Refractive index sensor based on a microhole in single-mode fiber created by the use of femtosecond laser micromachining

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A compact in-fiber refractive index (RI) sensor is presented that is based on a microhole created in a conventional single-mode fiber by the use of femtosecond laser micromachining. The transmission properties of such a device with a microhole of different diameters have been investigated in the wavelength region of 1500–1600 nm and in the RI range of 1.30–1.45. It is found that the relationship between the transmission and the RI is critically dependent on the size of the microhole in the fiber core region. The highest resolution obtained is \(6.70 \times 10^{-5}\), in the RI range of 1.37–1.42, when the microhole diameter is ~8 \(\mu m\), close to the fiber core size. The in-fiber RI sensor developed in this work is easy to fabricate and can be used to implement temperature-independent measurements. © 2009 Optical Society of America

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Fiber-based refractive index (RI) sensors are attractive means for chemical, biomedical, and environmental monitoring applications because of their compactness, light weight, convenience for in situ and/or remote measurements, and many other advantages provided by the optical fibers. Many in-fiber devices have been exploited for RI sensing by the use of conventional single-mode fibers (SMFs), tapered fibers, and photonic crystal fibers (PCFs), such as fiber Bragg grating (FBG), long period grating (LPG), and in-fiber interferometers, among others [1–6]. However, these RI sensors are either expensive or highly sensitive to environmental temperature changes [6].

The femtosecond laser has been a powerful tool for high precision ablation in a variety of materials including ceramics, metals, polymers, and transparent materials such as silica glass [7,8], owing to its high intensity over ultrashort pulse duration and good spatial resolution. Moreover, the materials can be removed in a fast and clean way, with negligible heat affected zones, thus avoiding any significant damage to the underlying substrate [9,10]. In recent years, microchannels, microslots, and Fabry–Perot interferometers in SMFs have been fabricated by the use of femtosecond laser processing together with chemical etching, which can be effectively utilized for RI sensing with an improved temperature insensitivity and a potentially low cost [11–14].

In this Letter we report a compact in-fiber RI sensor based on a microhole in a conventional SMF by direct femtosecond laser pulse ablation without chemical etching. Such a device is easy to fabricate, exhibits a good linearity in a broad RI region, has a high resolution, and can be effectively used to implement a temperature insensitive measurement.

In the experiments carried out, femtosecond laser pulses (\(\lambda=800\) nm) of 120 fs at a repetition rate of 1 kHz were focused onto the fiber (SMF-28) by a 10× objective lens with a NA value of 0.25 and a working distance of 7 mm, and the pulse energy used was 11 \(\mu J\). The fiber core diameter was 8.2 \(\mu m\), with a nominal effective index of 1.4682 (at 1550 nm). The fiber was mounted on a three-axis translation stage that was carefully adjusted so that the upper surface of the cladding was located at the beam waist. A broadband light source connecting the fiber at one end and an optical spectrum analyzer (OSA) with a resolution of 0.01 dB at the other end was used to perform a real-time measurement. Three types of microholes with different values of diameter \(D\) (defined at the core–cladding interface) were fabricated with laser irradiation times of 5, 15, and 150 s, respectively, controlled by a mechanical shutter. When irradiated with femtosecond pulses, the material in the focal volume is ionized through multiphoton ionization (MPI) or tunneling ionization (TI), before the ablation occurs at the target surface. This process is independent of the initial defects in the material; thus the drilling process is quite stationary. Two samples for each type were fabricated to verify the repeatability of the device, marked as S-6a and S-6b, S-8a and S-8b, and S-11a and S-11b with \(D\) measured as ~6.2 and 6.1, 7.9 and 8.0, and 11.0 and 11.0 \(\mu m\), respectively.

The fiber device created was subsequently immersed into a series of RI liquid samples (from Cargille Laboratories) to test its response to different hole indices. The RI of the liquids used was in the range of 1.30–1.45 (at 589.3 nm). Each time after the sample was measured, the device was rinsed with methanol carefully until the original spectrum (corresponding to the hole index of 1.0) could be restored and no residue liquid was left inside the microhole.

Figures 1(a)–1(c) show the normalized transmission spectra of S-6a, S-8a, and S-11a filled with different indices. The transmission of S-6a shows only a
The transmissions of S-11a and S-11b exhibit an ex-
ples that the transmission characteristics are very
1.37–1.42 at 1550 nm in our experiments, which im-
tions and (c) show the normalized transmission ver-
versus wavelength of samples S-6a, S-8a, and S-11a, respectively; (d) demonstrates the normalized transmission versus microhole index. The insets of (a)–(c) represent the morphology of S-6a, S-8a, and S-11a (side view), and the di-
eter of the microholes at the fiber core and cladding in-
face, respectively. The corresponding microhole diam-
eters for S-6a and S-6b, S-8a and S-8b, and S-11a and S-11b are 6.2, 7.9, and 11 μm, respectively.

very small change with the increase in wavelength as shown in Fig. 1(a). A more complex situation happens for sample S-8a, whose diameter is close to the core size. It can be observed from Fig. 1(b) that the trans-
smission spectra exhibit small fluctuations while being not monotonic with respect to the RI change. When D is further increased to 11 μm (sample S-11a), the transmission is essentially unchanged with the wavelength variation as shown in Fig. 1(c). As the relationship between the transmission and the microhole indices cannot be observed in a straightforward way, the curves (at 1550 nm) of the six samples were plotted in Fig. 1(d), from which it can be observed that the transmission of S-6a expe-
riences a sharp increase with the increase in the RI in the range of 1.31–1.41, at the rate of 71 dB/
refractive index unit (RIU), where a good linear rela-
tionship between the transmission and the RI can be
straightforward way, the curves (at 1550 nm) of the
mission behavior of S-6a and S-6b, S-8a and S-8b, and S-11a and S-11b are 6.2, 7.9, and 11 μm, respectively.

The light transmission behavior for the microholes of different diameters may be explained by the use of Fig. 2(a), where a constant transmission coefficient is assumed for all the RI solutions. When D < core size, part of the light passes through the microhole and dissipates owing to the small incident angle θ1 at the core–cladding interface. When D is close to the core size, no light can be directly guided in the fiber core without passing through the microhole; thus the transmission is critically dependent on the RI of the hole as will be discussed. If D > core size, the light re-
fracted from the hole–core surface will be guided owing to the large incident angle θ3 at the interface, thus reducing the transmission loss.

The light transmission behavior for the microhole close to the core size with different RIs may be ex-
pained by simple ray optics as shown in Fig. 2(b), where n_h and n_core are the RIs of the hole and the fi-
ber core, respectively, and n_h < n_core. Assuming that the incident angle of light to the hole is smaller than the critical angle, when n_h = n_1 is small, the first re-
fracted beam cannot be bounded in the core, but the second refracted beam may be guided. If n_h is in-
creased to a large value of n_2, both the first and the second refracted beams will be dissipated, and the transmission loss becomes large. When n_h is further increased to n_3, the first refracted beam will be di-
rectly guided, although the second one is dissipated. The first refracted beam should have a higher intens-
ty than the second one owing to the relatively low re-
fection at the hole–core interface; thus the trans-
mission loss becomes small. It becomes clear from the above discussion that, with the increase in the RI, the transmission loss is first increased and then de-
creased and, as a result, a dip appears in the trans-
mision curve within a certain RI region.

Note that the transmission loss of the air-filled hole is lower than that of the 1.30 RI liquid-filled hole as shown in Fig. 1(a). Similar discussions could be made as mentioned before with the ray optics model shown in Fig. 2(b). When n_h = n_air (n_air = 1.00 approxi-

Fig. 2. (Color online) Simple explanation of the transmis-
sion behavior of the microhole (a) with different hole diam-
eters and (b) of the fiber core size with different RIs.
In conclusion, we have demonstrated a compact RI sensor based on a microhole in a conventional SMF fabricated by direct femtosecond laser pulse ablation. The transmission properties of such a fiber device have been investigated within the wavelength region of 1500–1600 nm and in the RI range of 1.30–1.45. It is found that the microholes of different diameters show different RI sensitivities in the different index ranges, and the highest resolution obtained is 6.70 \times 10^{-5}, in the index range of 1.37–1.42, corresponding to the microhole diameter of \( \sim 8 \ \mu m \). The transmission behavior of the device was also investigated with a simple 2D finite-difference time domain (FDTD) model, and the numerical results are in good agreement with those obtained in the experiments. The RI resolution can be further improved by selecting the appropriate microhole diameter and/or increasing the number of microholes with the appropriate separation along the fiber length. Moreover, when compared with the microchannel passing through the whole cross section of the fiber, the robustness of the device can be guaranteed by limiting the microhole depth within the fiber core region. The microhole based in-fiber RI sensor developed in this work is easy to fabricate and exhibits a good temperature-independent measurement capability, which is important for practical applications.

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**References**