



Ultrasensitive cascaded in-line Fabry-Perot refractometers based on a C-shaped fiber and the Vernier effect

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Abstract: We propose and experimentally demonstrate a fiber refractometer based on a C-shaped fiber and the Vernier effect. The sensor is fabricated by cascading a single mode fiber (SMF) pigtail together with a C-shaped fiber segment and another SMF segment. Thus, the C-shaped fiber would constitute an open cavity (sensing cavity) in which test analytes could be filled, while the SMF segment would constitute another reference cavity. Due to the similar optical path length of these two cavities, the Vernier effect would be activated, thus forming spectral envelopes in the reflection spectrum of the sensor. Variations in the refractive index (RI) of analytes would result in the shifts of the spectral envelopes. Both theoretical calculations and experiments are carried out in the characterization of the sensor measuring liquid and gaseous analytes. The experimental sensitivity of the sensor is found to be ~ 37238 nm/RIU for gas RI measurement. The proposed sensor features the advantages such as ease of fabrication, extremely high sensitivity, capability of sensing of both gaseous and liquid analytes, small footprint, and good mechanical strength. Compared to other existing Vernier effect-based fiber refractometers typically fabricated using PCFs, the proposed sensor would allow analytes to have much easier and quicker access to the sensor probe.

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1. Introduction

Refractive index (RI) of liquid and gas is an essential optical parameter that is tightly related to the inherent physical and chemical properties of the substance as well as the environmental factors. Precise detection of RI of liquid or gaseous samples are routinely performed in the fields of food and beverage quality control, medical diagnostics, environmental monitoring, industrial oil production, and mining and energy industry, to name a few [1–3]. In the last two decades, R&D of fiber-optic refractometers has drawn tremendous interest in both academic and industrial fields due to their advantages including relatively high sensitivity, small footprint, immunity to electromagnetic interference, ease of integration with other optical and electrical components, and capability for applications in explosive or toxic environments.

To date, a variety of fiber-optic refractometers have been proposed based on different sensing mechanisms and fiber configurations which include fiber gratings, fiber-based surface plasmonic resonance (SPR), photonic crystal fibers and various types of fiber-based interferometers such as Fabry-Perot sensors and Mach-Zehnder sensors. Refractometers based on fiber gratings (e.g., fiber Bragg grating, long period grating or tilted fiber grating) normally operate by measuring

the shifts of grating resonant wavelength in response to RI variations. These fiber grating sensors feature the advantages of low cost and ease of fabrication [4,5]; however, their sensitivity is usually low due to the limited overlap between the analytes and fiber evanescent field. As to SPR fiber sensors, the fiber guided modes would be coupled into the SPR mode propagating along the metallic layer coated on fiber surface, when the phase matching condition is satisfied. Excitation of the SPR modes leads to emergence of a spectral dip in the transmission spectrum. Variations in RI of the analyte would modify the phase-matching condition, thus shifting the signature spectral dip. While SPR fiber sensors typically have relatively high sensitivities in the range of 10^3 – 10^4 nm/RIU, their fabrication is complicated and normally require sputtering deposition of metallic layers on fiber surface with precise nano-scale thickness [6–8].

Photonic crystal fibers (PCFs) could constitute versatile sensing platforms for RI measurements, and multiple sensing mechanisms could be adopted. For example, liquid-core PCFs guide by “bandgap effects”, and changes in RI of analytes filling the PCF would modify the fiber bandgap, thus shifting the transmission spectrum. Thanks to the almost full overlap between the liquid analytes filled in the PCF and the guided light, sensitivities of liquid-core PCF could be on the order of 10^3 nm/RIU [9,10]. Moreover, several research groups report solid-core PCF based fiber directional couplers, in which high-RI liquid analytes could be selectively filled into a specific micro-channel in the honey-comb structure of the PCF [11,12]. The liquid-filled channel and the center core would constitute two adjacently parallel waveguides, where resonant coupling of guided modes occurs at the phase-match wavelength. Changes in the RI of analytes would shift the resonant wavelength, and the sensitivities achieved could be greater than ~ 38000 nm/RIU [12]. Note that though these PCF-based directional couplers are extremely sensitive to RI variations, fabrication of PCF is somewhat sophisticated, as selective filling of test analytes into a micro-sized hole is technically challenging. Besides, the dynamic range of the sensor is also limited.

A variety of fiber-based interferometers such as Fabry-Perot (F-P) and Mach-Zehnder (M-Z) interferometers have been reported for RI sensing applications. F-P fiber refractometers could be fabricated by sandwiching a capillary fiber between two microstructured fibers, milling a microcavity in a SMF using fs-laser, or simply splicing a SMF between two SMFs with an offset [13–16]. Among the advantages of these F-P sensors are small footprint, simple structure, good stability. However, only moderate sensitivities of ~ 1000 nm/RIU could be achieved. M-Z interferometers could be fabricated by milling a groove in one core of a dual-core fiber, creating cascaded fiber tapers, or sandwiching a MMF or PCF between two SMFs, using dual-core fibers with embedded fluidic channels, etc. [17–21]. These M-Z fiber interferometers generally have the sensitivity ranging from 10^2 – 10^3 nm/RIU, which is still moderate. Besides, the use of tapered fibers or grooved fibers would considerably degrade the mechanical strength of the sensor structure.

To further enhance sensitivities of fiber-optic interferometers, researchers have recently proposed to incorporate the fiber interferometers with the so-called Vernier effect [22–31]. Typically, the Vernier effect could be observed in superimposed spectra of two cascaded interferometers with similar but not identical free spectral range (FSR). One interferometer works as the reference unit, while the other one works as the sensing unit. The resulting composite spectrum is the superposition of the two interferometric spectra and features spectral “beats” (periodic envelopes). The RI perturbations in the sensing unit would therefore sharply shift the envelopes, which would significantly magnify the sensitivity. For example, based on the Vernier effect, Tian *et al.* proposed a gas refractometer by cascading a SMF with a capillary fiber and a PCF to constitute two cascaded F-P cavities, and demonstrated a sensitivity of ~ 30899 nm/RIU [24]. However, this sensor based on a PCF would be only preferable for sensing of gaseous analytes rather than liquid analytes, which may be problematic to be filled in the probe. Yao *et al.* demonstrated a RI sensor based on parallel-connected dual F-P interferometers [25], and

each interferometer was fabricated by immobilizing a SMF into a capillary with the F-P cavity formed between the fiber end and an Al mirror attached on the capillary end. Though this sensor achieved a sensitivity up to ~ 30801 nm/RIU, a relatively complex gluing process was involved in the sensor fabrication. Recently, Gomes *et al.* reported that the Vernier effect fiber sensors using single-mode interferometers may have immeasurable spectral envelopes [26], because the period of the envelopes might be too large in wavelength domain, and thus extend out of the measuring range of a detection system. Therefore, they proposed to use a “few-mode” interference scenario in the sensing interferometer, so that the sensor would produce measurable envelopes, whilst preserving a highly magnified sensitivity. The proposed sensor also used parallel-connected dual F-P interferometers, and each interferometer was fabricated by sandwiching a multimode capillary fiber between two SMFs. A dramatically high sensitivity of $\sim 5 \times 10^5$ nm/RIU was achieved. However, to enable analytes to access the capillary probe, micro-holes were milled on the capillary using a focused ion-beam scanning electron microscope. This would considerably increase the fabrication complexity and cost. Microfibers were also frequently utilized for fabricating sensors based on the Vernier effect. Sun *et al.* reported a cascaded microfiber knot resonator fabricated by the “drawing-knotting-assembling” technique and achieved a sensitivity of ~ 6523 nm/RIU [28]; Zhang *et al.* recently proposed a double-helix microfiber coupler, and demonstrated a sensitivity up to ~ 27326 nm/RIU [30]. Note that these two sensors using microfibers have quite low mechanical strength.

In this paper, we propose a cascaded F-P cavity-based refractometer to detect RI variations of gaseous and liquid analytes. Fabrication of the sensor is quite straightforward. A short segment of C-shaped fiber is fusion-spliced with a SMF pigtail, and then another segment of SMF is spliced with the free end of the C-shaped fiber. The C-shaped fiber constitutes an open F-P cavity (sensing unit) where test analytes could be filled, while the segment of the SMF constitute a closed F-P cavity (reference unit). Optical length of these two cavities should be similar to activate the Vernier effect. RI variations in the open cavity would lead to shifts of the spectral beats in the transmission spectrum of the sensor. To detect the RI variations of gaseous and liquid analytes, respectively, we fabricate two sensor prototypes with different cavity lengths. Experimentally, sensitivity of the refractometer is found to be up to 37238 nm/RIU for gas RI detection. The advantages of the proposed refractometer include ease of fabrication, extremely high sensitivity, capability of sensing of both gaseous and liquid analytes, small footprint, and good mechanical strength. Compared to other Vernier effect sensors based on PCFs, the proposed structure based on C-shaped fiber features almost instantaneous response to analyte RI variations. Thus, this refractometer would be suitable for a variety of applications in the field of biochemical sensing, environment monitoring, air pressure and concentration detection, etc.

2. Sensing mechanism based on Vernier effect

Structure of the proposed sensor is illustrated in Fig. 1(a). A segment of C-shaped fiber with a length of L_1 is fusion-spliced between SMF₁ and SMF₂ (length: L_2). The interface between C-shaped fiber and SMF₁ forms Mirror₁ with a reflectance coefficient of R_1 , and the interface between the C-shaped fiber and SMF₂ forms Mirror₂ with a reflectance coefficient of R_2 . The interface between SMF₂ and surrounding medium forms Mirror₃ with a reflectance coefficient of R_3 . In this way, the C-shaped fiber constitutes an open F-P cavity (Cavity1) where gaseous or liquid analytes under investigation could be infiltrated, and SMF₂ constitutes a closed F-P cavity (Cavity2). Moreover, the C-shaped fiber together with SMF₂ also constitutes a F-P cavity (Cavity3) with the geometric cavity length of $L_1 + L_2$.

We could approximately calculate reflectance coefficients R_1 , R_2 and R_3 as:

$$R_1 = R_2 = \left(\frac{n_s - n_a}{n_s + n_a} \right)^2, \quad R_3 = \left(\frac{n_s - n_m}{n_s + n_m} \right)^2 \quad (1)$$

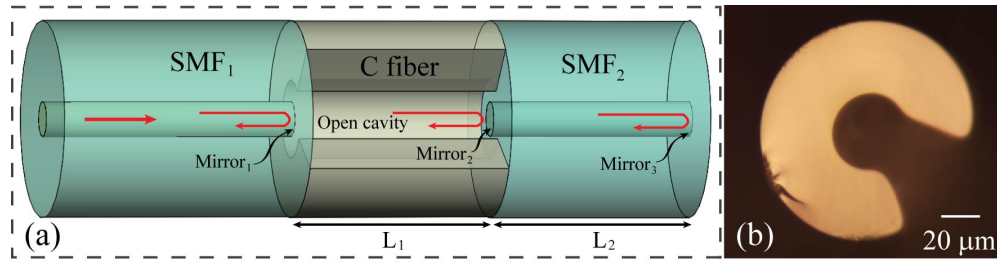


Fig. 1. (a) Schematic of the sensor probe structure; A segment of C-shaped fiber with a length of L_1 is spliced between a SMF pigtail and a segment of SMF with a length of L_2 . (b) Cross section of the C-shaped fiber.

where n_s is RI of the core material (Ge-doped silica) of the SMF, n_a is the RI of the analyte filling the open cavity, n_m is the RI of the medium surrounding the sensor probe. Guided light in SMF₁ is partially reflected by Mirror_{1–3}, respectively, as it propagates through the whole sensor structure. Therefore, the total electric field E_r of the reflected light could be considered as the sum of the electric field reflected by these three mirrors. Due to the relatively low reflectivity of Mirror_{1–3}, E_r could be calculated using the two-beam interference approximation [22,31]:

$$E_r = E_{in} \left[\sqrt{R_1} + A e^{-2i\varphi_1} + B e^{-2i(\varphi_1 + \varphi_2)} \right] \quad (2)$$

$$A = (1 - \alpha_1)(1 - R_1)\sqrt{R_2} \quad (3)$$

$$B = (1 - \alpha_1)(1 - \alpha_2)(1 - R_1)(1 - R_2)\sqrt{R_3} \quad (4)$$

where E_{in} is the input electric field, α_1 and α_2 are the transmission loss factors at Mirror₁ and Mirror₂, which are caused by modal mismatching and interface imperfections, φ_1 and φ_2 are the phase shift in the open and closed F-P cavities, and are calculated as:

$$\varphi_1 = \frac{2\pi n_a L_1}{\lambda}, \quad \varphi_2 = \frac{2\pi n_s L_2}{\lambda} \quad (5)$$

where λ is the wavelength of light in free space. The reflection spectrum function could be obtained from Eq. (6):

$$I_r = \left| \frac{E_r}{E_{in}} \right|^2 = R_1 + A^2 + B^2 + 2\sqrt{R_1}B\cos[2(\varphi_1 + \varphi_2)] + 2\sqrt{R_1}A\cos(2\varphi_1) + 2AB\cos(2\varphi_2) \quad (6)$$

Equations (2)–(6) suggest that the reflection spectrum of this structure is mainly determined by the interference of the light reflected by Mirror_{1–3}. In the reflection spectrum, spectral dips (or peaks) with different amplitudes would form periodic envelopes, which could be explained by the modified Vernier effect. Variations in refractive index of the analytes filled in the open cavity would cause shifts of the entire envelop, which constitutes the operation mechanism of this sensor. According to Ref. [22], sensitivity of this structure is magnified by M times as compared to the F-P interferometer with a single cavity (i.e., the open cavity), and M could be defined as:

$$M = \frac{FSR_1}{|FSR_1 - 2FSR_3|} \quad (7)$$

where $FSR_1 = \lambda^2/2n_a L_1$ is the free spectral range (FSR) of Cavity1, and $FSR_3 = \lambda^2/2(n_a L_1 + n_s L_2)$ is the FSR of Cavity3. Besides, the FSR of the envelop could be calculated as [22]:

$$FSR_E = \frac{FSR_1 \cdot FSR_3}{|FSR_1 - 2FSR_3|} \quad (8)$$

3. Experimental characterization and numerical calculation

Experimental fabrication of the gas refractometer probe is detailed as follows. The C-shaped fiber is fabricated via a standard preform heat-and-draw technique [32]. Firstly, a pure silica tube with an inner diameter of 4 mm and outer diameter of 12 mm is machined to create a lateral slot along its axis, thus resulting in a C-shaped fiber preform. Then, using a commercial fiber drawing tower (Yangtze Optical Electronics, Co. Ltd.), this preform is drawn into the C-shaped fiber at relatively low temperature of $\sim 1890^\circ\text{C}$ to maintain its structure. As shown in Fig. 1(b), the resultant C-shaped fiber has an inner diameter of $\sim 40\ \mu\text{m}$, and an outer diameter of $\sim 125\ \mu\text{m}$. We spliced the C-shaped fiber with a SMF pigtail (Thorlabs, SMF-28) using a fusion splicer (Fujikura, FSM-100P). The electric arc is centered mainly on the SMF using the manual mode of the fusion splicer to avoid the collapse or distortion of the C-shaped fiber during the discharge process. A single electric arc with a power of 300 bits (power units on this fusion splicer) and duration of 500 ms is applied in this splicing process. We subsequently cleave the C-shaped fiber to the designated length ($\sim 190.3\ \mu\text{m}$ for this gas sensor probe) with the aid of a long-working-distance microscope ($20\times$). Finally, the cleaved end of the C-shaped fiber is further spliced with another SMF segment following the same splicing procedure mentioned above, and this SMF segment is then also cleaved into the desired length ($\sim 137.3\ \mu\text{m}$ for the gas refractometer). Thus, the optical length of the C-shaped fiber cavity and SMF segment cavity is approximately equal. Schematic of the experimental setup for the gas refractometer is shown in Fig. 2. The light from a Supercontinuum source (Anyang, SC-5) is guided through a SMF circulator (from Port1 to Port2) to the sensor probe. The reflected light returned from the circulator (Port3) could be then analyzed by an optical spectrum analyzer (Anritsu, MS9740A). To characterize this gas refractometer, the sensor probe is inserted into a hermetical gas chamber, in which the air pressure could be regulated by an air compressor pump equipped with a built-in pressure gauge. The RI of the air in the chamber could be thus modified by changing the air pressure according to the following equation [33]:

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

where P is absolute air pressure (Pa) and T is temperature ($^\circ\text{C}$). In the following, we will carry out both numerical calculations as well as experiments to calibrate the sensor performance.

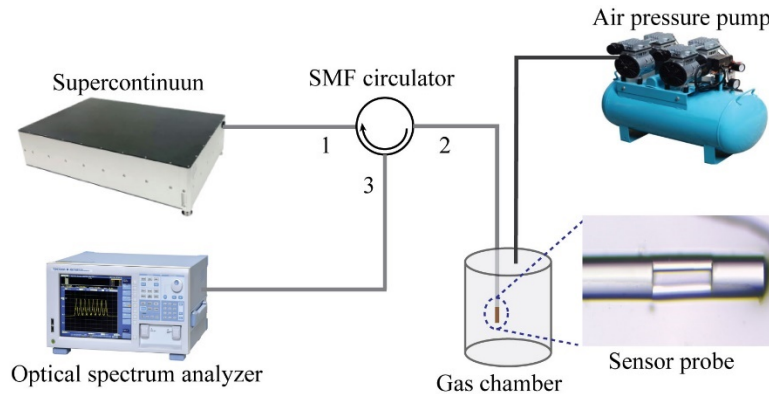


Fig. 2. Schematic of the experimental setup for the gas refractometer.

Using the structure parameters given above, we could theoretically calculate the reflection spectrum of the sensor under different air pressures (RIs). Thus, we let $L_1 = 190.3\ \mu\text{m}$, $L_2 = 137.3\ \mu\text{m}$, $n_s = 1.445$, $\alpha_1 = 0.4$, $\alpha_2 = 0.7$ [24]. The RI (n_a) of analyte in Cavity1 could be calculated using Eq. (9). As shown in the following experimental section, pressure of Cavity1 is increased

from ~ 0.101 MPa (atmosphere pressure) to ~ 0.901 MPa with a 0.08 MPa interval. Therefore, under a temperature of 20°C , n_a is in the range of 1.000269-1.002399 with an interval of 0.000213. Taking all these parameters into Eq. (1-6), we are able to calculate the reflection spectra. In Fig. 3(a), calculated spectra for different n_a are shown with a 15 dB offset. Clear envelopes could be observed in these spectra, and they exhibit a blue shift as the pressure in Cavity1 increases. Precise positions (black arrow in Fig. 3(a)) of the envelop peaks could be found by applying a Lorentz fitting on the individual points in the envelop profile. Based on the length of Cavity1 and Cavity2, FSR_1 and FSR_3 are calculated to be ~ 6.31 nm and ~ 3.09 nm, respectively. Thus, according to Eq. (8), FSR of the spectral envelop is estimated to be ~ 148.01 nm, which agrees well with the simulation result (~ 146.03 nm). In Fig. 3(b), we apply a linear fitting of the envelop shifts in response to the RI variations, and thus find the sensitivity to be 37687 nm/RIU.

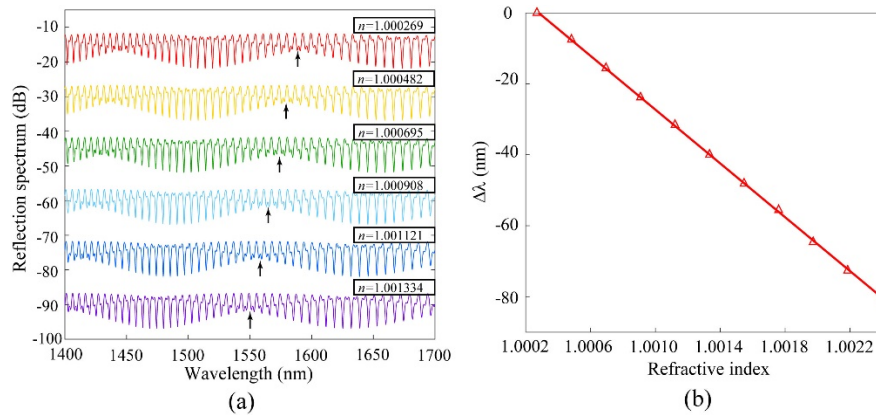


Fig. 3. (a) Reflection spectra theoretically calculated with different RIs (air pressures); (b) linear fitting of calculated shifts of the spectral envelop as a function of RI.

In our experimental characterization, an air compressor pump is used to gradually increase the pressure of the gas chamber from ~ 0.101 MPa (normal atmosphere pressure) to 0.901 MPa with a 0.08 MPa interval. Thus, under the room temperature of 20°C , RI of the gas chamber could be calculated using Eq. (9). The reflection spectra of the sensor probe are measured for each pressure as shown in Fig. 4(a), and the peak positions (marked with black arrows) of the envelopes are also found by applying the Lorentz fitting. As the pressure (RI) of the gas chamber increases, the envelopes (shown with a 15 dB offset) also has a blue shift. The FSR of the experimental envelop is ~ 147.23 nm, that also coincides well with the simulation result. In Fig. 4(b), we also present the linear fitting of the envelop shifts in response to RI variations of the gas chamber. From this fitting, we calculate the sensitivity of the sensor to be 37238 nm/RIU.

Based on the proposed structure, we also fabricate another sensor probe for sensing of liquid RI. The fabrication procedures follow closely to those used in the fabrication of the gas refractometer. In this sensor probe, lengths of the C-shaped fiber (Cavity1) and SMF segment (Cavity2) are $239.50\ \mu\text{m}$ and $244.05\ \mu\text{m}$, respectively. Thus, we let $L_1 = 239.50\ \mu\text{m}$ and $L_2 = 244.05\ \mu\text{m}$ while keeping other parameters (n_s , α_1 , α_2) consistent with the ones used in the above simulation for gas sensing, so we could calculate the reflection spectra of the sensor probe in response to different RIs of liquid analytes (Fig. 5(a)). Note that the RIs (n_a) of the analytes used in the calculation are consistent with the counterparts in the following experimental section. In Fig. 5(a), we show the calculation results in which clear spectral envelopes could be observed. These simulated envelopes (shown with a 10 dB offset) also feature a blue-shift, as the RI of analytes increases. FSR of the envelope in the simulated spectra is found to be ~ 37.50 nm, which is virtually consistent with the

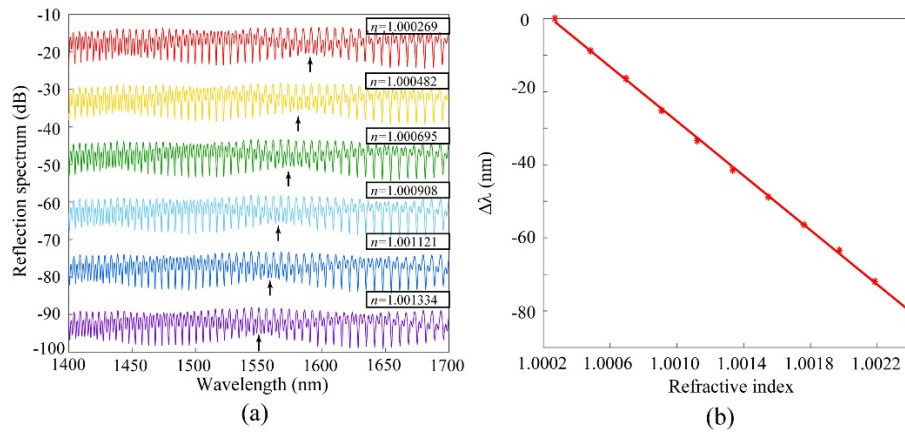


Fig. 4. (a) Reflection spectra experimentally measured with different RIs (air pressure); (b) linear fitting of the experimental shifts of the spectral envelope as a function of RI.

one (~ 35.99 nm) calculated using Eq. (8). Linear fitting of the envelope shifts suggests that the theoretical sensitivity of the sensor probe is 11658 nm/RIU for detection of liquid analytes.

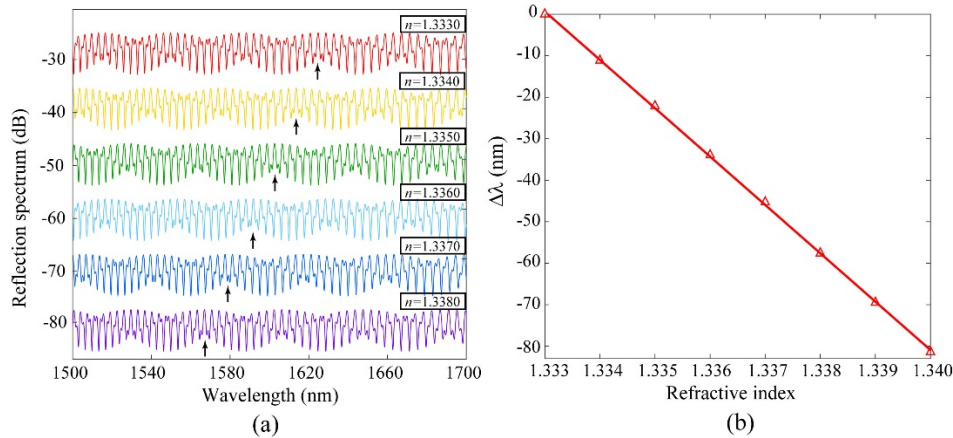


Fig. 5. (a) Calculated reflection spectra of the sensor probe filled with NaCl solutions of different RIs; (b) linear fitting of the envelope shifts in response to RI variations of NaCl solutions.

Experimentally, the sensor configuration is virtually the same as the gas refractometer, and the probe could be directly immersed into a reservoir filled with NaCl solutions (analytes). RI of the analytes could be varied by changing the NaCl concentrations of the solution. In our experiments, we gradually increase the RI of NaCl solutions from 1.3330 to 1.3380 with an interval of 0.001, which is also verified by the measurements based on an Abbe refractometer (ATAGO, DR-A1-Plus). Due to the large open-cavity structure, analytes could almost instantaneously access the cavity in the C-shaped fiber. As the analyte RI increases, the shift of experimental envelopes follow the same trend with the calculated counterparts (Fig. 6(a)). FSR of the experimental envelopes is found to be ~ 36.96 nm. Linear fitting of the envelope shifts suggest an experimental sensitivity of 11495 nm/RIU (Fig. 6(b)). The slight difference between the calculated sensitivity and the experimental sensitivity is mostly attributed to the errors in the measurement of cavity lengths.

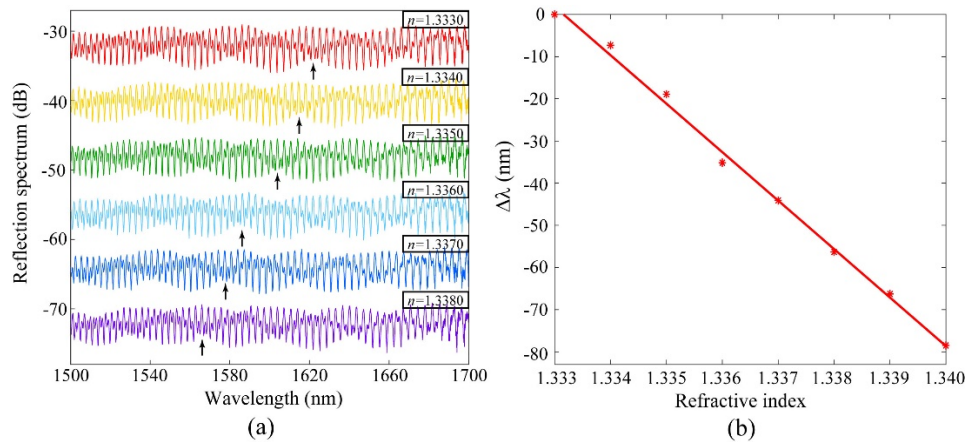


Fig. 6. (a) Experimental reflection spectra of the sensor probe filled with NaCl solutions of different RIs; (b) linear fitting of the experimental shifts of the spectral envelope in response to RI variations of NaCl solutions.

4. Discussions

Based on the theoretical and experimental results shown above, the refractometers using the proposed configuration feature ultrahigh sensitivities on the order of 3×10^4 nm/RIU. According to Eq. (7), one can always try to improve the sensitivity by diminishing the difference in optical path lengths (OPL) between the two cascaded cavities (Cavity1 and Cavity2). In theory, the sensitivity could virtually become infinite; however, this also comes at the consequence of the considerably increased envelop FSR, which may extend out of the measuring window. Therefore, one has to make a trade-off in the attempt to achieve higher sensitivities while preserving the practical measurability of the spectral envelope. From this perspective, Gomes *et al.* proposed to utilize a multimode interference rather than a single-mode one in the sensing interferometer and managed to produce a measurable envelop while achieving an extremely high sensitivity of $\sim 5 \times 10^5$ nm/RIU [26]. As the future work of this sensor project, we will try to balance the optical length of the dual cavities to further improve the sensitivity; however, the main goal of the current paper is to demonstrate the sensing scenario based on this C-shaped fiber and the Vernier effect. Though the sensitivity of the proposed sensor is one order smaller than that state-of-the-art sensitivity, it is still comparable to those of other fiber sensors using the Vernier effect. Besides, as compared to the dual-cavity sensor probes fabricated using PCFs [24] or capillary fibers with milled micro-holes (as fluidic channels) [26], our sensor based on the C-shaped fiber enable much easier and quicker access for both gaseous and liquid analytes thanks to its large open cavity. Moreover, PCFs with honey-comb microstructures are subject to physical distortion or damage in the fusion splicing or cleaving process, while the C-shaped fiber is much more robust.

Here, we also would like to mention several limitations of the proposed sensor. Firstly, performance of the sensor could be affected by temperature variations in the surrounding environment especially for measurements of liquid analytes, RI of which could be strongly altered due to their relatively high thermo-optic coefficients. Therefore, in practical applications, RI measurements should be performed in an environment with a stable temperature, otherwise thermal fluctuations should be considered and compensated. Secondly, the precise length of Cavity1 and Cavity2 of the practical sensor probe is dependent on the cleaving process. Though the cleaving is carried out with the assistance of a microscope, the cavity lengths after cleaving may have several-micron deviations compared to the designated lengths due to the minor misalignment of the fiber in a cleaver. However, this problem is virtually universal for all of the

fiber sensors which require high-precision cleaving, and would not significantly affect the sensor performance.

Finally, we also measure the stability of the proposed sensor. In the gas sensing process, we enclose the sensor probe in the gas chamber under a constant pressure, and then measure the reflection spectra every 5 minutes, perturbation of the envelop peak for each measurement is shown in Fig. 7. We conclude that the perturbation is typically in the range of ± 10 pm.

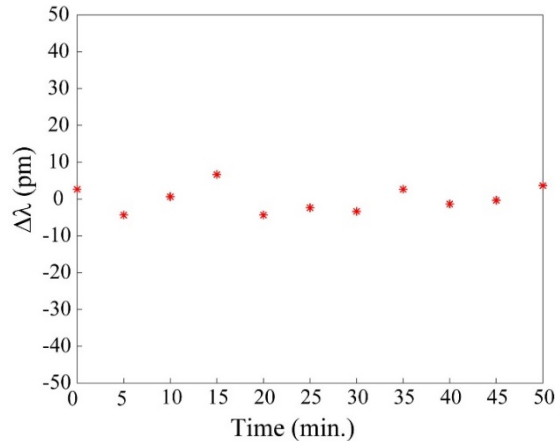


Fig. 7. Perturbation of the envelop peak in the reflection spectrum of the sensor probe under a constant pressure.

5. Conclusion

In this paper, we propose and experimentally demonstrate an ultrasensitive fiber refractometer which could detect minute changes in RI of both gaseous and liquid analytes. The sensor is fabricated by sandwiching a C-shaped fiber segment between a SMF pigtail and a SMF segment. The C-shaped fiber segment and SMF segment constitute two cavities. Due to the similar optical length of the two cavities, Vernier effect could be enabled. Thus, in the reflection spectra of the sensor probe, spectral envelopes could be formed and they shift sensitively in response to changes of analyte RI. Both numerical calculations and experiments are carried out to characterize the performance of the sensor. Experimental results suggest that the sensitivity of the proposed structure could be as high as 37238 nm/RIU. Note that this sensitivity could be even further improved by diminishing the difference in the optical length of the two cavities. This sensor features the advantages such as ease of fabrication, extremely high sensitivity, capability of sensing of both gaseous and liquid analytes, small footprint, and good mechanical strength. As compared to other Vernier sensors using PCFs, the proposed structure would enable a much easier access of the analytes into the open cavity as well as enhanced robustness during fabrication. We believe that this sensor would find its niche applications in the fields where precise RI detection is relevant, and these fields may include chemical sensing, monitoring of bio-binding events, gas concentration and pressure measurements, and precise temperature detection.

Funding. Shantou University (NTF18016); Department of Education of Guangdong Province (2020ZDZX3035, 2020ZDZX3037); Natural Science Foundation of Guangdong Province (2022A1515012571).

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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