

Photonic crystal fiber microtaper supporting two selective higher-order modes with high sensitivity to gas molecules

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A photonic crystal fiber consisting of three rings of air holes was tapered down to 3–5 μm . The voids of the fiber were collapsed so a solid microtaper was formed. In this microtaper two selective higher-order modes propagate and interfere. This makes the transmission of the taper to exhibit a sinusoidal pattern with subnanometric width fringes. It was found that the device was highly sensitive to gas molecules. The latter is attributed to surface refractive index changes, number of molecules enveloping the taper, and high sensitivity of the modes participating in the interference. © 2008 American Institute of Physics. [DOI: 10.1063/1.2973641]

Photonic crystal fibers (PCFs) are characterized by a periodic pattern of microscopic voids that are present all along the fiber. Owing to the holey structure these fibers have modal and guidance properties that may differ substantially from those of conventional fibers. Such properties can be exploited for a diversity of applications of scientific and technological interest.¹ The characteristics of the guided light in a PCF can be further modified by scaling down its internal structure, for example, through tapering.^{2,3} Such a postprocessing technique also allows to radically alter the microstructure of the PCF over a short region and to change dramatically the modal properties of the fiber. The tapering of PCFs is appealing since a combination of the initial distribution of the voids in the PCF with the tapering conditions determines the properties of the resulting taper.^{4–9} Here we report a PCF microtaper whose transmission exhibits sinusoidal interference patterns with a very short fringe spacing. The microtaper had diameters ranging from 3 to 5 μm and was fabricated with a specially designed single mode PCF. The peculiarity of such a taper is that it supports only two selective higher-order modes and that it exhibits high sensitivity to volatile organic compounds (VOCs) at room temperature. We found that the interference pattern shifted differently when the taper was exposed to vapor molecules of alcohols, methylene chloride, or chloroform. Thus, we believe that the tapers proposed here can be used for diverse industrial applications.

Unlike the interferometric approach reported here for detecting gas molecules previous approaches are based on absorption measurements.^{10–16} Acetylene^{10–12} or methane,^{13,14} for example, have absorption lines at telecommunications wavelengths. Thus if the voids of the PCF are filled with such gases one can analyze the transmission spectra. The drawbacks in this approach are the long time needed to fill the voids of the PCF with the gas and the critical launching conditions to inject and extract light to and from the PCF.^{10–14} Thin films combined with tapered PCFs or with long-period gratings inscribed in the PCF give also the possibility to detect hydrogen gas,¹⁵ or isopropanol and toluene

vapors.¹⁶ In these approaches the gas is absorbed by the film thus making the detection mostly dependent on the film.

A micrograph of the cross section of the PCF employed in the experiments and also a drawing of the taper are shown in Fig. 1. The minute bubbles around the taper represent the VOC vapor molecules. The PCF consisted of three rings of air holes in the cladding arranged in a hexagonal pattern and a missing hole at the center that played the role of a core.¹⁷ The diameter of the solid core was 17.5 μm , the average diameter of the voids was 3 μm , and the average hole spacing (pitch) was 8.8 μm . The outer diameter of the fiber was 125 μm . To taper the PCF we elongated it while it was being heated with an oscillating flame torch produced by a mixture of oxygen and butane. We fabricated PCF tapers whose diameters were in the range between 3 and 5 μm . The length of the taper waist was ~ 5 mm. The air holes of the PCF were permanently collapsed, which allowed us to convert the tapered section of the PCF into a solid microfiber. Although the latter may support several modes⁹ it was found that only two selective higher-order modes (HE_{05} and HE_{06}) survive when the waist diameter is in the 3–5 μm range. The two higher-order modes have quite different propagation constants and therefore they travel at very different speeds. As

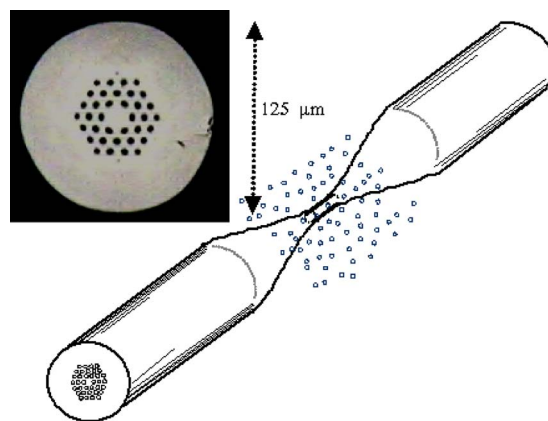


FIG. 1. (Color online) Cross section of the PCF used in the experiments. The drawing is a presentation of the PCF microtaper exposed to vapor molecules of volatile compounds.

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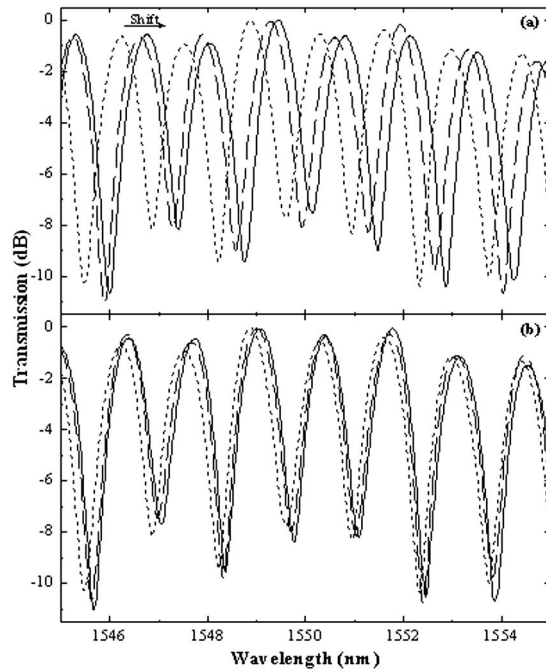


FIG. 2. Normalized transmission spectra of a $5\ \mu\text{m}$ thick interferometer in air (dotted lines) and VOC vapors. (a) Device spectra when it was immersed in vapor molecules of methylene chloride (dashed line) and chloroform (solid line). (b) Spectra when the device was enveloped by vapor molecules of methyl alcohol (dashed line) and isopropyl alcohol (solid line).

the modes propagate in the PCF taper they accumulate a phase difference given by $\phi_{56} = 2\pi\Delta nL/\lambda$, where $\Delta n = n_5 - n_6$, with n_5 and n_6 the effective indices of the modes. L is the length of the PCF taper waist and λ is the wavelength of the optical source. After propagating over the waist the modes enter the contracting zone in which they are recombined into a PCF core mode. As a result the transmission as a function of the wavelength of the microtaper is oscillatory. It can be calculated with the following expression:

$$T(\lambda) = I_{05}(\lambda) + I_{06}(\lambda) + 2[I_{05}(\lambda)I_{06}(\lambda)]^{1/2}\cos(2\pi\Delta nL/\lambda). \quad (1)$$

$I_{05}(\lambda)$ and $I_{06}(\lambda)$ are the power of the modes HE_{05} and HE_{06} , respectively. The period of the device is given by $P \approx \lambda^2/(\Delta nL)$. For higher-order modes the effective index difference Δn is large; therefore, the period of the interference pattern of a PCF microtaper can be very short, even for compact devices (L around 5 mm). It should be pointed out that the collapsing of the PCF voids during the tapering introduces losses of ~ 4 dB.

In tapers reported previously the modes participating in the interference are sensitive to liquids with indices ranging from 1.33 to 1.45.^{18,19} In our case, however, we have found that PCF microtapers were highly sensitive to gas molecules. The PCF tapers were exposed to different VOC molecules in an enclosed container by evaporating 2 ml of each VOCs at room temperature. We collected the transmission spectra of the tapers before and after the exposure to each VOC vapor. Figure 2 shows the response of a $5\ \mu\text{m}$ thick taper in air and when it was exposed to vapors of methylene chloride, chloroform, isopropyl, and methyl alcohol. It can be observed that the interference patterns shift to longer wavelengths in all cases. We found that the interference pattern returned to its original position when the VOCs were removed from the

container. We would like to point out that the interference patterns disappeared when the tapers were immersed in liquids regardless of their index.

Taking into account the volatile compounds under study here, we approach the results by considering the various processes involved by the vapors and their interaction with the bare PCF taper. Three principle approaches can be envisaged, i.e., that of adsorption/desorption, medium refractive index effect, and chemical binding. In the latter case we assume that no chemical reaction occurs between the siloxane groups on the fiber surface and the vapor molecules. The conditions are not conducive to promote formation of chemical bonds as no additional reagents were used (proton donor/acceptors or thin films) to initiate a reaction. In addition, the adsorption/desorption regime can be also excluded as all fibers experience a return to their original state once the VOCs have been removed from the chamber thus making this process negligible. Therefore, the changes recorded were due to complete envelopment of the taper by vapor molecules with the overall shift caused by a combination of the index of the volatile compound, density, and its volatility. The refractive index (in liquid state), density, and boiling point of methyl alcohol are, respectively, 1.328, $0.792\ \text{g}/\text{cm}^3$, and $64.8\ ^\circ\text{C}$. The corresponding values of isopropyl alcohol are 1.377, $0.786\ \text{g}/\text{cm}^3$, and $82\ ^\circ\text{C}$. We note that these alcohols have similar density but vary in index and boiling points. In this case the shift increases with the refractive index of the alcohol regardless of the fact that the volatility of isopropyl is less than that of methyl alcohol. When we consider methylene chloride, whose index, density, and boiling point are, respectively, 1.424, $1.325\ \text{g}/\text{cm}^3$, and $39.0\ ^\circ\text{C}$, a significant increase in shift is noted for the same change in refractive index of VOC, i.e., 0.05 (as in the case of the alcohols). Due to the experimental conditions, the same volume of VOC was analyzed in each case (2 ml) and we thus attribute the shift due to the combined refractive index and density (number of molecules) of methylene chloride. This is confirmed by chloroform whose larger shift coincides with an increased density ($1.480\ \text{g}/\text{cm}^3$) and refractive index (1.446).

Essentially what we have seen is a variance of this PCF microtaper toward volatile compounds. The shifts can be attributed primarily to the VOC's refractive index with density playing a smaller but important part. When we correlate the number of moles of each VOC used to achieve these initial shifts and subsequently adjust for the shift per mole of VOC (see Fig. 3), we see a clear dependence of the shift by increasing the refractive index for the same number of molecules of each VOC. The trend is not linear but shows larger increases for higher indices. It is possible that as we get closer to the refractive index of the fiber, we see an enhancement effect by the close matching of indices, thus creating greater shifts regardless of the lower volatility (chloroform has a boiling point of $62.2\ ^\circ\text{C}$). Another factor that contributes to the high sensitivity of VOC vapors in these tapers is the fact that higher-order modes have most of their energy in form of evanescent wave. Thus a minute change in the refractive index on the taper surface perturbs the interfering modes, which cause a remarkable change in ϕ_{56} .

In conclusion we have reported a photonic crystal fiber microtaper, which exhibits interference patterns with short periods owing to the beating between two higher-order modes. The interference pattern of such a device shifts re-

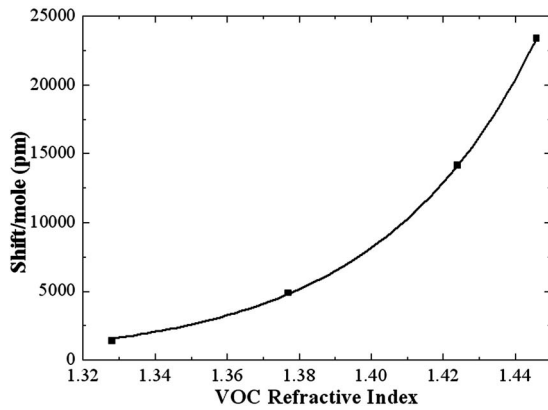


FIG. 3. Shift per mole as a function of the refractive index of the volatile compounds. The taper is that described in Fig. 2. The four points are experimental data and the continuous line is a fitting to the data.

markably when it is exposed to gas molecules. The shift of the interference pattern is attributed to surface refractive index changes caused by the presence of the molecules as well as the number of moles. Industrial applications of the interferometer proposed here can be envisaged since many gases are released by paints, cosmetics, beverages, foods, etc.

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