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FIBER OPTIC CALORIMETRY

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Abstract

A twin-bridge calorimeter using optical fiber as the sensor element was constructed and tested. This system demonstrates the principle and capability of using optical fibers for heat-flow measurements of special nuclear material. This calorimeter uses piezoelectric-generated phase-carrier modulation with subsequent electronic signal processing to allow phase shifts as small as $1 \mu\text{rad}$ to be measured. The sensing element consists of 21-m lengths of single-mode optical fiber wrapped around sample and reference chambers. The sensitivity of the calorimeter was determined to be 74 rad of phase shift per mW of thermal power. One milliwatt of thermal power is equivalent to 400 mg of plutonium ($6\% \text{ }^{240}\text{Pu}$). The system noise base was about 0.2 rad, equivalent to about 1 mg of plutonium.

INTRODUCTION

Calorimetric measurements have used electrical resistance sensors and have routinely measured plutonium and tritium materials with thermal powers down to 100 mW with accuracies of 1% or better for larger volume (>3 L) calorimeters. Fiber-optic sensors are a way of performing heat-flux measurements with even greater sensitivity. The impetus for using fiber-optic sensors in nuclear safeguards applications is that their greater sensitivity will allow low-power samples such as enriched uranium and small amounts of plutonium to be accurately measured. The technique for measuring phase shifts of coherent light transmitted through optical fibers using interferometric techniques has the potential of measuring samples with very low thermal powers (microwatts) with <1% accuracy. High-sensitivity fiber-optic sensors use the intrinsic physical properties of fiber optics to sense temperature. An increase in temperature causes an expansion of the fiber and this changes the total number of wavelengths of light traveling through the fiber as the temperature rises. At a wavelength of 633 nm, a 1°C rise in temperature causes a phase change of 91 rad for 1 m of silica fiber. Using a "true phase measuring" interferometric-demodulation approach which incorporates fringe counting, subfringe phase changes as small as $\pm 1 \mu\text{rad}$ can be measured. Although environmental factors such as acoustic noise can limit the actual measurement resolution, high-sensitivity measurements approaching μrad resolution have been attained with interferometric fiber-optic gyroscopes and underwater acoustic sensors.

The use of fiber optics as a communications medium has led to the development of low-cost fiber components that can be used as parts of a calorimeter system. In particular, the cost of high-grade single-mode optical fiber has dropped to \$0.05–\$0.10/m, allowing the use of large lengths of sensors at relatively low cost. This work describes the results of sensitivity testing of optical fiber as a substitute for the electrical resistance sensing element in a twin-bridge calorimeter configuration.

FIBER-OPTIC SENSITIVITY

An example of the sensitivity of an optical fiber is shown in Fig. 1, where the phase shift in a fiber-optic sensor due to temperature change was measured. The sensor formed an arm of a Michelson interferometer driven by a diode-pumped Nd:YAG laser at 1319 nm. The optical-fiber length was 1 km. The sensor was subjected to a temperature difference of 1.5°C . As can be seen in the figure, the response of the sensor was linear over the temperature range. The temperature sensitivity was $114680 \text{ rad}/^\circ\text{C}$. Measurement of the phase shift to 1 mrad corresponds to a temperature sensitivity of

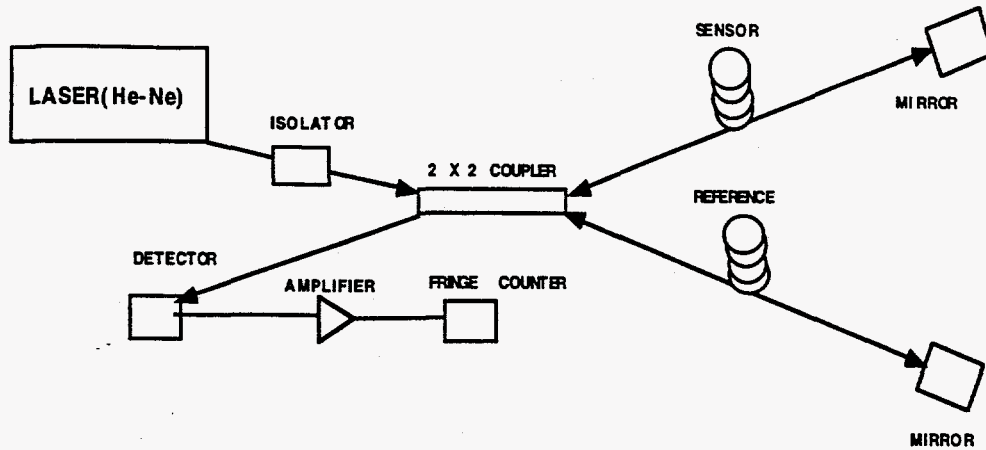


Fig. 2. Michelson interferometer fiber-optic sensor system.

Polarized coherent light emitted from a He-Ne laser at a wavelength of 633 nm was sent through PM fiber through a 2×2 coupler that splits to two sensing arms composed of PM fiber. One arm serves as the heat-flux sensor and the other as a reference sensor. After passing through the length of the sensor, the light is reflected and passed back through the sensors to the coupler. Because the sensor arms have a length within the coherence length of the laser (~ 10 cm), the light beams interfere constructively or destructively according to the relative phases of the two light beams. An isolator prevents the light from passing back into the laser and causing instability in its operation. The other arm of the coupler leads to a solid-state detector that detects the interference pattern emitted by the coupler. The maximum voltage from the detector corresponds to constructive interference and the minimum to destructive interference. A variation from maximum-to-minimum-to-maximum is one fringe shift, equivalent to 2π radians. The phase shift measurement is done with a special demodulator capable of counting to a small fraction of a radian. This module was built for Los Alamos National Laboratory by Optiphase. A more detailed schematic of the calorimeter setup is shown in Fig. 3 which shows details of the phase measurement system. The modulation frequency during our experiments was typically 20 kHz.

The interferometric demodulator, phase measurement system works by means of electronically analyzing a phase-generated carrier generated by piezoelectric (PZT) modulators, matched cylinders, placed in both arms of the interferometer. A detail of one of the temperature-sensing thermels is shown in Fig. 4. The thermel was fabricated by winding a single layer of fiber around an aluminum tube, 1 in. in diameter and capable of measuring a 1 in. \times 3 in. sample. The fiber tension was maintained with a force equivalent to approximately 35 g of weight. The fiber was held to the tube using a ultraviolet curable acrylate, similar in composition to the fiber jacket. Near the bottom end of the winding, a 1-in. diameter, 1-in. high PZT cylinder was press-fit into the inner diameter of the tube which enabled modulation of the interferometer. A portion of the concentric close-fitting PZT can be seen at the bottom of the sensing arm in Fig. 4. A sinusoidal voltage is fed to the PZT cylinders and causes the diameter of these cylinders to increase and decrease at the exciting frequency. This in turn generates a phase shift B at the same frequency f of the modulator. The change in dimension causes the fiber optic lead to be stretched at the same frequency. The equation describing interference portions of the received signal is

$$V(t) = K \cos[B \sin(2\pi ft + W) + \Phi] ,$$

where

Φ = phase of the interferometer (includes the phase shift due to heat and environmental interferences,

B = modulation depth of the PZT cylinders,

W = phase of the modulation,

f = modulation frequency, and

K = voltage/radian constant set by the electronic gain.

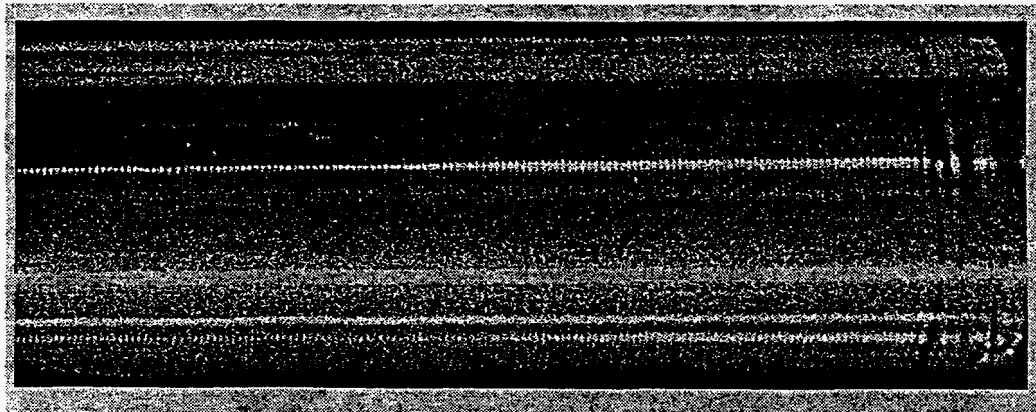


Fig. 4. Fiber-optic thermel.

The calorimeter was placed in a large screw-top calorimeter can that then fit into the well of a larger calorimeter that was used only for temperature control. A photograph of the unit being placed into the larger can is shown in Fig. 6. Temperature control was provided by a conventional water bath with the water temperature controlled to within 0.001°C . An electrical heater inserted into one of the arms of the fiber-optic calorimeter was used to provide known amounts of thermal power to test the sensitivity of the unit. Figure 7 shows the results of one of the measurements. From point A to point B there is no thermal power applied to the heater. A flat, stable baseline is observed. At Point B, 1 mW of thermal power, equivalent to the power generated by 400 mg of plutonium ($6\% \text{ }^{240}\text{Pu}$), was applied to the heater. After 100 min, the interferometer output stabilized to a new equilibrium baseline. The difference between the no-power baseline and the equilibrium phase shift at the 1 mW level was a phase shift of 74 rad, corresponding to 12 fringe shifts. At point C, the electrical power was turned off and the phase shift was reversed back to the original baseline. The same time to equilibrium, 100 min, to the no-power baseline, point D, was observed after the power was turned off. Multiple runs at different thermal power levels ranging from 1 to 64 mW were performed. Figure 8 shows that the instrument response ranged over 4800 rad and was linear over the power range. The overall sensitivity of the system as indicated by the slope of the straight line fit was $74.0 \pm 0.1 \text{ rad/mW}$. The sensitivity would be identical for a calorimeter of gradient design with the same sensor length.

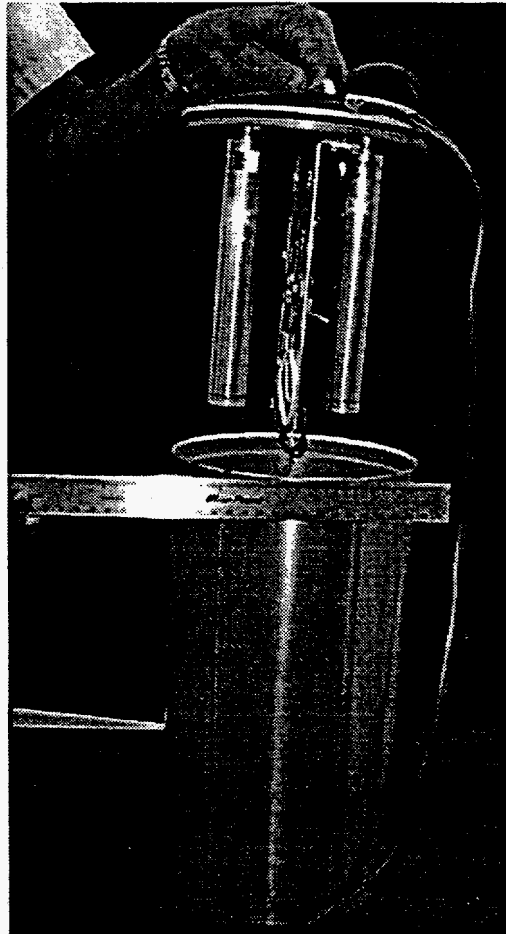


Fig. 6. Fiber-optic calorimeter.

The sensitivity of the calorimeter depends on the stability of the baselines used to determine the total phase shift. For this system, the uncertainty of the baseline was about 0.2 rad. This corresponds to a power of 3 μ W. This system thus has a sensitivity comparable to currently available high-precision calorimeters. In order to attain the higher sensitivities possible with this technique, interference from noise sources such as acoustics and laser phase noise will have to be reduced. The baseline noise can be reduced by using of a more stable diode-pumped Nd:YAG laser and acoustic cancellation techniques. The high attenuation of silica fiber of 12 db/km at 633 nm precludes its use for kilometer lengths of sensor fiber. The lower attenuations of 0.3–0.4 db/km in the 1300–1500 nm region requires a laser, detector, and fiber that operate in that wavelength band. All of these components are commercially available.

CONCLUSION

This work determined the phase response to temperature change of a single-mode fiber sensor and confirmed that it is capable of sensitive calorimeter measurements at low power levels. The sensitivity of a twin-bridge, fiber-optic calorimeter system was tested, and it demonstrated that a practical system could be used to measure the thermal powers. The base noise of the system, 0.2 rad, equivalent to 1 mg of plutonium, was comparable to current calorimeter capabilities. Greater sensitivity could be obtained with a more stable laser. Work is continuing to improve the noise performance of fiber-optic calorimeters.

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