One Centimeter Spatial Resolution Temperature Measurements in a Nuclear Reactor using Rayleigh Scatter in Optical Fiber

A. K. Sang*, D. K. Gifford, B. D. Dickerson, B. F. Fielder, M.E. Froggatt
Luna Technologies Inc, 3157 State St, Blacksburg VA 24060

ABSTRACT

We present the use of swept wavelength interferometry for distributed fiber-optic temperature measurements in a Nuclear Reactor. The sensors consisted of 2 m segments of commercially available, single mode optical fibers. The interrogation technique is based on measuring the spectral shift of the intrinsic Rayleigh backscatter signal along the optical fiber and converting the spectral shift to temperature.

Keywords: temperature, distributed sensing, Radiation, Nuclear Reactor, Nuclear, Atomic

1. INTRODUCTION

The nuclear industry has shown an emergent awareness of the possibilities offered by fiber optic technology for both data transfer and sensing applications [1, 2]. Distributed strain measurements may be used for structural integrity monitoring of the reactor containment buildings or nuclear waste repository. With strategic location, strain measurements may provide feedback for automated optimization and control of reactor operation or indication of an impending failure before it becomes catastrophic [3, 4]. Distributed temperature measurements may be used around the outside of the pressure vessel for water cooled reactors for structural fatigue monitoring. The capability to make distributed temperature measurements of various components is also desirable in order to assure safe site operation [5]. In-core temperature measurements of gas cooled reactors are particularly challenging due to the combination of high temperatures and high neutron fluxes.

The presence of ionizing radiation fields in nuclear facilities is a major challenge in the application of both electronic and photonic equipment and sensors. In optical fiber sensors, ionizing radiation produces wavelength-dependent radiation-induced attenuation which is exacerbated in measurement techniques whose working principle is based on intensity-related measurements [6, 7]. Even in the face of these challenges, however, the Nuclear Regulatory Commission (NRC) concluded in a study conducted in 1998 that fiber optic sensors have unique advantages in nuclear power plant monitoring and control applications, making this technology worthy of further examination. The advantages sited include immunity to electromagnetic interference, the potential for higher sensitivity and accuracy, smaller size and reduced weight, higher bandwidth and multiplexing capabilities [8]. The same group later examined the survivability of fiber optic temperature sensors in a nuclear power plant environment [9].

There are several methods available for extracting distributed temperature information from optical fiber. These include techniques based on Raman, Brillouin, and Rayleigh scattering as well as those involving multiplexed fiber Bragg gratings (FBGs). Techniques based on Raman and Brillouin scatter measurement typically employ optical time domain reflectometry (OTDR), thus are not well suited for applications that require high spatial resolution. Methods that employ FBGs can use either wavelength division multiplexing (WDM) or optical frequency domain reflectometry (OFDR) for signal demodulation. These methods achieve higher resolution than Raman or Brillouin scatter measurements but are often limited by the number of gratings that can be multiplexed in a single fiber.

In this paper, we present an initial feasibility test in which distributed temperature measurements are taken inside a nuclear reactor using selected, commonly available optical fibers. These measurements were made with centimeter scale spatial resolution over 2 m fiber segments. We use a commercially available instrument that implements swept wavelength interferometry (SWI) to measure the Rayleigh backscatter as a function of length along the fiber with high spatial resolution [10]. A sensor is formed by measuring the temperature-induced shift in the reflected spectrum of the Rayleigh backscatter in the location of the heating [11]. This technique can provide temperature measurements as precise as 0.6% full scale over spatial regions as small as 1 cm up to 850 °C. The data presented herein demonstrates successful distributed temperature measurements in an environment that is known to be challenging for optical and electrical sensors.

2. EXPERIMENT

2.1 Measurement technique

Rayleigh backscatter in optical fiber is caused by random fluctuations in the index profile along the fiber length. For a given fiber, the scatter amplitude and phase pattern as a function of distance is a random but static property of that fiber and can be modelled as a long, weak FBG with a random period. Changes in the local period of the Rayleigh scatter caused by an external stimulus (like temperature) in turn cause changes in the locally reflected spectrum. This spectral shift can then be calibrated to form a distributed temperature sensor.

In this work, polarization-diverse SWI is used to measure both the amplitude and phase of the Rayleigh backscatter signal. The measurement network used in the commercially available instrument is shown in Figure 1. Light from an external-cavity tuneable laser source (TLS) is split between the reference and measurement arms of an interferometer. In the measurement path, a 50/50 coupler further splits the light to interrogate a length of fiber under test (FUT) and return the reflected light. Another 50/50 coupler then recombines the measurement and reference fields. A polarization beam splitter and a polarization controller are used to split the reference light evenly between two orthogonal polarization states. The interference between the measurement field and these two polarization states is then recorded at detectors labelled S and P. SWI is used to measure the complex reflection coefficient of a FUT as a function of wavelength. The Rayleigh scatter as a function of length is obtained via the Fourier transform (see reference 10 for details).

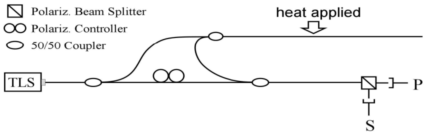


Figure 1. Optical network used for polarization-diverse measurement of Rayleigh backscatter.

A temperature sensor is formed by first measuring and storing the Rayleigh scatter spectral signature of the FUT at an ambient temperature. The scatter profile is then measured at a later time with heat applied along the length of the fiber. The scatter spectra from the two data sets are then compared along the entire fiber length in increments of Δx . For this work, Δx is in the centimeter range, with each segment representing an individual sensing element.

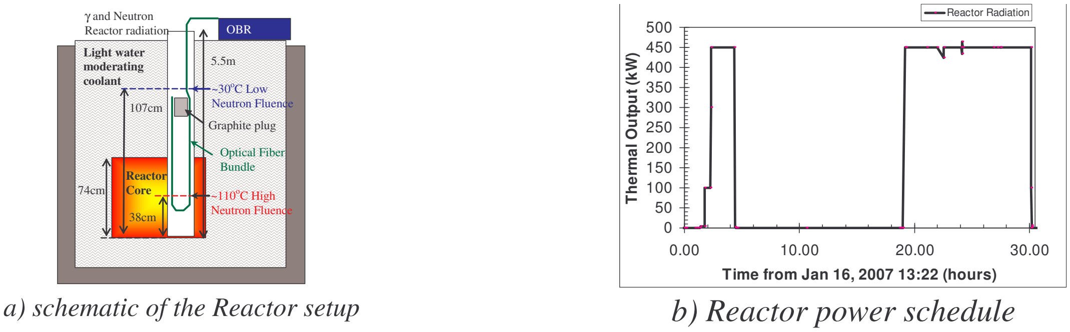
2.2 Test Facility

The tests conducted herein were performed in the Ohio State University Research Reactor (OSURR). The facility is a pool-type reactor that can continuously vary the thermal power from 0.1 – 100 % of a maximum of 500 KW. At full power the neutron flux is 1.2 x 10^{13} n/cm^2-s and gamma flux is 100 x 10^6 Rads / hour. The reactor has a 6.4 cm diameter tube that functions as a dry well which extends from the top of the reactor pool down into a position in the core grid along the south edge of the core [12].

2.3 Experimental setup

In this initial experiment, four commercially available optical fibers were prepared for nuclear radiation. These include 1) SMF28 – Polyamide coated, 2) 1550 nm Silica core – Acrylate coated, 3) 1550 nm 20 wt% GeO doped – Acrylate coated and 4) 1300 nm – Copper coated. The SMF-28 fiber and 1300nm copper coated fiber both have Germania-doped cores, approximately 5 wt% GeO.

The fibers were bundled into a loose tube buffer which was then looped and bonded to a 1 meter aluminum “L” bracket to form a 2 meter measurement area. The “L” bracket was then inserted into a 5-Meter, 3.8 cm diameter tube to facilitate insertion into the existing drywell of the OSURR. Arrays of thermocouples were located at two vertical locations 0.4 m and 1.1 m from the reactor floor to enable both in-core and ex-core irradiation measurements as illustrated in Figure 2a. The test was conducted at 90% thermal power (450KW) for 13 effective full power hours as illustrated in Figure 2b.



a) schematic of the Reactor setup

b) Reactor power schedule

Figure 2. Reactor setup and thermal output during test.

3. DISCUSSION OF RESULTS

Figure 3 shows the typical spectral response profile as a function of position of the candidate fibers. The position datum selected was referenced to the low neutron fluence thermocouple location. As a reminder to the reader, the spectral response is a relative measurement from a reference baseline; hence, the initial value begins nominally at zero. As expected, a mirrored spectral response from the two attachment paths on the aluminum bracket is reflected in the data (see fiber path illustration in Figure 2a).

Figure 4 and Figure 5 show the spectral response of the various fiber types to the thermal environment induced by the irradiation over the test period in the high and low neutron fluence measurement areas. The spectral shift is negative with an increase in temperature, hence, for simplicity in comparison, we show the negative spectral response of the optical fibers (left 'y' axis in Gigahertz). As expected, in the region of high neutron fluence, we see an increased temperature as indicated by the co-located, shielded thermocouple. We note that all four fibers clearly track the measured temperature, capturing similar thermal fluctuations experienced during the test. The copper coated fiber experiences the largest spectral shift of the test candidates in both the low and high neutron fluence regions. This is theorized to be a result of the effects of the thermal expansion of the coating increasing the fiber elongation, thus causing a proportionately larger spectral shift.

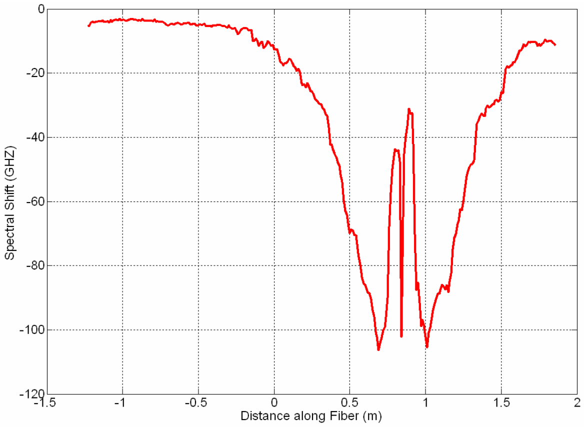


Figure 3 Spectral shift vs. position (SMF 28 Fiber 28 hrs)

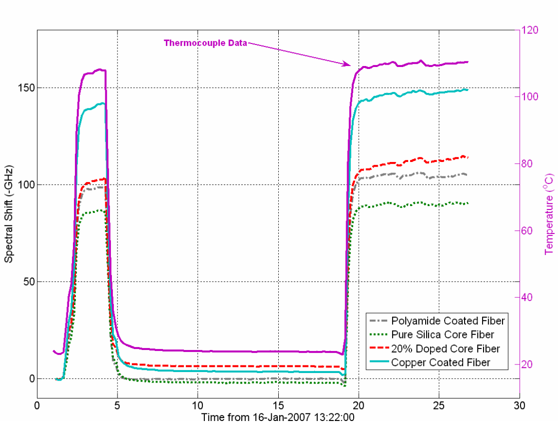


Figure 4 Spectral shift at high neutron fluence area

The data further shows evidence of dopant influence on the fiber spectral response to the temperature changes. Neglecting the copper-coated fiber (due to coating influence), the 20 wt% GeO doped fiber shows the largest spectral shift followed by the polyamide coated (5 wt% GeO doped) then the pure silica core (un-doped) fiber; showing a correlation of dopant level to the spectral shift of the optical fiber. Figure 6 shows the spectral shift as a function of temperature for the various fiber types. In all four cases, we see evidence of a linear correlation to temperature. The nonlinearity noticed between 40-50°C is thought to be as a result of the rapid temperature increase during reactor startup, as evidenced by the increase in the periodicity of the graph markers for all four candidate fibers.

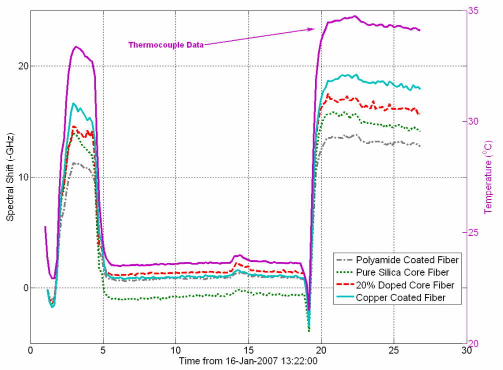


Figure 5 Spectral shift at low neutron fluence area

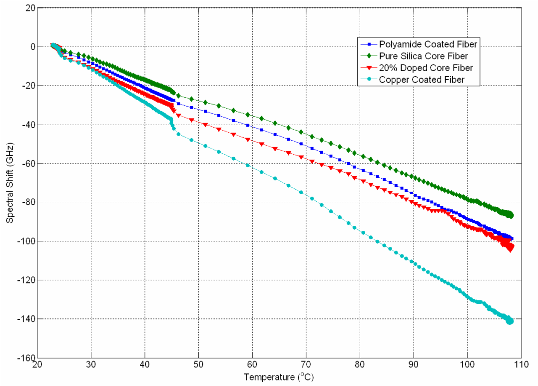


Figure 6 Spectral shift versus temperature

4. CONCLUSION

Luna Technologies has successfully demonstrated the unique ability of making one centimeter resolution temperature measurements in a radiation environment using Rayleigh scatter in commercially available single mode fibers over various coatings and dopant concentrations. This technique enables robust temperature measurements with high spatial resolution and good temperature accuracy. Temperature measurements can be performed on any telecommunications grade fiber over a span of 70 m or more with the primary thermal response being a function of the fiber coating and/or dopant level. This method represents a practical, economical approach for distributed thermal measurements in a radiation environment.

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