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Measurement of Macroscopic Radiation-Induced Changes in Optical Fiber

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Changing the World's Energy Future

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Introduction

Optical fiber technologies offer innovative measurement solutions that can potentially accelerate R&D activities and improve the competitiveness of advanced nuclear energy systems, since information transmitted via optical fiber is advantageous as a result of the fiber's low signal losses, wide bandwidth, immunity to electromagnetic induction effects, small and compact size. However, optical fiber undergoes optical properties changes in radiation fields, causing radiation-induced signal drift and leading to measurement errors in the physical parameters being sensed by optical-fiber-based sensors.

Radiation Effects on Optical Fibers

Intense radiation compacts the silica-based optical fiber, altering the fiber's refractive index (RI) and length. Radiation, primarily by attenuating and compacting the silica optical fibers, in many ways changes the optical, mechanical, and chemical properties of these fibers, thus affecting signal fidelity. Radiation-induced attenuation (RIA) increases the linear attenuation in silica-based fibers [1]. Different parameters govern the RIA levels and kinetics, and these parameters include the chemical compositions and manufacturing processes behind the fibers, the light-guiding properties of the fibers, the nature of the irradiation (e.g., x-ray, gamma ray, and neutron), the dose rate, the wavelength of the light used, the injected light power, and the irradiation temperature [1], [2]. On the other hand, radiation-induced compaction (RIC) causes structural changes in the fiber, leading to an overall density change [3]. While RIA leads to an RI change via the Kramer-Kronig relation [4], its determination is complex, and one must consider the spectrum over a wide frequency range [4]. RIC alters the RI through the Lorentz-Lorenz relation [5] and point dipole theory [6]. Until now, RIC has been calculated using various well-established and empirical equations. All these methods considered only the RIC when calculating radiation-induced RI/length changes. However, the RI and length may also change due to any specific phenomenon to which the fiber is subjected, including RIC, RIA, dopant diffusion, temperatures, stress relaxation of fiber, dose, and dose rate. In this regard, these methods fail to present the complete picture of radiation-induced changes in RI. As RI and length compaction are the input parameters for optical fiber sensors, accurate measurement of these parameters is crucial for predicting radiation's actual effects on optical fiber sensors, and for correcting sensor drift. Online measurement of radiation-induced changes in RI/length is a potential way of understanding structural changes in optical fiber exposed to a nuclear environment, thus aiding in the minimization of signal error.

Objective

The objective of this research is to measure radiation-induced macroscopic changes in optical fiber, using a simple optical-fiber-based cascaded Fabry-Perot interferometer (FPI). Compared to the conventional "cook-and-look" method, the analytical method based on the Lorentz-Lorenz relation, point dipole theory, etc., this technique offers unique features such as real-time determination of RI/length changes due to any specific phenomenon to which the fiber has been subjected, including RIC, RIA, dopant diffusion, stress relaxation of fiber, and temperatures. As a proof of concept to measure RI/length changes in optical fiber, we experimentally demonstrated real-time monitoring of temperature's effect on RI/length and used the cascaded FPI to measure the fiber's thermo-optic coefficient (TOC) and thermal expansion coefficient (TEC).

Current Status

Figure 1 shows the design architecture of the cascaded FPI for the measurement of RI/length changes in silica optical fiber. It consists of an air cavity (hollow) and a silica cavity (solid) contained within the same fiber (Fig. 1[a]). The air cavity is used to monitor the temperature-induced changes in cavity length, whereas the silica cavity can be used to measure the RI, using knowledge of optical science. To fabricate the cascaded FPI, simple cleaving and splicing processes were applied. As a first step, the single-mode fiber, capillary tube, and coreless (CL) fiber were cleaved using a cleaving tool (Fig. 1[b]), and then a fusion splicer was used to fusion splice the SMF-28 with the capillary tube (Fig. 1[c]). Next, a linear stage was used in conjunction with the cleaving tool to cleave the spliced capillary at a distance from the splicing point (Fig. 1[c]). A CL fiber was cleaved and spliced with the capillary tube to complete the air cavity (Fig. 1[d]). The CL fiber was chosen for the silica cavity in order to obtain information about the pure silica optical fiber. To construct the silica cavity, the CL fiber was cleaved at a distance from the point where

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the capillary and CL fiber had been spliced (Fig. 1[d]). A microscopic image of the fabricated cascaded FPI is shown in Fig. 1(e).

The fabricated cascaded FPI structure's measurements of the temperature-induced length variation in the air cavity, along with the RI variation in the silica cavity, are shown in Fig. 2(a) and (b), respectively. The measured TEC and TOC of the silica optical fiber are 5.53×10^{-7}/°C and 4.28×10^{-6}/°C, respectively, which is in good agreement with the value given in the literature value. Since the cascaded FPI can successfully monitor real-time RI/length changes in optical fiber, it is expected to also be able to measure those parameters in a radiation environment.

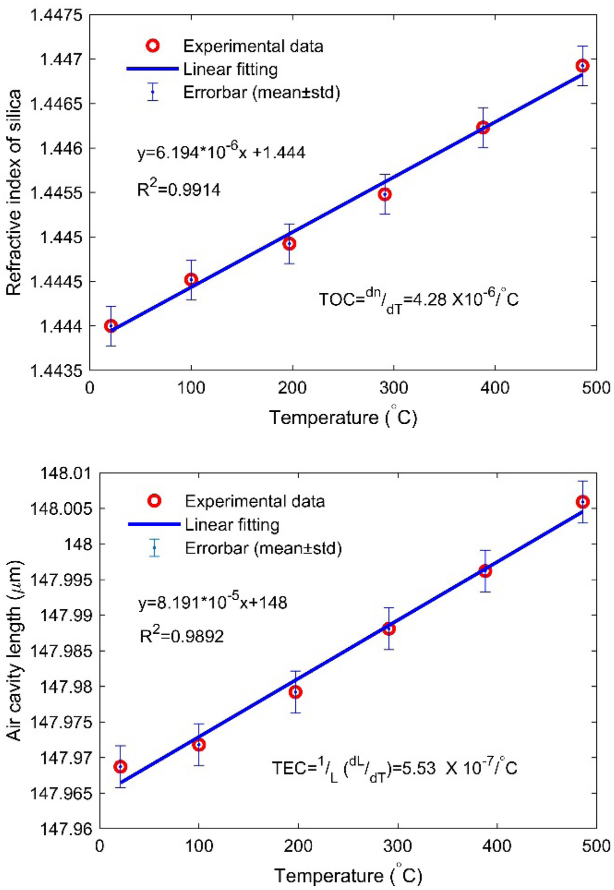

Figure 2. Real-time measurement of the temperature-induced changes in the silica optical fiber's TEC (top) and TOC (bottom)

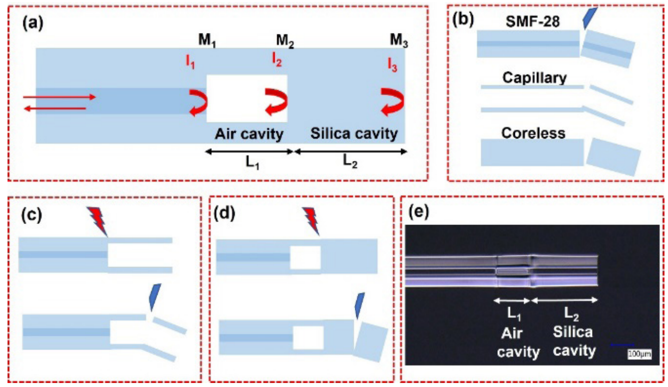

Figure 1. Schematic and fabrication process for the cascaded FPI: (a) schematic of the cascaded FPI, (b) cleaving of required fibers and capillary, (c, d) splicing and cleaving steps, and (e) microscopic image of the fabricated cascaded FPI.

Impact and Applications in the Nuclear Field

With applications of fiber optic technologies gradually penetrating into the nuclear field, the largest contribution to the nuclear community is expected to be the development of instrumentation to support the creation, testing, and qualification of nuclear fuels and materials. Research on fiber-optic-based systems will create opportunities for other measurement capabilities for in-pile instrumentation. It will also benefit the nuclear science community, as well as the scientific community at large.

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