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Twin-resonance-coupling and high sensitivity sensing characteristics of a selectively fluid-filled microstructured optical fiber

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Abstract: A twin-resonance-coupling phenomenon and the sensing characteristics of a selectively fluid-filled microstructured optical fiber (SFMOF) are proposed and demonstrated. The SFMOF is realized by selectively infiltrating refractive index fluid into a single air hole located at the second ring near the core of the MOF. Twin-resonance dips are observed in the transmission spectrum. Theoretical and experimental investigations reveal that the twin-resonance dips both result from the coupling between $\text{LP}_{01}^\text{c}$ silica core mode and $\text{LP}_{01}^\text{l}$ liquid rod mode. Their sensitivities strongly depend on the dispersion curves of the silica and fluid material. Sensitivities of 290 nm/°C (739,796 nm/RIU) and 591.84 nm/N (701.2 pm/µɛ) are achieved, which are the highest for a SFMOF-based device to date, to our best knowledge. Furthermore, the twin-resonance dips appear to shift in the opposite directions with changes in temperature or axial strain, providing a method to achieve two- or multi-parameter measurement in such a compact structure.

OCIS codes: (060.2370) Fiber optics sensors; (060.5295) Photonic crystal fibers; (060.2310) Fiber optics.

References and links

1. Introduction

Selectively fluid-filled microstructured optical fibers (SFMOFs), realized by infiltrating functional materials into one or several air holes of MOFs, have attracted considerable interests in recent years [1–8]. SFMOF based sensors or tunable photonic devices are distinguished for a number of excellent properties introduced by different functional materials, including the improved bending responses [1], ultrahigh refractive index (RI) sensitivity [2], enhanced axial strain sensitivity [3], high performance in polarizer [4] and extraordinary transmission and sensing characteristics in Sagnac interferometers [5,6]. Especially, resonance dips, introduced by mode coupling between the silica core mode and liquid rod modes in SFMOFs, provide a new way to achieve high sensitivity sensor. By resonantly coupling the LP_{01}^s core mode to LP_{01}^l liquid mode in an adjacent fluid-filled waveguide, Wu et al. first proposed a microfluidic RI sensor with the sensitivity of 30,100 nm/RIU (or 11.61 nm/°C), which was achieved through the selective infiltration of a single hole with fluid along a MOF [7]. An embedded coupler based on selectively filling a single air hole of a MOF was demonstrated by Wang et al. [2,3], resulting in the resonance coupling from the LP_0^s silica core mode to the LP_{01}^l or LP_{11}^l liquid rod modes. Sensitivities of 54.3 nm/°C for the temperature and −22 pm/μɛ for the axial strain were achieved, respectively. In a double-fluid-filled MOF, Liang et al. have simultaneously realized the mode coupling from LP_0^s silica core mode to LP_{01}^l liquid rod mode at 1310 nm and to LP_{11}^l liquid rod mode at 1550 nm [8]. They have demonstrated the simultaneous measurement of the temperature and force with a sensitivity of 42.818 nm/°C and −37.701 nm/N (or −38.041 pm/μɛ), respectively. However, the resonance coupling reported in the above-mentioned literature can be considered as single-resonance-coupling phenomenon, that is, the coupling between two specific modes only brings about a single-resonance dip in the transmission spectrum.

In this paper, a twin-resonance-coupling phenomenon in a SFMOF, achieved by infiltrating a liquid with RI of 1.47 for 589.3 nm at 25°C into a single air hole located at the second ring near the silica core, is demonstrated and investigated. Twin-resonance dips are observed in the transmission spectrum of the SFMOF. Theoretical and experimental investigations reveal that the twin-resonance dips both result from the coupling between the LP_0^s silica core mode and the LP_{01}^l liquid rod mode. This is very different from the single-resonance-coupling phenomenon, as shown in the previous reports [2,3] and [7,8]. The twin-resonance dips exhibit sensitivities as high as 290 nm/°C (739,796 nm/RIU) and 591.84 nm/N (701.2 pm/μɛ) to external temperature and axial strain in experiments, respectively. In addition, the twin-resonance dips appear to shift in the opposite directions alongside the changes in temperature or axial strain, providing a method to achieve two- or multi-parameter measurement with such a compact structure.

2. Theoretical analysis

Figure 1 illustrates the schematic diagram of the experimental setup for investigating the transmission spectra and sensing characteristics of the SFMOF. The light from a
super-continuum source (SCS) (600.0 nm-1700.0 nm) propagates through the SFMOF sandwiched between two sections of standard single mode fiber (SMF). The transmission spectrum is measured by an optical spectral analyzer (OSA) with the highest resolution of 0.02 nm. The SFMOF is straightened with a constant axial strain provided by a preset load in order to avoid the bending influence on the results. The SFMOF is achieved by infiltrating standard RI liquid (Cargille Laboratories, Inc.) into a single air hole located at the second ring near the silica core of a pure silica MOF, as shown in Figs. 1(b) and 1(c). The original pure silica MOF includes five rings of air holes arranged in a regular hexagonal pattern with a fiber diameter of 124 µm. The diameter of the air holes and the adjacent holes spacing are 3.64 µm and 5.85 µm, respectively.

![Fig. 1. (a) Schematic diagram of the SFMOF based sensing system; (b) Transverse cross-section of the refabricated SFMOF; (c) The perspective view for the simplified model with liquid rod highlighted by the red.](image)

The background silica has material refractive index (MRI) of 1.444 at 1550.0 nm and its material dispersion is considered using the Sellmeier equation [9]. The infiltrated liquid possesses an MRI of 1.47 for 589.3 nm at 25°C and a negative thermal-optic coefficient \( K_{\text{liquid}} \) of \(-0.000392\) RIU/°C. The material dispersion of the liquid is fitted by the Cauchy equation [10] as follows:

\[
    n_{MRI} = a + \frac{b}{\lambda^2} + \frac{c}{\lambda^4},
\]

where \( \lambda \) is the operation wavelength. Constants a, b and c are 1.456781, 440148.5 and \( 6.50 \times 10^{11} \), respectively.

![Fig. 2. Dispersion curves of the pure silica and the infiltrated liquid at different temperatures.](image)

According to the Sellmeier equation of silica and Eq. (1), we calculated the MRI dispersion curves of the silica and liquid at different temperatures and depicted them in Fig. 2. In our calculation, considering that the thermal-optic coefficient of the pure silica \( (K_{\text{silica}} = -7 \times 10^{-6}) \)
RIU/°C) is far less than that of the liquid $K_{\text{liquid}}$, the MRI of the silica core (ignoring the photo-elastic effect caused by strain or bending) is assumed unchanged with increasing temperature. As the red line shown in Fig. 2(a), MRI of the liquid rod is higher than that of the silica core (black line) in the spectral range investigated in this paper when the temperature is 45°C. Attribute to the negative $K_{\text{liquid}}$ of the liquid, its MRI monotonically decreases with the increasing temperature. It is obvious that in Fig. 2(b), when temperature increases to 51.7 °C, two dispersion curves firstly intersect at a critical point A (B) due to the difference in their curvature. Subsequently, there are two intersections with further rising temperature, as shown as the points A and B in Figs. 2(c) and 2(d). Moreover, the intersection A moves towards the shorter wavelength while the intersection B moves towards longer wavelength [Fig. 2(d)] with the continuously rising temperature. Then, the point A firstly moves out of the boundary in the shorter spectral range, leaving the point B at the longer spectral range [Fig. 2(e)]. Finally, when the temperature increases high enough, these two intersections vanish in the spectral range from 600.0 nm to 1700.0 nm as shown as Fig. 2(f).

The liquid rod with tunable MRI acts as a “satellite core” around the silica core. Particularly, the liquid “satellite core” is equivalent to the solid silica core at the intersections, where their MRIs are equal. According to the coupled-mode theory [11], resonance coupling between the $LP^{c}_{01}$ silica core mode and $LP^{l}_{01}$ liquid rod mode occurs at the intersections. Therefore, the dual intersections A and B on the MRI curves bring about twin-resonance-coupling regions as well as twin-resonance dips in the transmission spectrum.

![Fig. 3. The MRI dispersion curves of the silica core and liquid rod at 52.5 °C. The insets show the typical modal energy distributions at different wavelengths in the twin-resonance-coupling regions.](image)

The black and red curves in Fig. 3 represent the MRI curves of the silica core and the liquid rod within the spectral range from 600.0 nm to 1100.0 nm at 52.5 °C, generating two intersections at 692.3 nm and 985.5 nm, respectively. Owing to the quasi-symmetrical arrangement of air holes, an equivalent dual-core fiber is achieved with twin-resonance-coupling regions at the intersections. In order to analyze the twin-resonance-coupling processes in the SFMOF, numerical simulations based on full-vector finite element method (FEM) were performed. As can be seen from the modal energy distributions in the insets of Fig. 3, the two coupling regions are both formed by coupling the $LP^{c}_{01}$ silica core mode to $LP^{l}_{01}$ liquid rod mode. Moreover, mode coupling between the $LP^{c}_{01}$ mode and $LP^{l}_{01}$ mode exhibit the behavior of energy exchange at the twin-resonance-coupling regions. By comparing the modal distribution in the liquid rod at different wavelengths, significant changes in modal intensity are observed. The strongest resonance coupling occurs at...
the wavelengths where the phase-matching condition is satisfied, while the weak resonance coupling also coexists at the mismatching wavelengths. Numerical simulation results indicate that the closer the operation wavelength $\lambda$ is to the resonance wavelength $\lambda_R$, the higher energy coupling efficiency into the liquid mode is achieved. Hence, the strongest resonance between the LP$_{01}^c$ mode and LP$_{01}^s$ mode occurs at the two intersections, satisfying the phase-matching condition:

$$n_{\text{silica}}(\lambda_R(T), T) = n_{\text{liquid}}(\lambda_R(T), T).$$

After taking the derivative of Eq. (2) with respect to temperature, we deduce the sensitivity $S$ in response to the temperature $T$ and express it as follows:

$$S = \frac{d\lambda_R}{dT} = \frac{-\partial n_{\text{silica}}/\partial \lambda - \partial n_{\text{liquid}}/\partial \lambda}{n_{\text{silica}}'(\lambda) - n_{\text{liquid}}'(\lambda)},$$

where $n_{\text{silica}}'(\lambda)$ and $n_{\text{liquid}}'(\lambda)$ represent the first-order derivatives of the MRI curves for silica and liquid with respect to $\lambda$, respectively, corresponding to the slopes of the two curves in Fig. 3. According to Eq. (3), the difference in thermo-optic coefficients between the silica and the liquid is always positive in the spectral range investigated. While the slope for dispersion curve of the pure silica is larger in shorter spectral range and smaller in longer spectral range than that of the liquid material [Fig. 2 or Fig. 3]. This indicates opposite spectral responses to the increment of temperature at the twin-resonance-coupling regions. Particularly, an ultrahigh or theoretical infinite sensitivity $S$ is achieved at near the critical point A (B) [Fig. 2(b)], where $n_{\text{silica}}'(\lambda)$ equals $n_{\text{liquid}}'(\lambda)$ and the two dispersion curves share a common tangent line.

On the other hand, photo-elastic effect slightly reduces the MRI of the silica core when strain is axially loaded along the SFMOF at a constant temperature. With the reduced MRI of the pure silica and changeless MRI of liquid in this case, the black curve will gradually get lower away from the red one (in Fig. 3). Therefore, the two intersections as well as the twin-resonance dips will move towards each other with the increment in axial strain, exhibiting different spectral responses compared with that to the increasing temperature. Since the strong dependence of the sensitivity on the dispersion curves, an ultrahigh sensitivity near the critical point can also be achieved for axial strain.

3. Experimental results

![Fig. 4](image-url). The transmission spectra of the SFMOF corresponding to variations in temperature from 54.0 °C to 55.0 °C (a) and axial strain from the preset load to an extra 0.147 N (b).
In the experiment, an air hole at the second ring of the MOF hexagonal pattern is selectively infiltrated with 3.5 cm long liquid with the standard RI of 1.47, by the direct manual-gluing method described in detail in Ref [12]. A bit of air is also infiltrated into the selected air hole at both ends of the SFMOF to avoid high transmission loss caused by fusion splicing with this organic liquid. The SFMOF is fusion splicing to SMFs and placed inside the temperature chamber to investigate its thermal responses.

Figure 4(a) shows the transmission spectra of the SFMOF, corresponding to the temperature varying from 54.0 °C to 55.0 °C. The resonance coupling firstly appears in a wide spectral range near 764.0 nm at 54.0 °C shown as the black line. Then the twin-resonance dips A and B appear on both sides of 764.0 nm with the increasing temperature, which is consistent with the aforementioned theoretical analysis. The twin-resonance dips A and B shift towards opposite directions and the spacing between these two dips broadens to 300.0 nm within the temperature increment of 1 °C. In addition, since the mode coupling efficiency is in positive correlation to the size of the overlapping-region in view of the coupled-mode equations [11], dip A has lower loss than dip B as the results of better mode confinement and smaller overlapping region at the shorter wavelength range in the MOF.

Figure 4(b) demonstrates the spectral responses of the twin-resonance dips to axial strain at the constant temperature of 54.5 °C. The twin-resonance dips A and B show redshift and blueshift in response to the increment of axial strain, respectively. In contrast with the responses to the increasing temperature, the spacing between the two dips decreases gradually within the increment of strain from the preset load to an extra 0.1470 N, which also agrees with the theoretical analysis.

The specific sensitivities for the temperature and axial strain of the two resonance dips are further discussed, respectively. Figures 5(a) and 5(b) demonstrate the wavelengths dependence of the resonance dips A and B on the temperature in theory and experiment, respectively. The twin-resonance dips form firstly at 54.0 °C, and then the dip A shows blueshift while the dip B shows redshift with the increment in temperature. The wavelength variation in experiment (scatter) shows the same trend to the theoretical results (solid lines) except for a small deviation in temperature range. This is mainly because, reduced MRI of the silica core caused by the preset load is equivalent to raising the temperature for the resonance occurring. It is also seen in Figs. 5(a) and 5(b) that the absolute values of the sensitivities $S$ non-linearly decrease with the increasing temperature. The wavelength shift as high as 29.3 nm is obtained as the temperature.
$T$ varying from 54.2 °C to 54.3 °C. Thus, experimental sensitivity $S$ exceeding 290 nm/°C (739,796 nm/RIU) is achieved at about 54 °C, which is an order higher than that reported in Ref [2–8]. Even the lowest sensitivity of 92 nm/°C (234,694 nm/RIU) obtained at 55.5 °C is still as twice much as the previous results. Figures 5(c) and 5(d) theoretically and experimentally show the wavelength dependence of resonance dips A and B on the axial strain at the fixed temperature of 54.5 °C. Unlike the thermal responses discussed above, the dip A exhibits redshift while the dip B exhibits blueshift in response to the increment in axial strain. In this case, the experimental sensitivity $S$ nonlinearly increases with the increasing axial strain, which is also consist with the simulation results. The highest sensitivity for axial strain is up to 591.84 nm/N (or 701.204 pm/µε) at 236.8 µε, which is at least 18 times than the literature reported in [2–8]. However, even the lowest sensitivity also exceeds 258.503 nm/N (or 310.201 pm/µε) at 89.8 µε, which is 8 times larger than that reported in [2–8] as well.

4. Conclusion

In conclusion, the twin-resonance-coupling phenomenon and the ultrasensitive sensing characteristics of a SFMOF are demonstrated and investigated. Sensitivities as high as 290 nm/°C (739,796 nm/RIU) and 591.84 nm/N (701.2 pm/µε) are achieved in experiments, respectively. The strong correlation between the temperature (axial strain) sensitivity and the MRI curves is explained. Moreover, the resonance wavelengths can be adjusted and controlled via designing or changing dispersion curves of the fluidic materials filled in the MOF, providing a flexible method for achieving tunable photonic devices or detecting external changes associated with the RI in different spectral ranges. Furthermore, the different sensitivities of the twin-resonance dips to external changes show potentiality for two- or multi-parameter accurate measurement in physical, chemical and biochemical sensing with such a compact structure.

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