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Ultra-sensitive measurement of gas refractive index using an optical nanofiber coupler

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We report an ultra-sensitive gas refractive index (RI) sensor based on optical nanofiber couplers (ONCs). Theoretical analysis reveals that a dispersion turning point (DTP) exists when the diameter of the coupler is below 1000 nm. Thus, the evanescent field can be greatly enhanced, and the RI sensitivity can be significantly improved to infinity. Then we experimentally demonstrate a DTP and achieve ultrahigh sensitivities of 46470 nm/refractive index unit (RIU) and -45550 nm/RIU around the DTP using a 700 nm-thick ONC. More importantly, the unique twin dips/peaks interference characteristics around the DTP offers further enhancement on the sensitivity to 92020 nm/RIU. The demonstrated sensor not only shows vast potential in ultra-sensitive pressure sensing, acoustic sensing, gas and gas phase biomarkers detection, but also provides a new tool for nonlinear optics, quantum optics, and ultra-cold atom optics. © 2017 Optical Society of America

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The growing need for highly sensitive and robust gas sensors in a wide spectrum of fields has driven the study of various sensing schemes. For example, the detection of flammable gases, explosive gases, and toxic gases are critical in petroleum, chemical industries and environmental exposure monitoring [1,2]. Also, sensitive and selective assay of gas phase biomarkers such as volatile organic compounds (VOC) in exhaled breath is of important clinical value for early lung cancer diagnosis [3]. Moreover, in modern laser systems, where high power laser beams interact with or propagate in gaseous media, the precise determination of the nonlinear refractive index (RI) and pressure are essential [4]. Among the demonstrated sensing schemes, fiber-optic RI sensors are able to

sense the nearby presence of molecules in gas medium, along with its unique advantages of small footprint, low-cost, immunity to electromagnetic interference, as well as distributed sensing and remote sensing capabilities.

Though numerous fiber-optic RI sensors utilizing different sensing schemes have been developed, most of these studies are limited to aqueous solutions analysis. Quite few works focused on gaseous medium. Indeed, highly sensitive gas RI detection is fundamentally challenging for fiber-optic sensors mainly because of two reasons: first, there is a vast mismatch between the RI of gases (close to 1.0) and the effective RIs (ERIs) of propagating modes in fiber, which leads to a limited penetration depth of evanescent wave and weakens the interaction between the guided light and surrounding medium. Second, the RI change of gaseous medium to be resolved is extremely narrow compared to that of the aqueous solutions. Thus, directly adopting the fiber RI sensors which operate well in aqueous solutions to gas phase detection is unable to meet the required performance in gas sensing.

On the other hand, among the few reported fiber-optic gas RI sensing schemes, open cavity fiber Fabry-Perot interferometer is the most studied one, which is based on the measurement of changes in optical pass difference induced by the RI variations of the gas in the open cavity. The sensitivities of these sensors are typically about 561-1639 nm/RIU and are still relatively low [5-9]. Furthermore, by using the Vernier effect, the sensitivity can be enhanced up to 30899 nm/RIU [10]. Researchers also have tried to expand fiber-optic surface plasmon resonance sensors [11-13], fiber-optic Mach-Zehnder interferometers [14,15], and long period fiber gratings (LPG) [16] for gas RI sensing. However, the sensitivities of these sensors are limited within several hundreds of nm per RIU to few thousands of nm per RIU.

In this paper, we demonstrate an optical nanofiber coupler (ONC) based gas RI sensor which can achieve ultrahigh sensitivity by taking advantage of the dispersion turning point (DTP). Optical fiber couplers have been applied for various sensing applications in aqueous medium [17,18] and an ultra-high sensitivity of 39541.7 nm/RIU has been reported [19]. However, fiber coupler

based refractometers for gas sensing remain unexplored. Here, we first lay a theoretical foundation for reflective fiber coupler based gas RI sensors. Then we numerically investigate the dependence of ERIs of even and odd modes on fiber diameter (a) and find that the ERIs of odd modes approach 1.0 for ONCs ($a < 1000$ nm). Moreover, we discover the DTP for ONCs where the group ERIs of even mode and odd mode equal to each other. Leveraging on this DTP, the gas RI sensitivity can be significantly enhanced and approaches infinity. Furthermore, we experimentally validate the sensing mechanism in air and confirm a good agreement with the theoretical results. The sensor is nearly two orders of magnitude higher than most reported sensors. This evanescent wave based gas RI sensor can also facilitate specific surface coatings to realize ultrasensitive and selectivity detections of gas phase bio-chemical molecules.

Fig. 1. Schematic diagram of the ONC based gas RI sensing probe.

For the convenience of practical applications, here we use a reflective sensing scheme, as shown in Fig. 1. The device comprises two parts: an ONC which is composed of two parallel and closely packed nanofibers and two tapered regions; and two reflective arms. When light is launched into port 1, both even and odd supermodes are excited and power exchange occurs between the two modes as they propagate along the ONC. The reflected light at the end facets of arm 1 and arm 2 then couple back to the ONC, and eventually, we can obtain reflective spectra at ports 1 and 2. The spectral interference pattern is dependent on the surrounding RI (SRI), and by tracking the wavelengths of dips/peaks, the measured RI can be inferred.

Suppose light in single polarization (TE/TM) with a total power of P_0 and is launched into port 1, the output reflected complex amplitude of electrical fields E_{1out} and E_{2out} at ports 1 and 2 can be obtained through transfer matrix method [20]

$$\begin{bmatrix} E_{1out} \\ E_{2out} \end{bmatrix} = M \begin{bmatrix} E_{1in} \\ 0 \end{bmatrix} = M_{ONC}^b M_R M_{ONC}^f \begin{bmatrix} E_{1in} \\ 0 \end{bmatrix} \quad (1)$$

where E_{1in} is the input complex amplitude of electric field. M is the transfer matrix of the whole device. M_{ONC}^f , M_{ONC}^b and M_R are the transfer matrixes of the ONC for forward transmission, backward transmission, and the reflective arms, respectively. Given the symmetry of the ONC, we can write [20]

$$M_{ONC}^f = M_{ONC}^b = \begin{bmatrix} \cos(\phi) & -j\sin(\phi) \\ -j\sin(\phi) & \cos(\phi) \end{bmatrix} \quad (2)$$

where $\phi = (\beta_{even} - \beta_{odd})L/2$ denote the accumulated phase difference between the even and odd modes along the coupling length L , while β_{even} and β_{odd} are the propagation constants of the two modes, respectively. Here it is reasonable to neglect the tapered parts and only consider the phase term ϕ accumulated in the uniform waist region to simplify the model, considering the fact that the phase difference induced by the tapered regions is

much lower than the uniform waist region and it is far less sensitivity to SRI changes because of the relative large geometric size. The two reflective arms are similar to that of the Mach-Zehnder interferometers [21] and the transfer matrix can be expressed as

$$M_R = \begin{bmatrix} r_1 e^{j\alpha_1} & 0 \\ 0 & r_2 e^{j\alpha_2} \end{bmatrix} \quad (3)$$

where r_1 and r_2 are the reflection coefficients at fiber end facets of arm 1 and arm 2, and $\alpha_1 = 2\beta l$ and $\alpha_2 = 2\beta(l + \Delta l)$ stand for the supplementary optical phase induced by the reflective arms, respectively. Here $l, \Delta l$ and β denote the length of the upper reflective arm, length difference between the two reflective arms, and propagation constant in reflective arms, respectively. With Eq. (1), (2) and (3), we can get

$$\begin{bmatrix} E_{1out} \\ E_{2out} \end{bmatrix} = \begin{bmatrix} E_{1in}(r_1 e^{j\alpha_1} \cos^2 \phi - r_2 e^{j\alpha_2} \sin^2 \phi) \\ -jE_{1in} \sin \phi \cos \phi (r_1 e^{j\alpha_1} + r_2 e^{j\alpha_2}) \end{bmatrix} \quad (4)$$

Thus, the output optical power at port 2 can be obtained as

$$P_2 = \frac{1}{4} P_0 \sin^2 2\phi (r_1^2 + r_2^2 + 2r_1 r_2 \cos(2\beta \Delta l)) \quad (5)$$

Eq. (5) reveals that Δl causes an interference, which is undesirable. To eliminate this interference, we can angle cut one arm and cover it with refractive index matching oil. Then we get $r_2=0$, and the output power at port 2 as

$$P_2 = \frac{1}{4} P_0 r_1^2 \sin^2 2\phi \quad (6)$$

The phase term ϕ_N and the position of the N th dip λ_N satisfies

$$2\phi_N = (\beta_{even} - \beta_{odd})L = \frac{2\pi L(n_{eff}^{even} - n_{eff}^{odd})}{\lambda_N} = N\pi \quad (7)$$

Fig. 2. ERIs and evanescent power fractions of even mode and odd mode versus fiber diameter at wavelength 1300 nm. Insets: modal field profiles of even mode and odd mode ($a=700$ nm, $\lambda=1300$ nm).

Using a commercial software COMSOL Multiphysics 4.4, we calculate the ERIs (n_{eff}) and the power fractions of the evanescent waves (η) for the two supermodes at wavelength 1300 nm as functions of a . The RI of silica and air are obtained from dispersion formulas [22,23]. The results in Fig. 2 show that the ERI of even mode is larger than that of odd mode, and both values decrease rapidly as fiber diameter decreases below 1000 nm. The ERI of the odd mode approaches 1.0 and eventually the odd mode reaches a cut-off point when $a=605$ nm. Meanwhile, the evanescent wave portions of the both modes increase largely as a decreases. A large

proportion of evanescent field can provide a strong interaction between the propagating light and the ambient analyte. The insets in Fig. 2 present typical modal field profiles of the two modes in TE polarization supported by a 700 nm-thick ONC. To gain a more straightforward and detailed understanding on the sensing property of ONCs, we take a small variation from Eq. (7) and the RI sensitivity is obtained as

$$S = \frac{\partial \lambda_N}{\partial n} = \frac{\lambda_N}{-n_{\text{odd}}^{\text{even}}} \frac{\partial (n_{\text{eff}}^{\text{even}} - n_{\text{eff}}^{\text{odd}})}{\partial n} \quad (8)$$

where n_g^{even} and n_g^{odd} are the group ERIs of the two modes, which can be calculated through $n_g = n_{\text{eff}} - \lambda_N \partial n_{\text{eff}} / \partial \lambda$. And $G = n_g^{\text{even}} - n_g^{\text{odd}}$ represents the group ERI difference between the two modes.

Fig. 3. (a) Group ERI difference versus wavelength for ONCs. (b) Calculated RI sensitivities as a function of wavelength for ONCs (black circles display the cut-off points of the odd modes). (c) Simulated reflective spectra of a 700 nm-thick ONC with different SRIs.

Then we numerically calculate the group ERI differences (G) for a series of ONCs (a : 500-900 nm). The results in Fig. 3(a) clearly show that the curves of G for different ONCs behave similarly and they all exhibit zero points at certain wavelengths where $G=0$. These zero points are also known as dispersion turning points and they can only be satisfied when the group ERIs of the two modes equal to each other. According to Eq. (8), the RI sensitivity can reach infinity when λ_N is divided by 0. To gain a straightforward and detailed understanding on the ultra-sensitive property of ONCs at DTPs, we calculated RI sensitivities and the results in Fig. 3(b) show that the sensitivities are significantly enhanced towards $+\infty$ and $-\infty$ on left side and right side of DTP, respectively, as the interference dips/peaks approach the DTP, e.g., G approaches zero. The DTP can be tuned from 940 nm to 1670 nm simply by increasing fiber diameter from 500 nm to 900 nm. By utilizing the DTP, ultrahigh sensitivity of tens of thousands nm per RIU for low SRI of around 1.0 can be easily achieved, which is promising for gaseous medium sensing applications. The cut-off points of interference are also observed at longer wavelengths near the DTPs, as a result of the cut-off of the odd modes.

Fig. 3(c) shows the simulated reflective spectra of an ONC ($a=700$ nm, $L=6.51$ mm) with different SRIs. A distinctive DTP can be clearly observed around 1300 nm. As SRI decreases, the

interference dips/peaks on both sides tend to shift away from the DTP. The closer the dips/peaks are to the DTP, the greater the shifts are. During the shift, the broad peak at the DTP gradually splits into a pair of twin peaks and the peaks drift apart from the DTP as SRI decreases. Then, a shallow dip appears between the two newly formed peaks and it deepens as the twin peaks keep shifting away. Finally, the dip splits into a pair of twin dips and so forth.

To experimentally examine our theoretical findings, we employ ONCs to measure the RI changes of air induced by pressure changes. ONCs are fabricated by tapering two twisted standard telecom single mode fibers using a flame brushing method [24]. To keep the ONCs stable and robust, we fix them in specially designed chips. Then we polish the end face of the reflective arm ($r_1=0.04$) and angle cut the other arm and cover it RI matching oil to minimize reflection ($r_2=0$). The length of the two arms are ~ 2 cm. Fig. 4(a) shows the experimental setup for gas RI measurements where a broadband light source (BBS) is used as the incident light and an optical spectrum analyzer (OSA) is employed to record the reflection spectrum. An in-line fiber polarizer and a polarization controller (PC) are used to control the polarization state of light and all the measurements are conducted with TE polarization. The sensor is sealed inside a vacuum chamber which is connected to a vacuum pump and a vacuum meter. Fig. 4(b) shows the micrographs of a ONC ($L \sim 6.5$ mm; $a \sim 700$ nm; length of tapered transition regions, ~ 16 mm). Fig. 4(c) shows the reflection spectrum of the ONC under normal atmospheric pressure with a DTP located at ~ 1270 nm, which is close to that of the simulated value of ~ 1300 nm. On both sides of the DTP, the dips and peaks broaden as they come close to the DTP. On the right side, the interference fringes weaken and finally disappear as wavelength increases, indicating the cut-off of the odd mode as predicted in Fig. 3(b).

Fig. 4. (a) Experimental setup for gas pressure and RI detection. (b) Micrograph of an ONC ($a=700$ nm). (c) Reflective spectrum of the ONC.

For gas pressure and RI sensing, the relative pressure in the chamber is decreased from 0 to -80 kPa with a step of 10 kPa. To eliminate the influence of temperature perturbation, the sensing experiments are carried out in a cleanroom environment where the temperature is kept at 25.50 ± 0.15 °C. The RI changes induced by pressure changes are calculated according to Eq. (9) [25].

$$n_{\text{air}} = 1 + 7.82 \times 10^{-7} P / (273.6 + T) \quad (9)$$

The detailed variations of the reflection spectra in Fig. 5(a) show that the interference dips on both sides shift away from the DTP as relative pressure decreases, e.g. RI decreases, indicating that both positive and negative RI sensitivities are achieved. The closer the dips/peaks are to the DTP, the larger the shifts are, e.g. the higher the RI sensitivities are, which is in good agreement with our simulation results shown in Fig. 3(b) and (c). The pressure sensitivities and RI sensitivities of dips A, A', B, B', C and C' are summarized in Fig. 5(b), which shows that dips A and A' provide the highest positive and negative sensitivities for both pressure and RI, respectively. We plot the measured sensitivities and simulated results of an ONC ($a=700$ nm) in Fig. 5(c). Although the measured position of DTP shows a ~ 20 nm blue shift from the simulated value, the tendency of the measured sensitivity curve is similar to the simulated results, which well demonstrates our proposed sensing mechanism. More interestingly, the twin dips that are symmetrically located with respect to the DTP exhibit comparable sensitivities. This unique twin dips interference characteristics provide a new method for signal processing by tracing the separation distance Δd between the twin dips, which would further double the RI sensitivity. Fig. 5(d) displays the variations of distances between dips pairs AA', BB' and CC'. It is found that $\Delta d_{AA'}$, $\Delta d_{BB'}$ and $\Delta d_{CC'}$ all show linear responses to changes of both relative pressure and gas RI. The twin dips AA' provide the highest pressure sensitivity of -221.44 nm/MPa and gas RI sensitivity of -92020 nm/RIU, which is nearly two orders of magnitude higher than conventional gas RI sensors. Though even higher sensitivity can be achieved by tracing the broad peak that lies at the DTPs. The high non-linearity is undesirable for sensing applications. It should be noted that here we only use the ONC with a diameter of 700 nm for demonstration. A diameter of 900 nm could be the optimal value considering the robustness and the availabilities of light sources and optical spectrum analyzers.

Fig. 5. (a) Reflective spectra of the ONC with the relative pressure varying from 0 to -80 kPa. (b) Wavelength shifts of dips A, A', B, B', C and C' versus gas RI and relative pressure changes. (c) Comparisons between the measured sensitivities and simulated results. (d) Variations of distances between dips pairs AA', BB' and CC' versus gas RI and relative pressure changes.

In conclusion, we have demonstrated a highly sensitive gas RI sensor based on ONCs. Both ultrahigh positive and negative sensitivities are achieved theoretically and experimentally near the DTP. More importantly, by utilizing the twin dips interference characteristics around DTP, we achieve the highest gas RI sensitivity of -92020 nm/RIU using a 700 nm-thick ONC, which is nearly two orders of magnitude higher than most conventional gas RI sensors. Such exceptional sensing performance at low RI of ~ 1.0 not only reveals the vast potential in ultrasensitive pressure sensing, acoustic sensing, gas and gas phase biomarkers detection, but also provide new tools for nonlinear optics, ultrafast optics, quantum optics, and ultra-cold atom optics.

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