Fibre Bragg Grating based FOS for strain and temperature measurements

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***Abstract*—The paper presented here reports an overall view of the application of the inexpensive single-mode silica optical fibers in the nuclear industry for temperature measurements in radiation environment and the use of an hybrid optical fiber sensor system for simultaneously sensing the strain, temperature, and thermal strain of composite materials. The report is to help the research scholars and the beginners in the research development for various applications. The section-I reports on the interrogation of the inexpensive single-mode silica optical fibers with Luna Innovations' optical backscatter reflectometer to perform distributed temperature measurements at temperatures up to 1000 °C. The section-II reports on a hybrid optical fiber sensor system for simultaneously sensing the strain, temperature and thermal strain of composite materials.**

1. Introduction:

A range of sensor types are available including temperature sensors, strain sensors and accelerometers with applications varying from smart structures, to the oil and gas industry, to the life science industry [1], [2]. The techniques of distributed sensing for optic strain and temperature measurements like the examination of Brillouin and Rayleigh backscattered signals in an optical fiber using either an Optical Time Domain Reflectometer [3] or Optical Frequency Domain Reflectometer [11] have been useful for the Nuclear Regulatory Commission (NRC) in using fiber optics for advanced instrumentation in the nuclear power plants[4].

The Rayleigh backscatter sensing mechanism can be seen in work conducted by Luna Innovations [5]. The report on Rayleigh backscattered signals in an optical fiber using Optical Frequency Domain Reflectometer [11] determines an upper operational temperature limit of 650 °C for the distributed measurement technique based on Rayleigh backscatter using Corning's SMF-28e+ commercially available single-mode fiber. While the Rayleigh scatter mechanism involves the scattering of the fraction of the injected light along the length of the fiber due to random density fluctuations in the glass, the Rayleigh backscatter mechanism involves change of the phase of light from constructive to destructive interference with the reference light at a frequency related to its location along the fiber. This happens when some of the reflected light that travels back down the fiber combines with light from a reference fiber of known length coupled to the same tunable laser. A detector measures the interference pattern which can be decomposed to identify the location and magnitude of individual scatter points. The work done by Soller, Wolfe, and Fraggott [6] gives more detailed explanation of the optical fiber network and the measurement technique. A change in temperature and/or strain will modify the Rayleigh backscatter signature of the FUT, because it causes a change in the relative spacing among scattering centers which causes a spectral shift in the reflected signal. The spectral shift (relative to some reference scan at a known temperature or strained state) can be calibrated to a change in temperature or strain

The authors [11] in their report have taken continuous measurements of the Rayleigh backscattered signal to determine the amount of backscattered light as a function of temperature and position along the length of the fiber. These data were post-processed to determine the spectral shift in the Rayleigh backscatter signature. The spectral shift data were then calibrated to a change in temperature.

A schematic of the optical fiber network used to make measurements of the Rayleigh backscatter signal of the FUT [5] can be seen in Fig. 1.

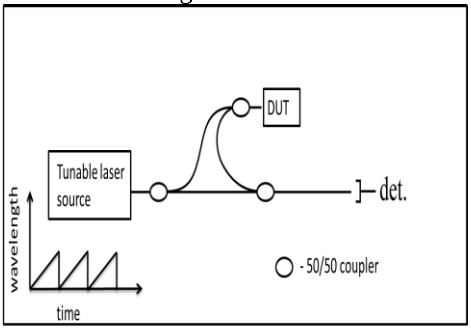

Fig 1. Optical fiber network to measure Rayleigh backscatter signal of (FUT) [5].

Measurements have been made using the Rayleigh backscatter signal in conventional single-mode fibers at low temperatures (<100 °C) [7]. This measurement technique has also been used to make distributed temperature measurements up to 850 °C using a gold-coated fiber [8] and distributed strain measurements of less than 60 microstrain using conventional singlemode silica fiber [9].

The fiber optic sensing technology has to be proven to survive in radiation environments for applications in the nuclear industry. There has been a considerable amount of previous work evaluating the performance of both optical fibers and sensors in radiation environments. Broadband optical transmission measurements of multi-mode silica optical fibers have been made at temperatures up to 1000 °C while being irradiated [10]. Distributed temperature measurements using the Rayleigh backscatter measurement technique in radiation environments seen up to 110 °C [5].

Corning's SMF-28e+ single-mode optical fiber which comes with multiple protective coatings to provide mechanical strength and strain relief can be used as FUT to measure the Rayleigh backscatter signal of fibers. at room temperature (22 °C) and elevated (up to 1000 °C) temperatures by means of Optical Backscatter Reflectometer (OBR) model 4600 (a swept-wavelength optical frequency domain reflectometer).

Conclusion: Temperature measurements have been successfully performed with Luna Innovations' OBR using the Rayleigh backscatter signal in a commercially available single-mode silica optical fiber for temperatures up to 600 °C. A quadratic calibration was applied to the calculated spectral shift of the fiber to relate the spectral shift to a temperature change. Significant degradation in the Rayleigh backscattered signal occurs at a temperature of 700 °C. At a temperature of 750 °C, the Rayleigh backscatter signature is altered significantly and the sensing mechanism, for this particular fiber, fails after approximately 8 hours at 750 °C [11].

Section-II

The measurement of temperature and strain for applications in the structural health monitoring of composite materials has been reported by using FOS [12] and the most widely used FOS type used for strain and temperature measurement in composite materials being Fiber Bragg Grating (FBG) sensors [13]. But, the problem of their high intrinsic temperature cross-sensitivity in employing FBGs as strain and temperature sensors indicate for further study and research work. Highly Birefringent (HB) polarization-maintaining (PM) fiber based polarimetric sensors can be made temperature insensitive but the measurement of strain requires a means of setting a zero strain reference.

The need for temperature measurement for reference purposes or a reference for zero strain involves the use of a second fiber optic sensor and the method is commonly referred to as "hybrid sensing". Many of the hybrid sensing approaches involve the combinations of FBGs with various types of sensor such as a long period grating (LPG) [14], [15], Fabry-Perot interferometer sensor [16], photonic crystal fiber (PCF) modal interferometer [17], and a fiber loop mirror using a small core micro-structured fiber [18]. Sensors based on gratings written in micro structured fibers [19] also discriminate between strain and temperature. A hybrid approach which involves an FBG sensor and a PM-PCF polarimetric sensor for simultaneous measurement of strain and temperature [20] has also been reported.

However, for an FOS embedded in composite structures, there is an influence of thermally induced strain in the composite material which results in two Bragg peaks when the FBGs are written in micro structured fibers as shown in the report [21]. The thermally induced strain of composite materials which significantly influences the temperature sensitivity of polarimetric sensors [22] can be measured by using a stripped PM-PCF sensor[23]. Thus, when a sensor is used for simultaneous measurement of temperature and strain, the measurement might result in errors because the sensor will be sensitive to both the temperature in free space and also when embedded in a composite material. This will give wrong results of the applied strain. A buffer (coating) stripped PM-PCF sensor [22] which is insensitive to temperature in free space, but once embedded in a composite material is affected by the thermal expansion of the composite material and therefore is capable of measuring thermally induced strain. Thus, the thermal strain is sensed using the coating stripped PM-PCF. The measurements of externally applied strain by a sensor can also result in error because the sensor would be sensitive to thermally induced strain. But, a buffer (acrylate) coated PM-PCF which is insensitive to thermally induced strain can be used for measurements of external applied strain independently from temperature [23]. Thus, the axial strain is sensed using the acrylate coated PM-PCF sensor. This is because the transverse CTE induced non uniform strain transfer [24] is apparently eliminated due to the presence of the buffer coating. A third sensor, an FBG, is used for composite material temperature measurements only. Thus, an hybrid optical fiber sensor system, consisting of three sensors (1) A coating stripped PM-PCF sensor (2) A polarimetric sensor- a polarimetric sensor based on an acrylate coated polarization maintaining photonic crystal fiber (PM-PCF and (3) A Fiber Bragg grating sensor (FBG), can be used for simultaneously sensing the strain, temperature, and thermal strain of composite materials. The hybrid sensor system presented in the report [25] operates in the intensity domain by converting the polarization and wavelength information from the polarimetric sensors and the FBG, respectively, into detectable linear intensity variations.

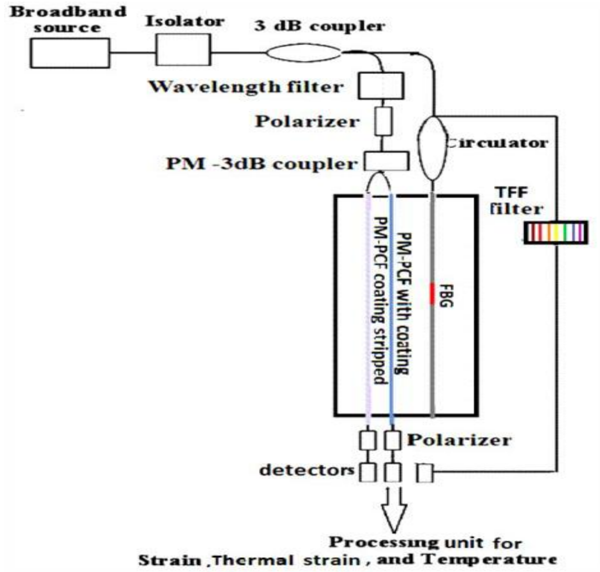

Fig. 2 Schematic of the hybrid polarimetric-FBG sensor system.

Subsequently, by deriving a characteristic matrix for the hybrid sensors, information about temperature, axial strain, and thermal strain can be simultaneously determined.

CONCLUSION:

By detecting the outputs of the three sensors in the intensity domain, information about temperature, axial strain and thermally induced strain can be simultaneously derived. The proposed sensor configuration can be employed in composite material structural health monitoring (SHM) applications [25].

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