Fabrication and numerical evaluation of the tapered single mode optical fiber:
Detection of change in refractive index

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Received 9 October 2006; revised 18 September 2007; accepted 5 November 2007

The fabrication of the tapered single mode fiber has been carried out. The tapered fiber is numerically evaluated for propagation behaviour of light by means of bound rays and tunneling rays in tapered portion. The nature of bound and tunneling rays as a function of refractive index is observed numerically, which shows that tapered portion of the fiber is suitable for sensor application. To make the fiber sensitive to refractive index of the medium other than core medium, it is etched up to fiber core using hydrofluoric acid (HF). The sensitivity of the sensor has been studied by varying the diameter of the etched portion in the fiber. The tapered portion is dipped in the DMSO solution having various molarity thereby exhibiting different refractive indices. The optical signal is passed through the fiber and output signal intensity has been measured with a wide wavelength photo-detector. The output intensity measured in voltage is found to be linearly dependent on the refractive indices surrounding the etched portion of the fiber. The result shows that the tapered single mode optical fiber is sensitive to refractive index of liquid at short (1 meter) as well as long (1.8 km) length of optical fiber. It also reveals that a distant detection and sensing can be carried out by a single mode tapered fiber sensors.

Keywords: Single mode fiber, Refractive index sensor, Evanescent waves, Signal attenuation

1 Introduction
The identification of refractive index of liquid is very important in biological and chemical systems. In recent years, numerous efforts have been directed towards the development of fiber optic chemical sensors and biosensors. It offers many advantages over other types of sensors such as small size, immunity to electromagnetic and radio frequency interference, remote sensing, multiplexing the information from a large number of sensors in a single fiber and in some cases the low cost. Optical fiber can be made to act as sensors by etching the clad region. Most etched sensors are based on multimode fibers and are modeled using the wave theory. Single mode etched fibers act much differently from the multimode tapered fiber and generally, hybrid of geometric ray and wave theory is used for modeling. The fundamental LP01 mode is supported in the core of single mode fiber. With increase of index difference along propagation axis, additional guided mode can be trapped. If the refractive index changes abruptly, one might expect that mode coupling will induce the reflection of transmissive LP01 mode and distribute the light power among cladding modes. One important application of etched tapered fiber is in evanescent wave absorption. The principle is based on the fact that light wave guided in a fiber has a power fraction in the cladding in the form of evanescent wave. When a light is incident on the core cladding interface in a fiber, it is either refracted into the cladding or reflected into the same core region according to Snell’s law. The reflected light in the core region due to total internal reflection is known as bound rays. The refracted light in the clad region, which is partially confined to the core, is known as tunneling rays. Bound and tunneling rays enhance the evanescent wave in the tapered region. There the fiber tapered etching can enhance the power fraction of evanescent wave in the cladding or outside the core so that it is sensitive to environmental changes. Multimode fiber tapering is easier to fabricate and use, but they have larger diameters and larger numerical aperture which leads to higher signal-noise ratio. Single mode etched fibers have larger power fraction in the cladding, it has very small diameters (6-8 μm), its numerical aperture is also lower, leading to low signal-noise ratio. Another important advantage of the etched single mode fiber (SMF) is that a small quantity of about 0.5 ml sample is sufficient to find the concentration of liquid on the
basis of change in refractive index of liquid. This is important when the procurement of the sample in large quantity is not possible.

In the present work, the tapered fiber is numerically evaluated for propagation behaviour of light by means of bound rays and tunneling rays in tapered portion as well as the transmission characteristics are investigated as a function of refractive index. In the experimental part, sensitivity of tapered fiber is carried out by means of dimethyl sulphoxide (DMSO) solution as a function of refractive index. The theoretical and experimental results show the potential of sensing the refractive index of chemical solutions and bio-liquids.

2 Evanescent Wave Theory

A ray of light through core medium travels via total internal reflection and is termed as bound rays. The intensity of the bound ray is contained completely in the core and can propagate indefinitely without loss of power. However, in case of bound rays, the electromagnetic field does not abruptly reduce to zero at the interface between core and cladding. The electromagnetic field decays exponentially with distance starting from the interface extending into the cladding; this extended field is called evanescent field. The evanescent field in the etched tapered region can directly interact with the analyte producing absorbance that can be coupled into the fiber core producing intensity modulation. In addition to bound rays, the other category of ray is called leaky rays or tunneling rays which are partially confined to the core region, and attenuate continuously radiating their power out of the core as they propagate along the fiber. This power radiation out of the waveguide results from a quantum mechanical phenomenon known as the tunnel effect.

The schematic structure of an etched single mode fiber is shown in Fig. 1. The geometric parameters, used to describe the etched fiber, are as follows: \( n_c \rightarrow \) refractive index of fiber core; \( n_{cl} \rightarrow \) refractive index of fiber cladding; \( n_{ex} \rightarrow \) refractive index of external medium; \( F_o \rightarrow \) radius of uniform fiber (indicating core and cladding); \( F_e \rightarrow \) radius of etched fiber; \( L \) is the length of etched portion of the fiber. The etched ratio, also called as taper ratio, is defined as \( T_{FR} = F_e/F_o \).

At the beginning of the etched region, the light propagates as a core mode and most of the energy is confined within the core. As the fiber is tapered, the difference between the refractive indices of the core and cladding is not large enough to confine the mode in the core. Therefore, the light begins to spread out into the cladding and propagates as a cladding mode that is guided by the boundary between cladding and air. As a result, the energy redistributes into the cladding and the intensity of the light decreases due to the relatively large diameter of the cladding. As the fiber is tapered down further, the intensity of the mode, which is now confined by the cladding external medium interface, increases again due to the rather small radius of the cladding. The position where the propagation mode transfers from the core mode to the cladding refers to as the transition point, or core-mode cutoff. There are, generally, three theoretical models to describe the propagation of light in, etched tapered single mode fiber such as scalar wave equation, full vector Maxwell equation and geometric ray theory. According to ray theory, a ray traveling in a fiber is described by two angles: the direction angle \( \Theta \) and skewness angle \( \Phi \) (which is the angle in the core cross-section between the tangent to the interface and projection of the ray path).

According to Snell’s law, \( \Theta_l = \cos^{-1}(n_{cl}/n_c) \) and \( \Theta_e = \cos^{-1}(n_{ex}/n_e) \) is the complementary critical angles between cladding/core and external medium/core respectively.

3 Experimental Details

3.1 Preparation of the sensing element

The experimental arrangement used to measure the output voltage from the etched single mode fiber liquid sensor as a function of the refractive index of the chemical solution is shown in Fig. 2(a and b). In Fig. 2 (a), light from a He-Ne laser operating at wavelength 632 nm is launched into one of the ends of the etched single mode fiber with the help of 20x lens and five axes fiber holder alignment system. The light energy coming out from the other end of the etched single mode fiber is launched on a silicon photo detector and output voltage is measured using digital multimeter (Meco make). The coated fiber of 50 cm length is left on the transmission arm and
collection arm so as to eliminate any unwanted backward and forward scattering from the etched end. In Fig. 2 (b), light from pigtailed laser source operating at wavelength 1300 nm is spliced with one of the ends of the etched single mode fiber. The other end of the etched single mode fiber is spliced with 1.8 km of fiber using pigtailed laser source having 1300 nm wavelength.

To fabricate etched tapered single mode fiber, the fiber is inserted inside transparent plastic cell. The fiber has core diameter of 8.2 μm and cladding diameter\textsuperscript{20,21} of 125 μm. The outer portion of the polyacrylate primary/secondary coating is stripped away with the help of ethyl acetate, and fiber is then cleaned with the help of acetone and deionized water. After removing of polyacrylate coating, the remaining fiber consists of only core and cladding. The outer diameter for this portion is 125 μm. It has been previously reported\textsuperscript{22} that the silica cladding of single mode fiber can be bioconically tapered at the fiber tip using hydrofluoric acid (48%). In our work, this method is modified to carry out etching of core-cladding at the center of fiber. The experimental set up of etching process is similar to the arrangement as shown in Fig. 2(a), wherein the fiber is immersed in hydrofluoric (HF) solution. The two ends of fiber are connected to a He-Ne laser source having wavelength 632 nm and the photo detector, respectively. The detector has uniform response for radiation in the wavelength range 400-1100 nm, and the power transmission through the etched portion is continuously monitored. The 2 ml hydrofluoric (HF) acid is poured inside cell to act as etchant. The etching rate of the fiber in 48% HF, can be estimated and it is found to be 5.2 μm/min. The time required for a typical etching process is less than 24 min. In this case, it is observed that for initial 21 min, there is no notable effect on the guiding wave. But as the uniform fiber diameter is reduced below 18 μm, there is a rapid loss of signal. Subsequently, the signal at the detector becomes zero when the fiber is totally dissolved after 24 min. Figure 3 shows the optical micrograph of tapered portion and uniform core portion surface of the fiber achieved by this method. The tapered uniform core portion acts as a sensing region. Here the etched uniform fiber core diameter is 6.6 μm and tapered diameter at scale portion is 16.5 μm.

3.2. Preparation of the test solution

To visualize the application of tapered fiber sensor, the solutions of varying refractive index was prepared by dissolving known mole percentage of dimethyl sulphoxide (DMSO) ranging from 0.5 to 12 moles in deionized water. The normal solution of DMSO has a refractive index\textsuperscript{12} of 1.4780, while refractive index of deionized water is 1.3340 as measured by Abee refractometer. The refractive index of the solvent of DMSO and DH\textsubscript{2}O varied linearly with the concentration, following the Lorentz-Lorentz law\textsuperscript{23}, which covered a refractive index range from water to the fiber core. The prepared solution is in molar concentration. Table 1 presents the molar ratio and its measured refractive index of test solution using Abee refractometer. The absorption ratio for different samples at 632.0 nm is measured using spectrophotometer (Systronics Double Beam Spectrophotometer 2201).

4 Results and Discussion

The computed numerical result in this paper is based on the taper geometry formed due to etching as...
shown in Fig. 1. While transmitting the rays through etched taper region, the light is divided into five parts such as bound rays in core (BRC), bound rays in clad (BRCL), tunneling rays in core (TRC), tunneling rays in clad (TRCL) and refracted rays (RR) by the cladding/external medium. Moreover, when light transmitting through uncladded etched core, the rays are divided into three regions only such as BRC, TRC and RR. The complementary critical angle, bound rays, tunneling rays and transmission loss with respect to external refractive index and etched diameter are calculated15.

Assuming the fiber is illuminated by a light source, when light is propagating through the etched taper region, it is divided into five parts viz; BRC, TRC, BRCL, TRCL and RR. The BRC is explained as bound rays passing through tapered fiber core region, which is given by Li’s invariance15:

\[
0 \leq \theta \leq \theta_1, \ 0 \leq \phi \leq \pi/2, \ \theta_1 = \sin^{-1}(T_{FR} \sin \theta_f) \quad \text{... (1)}
\]

TRC gives the tunneling rays guided by the taper region in the core:

\[
\theta_1 \leq \theta \leq \theta_2, \ 0 \leq \phi \leq \pi/2, \ \phi_1(\theta) = \sin^{-1}[(T_{FR} \sin \theta_f)/\sin \theta] \quad \text{... (2)}
\]

BRCL is the bound rays that can pass from tapered cladding region:

\[
\theta_1 \leq \theta \leq \theta_2, \ \phi_1(\theta) \leq \phi \leq \pi/2, \ \theta_2 = \sin^{-1}(T_{FR} \sin \theta_c) \quad \text{... (3)}
\]

TRCL is the tunneling rays which are guided by the tapered cladding region:

\[
\theta_2 \leq \theta \leq \theta_c, \ \phi_1(\theta) \leq \phi \leq \phi_2(\theta) = \sin^{-1}[(T_{FR} \sin \theta_c)/\sin \theta] \quad \text{... (4)}
\]

<table>
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<tr>
<th>Sample No</th>
<th>Molar ratio</th>
<th>Measured refractive Index</th>
<th>Absorption at 632.0 nm.</th>
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</thead>
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<tr>
<td>1</td>
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<td>1.341</td>
<td>0.241</td>
</tr>
<tr>
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<td>2</td>
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<td>0.261</td>
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<td>5</td>
<td>8</td>
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<tr>
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<td>0.313</td>
</tr>
<tr>
<td>8 Pure DMSO</td>
<td></td>
<td>1.480</td>
<td>0.333</td>
</tr>
</tbody>
</table>

Fig. 4 — (a) Execution of bound rays in the core due to taper region; etched ratio Vs core bound rays angle. (b) Tunneling rays guided by the tapered region in the core; taper ratio versus tunneling rays angle.

The refractive rays (RR) are the rays, lost as radiation by cladding and external medium. The transmission loss in the tapered region is calculated15 as:

\[
I_{taper} = (\pi/8) \sin^2 \theta_1 \int_0^\theta_2 \int_0^{\phi_2(\theta)} \sin \phi \cos \theta \sin^2 \phi \ d\theta \ d\phi \quad \text{... (5)}
\]

The combination of bound rays and tunneling rays in tapered cladding, contributes to the strength of evanescent field and depends on the various factors, viz., refractive index of core, refractive index of aqueous surrounding medium, the core radius and the operating wavelength. The fabricated fiber20 has core refractive index of 1.4623 and cladding refractive index of 1.4512. The calculation of bound and tunneling rays in tapered fiber core region is carried out by using Eqs (1) and (2) with the following parameters:

\[
\theta_1 = 0.1221; \ T_{FR} = 0.048 \text{ to } 0.144; \ \theta_c = 0.4119 \text{ to } 0.1749.
\]

Figure 4 (a and b) shows the execution of bound ray and tunneling rays in core region, as a function of taper ratio, respectively. As the fiber tapered radius goes on decreasing, the angle of ray confinement in a core also decreases, which gives increase in loss of power fraction in the tapered region. In other words,
the fiber taper can increase the power fraction of evanescent wave in the tapered region, the property which is used for sensing application.

The effect of external refractive index on tapered fiber is seen by observing bound and tunneling rays in tapered cladding region and is depicted in Fig. 5 (a and b) by using Eqs (3) and (4) with the following data.

\[
\begin{align*}
n_{\text{fex}} & = 1.32 \text{ to } 1.48 \\
T_{\text{FR}} & = 0.048 \text{ to } 0.144 \\
\theta_{\text{f}} & = 0.1221, \text{ and } \theta_{\text{c}} = 0.4119 \text{ to } 0.1749
\end{align*}
\]

As there is a change in external refractive index surrounding tapered fiber, bound rays are confined to the cladding region with very low loss of power fraction but tunneling rays are confined into fiber with very high loss of signal. As the refractive index surrounding the fiber goes on increasing, the bound rays are reflected back to the core region according to Snell's law. Although at the same time the tunneling rays, which are traveling through clad region \((n_{\text{fcl}})\) which lost as radiation, due to the external refractive index \((n_{\text{fex}})\) of medium it gives the increase in the angle of reflection in external refractive index medium. The transmission in single mode etched tapered fiber as per Eq. (5) is shown in Fig. 6, wherein \(I_{\text{taper}}\) is determined by taking values of \(\theta_{\text{c}}\) and \(\phi_2(0)\) for a particular value of refractive index. The values so obtained are transmission of light signals in taper region. The parameters used for calculation of transmission in Eq. (5) are as follows:

\[
\begin{align*}
n_{\text{fc}} & = 1.4623, n_{\text{fcl}} = 1.4571, n_{\text{fex}} = 1.34 \text{ to } 1.46 \\
F_{\text{TR}} & = 0.048 \text{ to } 0.144 \\
\theta_{\text{c}} & = 0.4119 \text{ to } 0.0561 \text{ and } \theta_{\text{f}} = 0.1221.
\end{align*}
\]

When the refractive index of external medium is close to cladding index, maximum portion of light gets lost through radiation. If the refractive index of external medium is in between the range of cladding/core refractive indices, light output is stable, since maximum light entering in cladding region becomes radiation; however, the light bound in the core region is not affected. On the contrary, for uncladded single mode taper, the light output will approach to zero when \(n_{\text{ext}}\) approaches \(n_{\text{fco}}\) since the cladding is not present.

While performing the experiment, a fix quantity of liquid solution with various molar concentrations is placed in the sensor cell and the corresponding output voltage is measured by digital multimeter. The height of test solution below and above the sensor fiber in the sensor cell is 1mm, which ensures that the fiber has uniform environment of the test solution. Figure 7 shows the experimental results for liquid sensing at 1 meter from the sensing element. It is observed that as the molar concentration of liquid goes on increasing, there is decrease in output voltage. The transmission loss of input beam recorded at the output is due to tapered region and variation in refractive index of the test solution. The refractive index surrounding the etched tapered portion works as passive cladding. Any small change in the refractive index surrounding the tapered portion of single mode fiber gives a change in optical transmission property.

We have also tested this sensor at a distance of 1.8 km after the etched portion of the fiber. The detection of both schemes is also divided in to two sets for 10 mm and 5 mm etched length at various diameters of 18 to 6 μm. While performing the experiment, the prepared test solution is placed in the
sensor cell of 18 μm with 10 mm etching length. At this stage, the sensitivity of the test solution is found to be low which is due to the fact that a very low evanescent waves are able to interact with outer medium. In order to increase the interaction of evanescent wave with outer medium, the etching diameter is lowered step wise from 16 to 12 μm, 12 to 10 μm, 10 to 8 μm, and 8 to 6 μm. It was found that the interaction of evanescent wave with outer medium is higher and hence, sensitivity is increased. The sensitivity is found to be higher for the etched fiber diameter of 6 μm. The higher sensitivity due to direct interaction of evanescent waves with test solution. Here, we observed that the fibers are very fragile due to long etched length and the required quantity of the test sample is higher. We have eliminated this problem by etching only 5 mm of fiber for sensing purpose. The advantage of 5 mm etching length is that the sensor gives higher output voltage than that of the sensor having 1 cm etching length, due to low attenuation loss. The observed results for various etched fibers are shown in Figures 7 (a and b).

In the second part of the experiment; single mode fiber of 1.8 km length is spliced after etched portion with splicing loss of 0.1 dB and the photo detector is spliced at other end of 1.8 km. It is found that the results are similar to that of the first part of sensing experiment, whereas the output voltage is lower which is due to the higher length of spliced single mode fiber. The experimented results for various etched diameters fibers are shown in Figs 7 (c and d) for 10 mm and 5 mm etching length of the fiber, respectively. These results suggest that the sensing communication of liquid is possible even in long haul optical fiber.

The response of fiber sensor can be grouped in three different modes of operation depending upon the surrounding refractive index (Fig. 7). In the first case, if the refractive index of surrounding etched portion is equal to original cladding refractive index, the wave guiding conditions do not change in the passive cladding and light have the same Gaussian intensity profile through out the fiber core and evanescent field in the cladding. In the second case, passive cladding has higher refractive index than core as well as original cladding, the fiber cannot give support to total internal reflection and light is refracted out of the core. In third case, passive cladding has lower refractive index than core and original cladding; fiber gives the small change in the gaussian beam intensity.

5 Conclusion

The model of taper in single mode fiber using geometric ray theory is provided to study ray transmission property through tapered fiber. Numerical analysis has been carried out to observe the effect of taper ratio and refractive index of
external medium on the sensitivity of the fiber. When the refractive index of external medium goes on increasing, the signal transmission is stable up to the range between refractive index of core-cladding. When the refractive index of external medium is greater than core refractive index, the transmission of signal is not possible. In the experimental part, we have demonstrated a simple technique for detecting the refractive index by inducing tapering on single mode fiber. The output intensity measured in voltage is found to be dependent on the refractive index of DMSO liquid surrounding the etched portion of the fiber. The technique described here has the advantage that, it has very small etched fiber radius (3 μm), its numerical aperture is also lower, leading to low signal noise and giving higher bandwidth.

Acknowledgement

The authors are thankful to Prof D B Yedekar, SRTM University, Nanded, for constant encouragement. One of the authors (VPK) also gratefully acknowledges Dr (Mrs) G S Lathkar, Principal, MGM College of Engineering, Nanded, for kind help.

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