INVESTIGATION OF THE USE OF SINGLEMODE AND MULTIMODE OPTICAL FIBERS FOR DISTRIBUTED TEMPERATURE SENSING

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Abstract: The optical fiber for Distributed Temperature Sensing (DTS) is mainly selected by considering two important parameters viz., the Raman anti-Stokes capture coefficient and the attenuation constant at anti-Stokes wavelength. In this paper, we investigate the use single-mode and multi-mode fibers for distributed temperature sensing through modeling/simulations and verify the same through careful experimentation.

1. INTRODUCTION

It is well known that Spontaneous Raman Scattering (SRS) in optical fibers may be used for distributed temperature sensing [1]. In this technique, absolute value of temperature experienced by the sensing fiber can be estimated by normalizing the anti-Stokes scattered light using the temperature-independent Stokes component. Employing such a normalization step, one can remove non-thermal effects such as fiber material attenuation and bend losses. This effect coupled with the optical time domain Reflectometry (OTDR) or optical frequency domain reflectometry (OFDR) principle provides a powerful method for distributed sensing of temperature over several kilometer long fibers [2].

One of the key aspects of the sensing fiber is its capture cross-section i.e., the fraction of backscattered radiation that is supported by the sensing fiber. Although single-mode fibers (SMF) are widely used for its low chromatic dispersion characteristics in communications, graded-index multi-mode fibers (MMF) are preferred for sensing applications because of their larger capture cross-section. In this paper, we investigate the relative merits of single-mode and multi-mode fibers for distributed temperature sensing based on Raman scattering coupled with OTDR.

2. DEMONSTRATION OF DISTRIBUTED TEMPERATURE SENSING

Figure 1 illustrates the experimental setup used for Distributed Temperature Sensing (DTS). In the setup, laser pulses are launched into the sensing fiber through an optical circulator. The backscattered radiation is optically filtered to extract the Stokes and anti-Stokes components and directed to the receiver using an optical switch. Spatial resolution ($\delta l$) is defined as the smallest length of the fiber over which any change of the measurand can be detected. In general, there is a strong trade-off between dynamic range (defined as the fiber loss range over which temperature could be reliably measured) and spatial resolution in Distributed anti-Stokes Raman Thermometry (DART) based sensors. For example,

to achieve minimum spatial resolution one has to launch the shortest possible light pulse into the fiber. But, the short duration of the laser pulse effectively covers only a short length of fiber at any instant and the corresponding backscattered power is low. This in turn limits the dynamic range or in other words, the distance over which the backscattered signal is above the noise level.

2.1. Receiver Design

The receiver design is driven by the OTDR equation, which is expressed as

$$ P_L - P_D + SNIR = R_i + C + 2L $$

where $P_L$ – Peak laser output power (dBm), $P_D$ – Receiver sensitivity (dBm), $SNIR$ – Improvement in SNR (dB), $R$ – Raman Backscattering coefficient (dB), $i$ – Stokes or anti-Stokes component, $C$ – Circulator and connector losses (dB), $L$ – Single-pass loss in fiber (dB). The anti-Stokes Raman scattering coefficient for single mode fiber at pump wavelength of 1550nm is in the order of $4e-11m^2/TZe$ at frequency shift of 13.2THz [2]. Since the Raman scattering coefficient is very small, one has to design high sensitive receiver for capturing anti-Stokes signal. By averaging the OTDR trace 256K times, one can get SNR improvement of 27 dB. Hence, to cover a sensing region of 10 km, the receiver needs to have...
sensitivity in the order of -84 dBm. The important parameters that decide the performance of OTDR are the spatial resolution and dynamic range.

The main goal of the design is to amplify the anti-Stokes signal in the order of hundreds of mV levels and provide a spatial resolution in the order of meters. In receiver design (Fig. 2), we have used Avalanche photodiode (APD), which is used for converting the optical signal to photocurrent. Transimpedance amplifier (TIA) based on a Texas Instruments Low Noise FET operational amplifier OPA 657 with a gain bandwidth product of 1.6GHz is used to convert the photocurrent to voltage. Differential amplifier follows TIA stage, which is designed by using Analog devices ultra low noise Differential input Differential output AD8139 amplifier which is having an unity gain bandwidth of 410MHz. The main advantage of using AD8139 is its internal common-mode feedback architecture allows its output common-mode voltage to be controlled by voltage applied to a pin therefore it is an ideal choice for driving the analog-to-digital converter (ADC). Differential design filters out the power supply and common-mode noise of the receiver. As shown in Fig. 1, the amplified electrical signals were first digitized using 10-bit Analog Devices ADC 9214. The digitized signals were averaged in the FPGA, which was working in tandem with two banks of SRAM to accomplish this task. Finally, the averaged traces were extracted through an USB port.

3. SIMULATION AND DEMONSTRATION OF RAMAN-OTDR USING SINGLEMODE AND MULTIMODE FIBERS

In our simulations, we start with an user interface that provides the characteristics of the optical fiber used, the desired circuit elements, and the sample temperature map. The model will then proceed to extract the backscattered spectral components, apply the bandpass filter function and other attenuation mechanisms such as circulator, connector, fiber losses. This process is repeated for a section of fiber corresponding to the pulsewidth and then finally the traces formed at the receiver circuit (including the averaged receiver noise). Simulation results of the model for a laser power of 85 mW, pulse width of 80 ns, fiber length of 10 km with three sections of fiber is heated to different temperatures for single-mode and multi-mode fibers are illustrated in the following sections.

3.1. Distributed Temperature Sensing using single mode fibers

The distributed temperature map for our experiments was created by housing three 30 m long spools of single mode fibers (SMF) maintained at 63, 5, 63 deg C temperatures respectively. The input temperature map given to the model and the corresponding output temperature map obtained from our model as well as our experimental setup are shown in the Figs 3, 4 respectively. A comparison of

![Fig. 3. Input Temperature map to the model](image)

![Fig. 4. Estimated and Experimental Temperature Map using SMF](image)
The Stokes spectral band, whereas for the singlemode fiber it is in the order of 6e-10 m^-1. However, it should be noted that SMF is an attractive choice for long sensing distances because of its low attenuation constant (0.25 dB/km compared to 0.5 dB/km for MMF). The distributed temperature map using MMF was created by housing three 30 m long spools of fibers maintained at 73, 5, 73 deg. C temperatures respectively. The characteristics of the SMF and MMF-based experimental setup are tabulated in Table 1.

The input temperature map used for the model and experiments is similar to that shown in Fig. 3 (except for a change in oven temperature setting). The corresponding output temperature map is shown in the Fig 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SMF</th>
<th>MMF</th>
</tr>
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<tbody>
<tr>
<td>Capture coefficient over anti-Stokes band (m^-1)</td>
<td>6e-10</td>
<td>20e-10</td>
</tr>
<tr>
<td>Background fiber losses (dB/km)</td>
<td>0.25</td>
<td>0.50</td>
</tr>
<tr>
<td>Losses in the experimental setup (dB)</td>
<td>4.5</td>
<td>10.1</td>
</tr>
</tbody>
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Table 1. Comparison of SMF and MMF fiber parameters

The performance parameters of single mode and multi-mode fibers are tabulated in Table 2. Based on the larger cross-section, one would expect better performance with MMF. However, the higher losses in multimode fiber components resulted in comparable performance for both SMF and MMF. The experimental results were found to be also consistent with our simulations.

**Table 2.** Performance comparison of R-OTDR based on SMF and MMF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SMF (10 Km)</th>
<th>MMF (4.9 Km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Resolution (m)</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Temp. Inaccuracy (Deg. C)</td>
<td>+/- 3.2</td>
<td>+/- 2.8</td>
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4. REFERENCES