Microfluidic tunable photonic band-gap device

P. Domachuk, H. C. Nguyen, and B. J. Eggleton
CUDOS, School of Physics, University of Sydney, Sydney, NSW 2006, Australia

M. Straub and M. Gu
Centre for Micro-Photonics and CUDOS, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia

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We introduce a method for tuning a photonic band-gap material by means of displacing microfluidic plugs. The fluid is introduced into air voids that constitute the structure of the photonic crystal and is displaced using a capillary heater. The photonic crystal geometry is obtained using a microstructured optical fiber, comprising a periodically spaced array of air holes that is interrogated in the transverse direction, creating a “tall microchip.” Optical spectra are compared to band structure calculations of an idealized band-gap material. © 2004 American Institute of Physics. [DOI: 10.1063/1.1667592]

Photonic band-gap (PBG) materials provide a rich range of phenomena, both experimentally and theoretically. PBG materials possess one or more photonic stop bands, with respect to frequency, that also depend on the crystallographic axis being presented. Being composed of periodic spatial modulations of refractive index, they can be conceptualized as being equivalent to the two- and three-dimensional periodic electronic crystal structures found in semiconductors and semimetals, providing the analogous band gap for photons. As well as being of fundamental interest, PBG materials have properties that make them useful for device applications. Wavelengths that lie within the band gap are forbidden from propagating through the material, lending PBG structures naturally to the application of filtering as well as confinement, such as planar waveguides and photonic crystal fibers. Wavelengths that lie outside the band gap may be strongly dispersed, leading to the “superprism” effect.

The next generation of optical devices must incorporate a degree of tunability in order to be truly versatile and necessarily include elements that are actuated at will. There is a field of tunable optical elements beginning to appear, such as thermally tuned optical devices, that enable a range of dynamic functionalities.

An emerging technology to facilitate this tunability is microfluidics. This is the utilization of microscopic volumes of fluids to perform tasks in situ, such as modifying optical properties of an air void, and thus the optical response, of a microstructured device. Conversely, the modification of an optical device by a fluid in a known way can be used as an environmental or analysis sensor.

In this letter, we develop a technique for the dynamic tuning of PBG materials through the controlled displacement of microfluidic plugs. The two-dimensional PBG material is provided by the transverse use of a photonic crystal fiber and the obtained spectra are compared to a band-structure calculation of an idealized PBG material. The band-gap properties of the material are then switched at will by moving the microfluidic plugs into and out of the optical interaction region through an induced pressure gradient.

Figure 1 illustrates the device geometry used in this experiment. The object of study is the center of the fiber, consisting of a photonic crystal made of an array of air holes embedded in a silica cladding. We use the PBG structure in the core to interact with light traveling transversely across the fiber, rather than using its band-gap properties to guide light along the fiber. This geometry naturally lends itself to this application that we term tall microchip (TMC) technology. This paradigm may be thought of as the generalization of the transverse fiber experiment presented here. That is, the creation of semiplanar waveguiding structures by the transverse use of microstructured optical fibers.

The fiber itself was fabricated by Crystal Fiber A/S (Denmark). It has a hexagonally packed array of air holes that are 0.8 microns in diameter with a crystal spacing of 1.4 microns with the main symmetry directions in reciprocal space indicated in Fig. 1. The central hole of the crystal lattice has been removed, creating a “defect” in the PBG

![Figure 1](image_url)

FIG. 1. Photograph of the experimental setup. Note the SMF to the left- and right-hand side and the PBG fiber in the center. The red HeNe scattered light is to indicate the light path in the geometry. Inset is a scanning electron microscope micrograph of the PBG structure with the irreducible Brillouin zone indicated.
material which, as shown by simulations, has no discernable effect in the transverse geometry. The regularity of the fiber in the usual propagation direction of the fiber ensures that the microstructured core may be considered a two-dimensional photonic crystal. Note also the irregularity in the hole diameter further away from the central guiding region.

The device geometry for demonstrating the TMC concept and tunable microfluidic functions is summarized in Fig. 1. The crystal fiber is sandwiched by two standard single mode fibers (SMFs) that are used to guide light into and take light from the PBG material. The light guided into the structure was from a white light source and the outgoing light was analyzed by an optical spectrum analyzer (OSA). The PBG material was characterized only in the \( \Gamma - M \) direction due to the large diameter air holes at the vertex of the hexagon, rendering the analysis of the \( \Gamma - K \) direction a much more complex proposition. Two polarizations are also defined, where transverse magnetic (TM) has its electric field parallel to the length of the fiber and transverse electric (TE) is perpendicular.

Figure 2 shows both a band-gap calculation and an experimental verification of the transverse PBG properties of this fiber. In the \( \Gamma - M \) direction, we see two band gaps open up at wavelengths of approximately 1.5 and 3 microns for both polarizations. It should be noted that the band-gap calculation was done for an infinite slab of uniform photonic crystal with the same properties as the inner ring of the crystal fiber and no central defect. Also, for the spectra in Fig. 2, the fiber is probed using a Fourier transform infrared (FTIR) spectrometer with an objective that uses a range of input angles simultaneously, thus impinging on the Brillouin zone from several directions. Despite this, the band gaps appear very close to their predicted position, despite the calculation approximations and lack of angular resolution. This analysis is in the spirit of earlier PBG work.\(^7\)

As expected, the spectral response of this structure can be adjusted and tuned by varying either the spacing of the air holes, the index of the background material, or the index of the air-filled region itself. In this letter, tunability is obtained by introducing a fluid into the air hole region and displacing it by utilizing a pressure gradient brought about by differential heating. This enters the realm of microfluidics, a field of study originally motivated by the need for small-volume biological assays and experiments.\(^8,9\)

An established framework exists for the description of continuous fluid flow within channels, \(^10\) namely, solving the Navier–Stokes equations for the channel geometry. However, on the microfluidic scale, body forces inside the fluid and surface tension become much more dominant factors in the description of fluid flow. The microscopic and atomic structure of the channel itself also plays a much greater role in microfluidic flow. This having been said, for this application, it is a reasonable approximation to consider the fluid as a Navier–Stokes flow and any air bubbles in the fluid may be treated as an ideal gas.\(^11,12\)

The fluid itself is introduced into the capillaries of the PBG by a procedure that aims to minimize extraneous wetting on the outside of the fiber and is detailed in Fig. 3. A
small drop of index matching oil is placed upon the cleaved end of a standard single mode fiber and the cleaved end of the PBG fiber is brought up against the meniscus of the fluid drop. The fluid then pulls itself into the voids by capillary pressure. The length of fluid drawn is of the order of a millimeter, far more than the optical interaction region in question which is indicated in Figure 3 by a drawn-in black line.

Once the fluid is introduced into the interaction region of the PBG fiber, the experiment is performed again, as described above. Figure 4 presents resulting spectra in comparison with other experimental setups. The results presented here are for unpolarized light. The lower dark line is for the experiment performed for the PBG fiber with no fluid. When fluid with index \( n = 1.300 \) is introduced, note that a lot of the features of the spectrum become attenuated due to the lowered index contrast between the PBG material and the surrounding silica. Similarly, fluid of index \( n = 1.51 \) causes a further flattening of features. Notice that the two spectra above have a transmission power comparable to that of a transverse SMF or no fiber at all. This is due to that fact that the unaltered PBG structure causes diffraction to at least first order, directing output light away from the core of the detector fiber. When the PBG structure is made transparent by fluids, however, this diffraction ceases, and more light reaches the OSA, giving about a 10 dB raise in peak power. When a fluid with index \( n = 1.800 \) is introduced, the PBG structure reasserts itself, with a more wavelength dependent structure seen in the lower lighter line.

To summarize, we have convincingly demonstrated the TMC geometry by experimentally showing PBG effects in a photonic crystal fiber interrogated transversely. In a move toward devices in this geometry, tunability was introduced by the displacement of microfluidic plugs within the structure.

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