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ANALYSIS OF SMS FIBER TEMPERATURE SENSORS USING OPTICAL TIME-DOMAIN REFLECTOMETRY

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ABSTRACT

This paper presents an experimental investigation of Single-Mode–Multimode–Single-Mode (SMS) fiber optic sensors interrogated using Optical Time-Domain Reflectometry (OTDR). The study examines modal interference within the multimode fiber (MMF) section and its influence on overall sensor performance. SMS-based OTDR sensors offer several advantages, including structural simplicity, low cost, and ease of fabrication. However, they also present limitations, such as relatively low temperature sensitivity compared to other fiber-optic temperature sensors, and resolution constraints determined by the OTDR noise floor. An experimental setup for characterizing SMS fiber sensors using OTDR is described, and results are analyzed in terms of sensitivity, resolution, and linearity to temperature variations. The analysis highlights the role of multimode interference, the thermal dependence of the effective refractive index, and the function of OTDR in signal acquisition and processing. The findings are compared to previous studies by Dey and Roy [1] and Hatta et al. *[2].*

1. INTRODUCTION

Temperature is one of the fundamental thermodynamic properties. Temperature measurement accounts for approximately 75% - 80% of the worldwide sensor market [3]. The broad range of temperature measurement techniques includes thermoelectricity, resistance, fluorescence, and spectral characteristics. The method can be invasive, semi-invasive, or non-invasive depending on the nature of contact between the measuring device and the medium of interest. Accuracy, sensitivity, life, size, cost, manufacturing constraints, dynamic response, temperature, and robustness determine the choice of conventional temperature sensors.

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However, harsh environments with high temperatures and pressures in nuclear energy production and aircraft turbines, strong electromagnetic radiation in high-voltage transformers, and highly corrosive chemicals in many industries present a challenge to electronic temperature sensors. Fiber-optic temperature sensors are gradually replacing conventional types due to their lightweight, low cost, fast response times, compact size, immunity to electromagnetic interference, remote detection, multiplexing, and distributed measurement [4]. These modern devices have attracted intense research interest in recent years [5], [6],[7]. Figure 1 depicts various optical fiber-based temperature sensors [8].

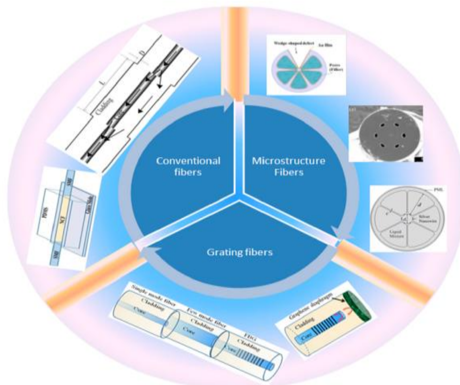

Figure 1: Summary of various optical fiber based temperature sensors [8].

Among various fiber sensor configurations, the SMS fiber structure shown in Figure 2, is one of the easiest to construct. It is simply a section of multimode fiber (MMF) spliced between two single-mode fibers (SMF). This device gives an effective sensing mechanism based on modal interference [9],[10].

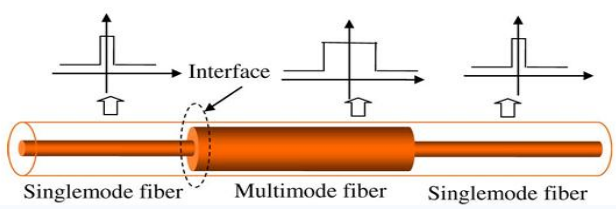

Figure 2. Schematic configuration of single-mode-multimode-single-mode fiber structure [11].

When light propagates from the input SMF into the MMF, multiple modes are excited. These modes interfere with each other as they propagate through the MMF, creating a modal interference pattern that is highly sensitive to external perturbations in the immediate environs [12]. The structure has emerged as a promising technology for sensors due to its simplicity, low cost, and ease of fabrication. By monitoring the changes in the interference pattern, fluctuations in temperature or stress can be tracked using Optical Time-Domain Reflectometry (OTDR).

OTDR is a powerful technique for characterizing optical fibers and detecting faults along their entire length [13]. This instrument launches a short pulse of light into the fiber and measures the backscattered and reflected light as a function of time. Analysis of the backscattered signal can provide information about the fiber's attenuation, reflectance, and the location of discontinuities [13], [1], [2]. The integration of OTDR with SMS fiber sensors enables both point measurement and distributed temperature sensing. For extended measurements, multiple SMS sensor elements can be multiplexed along a single fiber and interrogated remotely [10]. This approach holds promise for applications in industrial process control, structural health monitoring, and regional environmental sensing.

This paper aims to provide a performance analysis of short SMS fiber temperature sensors using OTDR. Many reports in the literature describe fibers in the kilometer range with centimeter-long MMF sections. First, we outline the theoretical model of modal interference within the MMF section and its sensitivity to temperature variations. Next is a description of the experimental setup and results demonstrating the feasibility and performance characteristics of the SMS-OTDR temperature sensor. The paper concludes with limitations and potential improvements of this sensing device

2.1 Theoretical Background

The operating principle of an SMS fiber sensor relies on the interference of multiple modes propagating within the MMF section. When light from the input SMF is launched into the MMF, it excites several guided modes with different propagation constants [9]. These modes propagate through the MMF section and interfere at the interface of the output SMF. The interference pattern, and hence the light coupled into the output SMF, is sensitive to changes in the MMF's refractive index and length, which are influenced by external parameters such as temperature and strain [9],[13],[1]. The electric field at the output of the MMF can be expressed as the superposition of these modes [11]:

$$E(z,t)=\sum_{m=1}^{M} A_m e^{(j(\omega t-\beta_m z))} \quad (1)$$

where $E(z,t)$ is the electric field along z and time t, A_m is the amplitude of the $m-th$ mode, ω is the angular frequency of the light, β_m is the propagation constant of the $m-th$ mode, and M is the total number of modes.

The intensity at the output of the MMF is given by:

$$I=|E(z,t)|^2=\sum_{m=1}^{M}|A_m|^2+2\sum_{m=1}^{M}\sum_{n=m+1}^{M}|A_m||A_n|\cos((\beta_m-\beta_n)z) \quad (2)$$

This equation shows that the output intensity is a result of the interference between different modes. Equation can also be viewed as the intensity of light transmitted through the SMS structure that can be approximated by:

$$I\approx I_0\left|\sum_{m=1}^{M} a_m e^{(j\varphi_m)}\right|^2 \quad (3)$$

where I_0 is the input intensity, a_m is the excitation coefficient of the $m-th$ mode, $\varphi_m=\frac{2\pi n_m L}{\lambda}$ is the phase accumulated by the $m-th$ mode, n_m is the effective refractive index of the $m-th$ mode, L is the length of the MMF section, λ is the wavelength of light.

2.2 Temperature Dependence of Modal Propagation

Changes in temperature (ΔT) or strain $(\Delta\varepsilon)$ induce changes in the effective refractive indices and the length of the MMF section, leading to a shift in the interference pattern and a change in the transmitted intensity. The interference pattern is sensitive to changes in the propagation constants

β_m, which are affected by variations in temperature, strain, and refractive index. The propagation constant β_m of the $m-th$ mode is given by [1]:

$$\beta_m = \frac{2\pi n_m}{\lambda} \tag{4}$$

where n_m is the effective refractive index of the $m-th$ mode and λ is the wavelength of the light. The temperature dependence of the effective refractive index can be expressed as:

$$\frac{dn_m}{dT} = \frac{\delta n_m}{\delta T} + \frac{\delta n_m}{\delta \lambda}\frac{d\lambda}{dT} \tag{5}$$

where $\frac{\delta n_m}{\delta T}$ is the thermo-optic coefficient, which represents the change in refractive index with temperature, and $\frac{\delta n_m}{\delta \lambda}\frac{d\lambda}{dT}$ accounts for the wavelength dependence of the refractive index and the thermal expansion of the fiber.

The change in the phase difference between two modes, $\Delta\varphi_m = (\beta_m - \beta_n)L$ due to a change in temperature ΔT can be approximated as:

$$\Delta\varphi_{mn} \approx \frac{2\pi L}{\lambda}\left(\frac{dn_m}{dT} - \frac{dn_n}{dT}\right)\Delta T \tag{6}$$

where L is the length of the MMF section.

This change in intensity can be detected by the OTDR and associated with the applied temperature or strain. OTDR measures the backscattered light from the SMS structure. The power of the backscattered signal is given by [14]:

$$P(z) = P_0 S \alpha_s s^{-2\alpha z} \tag{7}$$

where $P(z)$ is the backscattered power from a point at distance z along the fiber, P_0 is the launch power, S is the backscatter capture fraction, α_s is the scattering coefficient and α is the attenuation coefficient. Any changes in the SMS structure due to external factors will affect the depth and shape of reflection peaks, which is analyzed to determine temperature changes.

3. Experimental Setup

An experimental setup was mounted to characterize the performance of SMS fiber sensors using OTDR interrogation (Figure 3). Key components of the setup include SMS fibers were fabricated by splicing a 5 cm section of step-index multimode fiber (MMF) between two sections of single-mode fiber (SMF). The of the MMF section was optimized to enhance sensitivity [15].

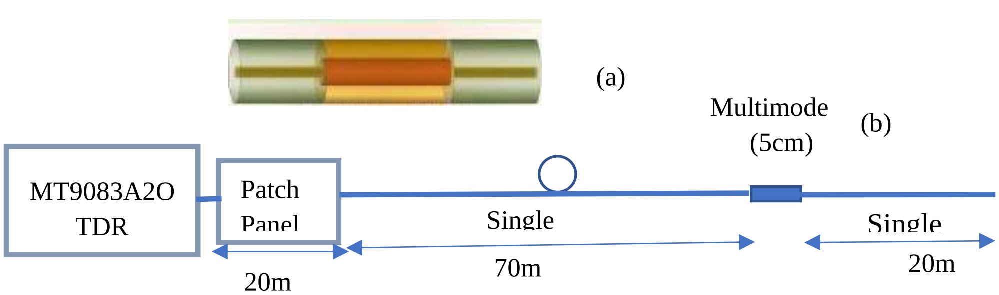

Figure 3: Experimental setup for temperature measurement (a) SMS structure, (b) OpticFiber setup.

Anritsu MT9083A Phase-OTDR was used to launch 50-nanoseconds light pulses into the fiber and analyze the backscattered signal. OTDR parameters such as pulse width and wavelength, were also optimized to achieve the best possible spatial resolution and signal-to-noise ratio.

The multimode fiber sensors were placed in a ceramic-insulated glass tube to control temperature variations [12]. The temperature was increased from 47°C to 260°C in steps of roughly 10°C with a Variac (see Figure 4). Each temperature was verified with a Digital thermometer. OTDR measured the backscattered light as a function of time, and the traces were acquired with its data acquisition system. The traces were extracted and analyzed with YOKOGAWA OTDR Viewer 4.0 software and changes in the backscattered signal from the SMS structure were correlated with the set temperatures.

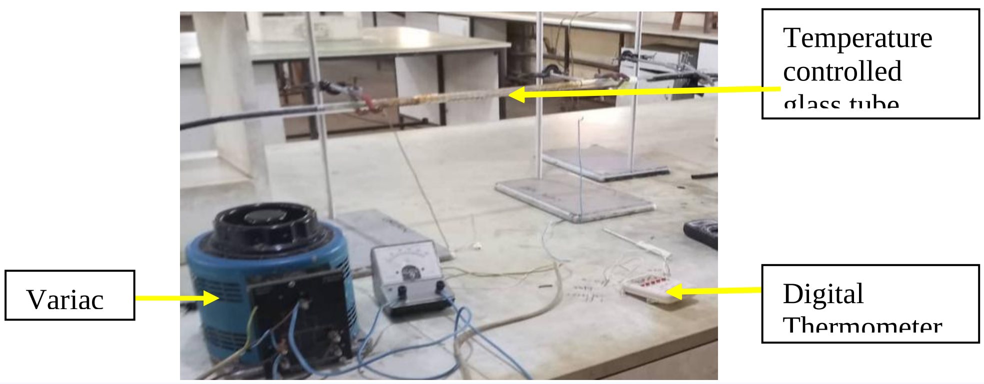

Figure 4: A 48 turn constantan wire wound round a glass tube for temperature control.

The experimental results showed that the OTDR traces exhibited a clear loss from 80m at the location of the MMF section. Depth and shape of the loss varied with temperature albeit in non-linear manner. Thus, it is not straightforward to determine the sensitivity of the sensor. Resolution of the sensor was limited by the noise floor of the OTDR and the stability of the laser source.

RESULTS AND DISCUSSION

Experiments were conducted to assess the performance of the SMS fiber sensors in response to temperature. The results showed that the backscattered signal from the SMS structure exhibited temperature dependence. Figure 4 is a full OTDR trace of temperature excursions. The section where a dip occurred at 84m down the fiber trunk similar to [2] is indicated by the transparent light blue rectangle. That region is expanded and analyzed for temperature changes in the trace in Figure 5.

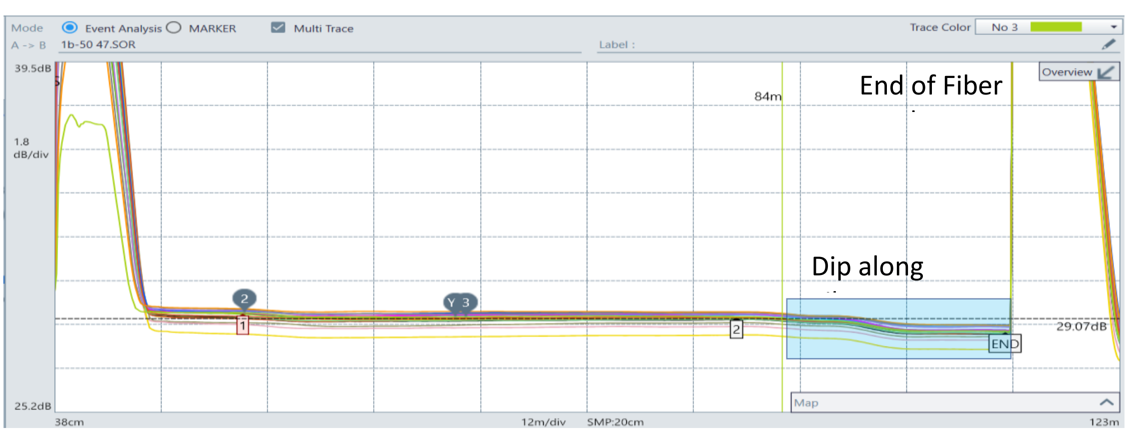

Figure 4. Yokogawa AQ9732 Full OTDR trace of the fiber setup.

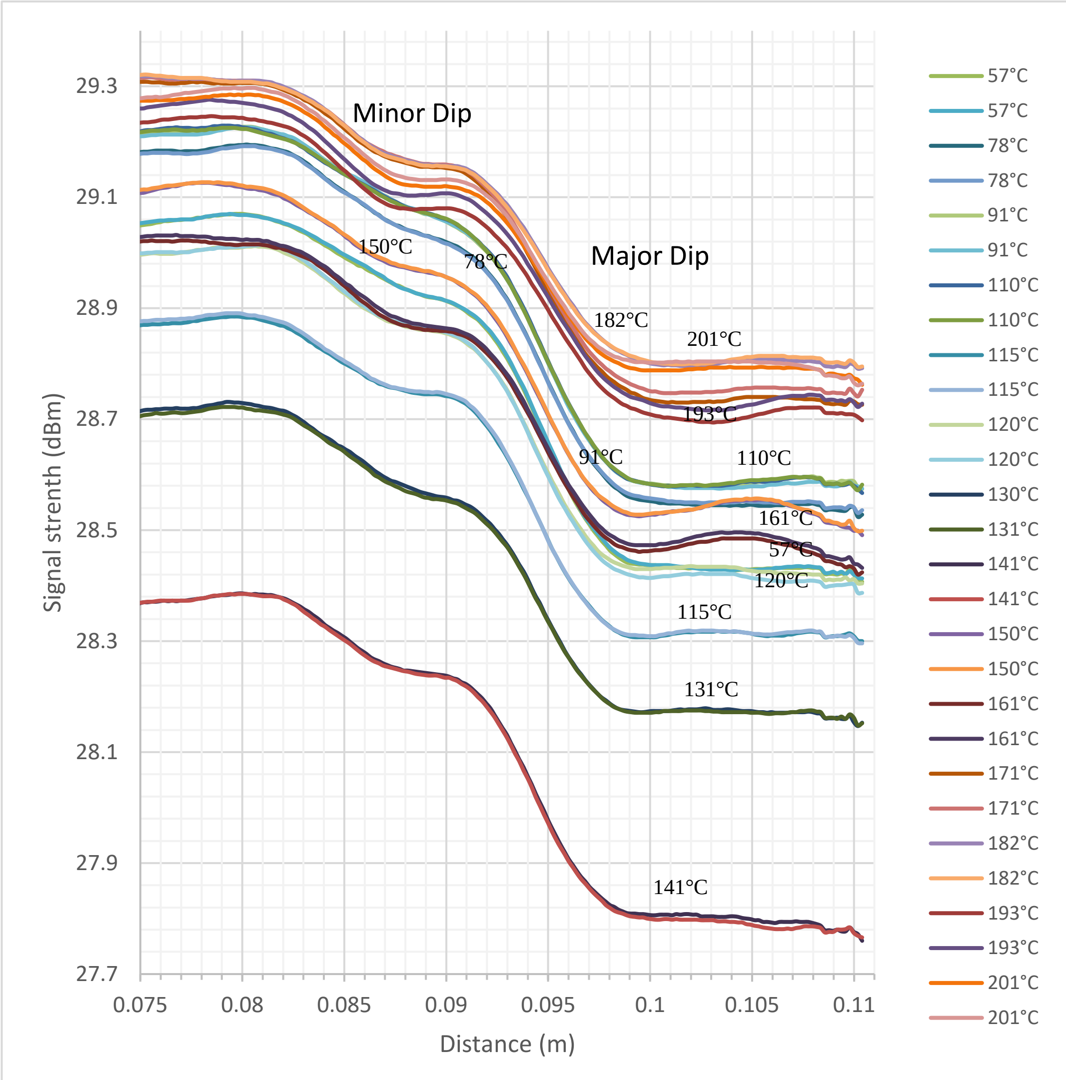

Figure 5: Expanded region of dip in OTDR fiber trace between 90 and 110m. The respective temperatures of associated traces are indicated.

To ensure measurement reliability, duplicate readings were recorded at each temperature point. Notably, the measured temperature did not exhibit a monotonic dependence on signal strength; instead, the variations appeared stochastic. This observation is consistent with the underlying physics. Rayleigh backscattering in optical fibers originates from random fluctuations in the refractive index along the fiber length. These microscopic inhomogeneities behave as dipole-like scatterers, re-emitting a small fraction of the incident probe light while preserving a fixed phase relationship with it [15]. The backscattered signal detected corresponds to the segment of the fiber occupied by the probe pulse at the time of scattering. The resulting backscatter amplitude can be likened to a spatially random Fiber Bragg Grating along the multimode fiber (MMF) section. It arises from the coherent summation of electric field contributions from numerous individual scatterers, as mathematically expressed in Equation (2). Variations in ambient temperature modulate the local spatial periodicity of these Rayleigh scattering centers, thereby inducing shifts in the reflected spectrum. Consequently, the reflected spectrum from each fiber segment shifts proportionally with temperature, as described by Equation (5).

Figure 6 presents a replot of the average signal strength (in dB) and the corresponding range at each recorded temperature. An overall increasing trend is observed, except in the interval between 115 °C and 161 °C, where a deviation from monotonic behavior is evident. This trend can be explained by the temperature dependence of the effective refractive index, as expressed in Equation (5), which is influenced by both the thermo-optic effect and the wavelength dependence of the refractive index. Consequently, temperature-induced changes in the phase difference between interfering modes affect the observed signal strength, in accordance with Equation (6).

The backscattered capture cross-section, scattering coefficient, and attenuation coefficient in the multimode fiber (MMF) segment all significantly influence the depth and shape of the reflection signal recorded by the OTDR [18]. [1] analyzed the impact of MMF length on the sensitivity of SMS fiber sensor probes under different external perturbations, including temperature, strain, and surrounding refractive index changes. Using COMSOL Multiphysics simulations, [16] further demonstrated that the tuning range of the transmission spectrum is highly dependent on the geometrical dimensions of the MMF or non-core fiber (NCF) region.

These findings suggest that external perturbations can influence multimode interference (MMI) by modifying the physical characteristics of the MMF segment. Supporting this, [2] experimentally showed that signal strength (or return loss) due to temperature variation is strongly dependent on the MMF length within SMS fiber structures, over a temperature range of 40 °C to 200 °C. Their results for MMF lengths of 50 mm, 60 mm, 70 mm, and 80 mm revealed a nonlinear response, which aligns with the non-monotonic variation observed in Figure 6

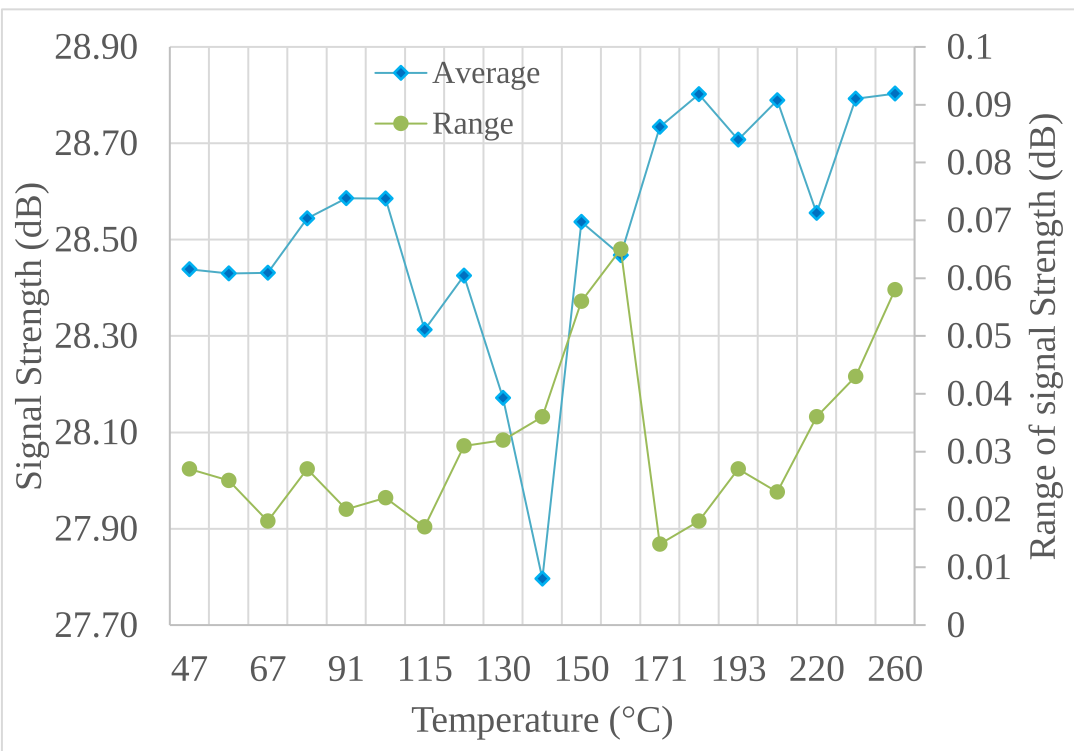

Figure 6: Average and range of signal strength of reflected traces

The full range of temperature measurement from 47°C to 260°C is presented in Figure 7. Here, overlapping traces in Figure 5 have been omitted for clarity. Thermometric properties in instrumentation are monotic in general. Non-monotonic nature of OTDR traces versus temperature points to the absence of papers on this measurement technique in the literature. This relationship is perplexing but can be fit with cubic splines or explored with neural networks. Perhaps this explains the explosion of device technology based on SMS fiber structure with linear characteristics [6], [7], [8].

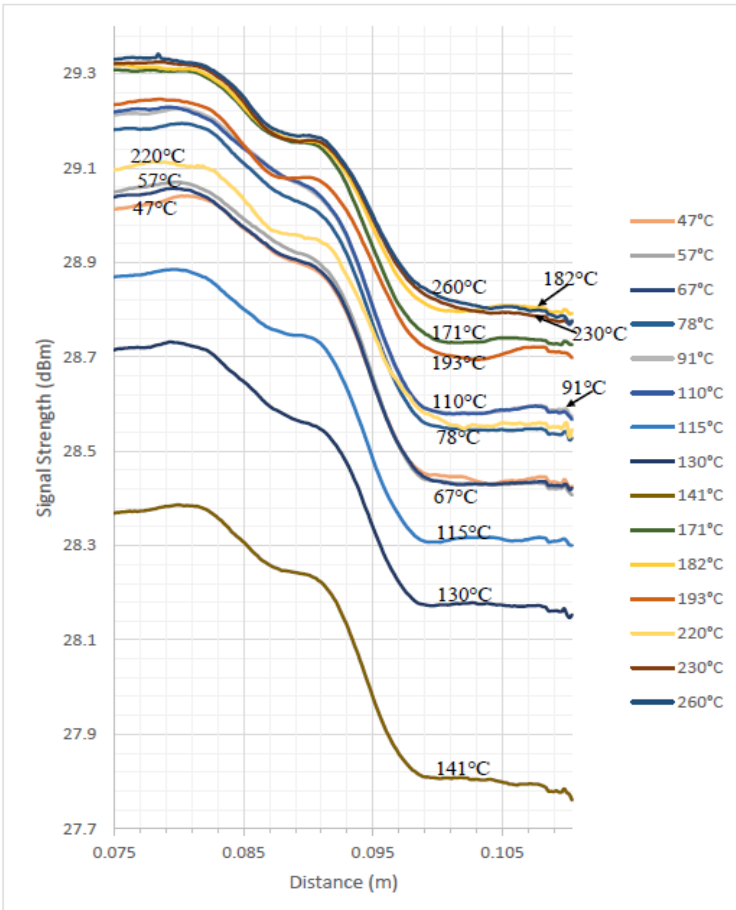

Figure 7: OTDR traces for various temperature excursions from 47°C to 260°C

CONCLUSION

This study has demonstrated the feasibility of using OTDR for interrogating SMS fiber sensors for temperature sensing applications. The SMS fiber sensors exhibited sensitivity to both temperature and strain, making them suitable for a wide range of applications. Further research is needed to optimize the sensor design and interrogation techniques to improve the sensor's performance and address limitations such as cross-sensitivity to other measurands. The development of advanced signal processing algorithms could also enhance the accuracy and reliability of the measurements. Future work will focus on optimizing the design of the SMS fiber structure, exploring new interrogation techniques, and developing signal processing algorithms to improve the performance of the sensor. Integration of machine learning models to improve the analysis of data [17].

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