One-dimensional temperature reconstruction for Raman distributed temperature sensor using path delay multiplexing

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One-dimensional temperature reconstruction for Raman distributed temperature sensor using path delay multiplexing

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The laser pulse width is the limiting factor for high spatial resolution measurement with a Raman distributed temperature sensor (RDTS). A 5 ns laser pulse from a RDTS system has a spatial resolution of 1 m. A methodology is proposed to improve this spatial resolution limit. © 2009 Optical Society of America

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1. INTRODUCTION

Optical fiber-based Raman distributed temperature sensors (RDTS) with inherent advantages such as immunity to electromagnetic interference, flexibility, low material reactivity, and long transmission distances are widely used for distributed and continuous temperature monitoring of oil plants, nuclear reactors, power cables, and environmental monitoring [1,2]. The major limitation of the RDTS is its spatial resolution capability. The spatial resolution is determined by the convolution between the laser pulse characteristics, the detector/receiver response, and the filter characteristics. For a rectangular pulse, it can be shown that the spatial resolution is given by [3]

$$L = \frac{c \times t}{2n_g}, \tag{1}$$

where t is the pulse width of the laser, n_g is the group refractive index, and c is the velocity of light.

A typical RDTS uses a 5 ns pulse width laser and has a spatial resolution of 1 m. Many groups have worked towards increasing the spatial resolution of the system.

Thorncraft *et al.* [4] used an Nd-YAG laser with a short pulse width of 200 ps, full width at half-maximum (FWHM), and a repetition frequency of 100 MHz. The output of this laser is frequency doubled to produce 532 nm pulses with a pulse width of 57 ps and FWHM to match the response of the detector and to increase Raman scattering. The backscattered Raman light from the single-mode fiber is directed to a filter through a coupler to filter the anti-Stokes lines. The anti-Stokes line is detected using a photomultiplier tube. The spatial resolution achieved is 5 cm with the integration time of 6 min and temperature resolution of 6 °C.

Kazuo Hotate *et al.* [5] used frequency-modulated continuous-wave lasers as the pump and probe in a Brillouin distributed sensor system. At certain points, the correlation between the probe and the pump is high, while in other regions it is low. At the position where the correlation peak takes place, the Brillouin gain spectrum takes the same shape of an intrinsic spectrum without the modulation. On the other hand, at other positions where the correlation is low, there is suppression of the gain. Thus, the gain spectrum obtained at the fiber end consists mainly of the gain at the position where the correlation-based continous-wave technique takes peak. Hence, the gain spectrum obtained at the fiber end enables the measurement of the strain at the position of the correlation peak. The system parameters are chosen so that only one peak stands in the region to be measured. The spacing of the peak depends on the frequency of modulation. Thus by varying the frequency of modulation, distributed measurement is possible. The spatial resolution is now the width of the correlation peak. The spatial resolution achieved is 2.9 cm when the probe and the pulse are modulated at 24.5 MHz. A similar approach can be used for spatial improvement of a Brillouin-based distributed temperature sensor.

Healey *et al.* [6] used the avalanche photo diode (APD) in Geiger mode such that even a single photon can trigger an avalanche. Two photons were launched into the fiber. The first photon was sent and swept in increments of 100 ns through a period defined by twice the time of flight in the fiber. The second photon was sent after a time greater than the time corresponding to the time of flight to the distant end of the fiber. The photon arrival rate was then computed by obtaining the running difference between the counts recorded in the fiber and the background sampling intervals. The apparatus was arranged to dwell at each point until a fixed number of photons was recorded, and then it moved to the neighboring point. Using this methodology, spatial resolution of 10 cm has been reported [7,8].

The problem with single photon counting is the large measurement time. This is overcome by using a multiphoton counting technique [9]. Höbel *et al.* developed a fast multi-time-interval analyzer with real-time processing

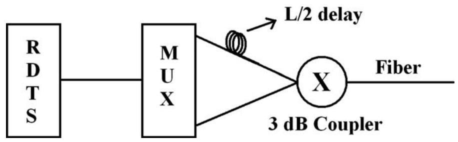

Fig. 1. Schematic of fiber sensor connected to the RDTS system through a fiber switch, which introduces path length offset between different measurements.

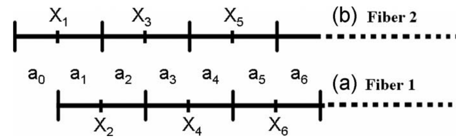

Fig. 2. (a) Fiber 1 without delay line. (b) Fiber 2 with a delay line of $a_0=L/2$ Major division corresponds to temperature measured through the RDTS. Minor division corresponds the spatial resolution to be achieved.

capability. It has a time resolution of 4 ns and covers in its 4096 channels a measurement range of 16.4 μs. They achieved a spatial resolution of 40 cm in a 1600 m long fiber.

The above-mentioned methods require that either the source (the pulse width of the laser/frequency modulation of probe and pump) has to be changed and/or the detector (APD in Geiger mode/multi-time-interval analyser) has to be changed. Denisov *et al.* have worked with fiber grids to improve the spatial resolution of RDTS [10,11].

Chi *et al.* [12] used delay lines to sample the Brillouin frequency shift in overlapped regions and used the decomposition of spectra of spontaneous Brillouin scattering signals for determining the temperature profile at interpolated regions.

In this paper, we present a delay line-based method applied to an RDTS. A one-dimensional temperature reconstruction for an RDTS is presented here.

2. METHODOLOGY

The proposed configuration consists of an RDTS system connected to a fiber sensor through a set consisting of an optical switch and a delay line (Fig. 1). The delay line introduces a path length offset of $L/2$. The fiber sensor is labeled as fiber 1 when there is no path offset (Fig. 1). The same fiber sensor connected to the same RDTS with a path length offset of $a_0=L/2$ is labeled as fiber 2. We can consider the fiber sensor to be comprised of many segments a_1, a_2, $a_3, \ldots . a_n$ of equal lengths of $L/2$. It is assumed that the temperature along each of the segments is uniform. The temperature profile over the section $\{a_1{:}a_2{:}a_3\ldots . a_n\}$ is $\{\theta_1{:}\,\theta_2{:}\,\theta_3\ldots\theta_n\}$. The temperature profile measured by the RDTS over the section $\{X_2{:}X_4{:}X_6\ldots X_n\}$, is $\{T_2{:}T_4{:}T_6\ldots T_n\}$ when it is measured through fiber 1. Similarly, the temperature profile measured over the section $\{X_1{:}X_3{:}X_5\ldots X_{n-1}\}$ is $\{T_1{:}T_3{:}T_5\ldots T_{n-1}\}$ when it is measured through fiber 2. (Fig. 2)

The temperature measured by fiber 1 is the convolution between the shape of the laser excitation pulse, the fiber back-scattering response, and the response of the receiver. Linear approximation suffices for engineering applications when the temperature across each of the segments $\{a_1{:}a_2{:}a_3\ldots . a_n\}$ is uniform. Temperature measured by fiber 1 over the section $\{X_2{:}X_4{:}X_6\ldots X_n\}$ is given by

$$T_2 = (1/2)(\theta_1 + \theta_2), \quad (2)$$

$$T_4 = (1/2)(\theta_3 + \theta_4). \quad (3)$$

Temperature measured by fiber 2 over the section $\{X_1{:}X_3{:}X_5\ldots X_{n-1}\}$ is given by

$$T_1 = (1/2)(\theta_0 + \theta_1), \quad (4)$$

$$T_3 = (1/2)(\theta_2 + \theta_3). \quad (5)$$

The set of equations, for the entire fiber can be represented in matrix form:

$$1/2\begin{pmatrix} \theta_0+\theta_1 & & & & & & \\ & \theta_1+\theta_2 & & & & & \\ & & \theta_2+\theta_3 & & & & \\ & & & \theta_3+\theta_4 & & & \\ & & & & \cdot\cdot\;\cdot\cdot & & \\ & & & & & \cdot\cdot\;\cdot\cdot & \\ & & & & & & \theta_{n-1}+\theta_n \end{pmatrix} = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ \cdot\cdot \\ \cdot\cdot \\ T_n \end{pmatrix}. \quad (6)$$

The number of variables is $n+1$ and the number of equations is n.

Equation (6) can be solved if at least one of the variables is known *a priori*. This is achieved by introducing a control zone/reference zone, with a known temperature profile. We have kept the reference zone at room temperature, the uniformity of which can be easily achieved.

3. EXPERIMENTAL SETUP

To implement the methodology described above, the spatial resolution L of the RDTS had to be determined. The RDTS divided the fiber into discrete sections, each of length L, over which the temperature was integrated. To measure L, a heater of dimensions 4 cm$\times$3 cm was moved along the length of the fiber. This heater acted as a delta temperature function. The heater was maintained at 80 °C. The RDTS measurement was taken at each heater position after the fiber temperature had attained equilibrium. At the beginning and end of each section, the RDTS response to such localized heating was minimal, while at the center of such discrete fiber sections the fiber response was maximal. It can be seen in Fig. 3 that the RDTS response function repeated itself over every discrete fiber section. A spline curve was fit and the peak po-

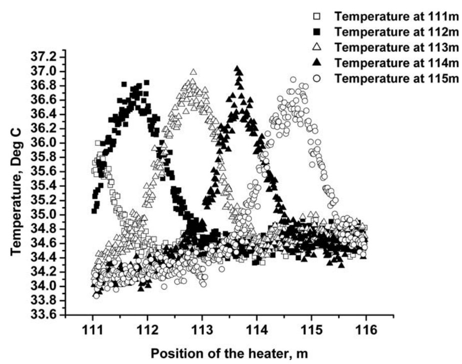

Fig. 3. Temperature measurement by the RDTS at consecutive positions along the length of the fiber as the heater is moved along the length of the fiber.

sition was calculated for each of the peaks. The average peak-to-peak position was 1.02 m. This is the spatial resolution of the RDTS.

After the discrete fiber sections were identified, a heater of length 0.51 m was used (length equal to half the spatial resolution) to heat exactly one-half of the discrete section. This ensured (see Fig. 2) that the temperature measurement would be reflected in only one section in each fiber. The two fiber measurements were separated by 0.51 m. The experimental set up consisted of an RDTS system connected to the fiber sensor through a set consisting of an optical switch and a delay line (Fig. 1). The fiber sensor used was acrylate-coated graded-index multimode fiber, 50 μm/125 μm.

The RDTS was connected to a two-channel multiplexer. The RDTS scanned the two channels every 10 s alternatively. One channel of the RDTS was connected to the input arm of a 3 dB coupler (2×1) by a fiber patch cord with an E2000 connecter compatible with the RDTS of length 2 m. The second channel was connected to the other input arm of the coupler by a similar fiber patch cord of length 2.51 m. Since spatial resolution of the system was 1.02 m, and $L/2=0.51$ m, an additional 0.51 m delay line was introduced to the measurement. The output arm of the coupler was connected to the fiber sensor.

4. RESULTS AND DISCUSSIONS

In this study, the whole of the fiber was maintained at uniform room temperature except for the heating zone at 94.5 to 95 m, which was heated to 80 °C. The temperature measured using fiber 1 is represented by dotted curves in Fig. 4. A second measurement made using fiber 2 is represented by dashed curves in the same figure. It can be seen that the delay line introduced in fiber 2 resulted in a shift in the peak position of fiber 2. The temperature corresponding to the segment 80 to 81 m is presented at 81 m, 81 to 82 m at 82 m, 82 to 83 m by 83 m, and so on.

The noise in the measurement is due to microbends, macrobends, and possible stresses induced during fiber laying. Also, the temperature of the heating zone measured by the RDTS on fiber 1 and fiber 2 is 40 °C and 41 °C, respectively. This is because the fiber averages the temperature profile over one pulse width.

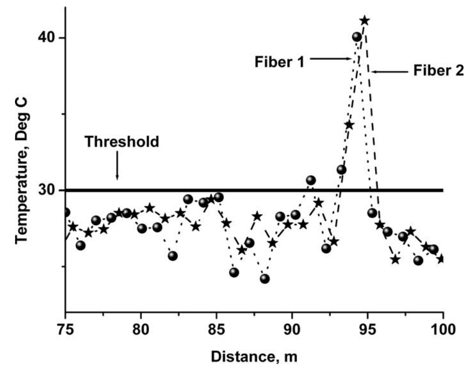

Fig. 4. Temperature measurement by fiber 1 (dotted curve) and fiber 2 (dashed curve). The two scans differ by path length$=L/2$. The spatial resolution is 1.02 m.

For computing the desired temperature profile, $\theta_1:\theta_2:\theta_3\ldots\theta_n$, we considered a reference zone to be comprised of 70 to 75 m, starting with $\theta_{x=70}=30$ °C. The temperature thus reconstructed with a spatial resolution of 0.51 m using Eq. (6) is shown in Fig. 5. It might be observed that though the spatial resolution is improved, error due to the noise is propagated and more pronounced at longer lengths away from the reference zone. To overcome this, a threshold filter was applied (solid line in Fig. 4), and measurements above this threshold were considered for computation.

The temperature profile thus obtained after threshold filtering is given in Fig. 6. It can be seen that a peak is represented at 95 m. The actual temperature at the heater measured using a thermocouple was 80 °C. The peak temperature obtained in this location was 83 °C, which is closer to that.

Usually improvement of the spatial resolution is at the cost of temperature resolution. This is the case when temperature is constant over longer lengths and spread over a few segments. If the pulse width is large (say, 10 ns for a 1 m spatial resolution) scattering over a large section of the fiber is integrated, and hence the measurement is more robust. For a shorter pulse width (say, 1 ns for a 10 cm spatial resolution), scattering is integrated over a smaller segment of sensor fiber, which gives rise to a lower temperature resolution. However we are considering here those cases where there is a temperature differential within the range of the pulse width. Hence in this

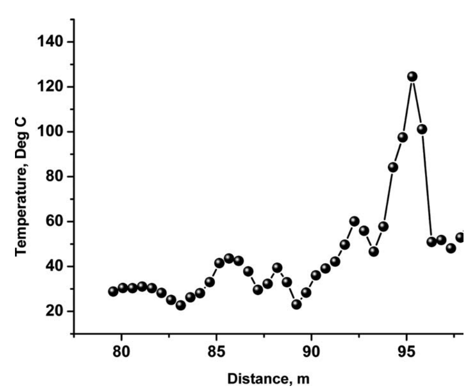

Fig. 5. Temperature reconstructed with spatial resolution of 0.51 m. Note error propagation along the length of the fiber.

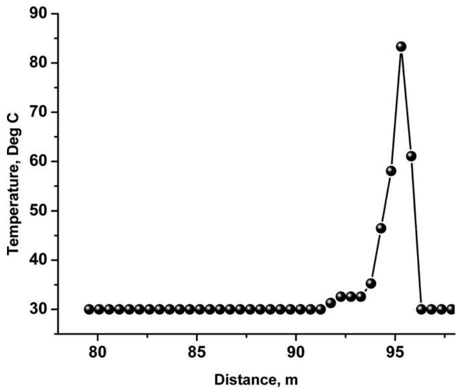

Fig. 6. Temperature reconstructed with spatial resolution of 0.51 m after applying a threshold filter (see Fig. 4).

methodology the improvement in spatial resolution does not affect the temperature resolution.

5. CONCLUSION

We have presented a methodology to increase the spatial resolution of a RDTS by using a single delay line. We have demonstrated improvement of the spatial resolution from 1.02 m to 0.51 m by using this method. The measurement cycle time of the RDTS is 10 s. Generally the fiber is connected to the RDTS and a measurement is taken only once. Since a path delay is introduced, the RDTS has to scan the fiber through the multiplexer twice—once without the path delay and another with the path delay. Thus the measurement time will be twice for improving the spatial resolution by two times. If spatial resolution has to be improved by three times, two path delays of $L/3$ and $2L/3$ have to be introduced. Thus the RDTS scans the fiber three times, increasing the measurement time by three times. So in general, if the RDTS spatial resolution has to be increased by n times, the measurement time also increases by n times. The number of delay lines can be increased for higher spatial resolution at the cost of measurement time. Therefore the spatial resolution and the measurement time have to be optimized specifically to an application.

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