Photonic Structures

Lateral Thinking With Photonic Crystal Fibers

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The introduction of photonic crystal fibers (PCFs) has enabled researchers to redefine the concept of optical fibers and extend their functionality beyond the realm of traditional optical transportation. The regular lattice of holes that characterizes PCFs gives rise to unique waveguiding properties, along with fascinating effects such as photonic bandgap (PBG) guidance, "endlessly single-mode" guidance and supercontinuum generation.[1] Until recently, however, the periodic nature of PCFs has been used only to enhance the fibers' longitudinal waveguiding characteristics.

We have introduced another application of PCFs: the manipulation of light propagating transversely across the fiber.[2] In other words we exploit the fact that the fiber's cross-sectional profile is essentially a two-dimensional (2D) photonic crystal (PC). Figure 1(a) illustrates such a geometry, with a scanning electron micrograph of a typical microstructure. The light enters the PCF from the side, interacts with the periodic microstructure and emerges on the far side as it would in a planar PC.[3] By studying its transmission and reflection characteristics both experimentally and through modeling, we have demonstrated that such a transverse fiber can indeed behave as a 2D PC. For instance, light emerges at a series of angles to form diffraction spots [Fig. 1(b)], and the transmission of certain wavelengths is suppressed by the PBG.

The existence of this transverse PCF geometry leads to the possibility that a range of planar-device concepts can be designed into the fiber microstructure. In this context, the simple yet flexible fabrication of PCFs gives the transverse fiber an advantage in many respects over the variety of existing PCs. These include: smooth walls which suppress scattering; a potentially arbitrary microstructure which adds flexibility to device concepts; and tunability.

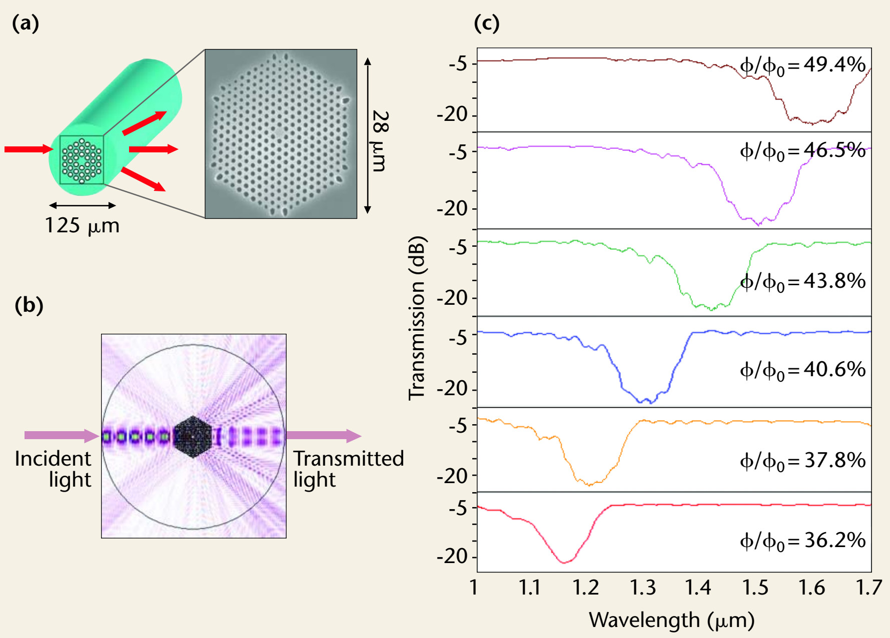

Figure 1. (a) Schematic of the transverse fiber geometry and a scanning electron micrograph of a PCF microstructure; (b) finite-difference time-domain simulation which illustrates the propagation of light across the PCF; (c) transverse transmission characteristics of a PCF as the fiber is tapered down to smaller diameters. The shift of the fundamental bandgap to shorter wavelengths, with decreasing fiber diameter, is clearly visible. The ratio of the tapered fiber diameter to the original fiber diameter is also shown.

We have already demonstrated a number of tunable transverse PCFs. The simplest is to fill the air-holes with a particular material. For example, the insertion of fluids into the air-holes gives rise to an adjustable refractive index contrast, thereby changing the spectral properties of the device. Because the fluid is mobile, dynamic tuning can be achieved by sweeping the fluid in and out of the optical path via thermal actuation.[4] Other materials, for instance liquid crystals tuned with varying electric fields, can be inserted to achieve a similar result. Furthermore, it is possible to taper the PCFs down to smaller diameters and hence scale down the periodic structure, modifying the spectral response. We have been able to reduce the pitch by a factor of three without significant hole-collapse.[5] In this way, we have succeeded in shifting and transversely probing the fundamental PBG down to the communications band from its typical wavelength position of approximately 3 µm [Fig. 1(c)].

This work may introduce a whole new fabrication paradigm. Microphotonic components can be created using transverse optical fiber sections which have planar functionality designed into them at the preform stage. Tapering and microfluidic techniques together provide a methodology with which the optical response of the device can be modified dynamically.

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Temperature Stability for Photonic Crystal Devices

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A general method has been developed to allow photonic crystal devices to operate in a variable temperature environment. Recent work in the photonic crystal area has focused on the achievement of high *Q*-factor cavities in which light is confined within a very small wavelength range.[1] While this is an advantage for achieving low threshold lasing, high sensitivity detection of chemical and biological species, and wavelength division multiplexed components for optical interconnects and optical communication systems, there is a price to be paid in terms of practical device operation and reliability in changeable ambient conditions. The higher the *Q* of the cavity, the more sensitive the device will be to small changes in environmental conditions.

The key to the performance of photonic crystals is a periodic dielectric function, which introduces a wavelength range over which light is forbidden to propagate. This range of zero transmission is known as the photonic bandgap (PBG). Light confinement within the PBG is achieved by introducing a defect, or break, in the periodicity of the dielectric function. As a result, a resonance, in which light can propagate, emerges in the PBG. Any changes to the dielectric function of the photonic crystal will change the resonance wavelength. Consequently, for photonic crystals with *Q*-factors above 10,000, even a few degrees C change in temperature could cause a 10 dB change in transmission at the resonance wavelength.

A new method has been developed to create temperature insensitive silicon-based photonic crystals. The temperature dependence of the silicon refractive index [$dn/dT \sim 2\text{-}4 \times 10^{-4}\ \mathrm{K}^{-1}$ for the visible and the near infrared (IR) regions] causes the resonance wavelength of silicon-based photonic crystals to red shift upon heating. We have shown that there exists a proper thermal oxidation condition (e.g., temperature and ambient oxygen content) which counterbalances this effect and leads to temperature insensitive photonic crystal resonances.[2] During oxidation, a thin layer of silicon is converted into silicon oxide. Because silicon oxide's thermal expansion coefficient is one-fifth that of silicon, as the operating temperature of a PBG device increases, silicon's thermal expansion is impeded, thus creating a compressive stress within the silicon. The dependence of silicon's refractive index on this resulting pressure ($dn/dP \sim -10^{-5}\ \mathrm{MPa}^{-1}$) is of the opposite sign to that of the temperature dependence on the refractive index.

The oxidation method has been demonstrated on one-dimensional porous silicon PBG microcavities (see Fig. 1). Scaling the oxidation method to other silicon-based photonic crystal structures will simply involve finding the proper oxide thickness for a given silicon feature size. The method could also be generalized to other pairs of materials.

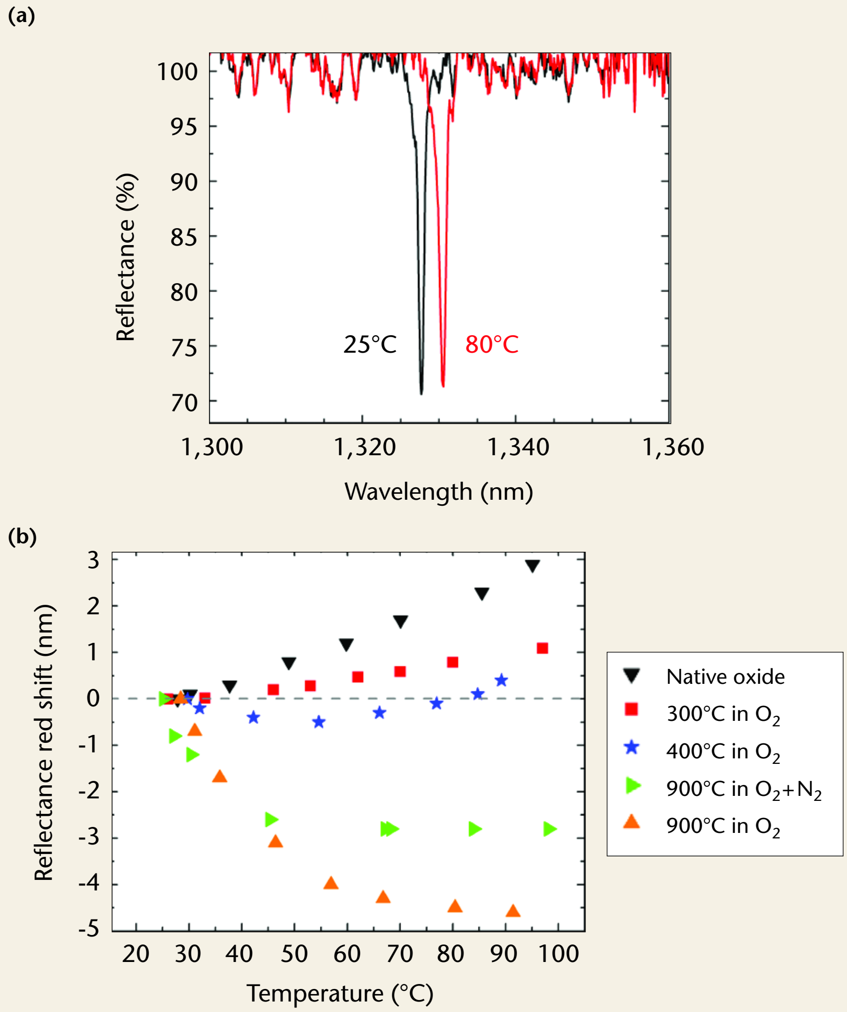

Figure 1(a) Reflectance of one-dimensional porous silicon PBG microcavity at two different temperatures. With no thermal oxidation, a significant red shift of the resonance wavelength occurs upon heating. **(b)** One-dimensional porous silicon PBG microcavity reflectance shift as a function of temperature for various oxidation conditions. Oxidation at 400 degrees C produces a nearly temperature insensitive microcavity resonance.

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