

# Raman-based distributed temperature sensor with 1 m spatial resolution over 26 km SMF using low-repetition-rate cyclic pulse coding

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We experimentally investigate the benefits of a new optical pulse coding technique for long-range, meter and sub-meter scale Raman-based distributed temperature sensing on standard single-mode optical fibers. The proposed scheme combines a low-repetition-rate quasi-periodic pulse coding technique with the use of standard high-power fiber lasers operating at 1550 nm, allowing for what we believe is the first long-range distributed temperature measurement over single-mode fibers (SMFs). We have achieved 1 m spatial resolution over 26 km of SMF, attaining 3°C temperature resolution within 30 s measurement time. © 2011 Optical Society of America

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Distributed fiber-optic sensors based on Raman scattering are becoming a widely adopted technology [1], with a range of industrial applications spanning from oil and gas pipelines (for fire and leakage detection), to fire-alarm systems, reservoir and power cables monitoring. Raman-based distributed temperature sensor (RDTS) systems exploit the strong temperature sensitivity of the anti-Stokes Raman backscattered light, which is, however, characterized by extremely low power values, resulting in challenging measurements and requiring the use of high-sensitivity photodiodes, as well as the acquisition of many traces to decrease the noise impact through averaging. To partially overcome the trade-off among temperature resolution, sensing range and acquisition times, RDTS systems commonly employ multi-mode fibers (MMFs) [2,3], which are characterized by higher backscattering coefficients and also allow for higher input peak power levels before the onset of nonlinearities [3]. Unfortunately, modal dispersion ultimately limits the RDTS spatial resolution when using MMFs. Although this issue can be partially overcome by using graded-index MMFs, the best achievable spatial resolution is still limited to several meters when operating over long sensing ranges (tens of kilometers). In spite of these limitations, for many applications a better spatial resolution would be highly desired over long distances, together with fast acquisition times and high temperature resolution.

In order to enhance the sensing performance of RDTS systems, optical pulse coding techniques have been proposed based on either directly or externally modulated semiconductor lasers in MMFs [2] and SMFs [4]. In both cases the strong potential in terms of signal-to-noise ratio (SNR) enhancement provided by optical coding has been somehow limited by the available power in semiconductor lasers. In particular, for RDTS systems operating on standard SMFs with pulse coding, the maximum peak power level from a semiconductor laser that can be reasonably coupled into the sensing fiber is of the order of few hundred milliwatts; however, in principle, up to

~3–4 W could be used before exciting detrimental nonlinear effects, such as stimulated Raman scattering.

Hence, the use of new coding schemes, which could be used with high-power pulsed lasers [such as Q-switched and rare-earth-doped fiber lasers (REDFLs)] and be applied to SMFs, are expected to provide a significant impact on RDTS applications, both from academic and industrial points of view. In particular, applications requiring long sensing distances could effectively exploit already-installed standard SMFs, as, for example, in power cables monitoring.

In this Letter we report, for the first time to our knowledge, on the implementation of a long-distance RDTS system with 1 m spatial resolution, operating at 1550 nm over standard SMFs. The sensor makes use of a new cyclic coding scheme, which allows the effective use of standard high-power pulsed lasers with low repetition rates. The combined benefits of cyclic coding and high peak power levels allow for temperature sensing over 26 km standard SMF, attaining a temperature resolution better than 3°C and a spatial resolution of 1 m along the whole fiber length, within 30 s acquisition time. However, much longer sensing distances can be achieved relaxing the spatial resolution and measurement times.

In RDTS systems an optical pulse is launched into an optical fiber and the spontaneous Raman scattering (SpRS) is measured by optical time-domain reflectometry techniques [1–3]. In particular, the intensity trace of the temperature-dependent anti-Stokes component has to be normalized by a temperature-independent trace, such as the Stokes SpRS or Rayleigh component [2,3], so that the intensity variations due to the local fiber losses are cancelled out. Unfortunately, the intensity of the SpRS is about 60–70 dB below the used peak power levels in the fiber; therefore, the backscattered optical power reaching the receiver is very low, constituting the main factor limiting the sensing performance of RDTS systems.

Some techniques based on optical pulse coding have been proposed to enhance the SNR of RDTS systems

[4], as well as of Brillouin-based distributed optical fiber sensors [5]. In those cases, in order to achieve 1 m spatial resolution, a CW light is intensity-modulated by sequences of 10 ns pulses, corresponding to a modulation frequency of 100 MHz. Unfortunately, this frequency is incompatible with the pulsed-laser technology typically used in RDTS systems, which is characterized by high peak power (several tens of watt), low repetition rates (a few hundred kilohertz) and very low duty cycles (typically 0.1%). To overcome this limitation, recently a new coding technique based on cyclic Simplex codes has been theoretically proposed [6]. In such a scheme, optical pulses are launched into the fiber at a low repetition rate, and the fiber is “filled” with a large number of optical pulses.

Cyclic codes differ from previously reported schemes, since they are based on a quasi-periodic bit sequence (in our case we employed a Simplex-based pattern), being repetitively sent along the fiber and applicable even in the case of low repetition rates and very low duty cycles. In particular, the use of cyclic codes is fully compatible with standard high-power pulsed-laser technology, requiring only an additional external modulator to be used as a fast chopper when direct laser modulation cannot be applied. In the proposed cyclic coding technique, a suitable bit sequence is continuously generated from the pulsed laser light according to an  $M$ -bit binary pattern  $P = \{p_0, \dots, p_{M-1}\}$ , where  $p_j = 0, 1$  (with  $j = 0, \dots, M - 1$ ), with a proper repetition rate to fill the fiber with  $M$  bits (spaced in  $M$  consecutive intervals). In such a scheme, the detected trace  $y$  at a given sampling instant results from the sum of many contributions linked to the single-pulse fiber response  $x$  and the pulse pattern  $P$  [6], and it can be written as

$$y(i + jH) = \sum_{k=0}^{M-1} p_{|j-k|_M} \cdot x(i + kH), \quad (1)$$

where  $i$  and  $j$  are integer indexes associated with a given sampling instant  $T_S$  [ $T_S = \Delta T \cdot (i + jH)$ , where  $\Delta T$  is the sampling period], and  $H$  is the number of sampling points within one interval (for theory details on cyclic coding please refer to [6]). Cyclic coding exploiting the Simplex pattern offers an SNR enhancement that is equal to  $(L+1)/(2\sqrt{L})$ , where  $L$  is the code length. The coding gain can be used to improve the temperature resolution

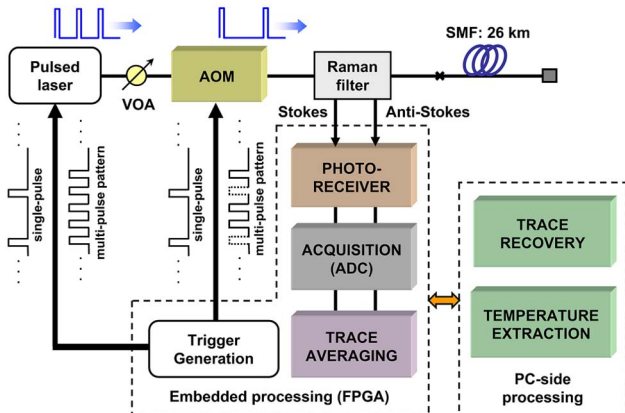


Fig. 1. (Color online) Experimental setup.

of a conventional RDTS, to extend the sensing distance of standard long-range RDTS systems based on MMFs (in this case, a worse spatial resolution is expected due to the significant dispersion resulting from the longer fiber), or to allow SMFs to be used for long-distance RDTS systems with meter or submeter scale spatial resolution.

Although a successful theoretical prediction of the scheme effectiveness has been reported in [6], so far there is no experimental evidence of the benefits and real sensing performance provided by this technique. In this work, the benefits provided by this novel coding method have been experimentally investigated, achieving what we believe is the first demonstration of a long-range RDTS with 1 m spatial resolution using SMFs.

The setup used in the experiment is shown in Fig. 1. The light source is a high-power REDFL at 1550 nm (50 W maximum peak power at 2.5 kHz rate), with 10 ns pulses and a maximum repetition rate of  $\sim 250$ – $300$  kHz. A variable optical attenuator has been used to adjust the input power into the fiber, and thus to avoid nonlinear effects. An acousto-optic modulator (AOM), controlled by a field-programmable gate array (FPGA), is used to generate the cyclic Simplex codeword to be launched into the fiber. The main function of the AOM is to act as a chopper, cancelling out laser pulses when a bit “0” is generated and letting pulses through when a bit “1” is expected. Pulses are sent into a 26 km standard SMF using a suitable optical filter, which also allows us to separate the SpRS Stokes and anti-Stokes components into two ports at the receiver side. Each receiver branch is composed of an avalanche photodiode, a high-gain electrical amplification stage, and a custom FPGA-controlled analog-to-digital converter, which is then connected to a computer for data logging.

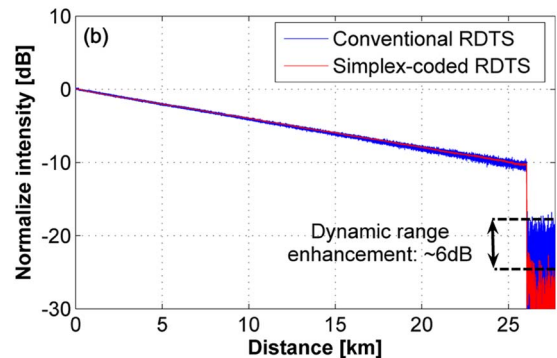
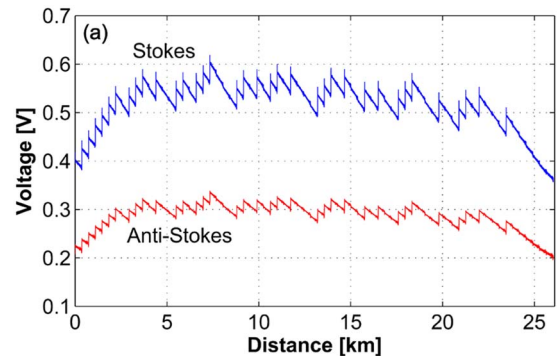


Fig. 2. (Color online) (a) 71 bit cyclic Simplex coded Stokes and anti-Stokes traces, (b) anti-Stokes traces obtained with conventional RDTS and cyclic-coded RDTS (decoded trace).

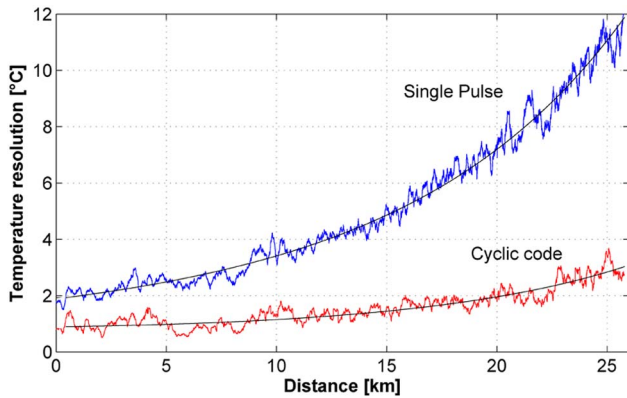


Fig. 3. (Color online) Temperature resolution versus distance, for both single-pulse RDTs and cyclic Simplex coded RDTs.

First, we have experimentally measured the threshold for nonlinear effects along the sensing fiber, a value that was found to be  $\sim 37$  dBm. However, we have employed a pulse peak power of 35 dBm in order to allocate some power margin. To estimate the SNR enhancement provided by the proposed cyclic code, measurements with coding are compared to the ones obtained by the conventional technique, using the same acquisition time and the same peak power. The repetition rate of the laser has been set to  $\sim 230$  kHz, and, hence, 71 bits have been allocated along the whole 26 km long SMF.

Figure 2(a) shows the acquired coded anti-Stokes and Stokes traces, where we can observe the repetition period of the bits corresponding to a 435 m fiber distance, which is linked to the laser repetition rate ( $\sim 230$  kHz). After decoding of the distributed-coded traces, the single-pulse response of the fiber for the anti-Stokes and Stokes components are recovered with an extended dynamic range as well as an improved SNR compared to the standard single-pulse technique. Figure 2(b) actually shows a comparison of the normalized anti-Stokes traces obtained with the conventional scheme and with the distributed codes (after decoding), both measured with 100 k time-total averaged traces, corresponding to the same 30 s measurement time. By calculating the root mean square of both normalized traces, the experimentally achieved coding gain (equivalent to the SNR enhancement) was found to be 6.0 dB, which is in good agreement with the expected theoretical value (6.3 dB).

Note that the performance of standard RDTs with SMFs is affected by a very low achievable SNR, an issue that strongly impacts on the final temperature resolution of the sensor, as reported in Fig. 3. Actually, we can observe that the single-pulse RDTs provides a poor temperature resolution, which in our experiment resulted equal to  $12^\circ\text{C}$  at 26 km distance (see Fig. 3); the use of distributed optical coding improves the attainable resolution down to  $3^\circ\text{C}$  at the same distance. A comparison with the conventional RDTs (where a  $3^\circ\text{C}$  resolution is achieved at  $\sim 8$  km distance) shows that the proposed technique can offer a sensing range enhancement of about 18 km (using 71 bits cyclic codes).

To evaluate the spatial resolution achieved in our experiment, the temperature of the last few meters of fiber (near 26 km distance) has been increased up to  $55^\circ\text{C}$ , while the rest of the fiber is kept at room temperature

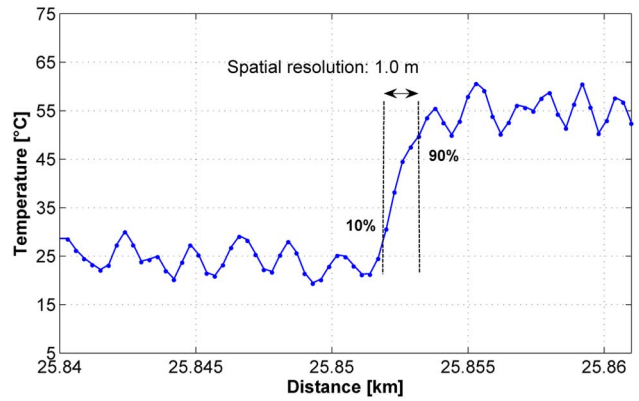


Fig. 4. (Color online) Temperature profile versus distance, near  $\sim 26$  km distance, with cyclic Simplex coded RDTs.

( $25^\circ\text{C}$ ). Figure 4 shows the measured temperature profile, where a spatial resolution of  $\sim 1.0$  m can be observed (10%–90% response distance to a temperature step).

It is worth mentioning that the use of distributed coding in SMF allows for temperature resolutions similar to what is typically achieved over MMFs (using conventional RDTs) [3]; however, the attainable spatial resolution using SMFs is significantly better than over MMFs. Moreover, the proposed technique can enable the use of already-installed SMFs (e.g., for telecommunication purposes) for high-spatial-resolution sensing over long ranges, without the need of installing new MMF cables. Note that the absence of intermodal dispersion in SMFs also potentially allows for long-range sensing with sub-meter spatial resolution, which is in practice impossible to achieve with conventional RDTs systems over MMFs.

In conclusion, we have experimentally investigated the benefits of cyclic coding techniques on long-range RDTs systems. The proposed scheme enables the use of SMFs and high-power pulsed-laser technology for long-range sensing, overcoming the spatial resolution degradation that affects standard RDTs systems based on MMFs as well as the limited SNR of standard RDTs over SMFs. This feature can actually allow for long-distance sensing with meter or submeter resolution. In particular, we implemented an RDTs operating over 26 km of standard SMF with 1 m spatial resolution,  $3^\circ\text{C}$  temperature resolution, and 30 s measurement time.

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