Refractive index sensitivity enhancement of optical fiber cladding mode by depositing nanofilm via ALD technology

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Abstract: The atomic layer deposition (ALD) technology is introduced to enhance the sensitivity of optical fiber cladding mode to surrounding refractive index (SRI) variation. The highly uniform Al₂O₃ nanofilm was deposited around the double cladding fiber (DCF) which presents cladding mode resonant feature. With the high refractive index coating, the cladding mode resonant spectrum was tuned. And the sensitivity enhancement for SRI sensor was demonstrated. Through adjusting the deposition cycles, a maximum sensitivity of 723 nm/RIU was demonstrated in the DCF with 2500 deposition cycles at the SRI of 1.34. Based on the analysis of cladding modes reorganization, the cladding modes transition of the coated DCF was investigated theoretically. With the high performance nanofilm coating, the proposed SRI sensor is expected to have wide applications in chemical sensors and biosensors.

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References and links


1. Introduction
Fiber-optic refractive index (RI) sensors have been widely researched in the fields of chemical sensor and biosensor [1]. They have emerged as one of the most attractive technologies in recent years due to the advantages of the compact size, high sensitivity, multiplexing, and remote-sensing capabilities. In order to realize the optical fiber-based RI sensors, the evanescent wave is widely applied through various special fiber structures [2–5], such as tapered fibers, long period gratings, microstructure optical fibers, D-shape optical fibers, and bent optical fibers To enhance the sensitivity of surrounding refractive index (SRI) variation around these optical fibers, in general, the evanescent field propagating in the fiber needs to be enhanced. Recently, a nanofilm coating technique has been proposed and investigated to enhance the evanescent field in optical fibers for RI sensing [6–10]. The reports show that it requires hundreds of nanometer thickness coating to achieve sensitivity enhancement. Because of the rod shape of optical fibers, only coating techniques based on solutions were used to realize homogeneous film deposition, including self-assemble method [11] and dip-coating method [12]. However, the two methods have some limitations. The self-assemble method is based on layer-by-layer process which can control precisely the thickness of film, but the loss of the coating is relatively high [12]. The dip-coating method is based on some solution, but the choices of coating materials are limited and the thickness is difficult to be controlled. In addition, it needs a relatively long time to stabilize the properties of the solution-derived film [13].

In this work, the atomic layer deposition (ALD) technology is proposed to coat the nanofilm onto optical fibers for enhancing the sensitivity of evanescent wave RI sensor. The ALD technology is a self-limiting thin film deposition process [14], which has a number of advantages compared to the self-assemble and dip-coating methods including [15]: (a) the thickness of coated film can be precisely controlled. (b) the conformal deposition feature ensures the deposition of uniform film on irregularly shaped surface, for example optical fiber surface. (c) many materials with different refractive indexes are available for deposition films. (d) the good mechanical properties of the ALD film guarantee the optical fiber sensor performance. Moreover, the ALD equipment generally has a large reaction chamber, in which a large batch of sensor heads can be coated simultaneously for the mass production. Here we apply the ALD film onto double cladding fibers (DCFs) which exhibit the cladding mode resonant feature [16, 17]. The sensitivity enhancement of the excited cladding mode to SRI has been demonstrated by using ALD coating technology.

2. Modes reorganization in the coated DCF
The refractive index profile of the coated DCF is depicted in Fig. 1. The DCF consists of core, inner cladding and outer cladding. The core and the outer cladding are made of pure silica, whereas the inner cladding is made of boron doped silica. Therefore, the refractive
index of the inner cladding is lower than that of the core and the outer cladding. As the DCF is coated with a high refractive index nanofilm, the fiber presents a four-layer structure. Due to the thin thickness depressed inner cladding, the DCF can be regarded as a coaxial twin waveguides coupler. The mode coupling exists between the core (rod waveguide) and outer cladding (tube waveguide). According to the mode coupling theory, a particular cladding mode can be resonantly excited in the DCF [16]. By splicing a piece of DCF with standard single mode fibers (SMFs), a DCF-based sensor can be constructed. Such sensor has the typical transmission spectrum with a rejection band centered at where the cladding mode resonance takes place.

![Fig. 1. The refractive index profile of the coated DCF.](image)

According to the coupled mode theory analysis for the bare DCF, the resonant wavelength is determined by the phase matching condition that the waveguide dispersion curves of the core mode and the cladding mode intersect. For the DCF with a high refractive index nanofilm coating, the dispersion curves of the cladding modes will be modified, which induces the change of phase-matching condition. The cladding modes reorganization behavior was studied theoretically in this work. Here the refractive index profile is set as $n_1 = n_3 = 1.456$, $n_2 = 1.454$, $n_4 = 1.62$, and $n_5 = 1$, which corresponds to the fabricated DCF. Figure 2(a) demonstrates the dependence of the effective refractive index of the first eight cladding modes on the coating thickness. With increasing the thickness of coating, the effective indexes of the cladding modes increase slightly. As the coating reaches some particular thickness values, the effective refractive index of the cladding modes will sharply increase, for example the 250 nm thickness. It is found that the effective refractive index of the lowest cladding mode goes beyond the refractive index of cladding material, which indicates the lowest cladding mode will not be a guided mode in the cladding as the coating thickness exceeds 250 nm. The original second lowest cladding mode becomes the lowest cladding mode. The other higher cladding modes perform the similar trends transiting to the adjacent lower mode respectively at the particular coating thickness. As a result, the guided cladding modes are reorganized. The modes reorganization will repeat as the coating thickness continues increasing as shown in Fig. 2(a). Besides the thickness of coating, the transition behavior also depends on the refractive index of the coating. As shown in Fig. 2(b), with increasing the coating refractive index, the transition curve shifts towards the thinner thickness direction. A faster transition process is obtained at higher coating refractive index.
The cladding modes reorganization behavior can be explained through the optical waveguide theory. For the coated DCF, the effective refractive indexes of the cladding modes are determined by the refractive index and the thickness of the film. When increasing the refractive index or the thickness of the coating, the effective refractive index of the guided modes will be increased [18, 19]. The cladding mode field will shift toward high refractive index coating. Here for a given film refractive index (i.e. $n_{Al2O3} = 1.62$), when the coating becomes thick enough to cause the effective refractive index of the lowest order cladding mode beyond the cladding material refractive index, this lowest order cladding mode will transit to a guided mode in the coating film waveguide. We calculated the dispersion curves in the coated DCF with the effective refractive index higher than the fiber cladding material index, as shown in Fig. 2(c), it can be seen that the guided modes exist in the film after the transition condition. With increasing the coating thickness, more guided modes are transited to the coating film waveguide.

The transition behavior can also be demonstrated through the mode distribution change before and after the transition point. To avoid confusion, the mode order labels are for the bare DCF. We calculated the mode fields of cladding mode $LP_{05}$ for the bare DCF and $LP_{06}$ for the 400nm film coated DCF as shown in Figs. 3(a) and 3(b), respectively. These two mode fields present very similar profile, indicating that the coating causes the original $LP_{06}$ to transit to the adjacent lower mode. Such transition happens to the rest cladding modes in the same manner. Additionally, beyond the transition thickness, a guided mode appears in the coating film, which is the lowest order mode for the film waveguide, as shown in Fig. 3(c).

3. The sensitivity of the coated DCF to SRI

When utilizing the coated DCF to test surrounding liquid refractive index, the change of SRI is equivalent to the change of coating thickness in terms of shifting the effective index of the cladding modes [8]. Based on the modes reorganization feature, when we set the cladding modes to work in the transition region, the sensitivity to SRI change can be enhanced by the coating on the DCF. To optimize the sensitivity of the coated DCF, the working point should be adjusted to the half way of the transition curve, which ensures a maximum shift in effective index [18]. This optimization sensitivity depends mainly on the coated film features.
(thickness and refractive index) and SRI. Firstly, a SRI should be selected at middle value of measurement range of the sensor. Secondly, an optimization coating thickness is calculated for the coating refractive index ensuring the maximum sensitivity. Because the coating refractive index is determined by the coating material, it is more convenient to tune precisely the DCF sensor to the maximum sensitivity condition through the coating thickness. We simulated the sensitivity of the DCF sensors coated with two distinct materials with refractive indexes of 1.6 and 2.0 when SRI is 1.34. As shown in Fig. 4, the maximum sensitivities are obtained at 200 nm and 80 nm thickness for the coating refractive indexes of 1.6 and 2.0, respectively. Additionally, the maximum sensitivity of the DCF sensor with coating refractive index of 2.0 is higher than that with the refractive index of 1.6. The simulation results are consistent with the results shown in Fig. 2(b). Compared to the coating with the refractive index of 1.6, the refractive index of 2.0 has a thinner transition thickness. Therefore, we can get higher sensitivity with higher coating refractive index. By using ALD technology, some high refractive index materials are good choices to realize this purpose, such as TiO$_2$, Ta$_2$O$_5$.

![Fig. 4. Sensitivity of DCF coated with nanofilm to SRI.](image)

4. Fabrication of the Al$_2$O$_3$ nanofilm coated DCF sensor

By using a boron doped double cladding fiber, a SMF-DCF-SMF structure was fabricated through standard splicing method firstly. The length of doped DCF is 1.3 cm. Then an Al$_2$O$_3$ nanofilm was deposited around the SMF-DCF-SMF sensor to enhance the sensitivity to SRI variation, as depicted in Fig. 5(a). The Al$_2$O$_3$ nanofilm was deposited by using an atomic layer deposition equipment (TFS 200, Beneq). The reaction chamber is disc shape whose diameter and height are 22 cm and 3 cm respectively. The detailed deposition process is described as following. Firstly, two precursors and N$_2$ gas were valve controlled and purged into the heated reacting chamber in the way of pulse. The two precursors are TMA (Al(CH$_3$)$_3$) and O$_3$. The purged order is TMA-N$_2$-O$_3$-N$_2$. The chemical reaction formula is 

$$4\text{Al}(\text{CH}_3)_3 + 3\text{O}_2 \rightarrow 2\text{Al}_2\text{O}_3 + 6\text{C}_2\text{H}_6.$$  

The deposition temperature is 210°C. After the whole process, the monolayer Al$_2$O$_3$ is deposited and one reactive cycle is completed. By repeating the depositing cycle, the thicker Al$_2$O$_3$ film can be deposited layer-by-layer and the thickness can be controlled precisely by the number of cycles. A typical deposited Al$_2$O$_3$ film on the DCF was tested by using SEM, as shown in Fig. 5(b). The film exhibits uniform distribution. Four sensor fibers deposited with 500, 1000, 2000 and 2500 cycles were prepared to get the deposition rate. As shown in Fig. 5(c), the relationship between thickness and deposition cycle number presents good linear behavior. The deposition rate is approximate 0.094nm/cycle.
The transmission spectra of the prepared the DCFs deposited with various thickness of Al₂O₃ nanofilm were measured as shown in Fig. 6(a). By increasing the deposition cycles, the dip of transmission spectrum shifts toward the longer wavelength. Since the high refractive index coating increases the effective refractive index of cladding mode, the phase matching point shifts to the longer wavelength [17]. In addition, the change of wavelength shows a nonlinear relationship with the deposition cycle as shown in Fig. 6(b).

5. Experiments for SRI sensor

The DCFs with various thicknesses of Al₂O₃ coating were characterized for surrounding refractive index sensing. The sensor heads were immersed into the deionized water mixed with glycerin, whose refractive index can be adjusted from 1.334 to 1.435 by changing the concentration of glycerin. The refractive index of the solution was measured by using an Abbe refractometer with the resolution of 0.0001 at 589-nm wavelength. The transmission spectra of the DCFs coated with 500 layers and 1000 layers subjecting to various SRI are shown in Figs. 7(a) and 7(b), respectively. It can be seen that the resonant spectra shift toward the longer wavelength with increasing SRI. The spectra shift amount of the DCF coated with 1000 layers is larger than that of the DCF coated with 500 layers.
In order to investigate the enhancement behavior of the Al$_2$O$_3$ nanofilm with different thickness, the relationship between the resonant wavelength shift and SRI were tested for different coating cycles, as shown in Fig. 8. It shows that the sensitivity was enhanced due to the nano size coating. A maximum sensitivity of 723 nm/RIU was obtained at the SRI of 1.34 for the DCF with 2500 cycles coating, which is 13.5 times that of the bare DCF. In addition, by comparing the responses of two sensor heads with 2000 cycles and with 2500 cycles, it is found that the sensitivity is increased at lower SRI, but is decreased at higher SRI with the additional 500 deposition cycles. This effect is attributed to the dependence of effective refractive index on the SRI. The change in the SRI is equivalent to the change of coating film thickness, which results that the transition point of SRI moves toward a lower value with increasing the coating thickness. This behavior is consistent with in the observation of LPGs with high refractive index coating, which adjusts the transition value by changing coated film thickness [6, 12, 20].

6. Conclusion

In this work, we reported the sensitivity enhancement of fiber cladding mode by using atomic layer deposition technology for SRI sensor. By using ALD technology, the uniform Al$_2$O$_3$ nanofilm was deposited around the DCF. The thickness was precisely controlled through the numbers of deposition cycle. The deposition rate was approximate 0.094nm/cycle. With the Al$_2$O$_3$ nanofilm coating, the sensitivity of DCF was enhanced. The sensitivity of 723 nm/RIU was demonstrated in the DCF with 2500 deposition cycles at 1.34 SRI. Additionally, the DCF
with high refractive index coating was numerically investigated. The behavior of sensitivity enhancement under different coating thickness and refractive index was analyzed through the cladding mode reorganization feature. More work need to be done to improve the performance of the ALD derived sensor. Through depositing ALD nanofilm with different refractive index and thickness, we can further enhance the sensitivity and realize high sensitivity for different SRI range, which is under studying in our lab.

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