Intrinsic polymer optical fibers for large deformation strain sensors

Kara Peters, Sharon Kiesel, Omid Abdi, Tasnim Hassan, and Mervyn Kowalsky

Single-mode fibers demonstrate coherent lightwave propagation and show promise as interferometry-based sensors for large-scale strain applications.

Large deformation strain sensors have application in concrete and steel structures designed to resist earthquake loadings, as well as other potential uses, including morphing aircraft structures and highly flexible space structures. Research indicates that sensors comprising polymer optical fibers (POFs) have several advantages over more commonly used silica fibers. They exhibit high failure strain, are more flexible, and do not require a protective coating to prevent moisture ingress.

Previous research has demonstrated that the inherent displacement phase sensitivity of a single-mode POF is 14% greater than that of comparable and commonly used silica single-mode optical fibers. Additionally, the fabrication of relatively low attenuation single-mode POFs designed to operate at near infrared wavelengths has permitted the writing of high deformation Bragg grating sensors and filters with a large tuning range. For these studies, the maximum strain range achieved was on the order of 6%. We have found that the maximum usable strain range in a POF without a fiber Bragg grating is in fact much greater than the yield strain of the optical fiber.

We recently demonstrated that single-mode PMMA (polymethylmethacrylate) optical fibers can be used to measure strain up to approximately 15% elongation of the fiber. The PMMA fiber that we used (from Paradigm Optics) was designed for single-mode operation at red light wavelengths. Its mechanical behavior varies strongly with strain rate, as might be expected for polymeric materials, with yield strain of 3–5%. To predict the phase sensitivity of the POF sensor to applied axial strain in both the small and large deformation regions, the classic displacement phase sensitivity formulation was extended to include both the finite deformation of the optical fiber and nonlinear strain optic effects. While it was not known beforehand whether both these effects were important, subsequent testing has shown them to be on the same order of magnitude.

Using a Mach–Zehnder in-fiber interferometer (see Figure 1), we were able to successfully measure the phase shift up to 15.8% elongation of the POF, as plotted in Figure 2. At

Continued on next page
this point it was not known whether the coherent propagation strain limit was due to induced birefringence in the fiber, other polarization issues, changes in the core mode field diameter, or whether it genuinely represented the end of coherent light propagation. It was observed, however, that all light propagation through the fiber ceased shortly above this strain limit. The mean value of phase shift sensitivity was measured to be $1.39 \times 10^7$ rad m$^{-1}$.

Inasmuch as the final goal of this project was to embed the POF sensor in structural components for monitoring of infrastructural systems, its compatibility with various sentence materials was tested. Fiber pull-out tests demonstrated that cementious materials provided the strongest bond to the POF and did not apply enough transverse compressive stress during cure to prevent light transmission through the fiber. Additionally, a method of precasting the POF sensor into smaller concrete samples was developed to permit embedment in full-scale structural members (see Figure 3).

The practical challenges of implementing POF large deformation sensors include high material attenuation of PMMA (see Figure 4). Therefore, for large structural applications the sensor must be spliced to silica optical fibers to act as the ingress and egress channels. The fact that these single-mode POFs are still experimental means that new coupling strategies had to be developed together with new preparation techniques based on high-temperature cutting. For the practical application of a single-mode POF interferometer as a strain sensor, further investigations are under way to measure its response to cyclic loading.

These results indicate that interferometry-based single-mode POF sensors can be used for strain ranges over twice that of POF Bragg grating sensors and three times that of silica in-fiber interferometers. This work also demonstrates that coherent light waves can be propagated in a polymer optical fiber well beyond the yield strain limit.

This work was supported by the National Science Foundation through grant CMS 0428301 (Shih-Chi Liu, program manager).
Author Information

Kara Peters and Sharon Kiesel
Department of Mechanical and Aerospace Engineering
North Carolina State University
Raleigh, NC

Kara Peters received her PhD degree in aerospace engineering from the University of Michigan in 1996. Until 2000, she was a research collaborator at the Ecole Polytechnique Fédérale de Lausanne, Switzerland, in the Laboratory of Applied Mechanics and Reliability. In 2000, she joined the faculty of the Department of Mechanical and Aerospace Engineering at North Carolina State University, where she is currently an associate professor.

Sharon Kiesel received her BS and MS degrees from North Carolina State University in materials science and engineering. In 2007 she also completed her PhD there in the Department of Mechanical and Aerospace Engineering. Her research focus is the development of intrinsic single-mode POF sensors for large deformation strain sensing. Currently she works for MTS in Apex, NC.

Omid Abdi, Tasnim Hassan, and Mervyn Kowalsky
Department of Civil, Construction, and Environmental Engineering
North Carolina State University
Raleigh, NC

Omid Abdi is a doctoral candidate. He is currently working on the use of advanced sensors for monitoring and assessment of civil infrastructures.

Tasnim Hassan received his PhD in engineering mechanics from the University of Texas at Austin in 1993. He joined the faculty of the Department of Civil, Construction, and Environmental Engineering at North Carolina State University in 1995, where he is currently an associate professor. His research interests include fatigue failure of metallic materials and structures, constitutive modeling, numerical analysis, and sensor applications.

Mervyn Kowalsky is an associate professor. He received his BS, MS, and PhD (1997) degrees in structural engineering at the University of California at San Diego. His main area of research is earthquake engineering, with a focus on seismic design and analysis of concrete and masonry structures, including the use of advanced sensors for monitoring and assessment.

References