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

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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.

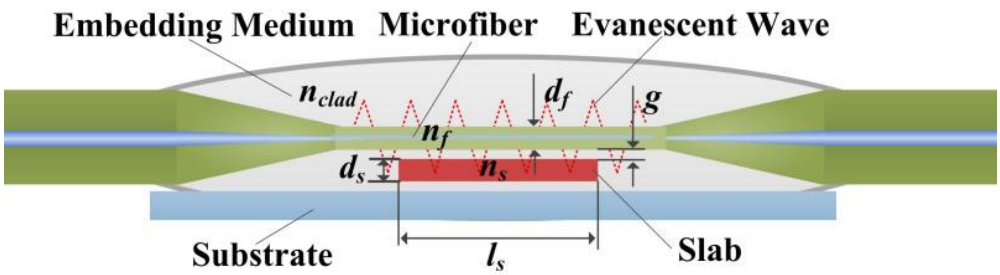

Fig. 1. Geometry of the microfiber-to-slab coupler.

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.

$$\lambda_m = \frac{2\pi d_s \sqrt{n_s^{\,2} - N_f^{\,2}}}{m\pi + 2\tan^{-1}\delta \dfrac{\sqrt{N_f^{\,2} - n_{clad}^2}}{\sqrt{n_s^{\,2} - N_f^{\,2}}}} \tag{1}$$

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 δ 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 λ_m is strongly dependent on the refractive index of the slab ns. 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 ns 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_λ can be calculated for both transverse electric (TE) and transverse magnetic (TM) polarizations, respectively, with the results as

$$(s_\lambda)_{TE} = \frac{\Delta\lambda_m}{\Delta n_s} = \frac{\lambda_m n_s}{(n_s^2 - N_f^2)} + \frac{\lambda_m^2 n_s \sqrt{N_f^2 - n_{clad}^2}}{\pi d_s (n_s^2 - N_f^2)(n_s^2 - n_{clad}^2)} \tag{2}$$

and

$$(s_\lambda)_{TM} = \frac{\Delta\lambda_m}{\Delta n_s} = \frac{\lambda_m n_s}{n_s^2 - N_f^2} + \frac{\lambda_m^2 n_s \sqrt{N_f^2 - n_{clad}^2}\,(2N_f^2 - n_s^2)}{\pi d_s n_{clad}^2 \left(\frac{n_s^4 (N_f^2 - n_{clad}^2)}{n_{clad}^4 (n_s^2 - N_f^2)} + 1\right)} \tag{3}$$

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

Figure 2 shows the dependence of the device sensitivity S_λ 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_λ 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_λ tends to approach a relatively stable value and the coincidence of S_λ 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.

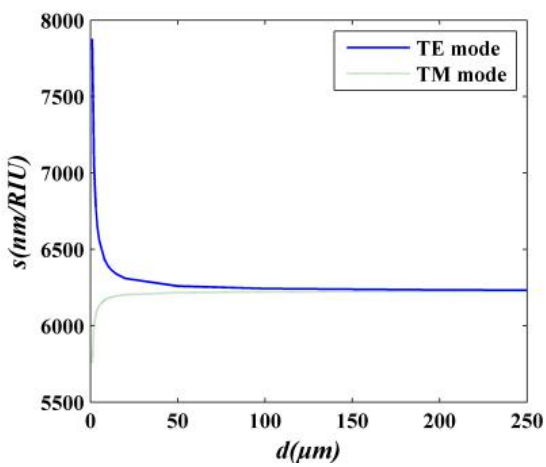

Fig. 2. Variations of S_λ as a function of the thickness of the slab d_s. (n_s=1.55, n_{clad}=1.40, d_f=2μm, and λ_m=1550nm).

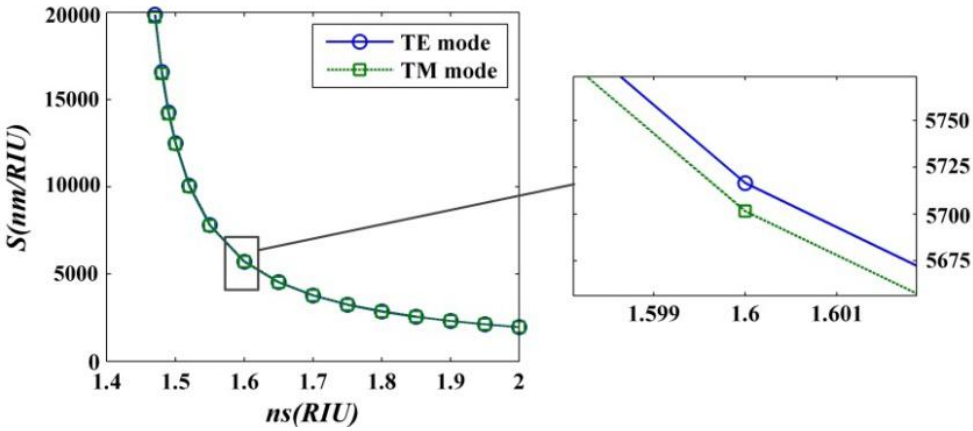

Fig. 3. The dependence of S_λ on the refractive index of the slab ns (d_s =100μm, n_{clad}=1.42, d_f=2μm, and λ_m=1550nm). Inset shows the partial enlarged drawing with n_s=1.60.

Figure 3 depicts how the device sensitivity S_λ changes with the refractive index of the slab. With the decrease of n_s from 2.0 to 1.47, S_λ performs an exponential growth. S_λ reaches nearly 20000nm/RIU (where RIU is refractive index unit) at n_s =1.47 for d_s=100μm, n_{clad}=1.42, d_f=2μm, and λ_m=1550nm. This means that smaller n_s is beneficial to enhance the resonant-wavelength-shift sensitivity of the microfiber-to-slab sensors. However, ns 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_λ and ns 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 100μm is assumed here and the coincidence of S_λ 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 λ_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 λ_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_λ on d_f, n_{clad}, and λ_m can be obtained with the results indicated in figure 5. In these figures, the solid, dotted and dashed lines are plotted for λ_m=1520nm, 1550nm and 1580nm, respectively. Comparing the curves in figure 4 and figure 5, we can observe that the tendency of S_λ changing with d_f, n_{clad}, and λ_m is similar to that of N_f varying with d_f, n_{clad}, and λ_m, which implies that a direct proportional relationship exists between the device sensitivity $S\lambda$ and Nf of the fundamental mode in the microfiber. When d_f and n_{clad} increase or λ_m decreases, N_f increases, resulting in an increase of S_λ.

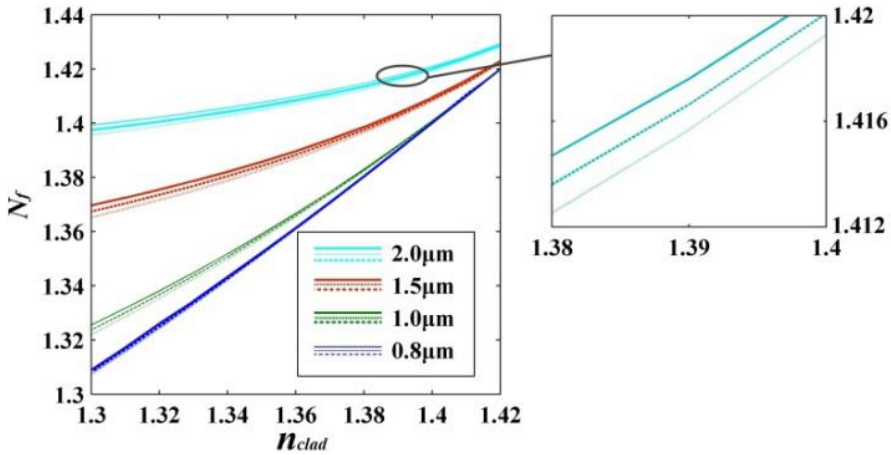

Fig. 4. The relationship between N_f and n_{clad} for several representative values of the microfiber diameter and resonant wavelength. The solid, dotted and dashed lines are plotted for λ_m=1520nm, 1550nm and 1580nm, respectively.

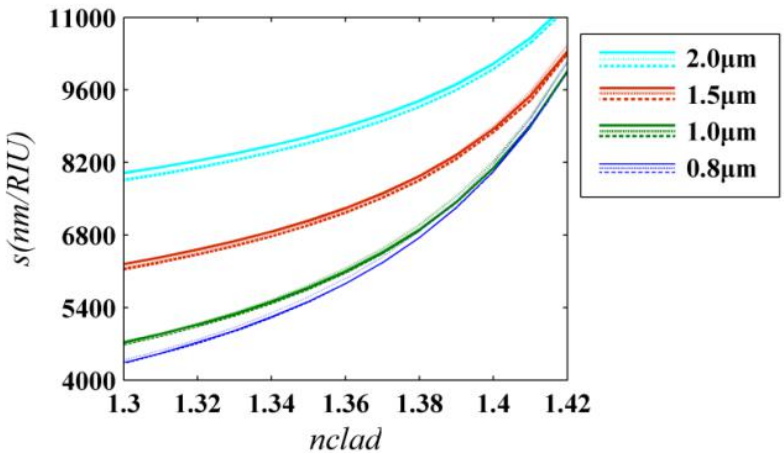

Fig. 5. The relationship between S_λ and n_{clad} for several representative values of the microfiber diameter and resonant wavelength (d_s=100μm, n_s=1.50). The solid, dotted and dashed lines are plotted for λ_m=1520nm, 1550nm and 1580nm, respectively.

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 β_f will lie deep within the range of propagation constants of the continuum slab modes β_{sm} 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 figure5, higher resonant-wavelength-shift sensitivity S_λ comes from smaller

difference of N_f relative to n_s. Either decreasing ns or increasing N_f will make S_λ 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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