A NEW ROUTE TO HIGH SENSITIVITY PRESSURE SENSORS

Research at Universidade Estadual de Campinas (Unicamp) and at Instituto de Estudos Avançados (IEAv) reveals new designs for optical fiber pressure sensors.

By **LEXI CARVER**

OPTICAL FIBERS. TO THE AVERAGE PERSON, the phrase might conjure up an image of glowing hairs twisted artistically into a beautiful shape or fountaining out of a lamp holder. But these light-transmitting silica strands are much more than decoration. Since their development in the 1950s, optical fibers have been used for power transmission, communication, imaging, and sensing.

Specifically, they are often used in situations where other sensing techniques can fail. Since optical fibers are dielectric and versatile, they can be used in environments like vacuum chambers and the ocean floor.

» FROM FIBER OPTICS TO PRESSURE SENSORS

STANDARD OPTICAL FIBERS are designed to act in telecommunications setups and, usually, are not useful for sensing purposes. In order to make optical fibers sensitive to a parameter of interest, processing procedures such as the imprinting of fiber gratings are necessary, or specialty microstructured optical fibers can be employed. Microstructured fibers show promise for obtaining highly sensitive pressure sensors used in activities such as petroleum exploration, where technicians and engineers can use them to detect fluid pressure. Figure 1 presents some examples of optical fibers able to act as pressure sensors, as reported in the literature.

Typically, microstructured optical fibers for pressure sensors are configured so that the application of an external load causes an asymmetric stress distribution within the fiber. This in turn causes variations in the fiber birefringence — a material property referring to an optically anisotropic refractive index — which can be measured for sensing purposes.

"Advantages of optical fiber-based sensors include high sensitivity, electromagnetic immunity, and the possibility of functioning in harsh environments," says Jonas Osório from Unicamp. "They are usually very compact, lightweight, and provide great liberty when choosing a sensor's characteristics."

But the fibers reported to

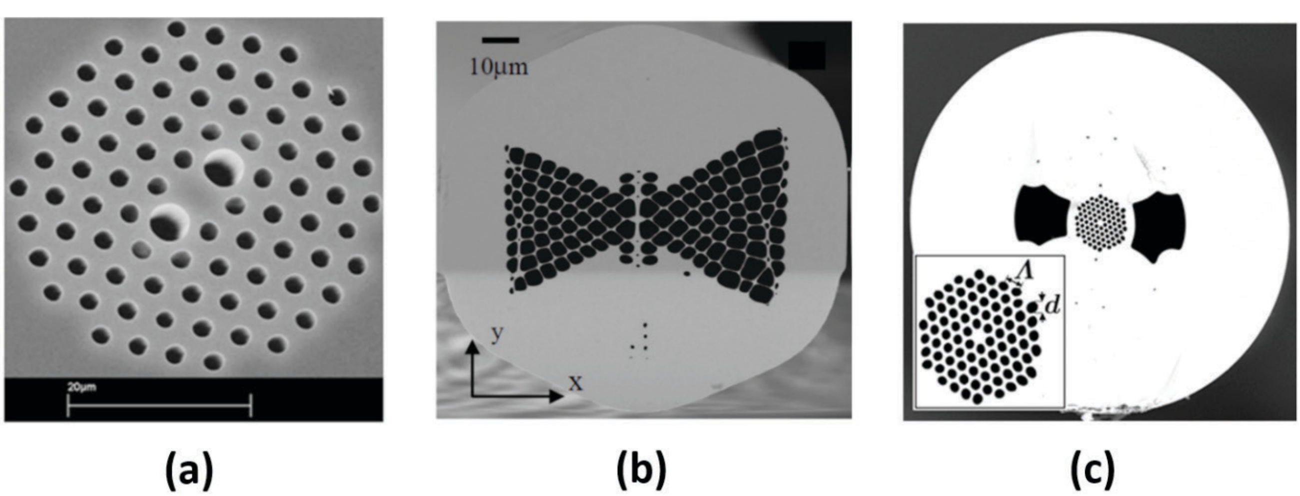

Figure 1. Microstructured optical fibers used in pressure sensing measurements. (a) Photonic-crystal fiber[1]; (b) microstructured fiber with a triangular lattice of holes[2]; (c) side-hole photonic-crystal fiber[3].

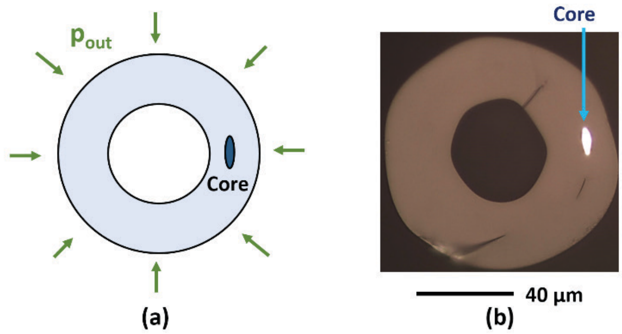

Figure 2. (a) Concept of embedded-core capillary fiber, showing a cross section of the tube with an embedded core, under hydrostatic pressure. (b) Embedded-core fiber cross section.

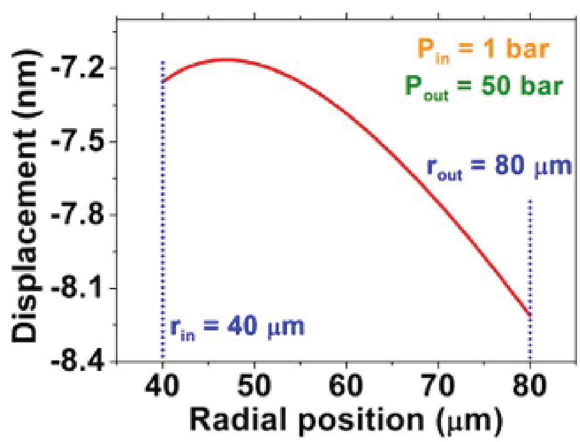

Figure 3. Study of a pressurized capillary fiber without the embedded core, under pressure. The displacement profile was initially studied for an inner radius of r_{in} = 40 µm, an outer radius of r_{out} = 80 µm, an inner pressure pin of 1 bar, and an outer pressure pout of 50 bar.

date have very sophisticated microstructures and usually require several drawings and a delicate manual procedure for assembling the structure. At Unicamp and IEAv in Brazil, work is being done to develop a different type of optical fiber — an embedded-core capillary fiber — which can act as a highly sensitive pressure sensor. This type of fiber requires a simpler fabrication process that involves a preform preparation method and direct fiber drawing.

» A CLOSER LOOK AT GEOMETRIC CHARACTERISTICS

THE EMBEDDED-CORE CAPILLARY fiber is a silica capillary tube endowed with a germanium-doped region (the fiber core) placed inside the capillary wall (Figure 2 shows representations of the fiber structure and cross section). In contrast to the fibers presented in Figure 1, the embedded-core fiber is much simpler than the typical microstructured fibers employed in pressure sensing applications.

Alongside Marcos Franco and Valdir Serrão from IEAv, Jonas Osório and Cristiano Cordeiro from Unicamp investigated pressure-induced birefringence in microstructured fibers in order to develop and validate a new design concept. They focused on fibers designed to sense hydrostatic pressure — pressure induced by a fluid at rest, such as a body of still water surrounding the sensor. However, they diverged from existing designs by using capillary fibers (very thin, hollow tubes) instead of solid fibers with a pattern of air holes that permits asymmetric stress distributions.

Ultimately their goal was to maximize the birefringence dependence on pressure variations, since this would improve the sensing capabilities of the fiber. Beginning from an analytical model, they studied pressure-induced displacements and mechanical stresses in the capillary walls (Figure 3).

The analytical model showed that applied pressure generates an asymmetrical stress distribution inside the capillary wall due to the capillary structure. Via the photoelastic effect, these stresses cause variations in the material refractive index that are different along the horizontal and vertical directions, generating the desired birefringence.

» MAXIMIZING PRESSURE-DEPENDENT PROPERTIES

USING THE COMSOL MULTIPHYSICS® software, Franco, Serrão, Cordeiro, and Osório added the elliptical core, a germanium-doped region inside the silica capillary wall, to their mathematical model. Through their simulation, they obtained the change in modal birefringence as a function of the applied pressure and the location of the core in the capillary wall (Figure 4). Modal birefringence describes birefringence of the optical modes that can travel through the fiber core.

The model calculated the effective refractive indices of the fundamental modes for different pressure conditions. These modes occur when incoming electromagnetic waves are

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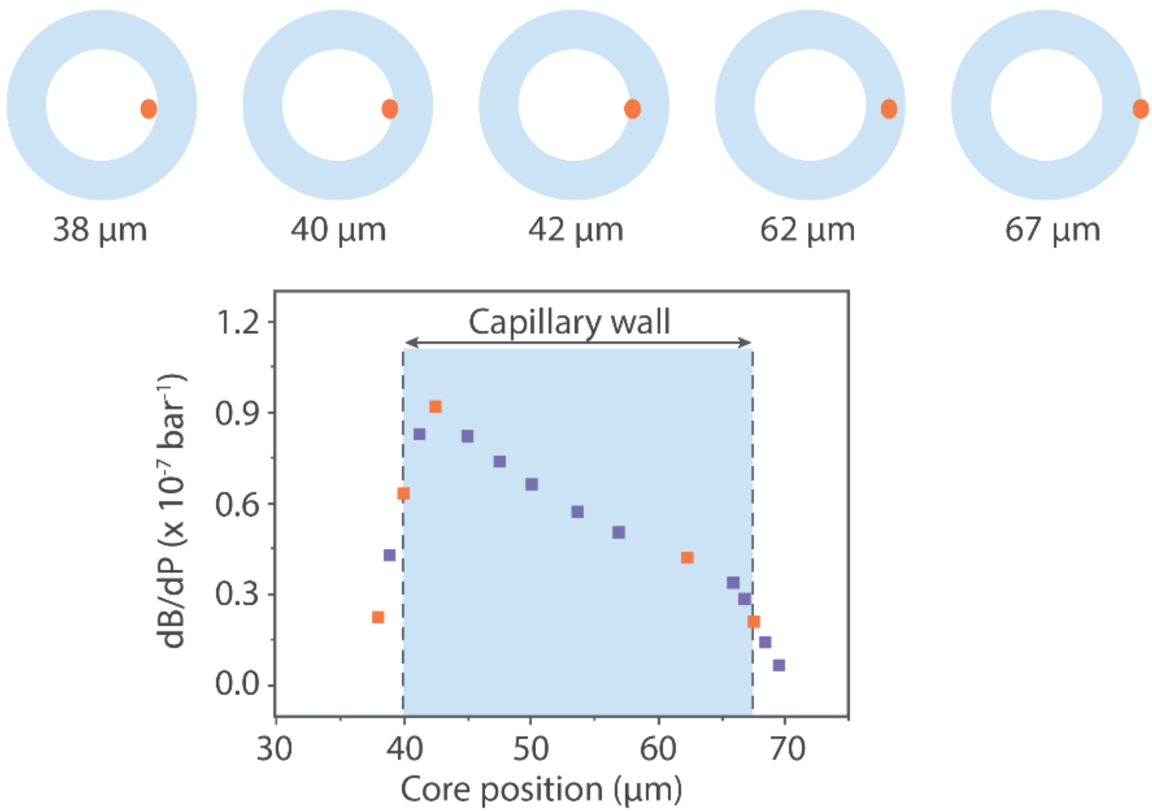

Figure 4. Changes in modal birefringence as a function of the position of the germanium core within the capillary wall. The case with the highest changes in birefringence due to pressure variations occurs when the core is very close to the inner radius of the fiber (top center case).

guided through the fiber core. They discovered that to make the birefringence as dependent on pressure as possible and therefore maximize the sensitivity of the sensor, it was necessary to embed the core area completely within the capillary structure, close to the inner wall. As they analyzed the changes in stress distribution for different geometries, they discovered that the birefringence derivative with respect to pressure values was higher for fibers with thinner walls and for positions closer to the inner radius of the capillary.

» A NEW ROUTE TO MICROSTRUCTURED OPTICAL FIBER SENSORS

THANKS TO THEIR RESEARCH in exploring birefringence pressure dependence, Franco, Serrão, Cordeiro, and Osório laid out a new way to simplify the production of microstructured optical fibers and confirmed that their design would perform properly as a pressure sensor. They compared the sensitivity of their concept to existing, more complicated fiber structures and determined that their design produced similar results but required less assembly work. The embedded-core fiber provides a new route for obtaining highly sensitive optical fiber pressure sensors, and will make it easier for petroleum explorers to evaluate the fluids they extract in real time. ◎

References

The research team identified the embedded-core fiber as a new route towards the simplification of optical fiber-based pressure sensors. The developed research was recently published in Scientific Reports, by Nature Publishing Group (nature.com/articles/s41598-017-03206-w).

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