (37 °C) compared to actual temperature. This feature can be exploited to detect highly spatially localized hot temperature spots. Finally, we have investigated the DTS system repeatability and stability within a broad operating temperature range of DTS equipment itself (from -10°C to 60°C). We have repeated several measurements with set-up 1, maintaining constant operating and temperature conditions for the DTS equipment (0.5 m sampling interval, 1.0 m spatial resolution setting, 10 min measurement time). Fig. 5 shows the repeatability (mainly related to temperature resolution) obtained when 100 m of sensing fiber (at about 4270 m) are heated to 82 °C. Similar measurements have also been performed at different temperatures, obtaining differences smaller than 1 K over several measurements along the fiber. By increasing spatial resolution settings (3.0 m), differences below 0.2 K can be seen among several measurements at about 4 km distance.

5. CONCLUSIONS

In conclusion, we have demonstrated for first time high performance Raman-based DTS for short-to-medium distance applications (up to 8 km). Using complementary correlation Golay codes, graded-index MMF and low-power external cavity lasers at 1064 nm, the proposed DTS system (Agilent N4385A) provides high repeatability of temperature measurements and a high spatial and temperature resolution up to 8 km sensing distance (for example, better than 1 m and 0.3 K with 10 min measurement time over ~ 4 km). Finally this combination enables also the use of standard semi-conductor lasers used in the telecom industry, which are known for long life-time, in Raman-based DTS.

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