Pressure Sensing Based on Nonconventional Air-Guiding Transmission Windows in Hollow-Core Photonic Crystal Fibers

Rafael Euzebio P. de Oliveira, Christiano J. S. de Matos, Juliano G. Hayashi, and Cristiano M. B. Cordeiro

***Abstract*—Non-conventional core-guided transmission windows within the visible spectral range are identified in commercial hollow-core photonic crystal fibers designed to operate at 1550 nm. These windows are likely to be related to higher-order cladding photonic bandgaps and are found to be highly dependent on the cladding microstructure, thus being affected by pressure-induced stress/deformation. 20-cm-long fiber samples are then used to demonstrate simple and temperature-independent hydrostatic pressure sensing with two different setups. While in the first setup pressure is externally applied to the fiber and results in operation in the hundreds of $\mathrm{kgf/cm^2}$ (or tens of MPa) range, the second setup applies pressure directly to fiber internal microstructure and is sensitive to pressures down to a fraction of $\mathrm{kgf/cm^2}$ (hundredths of MPa). The fact that pressure is directly transduced into transmitted power greatly simplifies the required sensor interrogation setup.**

***Index Terms*—Hollow-core photonic crystal fiber, photonic bandgap modes, pressure sensor.**

I. Introduction

OPTICAL fiber sensors have well known advantages over their electrical counterparts, such as electromagnetic immunity, light weight, small size and suitability to harsh environments [1]. They have been extensively used, for example, for displacement, strain, temperature and pressure sensing [2].

Most pressure sensors using conventional optical fibers require that pressure be translated into another parameter before being transduced into an optical measurand (generally intensity) [2]. This usually requires complex mechanical and optical apparata and is not readily applicable to certain environments. Some sensors use fiber Bragg gratings for pressure measurement [3]. Attaching the grating to a mechanical assembly that stretches with pressure converts pressure into strain and increases the device sensitivity. In other sensors, polarization changes in highly birefringent conventional fibers are exploited [4]. In any case, these sensors' sensitivity to temperature is an issue and compensation techniques are needed [5].

Pressure sensors using photonic crystal fibers (PCFs) have been proposed using highly birefringent solid-core PCFs and are based on monitoring state of polarization changes due pressure-induced birefringence [6]–[8]. One of the most remarkable advantages of these PCF-basedsensors is their low temperature sensitivity, as well as their suitability to harsh environments [8]. Nevertheless, determining the state of polarization can require a somewhat complex interrogation setup.

Hollow-core photonic crystal fibers (HC-PCF), on the other hand, can offer some interesting sensing possibilities when their core and/or cladding are fluid filled. They have been more widely studied for chemical and biological sensing [9]–[13], but in some cases sensing of physical parameters such as voltage [14] has been proved possible. However, for physical measurands, such an approach may prove impractical and generally leads to cross-sensitivity of several parameters.

Little work has been done with unfilled HC-PCFs for sensing. In one of the few studies undertaken so far, a ~ 200-μm section of an HC-PCF was spliced between conventional fibers, forming a Fabry-Perrot cavity whose length varied when the fibers were tensioned. A strain sensor was, thus, demonstrated [15]. Also, gyroscopes based on air-core photonic bandgap fibers have been reported [16]

It is well known that refractive-index and structural changes in the microstructured cladding of an HC-PCF affect the photonic bandgap spectra [17]. However, to the best of our knowledge, no sensor has been demonstrated that exploits stress- and/or deformation-induced changes in the photonic bandgap spectrum. In this case, which can be of particular interest for pressure sensing, the measurand is directly transduced into the transmitted intensity at a given wavelength close to the bandgap edge, making the interrogation setup extremely simple. However, high sensitivity to stress and deformation requires narrow transmission windows or sharp band edges, which are not always directly obtained in the fundamental bandgap of HC-PCFs.

The transmission windows associated to higher-order bandgaps tend to be narrower than those related to the structure's fundamental bandgap [18], [19]. Nevertheless, in HC-PCFs these windows are so lossy that are generally not observed. The high loss is related to the presence of the thin silica webs that are required to hold the high-index inclusions (silica strands in this case) in place and that give rise to coupling with lossy cladding modes [18].

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R. E. P. de Oliveira and C. J. S. de Matos are with Grupo de Fotônica, Universidade Presbiteriana Mackenzie, São Paulo, SP 01302-907, Brazil (e-mail: alfaer@gmail.com; cjsdematos@mackenzie.br).

J. G. Hayashi and C. M. B. Cordeiro are with Instituto de Física "Gleb Wataghin" (UNICAMP), Campinas SP 13083-970, Brazil (e-mail: julianogrigoleto@hotmail.com; cmbc@ifi.unicamp.br).

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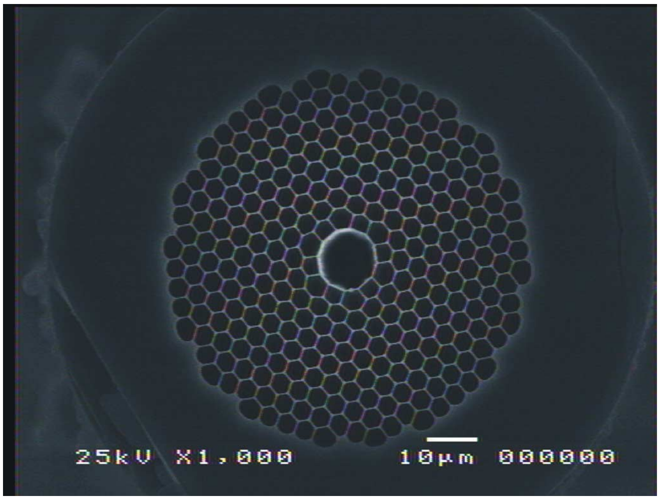

Fig. 1. Scanning electron micrograph of the transverse section of the hollow-core PCF sample I (HC -1550–02 I).

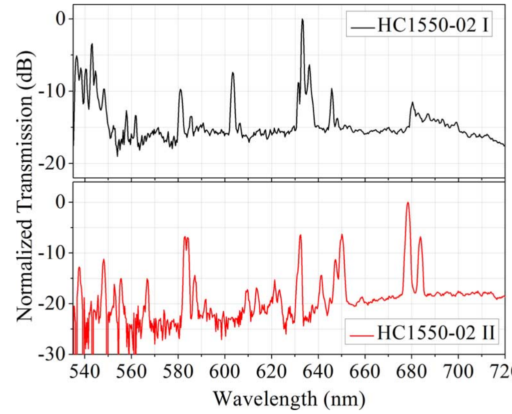

Fig. 2. Transmission windows in the visible spectral range in samples HC-1550–02 I (top) and HC-1550–02 II (bottom).

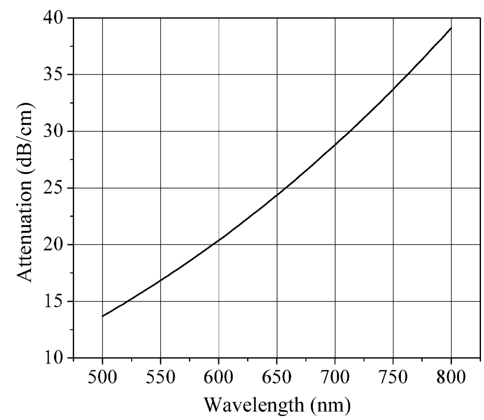

Fig. 3. Calculated attenuation for the fundamental core mode of HC1550–02 if only Fresnel reflection is accounted for as a guiding mechanism.

In this work we propose, demonstrate and preliminarily characterize a pressure sensor based on stress/deformation-induced transmission changes in commercial HC-PCFs. For this purpose, we identified and used narrow-bandwidth transmission windows within the visible optical range that are possibly related to higher-order photonic bandgaps. These windows were found to be very susceptible to the structural deformations and the pressure applied directly to the fiber modulated the transmitted optical intensity. Two different sensor setups were designed so that pressure could be applied externally or to its internal microstructure and resulted in operation in the hundreds or few $\mathrm{kgf/cm^2}$ ranges, respectively. The observed transmission windows were found to be temperature independent up to $\sim 100^{\circ}\mathrm{C}$, resulting in temperature-independent pressure sensors.

II. Transmission Windows

The fiber used in the experiments was the commercial model HC-1550–02, provided by Crystal Fiber A/S. Fig. 1 shows the transverse section of one of the samples employed (called here sample I). From this picture, the pitch and air-filling fractions are determined to 3.86 μm and 0.96, respectively. Although designed for 1550-nm bandgap guidance, this fiber also presented in the visible region several spectrally-narrow core-guiding transmission windows (Fig. 2) that are observable for fibers of up to ~ 40 cm but vanish for longer fibers.

These windows were found to be highly sensitive to the exact fiber structure, which can be confirmed through comparison of the transmission spectra measured for two samples of the same fiber model but with different fabrication dates (i.e., different preforms). Such spectra are shown in Fig. 2 for samples hereafter called I and II, each with a 20-cm length.

It is possible to note that, although both fibers present the mentioned windows, their profiles notably differ. A structural change resulting from pressure-induced stress/deformation is, thus, expected to similarly yield spectral changes. It is important to note that varying the coupling conditions around its optimum point did not result in noticeable changes in the transmission spectrum, which is crucial for reproducible sensing measurements.

The wavelength dependence and the loss value observed in the transmission spectra suggest that light is guided by cladding-bandgap confinement, rather than by partial reflection in a capillary-like structure [20]. The latter mechanisms would lead to the smoother spectral dependence shown in Fig. 3 and that was numerically calculated from the standard wave-equation [21] for the fundamental (leaky) mode in a capillary. For this calculation, the cladding was assumed to be composed of a solid material with refractive index equal to the effective cladding refractive index of HC-1550–02, which was numerically calculated for each wavelength of interest using the method described in [22]. From the Fig. 3 it is possible to conclude that, for our sample length ($\sim$ 20 cm), capillary guiding would result in an attenuation at 633 nm of ~ 460 dB, while the attenuation at this wavelength for sample I is estimated to be of ~ 0.8 dB/cm.

The mode guided by sample I at 633 nm has been characterized in more detail and correspond to a single-transverse-phase fundamental mode. Fig. 4 shows the intensity distribution within the fiber core, as measured by imaging the fiber output on a CCD camera. The mode presents an elliptic shape with an ellipticity, defined as the ratio between the full widths at half maximum of the short and long axes, of ~ 0.93. This shape is believed

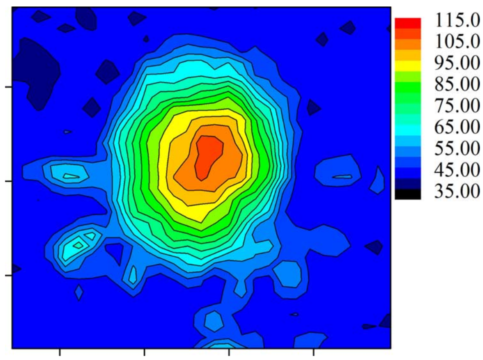

Fig. 4. Transverse intensity distribution (in arbitrary units; contour lines in steps of 5) of the guided mode at 633 nm in fiber sample I.

to be connected with the slight fiber core ellipticity of ~ 0.95, which can be seen in Fig. 1. Note also that the light is well confined within the core, excluding the possibility of the transmission windows being connected to cladding-mode propagation.

Additional work is currently under way to clarify the mechanism for the observed air-guiding transmission windows. As mentioned earlier, capillary guiding can be ruled out and light may be confined to the core by higher-order cladding bandgaps. As these bandgaps tend to be highly sensitive to the exact structure, numerical modeling is challenging. The relatively high measured transmission losses are likely to be related to confinement loss mediated by the cladding silica webs [18], which may also be responsible for the sharp spectral profile of the transmission windows. The high loss may also be connected to non-uniformity of the fiber along its length, as discussed in more details in Section III-B. Nevertheless, differences in the transmission spectrum of fiber sections from the same sample, but distanced from each other by over a meter were not noticeable.

III. Pressure Sensing

Exploiting the sensitivity to fiber deformation of the narrow transmission windows, we propose the application of the studied fibers as pressure sensors. Two different setups to apply pressure were assembled and tested. In the first, pressure is externally applied to a small section of the fiber. In the other setup, one of the fiber tips is exposed to pressure, so that the internal microstructure is pressurized. These two setups show very different responses to pressure. While hundreds of $\mathrm{kgf/cm^2}$ can be measured when pressure is applied externally, a few $\mathrm{kgf/cm^2}$ can be sensed when the pressure is applied internally. This ability to operate in very different measurand ranges, the observed temperature insensitivity, and the fact that pressure is directly transduced into intensity (resulting in simple interrogation setups) are the main advantages of the proposed sensors.

A. External Pressure

The setup used to externally apply pressure to the fiber is schematically shown in Fig. 5. A PCF-based supercontinuum source was coupled into the 20-cm HC-1550–02 samples with a $40\times$ objective lens. The pressure was applied to roughly a 3-cm-long section of the fiber that traversed an oil-filled pressure chamber connected to a hydraulic pump. The gauge pressure was measured with a manometer and the optical output was

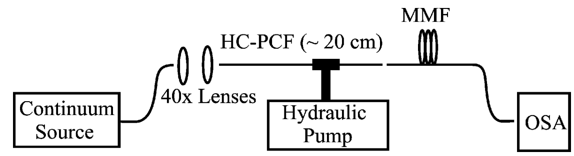

Fig. 5. Experimental setup used to apply external pressure to the HC-PCF.

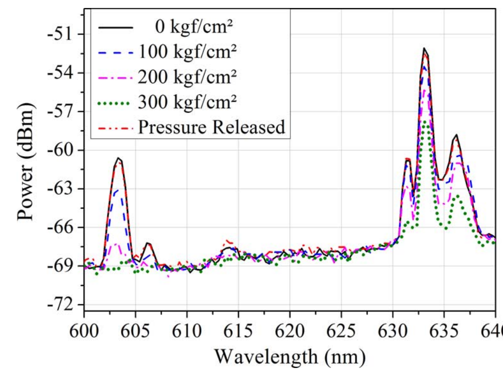

Fig. 6. Transmission spectrum of fiber sample I for different gauge pressures.

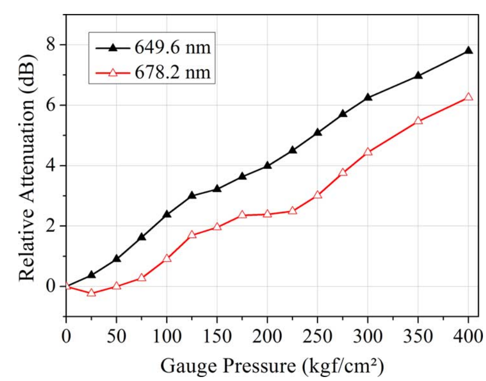

Fig. 7. Relative attenuation as function of gauge pressure in fiber sample II at 649.6 nm and 678.2 nm.

butt-coupled to a multimode fiber (MMF) connected to an optical spectrum analyzer (OSA).

When pressure is applied, the transmission windows in the visible are observed to present increased attenuation. Fig. 6 shows the power transmitted in some of these windows in sample I, as a function of gauge pressure from 0 (i.e., ambient pressure) to 300 $\mathrm{kgf/cm^2}$. When pressure is released the spectral peaks return to their initial positions within ~ 0.3 dB. The same trend is observed with fiber sample II, for which Fig. 7 shows the measured attenuation, relative to the zero gauge pressure case, as a function of the gauge pressure in two visible windows at ~ 650 nm and ~ 678 nm.

Note that in both fibers, each bandgap is differently affected by gauge pressure, which may be exploited for self-referenced sensor calibrations. Also, the results are found to be reproducible. The sensor response is suitable for pressures in the few hundreds of $\mathrm{kgf/cm^2}$ range. It is worth highlighting that transmission within the infrared was not found to be affected by pressure, possibly because of the higher robustness of guidance, and can also be exploited for referencing.

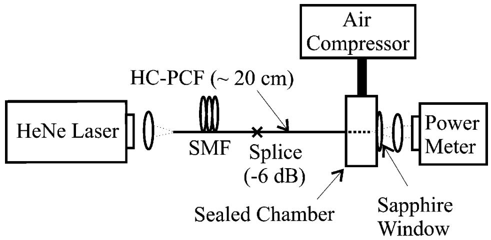

Fig. 8. Experimental setup used to apply internal pressure to the HC-PCF.

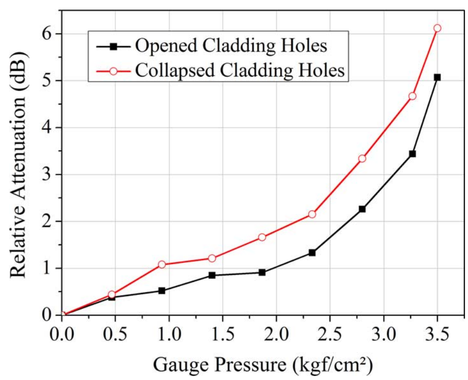

Fig. 9. Relative attenuation as a function of gauge pressure in fiber sample I when the cladding holes are opened and closed near the HC-PCF fiber tip.

The setup described here can be fully fiber integrated if both HC-PCF tips are spliced to conventional fibers. Multi-point sensors can also be developed, provided that splice losses are improved, if multiple short HC-PCF sections are interleaved with lengths of conventional fiber and optical time domain reflectometry is employed for sensor interrogation. Totally distributed sensors cannot be developed due to the high propagation losses of the used transmission windows.

B. Internal Pressure

The setup used to internally apply pressure to the HC-PCF, shown in Fig. 8, uses a sealed chamber where the output fiber tip is placed. Light from a He-Ne laser is coupled into a conventional fiber that is single-mode at 633 nm (SMF), with a 20 $\times$ objective lens. The SMF is spliced to fiber sample I with a non-optimized splice loss of 6 dB. Light outputting the HC-PCF is collected through a sapphire window in the pressure chamber by a 10 $\times$ objective lens and directed to either an imaging camera or an optical power meter. Pressure is applied with an air compressor coupled to the sealed chamber. A manometer connected to the compressor yielded the measured gauge pressures.

As the fiber tip is exposed to pressure, air flows into the fiber inducing stress and deformation to the structure. As with external pressure, internal pressure increases the attenuation of the transmitted light. Fig. 9 shows how the attenuation in fiber sample I increases at 633 nm with gauge pressure. In addition to the case in which the fiber tip is simply placed in the sealed chamber and air flows into cladding and core holes, Fig. 9 shows results for which the cladding holes were blocked near the fiber tip so that air flows solely into the core. The cladding holes were blocked with the use of a fiber fusion splicer, as described in [23]. The latter case proved to be more sensitive to pressure, with up to $\sim$ 1 dB higher induced attenuation for the higher applied pressures. The increased sensitivity is believed to be related to more stress/deformation obtained when the air flows only into the core. When the cladding holes are opened, some counter pressure is created in the cladding that may reduce stress and deformation.

Note that pressures of a few $\mathrm{kgf/cm^2}$ induce significant attenuation, while with external pressure hundreds of $\mathrm{kgf/cm^2}$ were required. This feature is attributed to the higher susceptibility to stress and deformation of the thin internal microstructure, while externally pressure must also deform the 25-μm thick solid silica jacket. For this reason, the operation range with external pressure may be expected to shift towards lower values if the PCF section submitted to pressure is chemically etched.

As was pointed in the end of section II, the non-uniformity along the HC-PCF length [24] may be an important loss factor for the observed narrow transmission windows. This assumption is supported by the observation of a transient time of tens of second for the transmitted power to stabilize after the pressure is internally applied in longer fibers (~1 m) at 1064 or 1550 nm. This transient is likely to be related to the air flow along the fiber, which initially generates a pressure gradient. The attenuation is found to be higher immediately after pressure is applied or released and to gradually decrease until it stabilizes when the pressure is equally distributed along the fiber. The pressure-induced infrared attenuation for this case was noticeable due to the longer length of fiber exposed to pressure. The transient time is not noticeable in shorter fibers (~20 cm) at the high loss, visible, transmission windows.

The loss sensitivity to temperature was evaluated with the internal pressure setup, both with and without pressurizing the fiber. No noticeable transmission change was observed for temperatures up to $\sim$ 100°C. For higher temperatures the loss varied in a complex way, which requires further investigation. The results, therefore, indicate that the PCF can act as a temperature-independent pressure sensor up to 100°C. The same feature is expected for the external pressure setup.

IV. Conclusions

Two different temperature-independent pressure sensor setups, with operation points in the few and hundreds of $\mathrm{kgf/cm^2}$, have been proposed and demonstrated based on commercially-available hollow-core photonic crystal fibers. The setups exploit air-guided modes found to exist in non-conventional transmission windows within the visible spectrum. These windows are likely to correspond to higher-order photonic bandgaps and are extremely sensitive to the photonic crystal cladding and to pressure-induced changes in its microstructure.

The work described here opens new and exciting possibilities both in fundamental and in applied research on hollow-core photonic crystal fibers. In the fundamental research side, further theoretical and experimental investigation is required to fully understand the origins of the observed transmission windows. Their spectral profile may possibly be exploited for highly sensitive characterization of the fiber microstructure and of its longitudinal uniformity. Such a characterization method may lead to additional improvements in the fiber fabrication techniques, which may result in transmission windows with lower losses and a higher fiber-to-fiber reproducibility. In the applied research side, the pressure sensors need to be further characterized to meet real-world requirements and may be further optimized to present custom-designed sensitivities (for instance, by chemically etching the silica jacket and by externally applying pressure) and multi-point sensors may be developed. Further understanding the emergence of the transmission widows may also enable to design sensing fibers with increased pressure sensitivities and with customized operation wavelengths.

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Rafael E. P. de Oliveira was born in São Paulo, Brazil, in 1984. He received the degree in electrical engineering from Universidade Presbiteria Mackenzie, São Paulo, Brazil, where he is currently pursuing the M.Sc. degree.

His main research interest is photonic crystal fiber with application in optical fiber sensing.

Christiano J. S. de Matos was born in Rio de Janeiro, Brazil, in 1975. He received the B.Sc. and M.Sc. degrees in physics from Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio) and the Ph.D. degree from Imperial College London, U.K.

He is a Professor with the Universidade Presbiteriana Mackenzie, São Paulo, Brazil, where he develops experimental research work in photonic crystal fibers and nonlinear fiber optics with applications to fiber sensing and telecommunications.

Juliano G. Hayashi is an undergraduate student in the Physics Institute at the State University of Campinas (UNICAMP), Campinas, Brazil.

His research interest is in the use of photonic crystal fibers for the development of all-fiber devices.

Cristiano M. B. Cordeiro received the B.Sc. and M.Sc. degrees in physics from PUC, Rio de Jainero, Brazil, and the PhD degree from the State University of Campinas (UNICAMP), Campinas, Brazil.

Since 2008, he has been a Professor in the Physics Institute at UNICAMP. His research area, in the field of experimental optics, is related with the study and development of specialty optical fibers with new functionalities, including the design and fabrication of new structures and the development of devices and sensors based on photonic crystal fibers.