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Investigation of a novel SMS fiber based planar multimode waveguide and its sensing performance

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Abstract: A novel, MMI-based all-fiber structure, which consists of two single-mode fibers and a multimode fiber polished on both sides, is described. The light propagation characteristics of this fiber structure, as well as its superior sensing performance, are analyzed theoretically by using the beam propagation method (BPM). This fiber structure demonstrates a significant spectral response to changes of the surrounding refractive index (RI), and the measured results exhibit good agreement with the predicted data. The measured average RI sensitivity is as high as 151.29 nm/RIU over an RI range from 1.3450 to 1.4050, when the polished depth is 30 µm on both sides of the multimode fiber. This fiber structure can be an advantageous platform for various applications, especially for a lab-on-fiber type sensing application.

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1. Introduction

Multimode interference (MMI), referring to convergence and divergence of a number of modes, generally exists in multimode fibers and waveguides. Over the past few decades, much effort has been devoted to the investigation of the MMI phenomenon and its induced self-imaging effect [1–3]. So far a range of integrated optical devices based on MMI, including beam splitters [4], combiners [5] and multiplexers [6], have been successfully investigated, that significantly promotes the development of telecommunication networks. However, for those multimode waveguide based photonic integrated circuits, the misalignment and insertion loss between MMI waveguide and silica optical fiber always induce low coupling efficiency and information missing at the coupling joint section of both. The multimode optical fiber (MMF), by contrast, exhibits an ultra-low splicing loss with existing optical fibers, and relatively easy integration with other optical fibers to form robust devices. Thus, the MMF has been a widely used optical medium for various applications, such as microscopy [7], laser [8], sensors and transducers [9,10].

The single-mode-multimode-single-mode (SMS) fiber structure, comprising a length of multimode fiber (MMF) and two single-mode fibers (SMFs), has become a promising research topic as a result of its easy fabrication, electromagnetic field immunity etc. Notably, numerous sensors based on an SMS fiber structure were proposed over the past decade, such as temperature sensors [11] and strain sensors [12,13]. However, the sensing capability of the
standard SMS fiber structure for other environmental parameter measurement is weak because the cladding of the MMF prevents its evanescent field interacting with the surrounding environment. Recently, many effective fiber optic process techniques have been combined with the SMS fiber structure, including tapering [14], etching [15,16], twisting [10], bending [17], side polishing [18] etc. Among them, the side polished single-mode fiber (SP-SMF) and the single-mode-side polished multimode-single-mode fiber (SSPSMS) have demonstrated that the fiber optic side polishing technique can be effectively incorporated within standard SMF and MMF [18–20]. Additionally, the side polished fibers afford many advantages for sensing measurement and provide a versatile platform for two-dimensional materials.

In this work, a dual side-polished single-mode-multimode-single-mode (DSPSMS) fiber structure has been successfully fabricated and its performance as a RI sensor is described. To the best of our knowledge, this is first time that the side polishing technique has been successfully deployed in an SMS fiber on both sides. The MMI properties of the MMF polished on two sides are analyzed using the beam propagation method (BPM), and furthermore, the transmitted spectral response as a function of the surrounding RI changes is investigated theoretically when the side polished depth (SPD) is varied as 10, 20 and 30 μm. The fabrication process and microscopic observation of several experimentally prepared fiber samples with different SPD are presented. Finally, to verify the theoretical models, the RI sensing performance of this fiber structure and the relationship between RI sensitivity and SPD are experimentally measured. Good agreement between the two sets of results has been established.

2. Theoretical analysis and simulation

![Fig. 1. Schematic of (a) the DSPSMS fiber structure and (b) cross section of multimode fiber polished on both sides.](image)

As shown in Fig. 1(a), the DSPSMS fiber structure consists of two input/output SMFs and a length of MMF polished on both sides. Here, a three-dimensional cartesian coordinate system has been established to represent the geometry of the DSPSMS fiber structure. Explicitly, two flat regions of MMF polished on both sides are defined to be parallel to the x-z plane, while the light is launched from SMF into MMF along the optical axis in the z-direction. It is noteworthy that the MMF exhibits centro-symmetry as opposed to a purely circular symmetry following the polishing process. The ideal polished cross-section of the polished MMF is illustrated in Fig. 1(b). Here, the radii of the MMF core and cladding are denoted as $r_{\text{core}}$ and $r_{\text{clad}}$, respectively, while the SPD is illustrated as $d$, and thus the residual thickness of MMF is $2(r_{\text{clad}}-d)$. In order to reduce complexity of the calculation, a few of ideal assumptions have been introduced, in which the mismatch of RI and misalignment between SMF and MMF are considered negligible. It is well known that light propagates in the SMF in the fundamental mode ($LP_{01}$), which can effectively excite higher-order modes ($LP_{mn}$) as the light enters the MMF. When the radiation loss of transmitted light is ignored, the light propagation
characteristic within the DSPSMS fiber structure can be calculated. According to MMI theory [2], the electric field can be described as follows:

\[
E(x, y, 0) = \sum_{m=1}^{M} a_m F_m(x, y)
\]  

(1)

where \( E(x, y, 0) \) is field distribution of fundamental mode within the SMF, while \( F_m(x, y) \) is field distribution of \( m \)-th mode excited within MMF. And the excitation coefficient \( a_m \) can be calculated as follows:

\[
a_m = \frac{\int_0^\infty \int_0^\infty E(x, y, 0) F_m(x, y) dx dy}{\int_0^\infty \int_0^\infty F_m(x, y)^2 dx dy}
\]  

(2)

In the MMF, the field distribution changes with light propagation distance as a result of MMI. When light arrives at an axial propagation position of \( z \), the modified field distribution can be described as follows:

\[
E(x, y, z) = \sum_{m=1}^{M} a_m F_m(x, y) \exp(i \beta_m z)
\]  

(3)

where \( \beta_m \) denotes the propagation constant. From Eq. (3), it is found that the field distribution within the MMF is strongly dependent on the propagation distance \( z \). On this basis, the coupling loss can be calculated as follows [21]:

\[
L(z) = 10 \log_{10} \left( \sum_{m=1}^{M} a_m^2 \exp(i \beta_m z) \right)
\]  

(4)

Fig. 2. (a) Coupling loss with different propagation distance; calculated mode field distribution at propagation position of (b) 0 \( \mu \)m; (c) 20150 \( \mu \)m; (d) 31930 \( \mu \)m and (d) 41000 \( \mu \)m.

The SMF and MMF used in this investigation are respectively SMF-28 and AFS 105/125S, and \( d \) was initially set to 20 \( \mu \)m. Based on the above equations, the relationship between the coupling loss and different propagation distances is plotted in Fig. 2(a). In this theoretical model, both of the input and output SMFs length were 1000 \( \mu \)m, while the length of the polished MMF section was 40000 \( \mu \)m. Owing to the MMI, the coupling loss fluctuates within the propagation distance from 1000 \( \mu \)m to 41000 \( \mu \)m. Furthermore, the mode field distribution evolution within the DSPSMS fiber structure also needs to be described. Four representative axial propagation positions \((z = 0 \mu m, 20150 \mu m, 31930 \mu m, 41000 \mu m)\) were selected for illustrating the results of the calculation, which are marked as A, B, C, D respectively in Fig. 2(a). The corresponding results calculated at these four positions are
shown in Figs. 2(b)-2(e). Figure 2(b) presents the mode field distribution at the initial position, which remains unchanged due to the circular symmetry when light propagates along the SMF. After the light enters the MMF, a series of complicated mode patterns occur as a result of MMI, and the mode field distribution is no longer circularly symmetrical, being replaced by the centro-symmetry referred to earlier. Figures 2(c) and 2(d) present the mode field distribution at the propagation positions B and C in Fig. 2(a) respectively. The coupling losses in these two positions were calculated as −4.29 dB and −39.32 dB at the propagation positions B and C respectively. Figure 2(e) presents the output mode field distribution at the end of the MMF. These simulated results suggest that a strong MMI evolution with propagation distance can be observed within the DSPSMS fiber structure. From this calculation it was determined that the coupling loss is strongly related to intensity distribution within MMF core.

![Figure 3: Calculated Transmission Spectrum of DSPSMS Fiber Structures](image)

Fig. 3. The calculated transmission spectrum of DSPSMS fiber structures with $d = 10 \mu m$, $20 \mu m$, and $30 \mu m$ at the RI value of 1.3450.

The DSPSMS fiber structure offers many opportunities for access to a wide range of sensing applications e.g. chemical and biomedical, as the structure is sensitive to the surrounding RI measurement over an ultra-long evanescent field interaction length. According to the measured results in previous papers [22], the RI sensing performance is strongly dependent on the SPD for optical fibers polished on one side. Thus, it is proposed that for the DSPSMS fiber structure of this investigation there exists a similar relationship between RI sensitivity and SPD. In this case a simulation based model has been established to predict the RI sensing performance. Firstly, assuming the surrounding RI value is set to 1.3450, we calculated the transmission spectrum of three DSPSMS fiber structures with $d = 10 \mu m$, $20 \mu m$ and $30 \mu m$. The calculated results in Fig. 3 show that the corresponding interference dip wavelength undergoes a significant blue-shift as the SPD increases, which is attributed to the following equation [23]:

$$\frac{2\pi}{\lambda_{ij}} \Delta n_{eff} L_{MMF} = \text{const}$$

(5)

where $\Delta n_{eff}$ denotes the effective RI difference between i-th mode and j-mode of the MMF, which corresponds to the interference dip wavelength $\lambda_{ij}$ and the length of MMF polished on both sides $L_{MMF}$. With SPD is increased, the effective RI difference $\Delta n_{eff}$ has a corresponding decrease, and thus the interference dip shifts to shorter wavelength. On the other hand, when the external RI increases, the effective RI difference $\Delta n_{eff}$ exhibits a corresponding increase, resulting in a red-shift of the interference dip. When the surrounding RI value is increased
from 1.3450 to 1.4050, the calculated transmission spectrum is shown in Figs. 4(a)-4(c). From these three results, it is clear that transmission spectrum undergoes a red shift as response to the RI value increase, especially for interference dip. Finally, the relation of wavelength shift of interference dip and the RI values are plotted and fitted in Fig. 4(d). From the calculated results, it is clear that as the SPD increases, the interference dip undergoes a larger wavelength shift for an RI increase for 1.3450 to 1.4050, specifically 2.51 nm for $d = 10 \mu m$, 6.03 nm for $d = 20 \mu m$, and 12.81 nm for $d = 30 \mu m$.

![Image](image.png)

Fig. 4. The calculated transmission spectrum evolution of DSPSMS fiber structure with (a) $d = 10 \mu m$, (b) $20 \mu m$ and (c) $30 \mu m$, within the RI range of 1.3450-1.4050. (d) The relationship between wavelength shift and different RI values for $d = 10 \mu m$, 20 $\mu m$ and 30 $\mu m$.

3. Fabrication and experiments

The experimental setup for fabricating the DSPSMS fiber structure is similar to that introduced in a previous paper by the authors of this article [18]. In fabrication process, a fiber optic side polishing system is employed, which consists of three elements: a control system, a CCD camera for observation and a polishing arrangement. The prepared SMS fiber structure was firstly fixed in a straight line between two fiber holders and fixed via two standing pulleys to provide tension to maintain the straightness of the fiber. A grind wheel with abrasive papers was used to polish the MMF section. It is worth noting that the fiber structure needs a 180-degree rotation in the radial direction after one side of the DSPSMS fiber structure is successfully side polished, which plays a crucial feature of the fabrication process of the DSPSMS fiber structure. For this, we used a marked tape attached to the surface of the SMS fiber structure, so as to precisely adjust the rotation to 180-degrees. On the other hand, its side polished length is determined by controlling the movement distance of the grinding. The influence of the abrasive paper on surface roughness of the prepared fiber structure has been discussed in a previous article by the authors of this article [20]. The accurate operation of the process described above enabled the successful fabrication of three DSPSMS fiber samples with centro-symmetry. Figures 5(a)-5(d) present the cross-sectional microscopic images of three fabricated MMF polished on both sides and an MMF on which no polishing has been performed. From Fig. 5, it can be observed that only the cladding of the
MMF is polished off when \( d \) is no more than 10 \( \mu \text{m} \), and the core of the MMF is partly removed as \( d \) increases.

![Microscopic images of cross section of MMF polished on both sides](image)

Fig. 5. Microscopic images of cross section of MMF polished on both sides with (a) \( d = 0 \) \( \mu \text{m} \); (b) \( d = 10 \) \( \mu \text{m} \); (c) \( d = 20 \) \( \mu \text{m} \); (d) \( d = 30 \) \( \mu \text{m} \).

Figure 6 illustrates the experimental setup for the RI measurement. During this experiment, the DSPSMS fiber structure was fixed on a polymer plate using ultraviolet setting glue, which can effectively improve its stability and repeatability. The input/output SMFs of the DSPSMS fiber structure are respectively connected to a supercontinuum source (YSL SC-Series) and an optical spectrum analyzer (OSA, YOKOGAWA AQ6370D) for launching/receiving the broadband light signal (1200 nm-1700 nm). A glycerine solution was chosen as the RI change inducing liquid, which was prepared by mixing glycerine and deionized water. A laboratory dropper was used to drop the glycerine solution to fully cover the DSPSMS fiber structure, and a self-built polymer wall was used to completely surround the structure to avoid leakage of the glycerine solution. Prior to each measurement, the fiber structure was carefully washed using deionized water and ethanol in sequence to eliminate the influence of other RI change inducing liquids. Eventually, the transmission spectrum evolution induced by the surrounding RI variation was measured using the OSA.

![Experimental setup for RI measurement](image)

Fig. 6. Experimental setup for RI measurement.

4. Results and discussion

The experimentally measured results of the DSPSMS fiber structure over RI range of 1.3450-1.4050 with increment of 0.01 are shown in Fig. 7. Transmission spectra are presented for the three DSPSMS fiber structures with different SPD (\( d = 10 \) \( \mu \text{m} \), 20 \( \mu \text{m} \) and 30 \( \mu \text{m} \)), in Figs. 7(a)-7(c) respectively. From them, it can be observed that there exists a clear red-shift (4.23 nm for \( d = 10 \) \( \mu \text{m} \), 5.18 nm for \( d = 20 \) \( \mu \text{m} \), and 9.16 nm for \( d = 30 \) \( \mu \text{m} \)) in the transmission spectrum of all three fiber structures. In addition, it can also be observed that the interference
dip shifts to shorter wavelengths as $d$ increases, which can be explained by Eq. (5). The increase of $d$ leads to a decrease of $\Delta n_{fg}$, and thus the occurrence of the blue-shift of the interference dip. Figure 7(d) shows that the dependence of the interference dip wavelength shift on RI values for the three DSPSMS fiber structures, agrees well with the calculated results in Fig. 3. Figure 7(e) presents measured and calculated wavelength shift evolutions versus RI values for $d = 20 \mu m$, which also demonstrates a good agreement between measured results and calculated results. The discrepancy between the calculated results and measured results may be attributed to the surface roughness of fabricated fiber structures and some simplified calculations used in simulation model. Moreover, the measured data could be fitted using a polynomial function, which means that the RI sensitivity of the DSPSMS fiber structure of this investigation increases more significantly as the surrounding RI values become closer to that of MMF core. On the other hand, the DSPSMS fiber structure with larger $d$ has a higher RI sensitivity over the entire RI range. Thus, the DSPSMS fiber structure of this investigation has excellent potential for use in ultra-sensitive RI measurement applications over an RI range around 1.4446, especially when the SPD can be furthermore optimized. In this experiment, the fiber structure has an average sensitivity as high as 151.29 nm/RIU over an RI range from 1.3450 to 1.4050 when $d = 30 \mu m$.

![Graphs and diagrams](image)

Fig. 7. Transmission spectrum of DSPSMS fiber structure with different RI values for $d$ respectively at (a) 10 $\mu m$, (b) 20 $\mu m$, (c) 30 $\mu m$; (d) Dependence of wavelength shift of the corresponding interference dip for $d = 10 \mu m$, 20 $\mu m$, 30 $\mu m$; (e) comparison between measured results and calculated results for $d = 20 \mu m$.

In addition, the advantage of the dual side-polish scheme in improving RI sensing performance is also determined by comparing it with a traditional SMS fiber structure, with the MMF polished on one side only (an SP-SMS fiber structure). Note that there is no point in including an unpolished SMS fiber structure in the comparison due to the presence of a complete cladding, a traditional SMS fiber structure cannot directly detect a surrounding RI value variation. Table 1 shows a comparison of the RI sensing performance of the SP-SMS fiber structure and the DSPSMS fiber structure for RI sensing under the headings of RI range and RI sensing sensitivity. In Ref [23], a highly sensitive RI sensor based on SP-SMS fiber structure was investigated. Note that it is essential to compare the RI sensing performance of these two fiber structures for the same RI range, therefore, an approximate RI range of 1.3-1.4 is selected for this purpose. For the SP-SMS fiber structure, its maximum RI sensitivity is about 65 nm/RIU within the RI range 1.33-1.39. For the DSPSMS fiber structure of this work, it can achieve a superior maximum RI sensitivity of 151.29 nm/RIU within RI range of 1.3450-1.4050. It is clear that dual side-polish can effectively improve RI sensing...
performance, which is mainly attributed to the increased evanescent field interaction with the local environment.

Table 1. Comparison of the RI sensing performance between SP-SMS and DPSMS

<table>
<thead>
<tr>
<th>Structure</th>
<th>Process technique</th>
<th>RI range</th>
<th>Sensitivity (nm/RIU)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP-SMS</td>
<td>Side polish</td>
<td>1.33-1.39</td>
<td>65</td>
<td>[23]</td>
</tr>
<tr>
<td>DPSMS</td>
<td>Dual side-polish</td>
<td>1.3450-1.4050</td>
<td>151.29</td>
<td>This work</td>
</tr>
</tbody>
</table>

Finally, the temperature dependence of the DPSMS fiber structure is also investigated both theoretically and experimentally. It is well known that the dimensions and refractive index of the fiber structure undergo a slight change when the surrounding temperature is changed, referred to as the thermal expansion effect and thermo-optical effect, respectively. For a silica fiber, the thermal expansion coefficient (TEC) and thermo-optical coefficient (TOC) are 6.9 × 10^-6 / °C and 5 × 10^-7 / °C. Here, when the TEC and TOC are incorporated into the theoretical model introduced in Section 2, and the SPD is set to 20 µm, we obtain a transmission spectrum evolution within temperature range of 20 °C – 40 °C, as shown in Fig. 8(a). From the model, one can see that the interference dip at 1495 nm undergoes a red-shift as temperature is increased from 20 °C to 60 °C with an increment of 10 °C. The relationship between wavelength shift and temperature is calculated and plotted in Fig. 8(b). From this, the temperature dependence of the DPSMS fiber structure is found to have a relatively low value of 8.39 pm/ °C. In addition, the temperature dependence of the DPSMS fiber structure is also investigated experimentally. The fabricated fiber sample is placed on a heating stage, for which the temperature can be precisely controlled. When temperature is increased from 30 °C to 75 °C with an increment of 5 °C, the transmission spectrum evolution is recorded by an OSA, and the relation of interference dip wavelength and temperature is plotted in Fig. 8(c). From this, it is found that the maximum wavelength shift is just 0.6 nm when temperature is increased from 30 °C to 75 °C. The measured results in Fig. 8(c) also present a step-like tendency, which is a result of the limited resolution of the OSA used. The average temperature dependency is as low as 11.15 pm/ °C. The discrepancy between the calculated and measured temperature dependencies is attributed to certain uncontrollable factors such as the surface roughness of polished fiber and the effect of temperature changes on surrounding environmental parameters, such as humidity and air flow etc. In summary, we have demonstrated theoretically and experimentally that our proposed DPSMS fiber structure has a low temperature dependence.

Fig. 8. Temperature dependence of the DPSMS fiber structure. (a) The calculated transmission spectrum evolution with temperature increasing from 20 °C to 60 °C; (b) the calculated and (c) the measured relationship between wavelength shift and temperature.
5. Conclusion

In conclusion, a novel DSPSMS fiber structure is fabricated from a standard SMS fiber structure by employing a side polishing technique, which is reported for the first time. Through calculating the light propagation characteristic of MMF polished on both sides, it was found that the resulting transmitted mode field distribution is dependent on the degree of centro-symmetry and gives rise to complicated MMI patterns. The sensing performance of this fiber structure was also calculated and these demonstrated that it has a high dependence on SPD. Three DSPSMS fiber samples with different SPD values ($d = 10 \, \mu m$, $20 \, \mu m$ and $30 \, \mu m$) were successfully fabricated and their physical appearance was compared with a standard MMF using microscopic imaging. The experimental results have shown that over an RI range from 1.3450 to 1.4050, the measured average RI sensitivity is as high as 64.82 nm/RIU for $d = 10 \, \mu m$, 85.29 nm/RIU for $d = 20 \, \mu m$, and 151.29 nm/RIU for $d = 30 \, \mu m$.

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