Sensitivity investigation of the microfiber-to-slab evanescent wave sensors

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Abstract. Microfiber-to-slab sensor is comprised of a tapered fiber in evanescent contact with a multimode slab waveguide. The effects of the sensor configuration parameters on its evanescent wave sensitivity were investigated through theoretical analysis. On the basis of that, the rules for fabricating a microfiber-to-slab sensor with high device sensitivity were presented. By optimizing geometry parameters, it was shown that the resonant wavelength sensitivity can be as high as nearly 20000 nm/RIU. The conclusions derived from our work may be used for design and optimization of microfiber-to-slab devices for practical applications.

1 Instruction

Recently, microfibers have been attracting much attention since they offer a number of enabling optical and mechanical properties, such as strong confinement, large evanescent field and great configurability [1-2]. Owing to small dimensions of microfiber, evanescent wave leaking from the physical boundary of microfiber is sensitive to the external material. As the microfiber is located sufficiently close to the cladding slab, strong coupling will occur between the guided modes in the fiber and modes in the slab. Thus an evanescent-field coupler utilizing a microfiber and an overlay slab could be constructed [3-6]. Moreover, when the electro-optic, magneto-optical, thermo-optic or other kinds of functional materials are adopted as the slab waveguide, the resonance spectra of the coupler will be sensitive to the externally applied electric field, magnetic field or temperature field. Accordingly, a variety of optical microfiber-to-slab evanescent wave based field sensors have been successfully demonstrated [7-12]. Owing to the all-dielectric structure, these sensors are immune to electrical noise and electromagnetic interference, have large bandwidth and high mechanical stability. However, the main drawback of the microfiber-to-slab sensors is the lower intrinsic sensitivity, which seriously restricts their practical applications.

In this paper, a detailed analysis of the sensing performance of the microfiber-to-slab device was presented by the theoretical and numerical simulations. And the effects of the sensor geometry parameter for the device sensitivity are systematically discussed. From these results, we conclude the rules for fabricating a microfiber-to-slab sensor with high
device sensitivity. These results can facilitate the design and optimization of the microfiber-to-slab evanescent wave sensors for the practical applications.

2 The sensor construction and operating principle

As illustrated in figure 1, the microfiber-to-slab coupler is comprised of a microfiber in evanescent contact with a multimode slab overlay waveguide. To make the coupler robust in structure, a plate of glass was adopted as the substrate to support the fiber and slab. And the gaps among them were filled with a type of curable polymer as the new cladding to protect the sensor from external disturbances. The microfiber used here can be tapered from the standard single-mode fiber by flame-brushing technique. When the waist diameter of the standard single-mode fiber is tapered down to sub-wavelength dimensions, the original fiber core may effectively disappear and large evanescence power will spread into the external polymer. As the microfiber and a slab waveguide are in sufficient proximity, the evanescent mode fields of the two waveguides will overlap. Resultantly, resonant mode coupling between the fiber and the slab waveguide will take place.

![Diagram](image)

Fig. 1. Geometry of the microfiber-to-slab coupler.

According to the coupled mode equations, the resonance wavelength can be logically given from the eigenvalue equations of the optical fiber and the multimode slab.

$$\lambda_m = \frac{2\pi d_s \sqrt{n_s^2 - N_{fs}^2}}{m\pi + 2\tan^{-1}\delta \sqrt{N_{fs}^2 - n_{clad}^2}} \sqrt{n_s^2 - N_{fs}^2}$$  \hspace{1cm} (1)

where $n_s$ and $n_{clad}$ represent the corresponding refractive index of the slab and the embedded polymer, respectively. $d_s$ is the thickness of the slab, $m$ is the mode order of the slab waveguide and $\delta$ refers to the polarization-dependent constant (1 for TE mode, $n_s^2/n_{clad}^2$ for TM mode).

From Eq. (1), it is obvious that the resonance wavelength $\lambda_m$ is strongly dependent on the refractive index of the slab $n_s$. When the electro-optic, magneto-optical, thermo-optic or other kind of functional materials are chosen as the slab waveguide, the externally applied field may cause a change in the refractive index of the slab $n_s$ and thus results in a shift in the resonant wavelength $\Delta \lambda_m$.

3 Sensitivity and analysis

3.1 Simulation Results
The device sensitivity is related to the ratio of the shifts in the resonant spectrum to the changes in the refractive index of the slab waveguide. By taking the derivative of Eq. (1), the device sensitivity $S_\lambda$ can be calculated for both transverse electric (TE) and transverse magnetic (TM) polarizations, respectively, with the results as

\[
(s_\lambda)_{TE} = \frac{\Delta \lambda_m}{\Delta n_s} = \frac{\lambda_m n_s}{n_s^2 - N_f^2} + \frac{\lambda_m^2 n_s \sqrt{N_f^2 - n_{clad}^2}}{n_d n_{clad} (n_s^2 - N_f^2)(n_s^2 - n_{clad}^2)}
\]  
\[
(s_\lambda)_{TM} = \frac{\Delta \lambda_m}{\Delta n_s} = \frac{\lambda_m n_s}{n_s^2 - N_f^2} + \frac{\lambda_m^2 n_s \sqrt{N_f^2 - n_{clad}^2}}{n_d n_{clad}^2 (n_s^2 - N_f^2)(n_s^2 - n_{clad}^2)}
\]  

From Eq. (2) and Eq. (3), it can be found that the value of the device sensitivity $S_\lambda$ is synthetically determined by the geometry parameters of the coupler including $d_s$, $n_s$, $n_{clad}$, $N_f$, and the resonance wavelength $\lambda_m$.

Figure 2 shows the dependence of the device sensitivity $S_\lambda$ on the thickness of the slab for both TE and TM polarizations. It can be found that, when the slab thickness is thinner than 50μm approximately, the value of $S_\lambda$ for TE polarization increases sharply with the decrease of the waveguide thickness, whereas it presents an opposite variation tendency for TM polarization. However, as the waveguide thickness increases to be larger than 50μm, both curves indicate that $S_\lambda$ tends to approach a relatively stable value and the coincidence of $S_\lambda$ for TE and TM polarizations takes place. In this case, the waveguide thickness has little influence on the device sensitivity and the birefringence effect can be neglected. This phenomenon can be attributed to the fact that for a thick isotropic slab the phase shifts associated with the evanescent field boundaries is negligible and the resonance coupling between the matched modes is polarization independent at this time [13]. These results suggest that the slab waveguide with larger thickness is preferred in fabricating polarization-independent microfiber-to-slab based sensors. But if the adopted slab thickness is thinner than 50μm approximately, the birefringence effects should be considered and the couplers with the TE polarized light launched into the fiber would exhibit superior sensitivity.

![Fig. 2. Variations of $S_\lambda$ as a function of the thickness of the slab $d_s$. ($n_s=1.55$, $n_{clad}=1.40$, $d_f=2\mu m$, and $\lambda_m=1550nm$).](image)
Figure 3 depicts how the device sensitivity $S_\lambda$ changes with the refractive index of the slab $n_s$. With the decrease of $n_s$ from 2.0 to 1.47, $S_\lambda$ performs an exponential growth. $S_\lambda$ reaches nearly 20000 nm/RIU (where RIU is refractive index unit) at $n_s = 1.47$ for $d_s = 100 \mu m$, $n_{clad} = 1.42$, $d_f = 2 \mu m$, and $\lambda_m = 1550 nm$. This means that smaller $n_s$ is beneficial to enhance the resonant-wavelength-shift sensitivity of the microfiber-to-slab sensors. However, $n_s$ should not go below the effective index of the microfiber waveguide $N_f$. When $n_s < N_f$ most of the light power initially launched into the fiber will remain in the vicinity of the fiber, and very little power could be coupled from the fiber to the slab waveguide mode due to phase mismatch. By further comparing the two curves in figure 3, it can be observed that the relationship between $S_\lambda$ and $n_s$ for TE mode is approximately in accordance with that for TM mode. This is attributed to that the slab waveguide with a larger thickness of 100 μm is assumed here and the coincidence of $S_\lambda$ for TE and TM polarizations occurs, which agrees with the theoretical analysis indicated in figure 2.

In Eq. (2), $N_f$ is the effective index of the guided mode travelling along the microfiber. Here only the fundamental rigid mode is considered. According to the fiber mode theory, $N_f$ has a strong dependence on the microfiber diameter $d_f$, the refractive index of the fiber core $n_f$ and the embedded cladding $n_{clad}$ and the resonance wavelength $\lambda_m$. It can be numerically calculated by solving the eigenvalue equation for the fundamental mode propagating in the microfiber. Figure 4 shows the dependence of $N_f$ of the rigid mode on $d_f$, $n_{clad}$, and $\lambda_m$, assuming the refractive index of the silica fiber core to be $n_f = 1.464$. Then, by substituting the data in figure 4 into Eq. (2), the dependence of $S_\lambda$ on $d_f$, $n_{clad}$, and $\lambda_m$ can be obtained with the results indicated in figure 5. In these figures, the solid, dotted and dashed lines are plotted for $\lambda_m = 1520 nm$, 1550 nm and 1580 nm, respectively. Comparing the curves in figure 4 and figure 5, we can observe that the tendency of $S_\lambda$ changing with $d_f$, $n_{clad}$, and $\lambda_m$ is similar to that of $N_f$ varying with $d_f$, $n_{clad}$, and $\lambda_m$, which implies that a direct proportional relationship exists between the device sensitivity $S_\lambda$ and $N_f$ of the fundamental mode in the microfiber. When $d_f$ and $n_{clad}$ increase or $\lambda_m$ decreases, $N_f$ increases, resulting in an increase of $S_\lambda$. 

![Figure 3](image-url)
Fig. 4. The relationship between $N_f$ and $n_{clad}$ for several representative values of the microfiber diameter and resonant wavelength. The solid, dotted and dashed lines are plotted for $\lambda_m=1520$nm, 1550nm and 1580nm, respectively.

Fig. 5. The relationship between $S_\lambda$ and $n_{clad}$ for several representative values of the microfiber diameter and resonant wavelength ($d_c=100\mu$m, $n_f=1.50$). The solid, dotted and dashed lines are plotted for $\lambda_m=1520$nm, 1550nm and 1580nm, respectively.

3.2 Discussions

According to the coupled mode theory, the light transfer between the fiber and the slab waveguide in the slab coupled microfiber sensor strongly depends on the relationship between their refractive index $N_f$ and $n_s$. If $N_f>n_s$, large fraction of the incident power will remain in the fiber. This will result in phase mismatch, and the coupling between the two waveguides will be ineffective. When $N_f<n_s$, the fiber propagation constant $\beta_f$ will lie deep within the range of propagation constants of the continuum slab modes $\beta_{sn}$ and the fiber mode can be essentially synchronous with one of the slab modes. In this case, effective power coupling will occur from the fiber to the slab. Moreover, smaller the value of $N_f$ relative to $n_s$, stronger will be the power coupling from the launched fiber to the slab, and thus higher device sensitivity will be. Therefore, as shown in the simulated results of figure 3 and figure 5, higher resonant-wavelength-shift sensitivity $S_\lambda$ comes from smaller...
difference of \( N_f \) relative to \( n_s \). Either decreasing \( n_s \) or increasing \( N_f \) will make \( S_\lambda \) increase significantly.

4 Conclusions

We investigated the sensing properties of the microfiber-to-slab coupler based sensor as a function of its configuration parameters by the theoretical analysis and numerical simulations. On the basis of that, we could conclude that the device sensitivity and polarization characteristics of the coupler depend primarily on the refractive index, the thickness (or diameter) and the length of the slab, fiber and cladding. Higher device sensitivity generally came from smaller difference between the slab index and the effective index of the fiber. By optimally selecting matched geometry parameters, the potential resonant-wavelength-shift sensitivity could be as high as approximately 20000nm/RIU. These results hold great promise for the development of functional and sensitive microfiber-to-slab coupling devices.

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References

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