We report an optofluidic resonator refractive index sensor based on an integrated structure constructed by a free-space coupling architecture. It uses a symmetrical metal-cladding hollow-core waveguide and a prism to generate surface plasmon polarization. The sensor achieves very high sensitivity by coupling the core mode to ultrahigh-order modes in the waveguide layer that can obtain a refractive index of a detailed low-order value of $1 \times 10^{-6}$. We demonstrate the device through infiltration of different fluids into the hollow core along an optofluidic resonator. A detection limit of $1 \times 10^{-6}$ refractive index units has been derived from measurements. The presented method can be applied to the detection of molecular structures and biochemistry.

High-precision measurement of the refractive index (RI) is very important and popular in the fields of sensors, medicine, biology, and molecular structure [1]. In the context of detection of biomolecules, the optical detection of small changes in the RI within solutions has received considerable attention recently. In optical detection technology, label-free detection does not require the sample, usually a liquid analyte, to be marked with fluorescent dyes but rather relies on the detection of tiny RI changes due to bonding events, e.g., antibody–antigen interaction. The ability to detect smaller concentrations of molecules results from the smaller detection limits of changes in the RI. Actually, there are a number of optical platforms designed to achieve lower limits of changes of the RI, and their schemes have been investigated with the aim of realizing simple, highly sensitive, real-time optical biosensors capable of working with small analyte volumes [2]. Due to reduced analyte volumes, the integration of analyte waveguide channels in optical structures provides a means to enhance the performance of resonant RI sensors, increase sample-mode interaction and thus to enhance sensitivity [3]. Many fiber-based surface plasmon resonance (SPR) sensors have been reported. So far, different SPR sensor configurations with multimode, single-mode, and polarization maintaining fibers coated with a thin metallic layer have been proposed [4–6], for instance, high-quality microfluidic channel photonic crystal fibers (PCFs) [7], which can be controllably filled with ultra-small volumes of analytes (femtoliter to sub-nanoliter). Owing to their proximity to the optical core, these channels can have good overlap with the optical mode of the fiber, making them a natural candidate for sensing schemes. Existing PCF RI sensors rely on the shift in wavelength of a resonant feature, which may be introduced by interferometric arrangements, a Bragg or long period grating (LPG) [8], or by bandgap effects [9]. To date, the most sensitive PCF sensors demonstrated rely on a long period fiber grating in a fluid-filled PCF with a maximum sensitivity of 1500 nm/RI unit (RIU) and a detection limit of $1 \times 10^{-5}$ RIU [10]. The evanescent waves in PCFs allow the excitation of the surface plasmon waves supported by a thin metallic layer that coats the fiber. Optical fibers, and also miniature optical spectrum analyzers, allow the development of low-cost, very compact, and portable SPR sensors that can be used for the detection of different analytes in the field. However, the resonant features of evanescent waves are generally broad, limiting the achievable detection limit [11]. Recently, some original resonators have enriched the RI sensor field, such as microring resonator [12–14] and silicon microring resonator [15]. L. Gounaridis achieved a high-performance RI sensor based on low $Q$-factor ring resonators and fast Fourier transform (FFT) processing of wavelength scanning data and extended the detection limit to approximately $8.5 \times 10^{-7}$ RIU [14].

Here, we describe a sensor architecture that integrates a hollow-core metal-cladding optofluidic resonator and a prism to generate surface plasmon polarization. Our strategy can be described as follows. A series of discrete guided modes can be excited at certain extremely small incident angles (incident angle $\theta_i < 5^\circ$). These modes are called ultrahigh-order modes (UOMs) [16] in our terminology, since the order of these modes is extremely large, and their effective RI is small when the incident angle fulfills the phase match condition [17]. However, the light beam is coupled from free space with a large incident angle. It is difficult to differentiate the adjacent guide modes because the mode density in the optofluidic resonator is extremely large, and the corresponding attenuated
The figure of merit (FOM) can be defined as $\text{FOM} = \frac{\Delta R}{T \cdot \Delta n}$, where $T$ denotes reflectance, and $\Delta n$ denotes RI variation [19]. At the UOM dip, FOM is calculated to be $9 \times 10^5$. This research combines the SPR technology and the UOMs and successfully creates a new chip, which combines the symmetrical metal-cladding hollow-core waveguide (SMHW) and the prism, as shown in Fig. 1. It can scan for the angles of SPP and UOMs as a whole structure instead of operating as two separate parts. Measuring the SPP can roughly determine the range of the analyte RI. Then, by using the five continuous UOMs, measurement of the exact value of the RI can be achieved.

As shown in Fig. 1(a), the optofluidic resonator consists of five layers from top to bottom. The middle three layers form the guiding layer to support oscillating guided modes. From the top to bottom, these five layers are a 40 nm Ag coupling layer, a 0.1 mm sample layer, another 0.3 mm high glass cylinder, and a 300 nm Ag substrate. The size of the circle sample channel is 0.12 mm $\times 0.1$ mm$^2$. All parts are optically contacted with excellent parallelism, except the Ag layers are prepared by thermal evaporation coating technology. A 40 nm Ag film has been constructed at the bottom of the prism, which plays two different roles in chips. On one hand, it is used to excite the SPP combination with the prism, as shown in Fig. 1(b). On the other hand, it acts as a coupling layer for SMHW, as shown in Fig. 1(c). When the light beam is coupled from free space with a large incident angle, it is difficult to differentiate the adjacent guide modes because the mode density in the SMHW is extremely large, and the corresponding ATR dips overlap with each other. Furthermore, a series of discrete guided modes can be excited at certain extremely small incident angles. In our terminology, the orders of these modes are extremely large, and their effective RI is small. From the ray-optical perspective within the same longitudinal propagation distance, the UOM is rebounded at the interfaces more times, and the ray propagation length is longer, since the incident angles of the UOM at the top and bottom interfaces of the guiding layer are extremely small. As a result, the UOMs hold many peculiar optical properties different from the low-order modes.

The numerical simulation demonstrates the resonance modes with varied incident angle conditions, and the curves of resonance modes are plotted. The dielectric constant of the glass and the Ag are $n_1 = 1.51$, $\varepsilon_1 = -18.23 + i0.42$, and $n_2 = 1.0$, respectively. A collimated light beam from a diode laser of 632.8 nm is incident on the top surface of the gold film, and the angular scan is carried out. According to the theory of resonance modes, using boundary conditions, the relationship between reflectivity $R$ and incident angle $\theta_i$ can be expressed by Eq. (1) [23]:

$$R = \left| \frac{\gamma_{23} + j\gamma_{012} e^{-2i\beta d_1}}{1 + j\gamma_{23} \gamma_{012} e^{-2i\beta d_1}} \right|^2.$$  

$\gamma_{23}$ and $\gamma_{012}$ in Eq. (1) are given by

$$\gamma_{23} = -\frac{i e_2 k_3 + e_3 \alpha}{i e_2 k_3 + e_3 2\alpha},$$

$$\gamma_{012} = \frac{\gamma_{12} + j\gamma_{01} e^{2i\beta d_1}}{1 + j\gamma_{12} \gamma_{01} e^{2i\beta d_1}} = 1,$$

where $\gamma_{12}$ and $\gamma_{01}$ are

$$\gamma_{12} = \frac{i e_1 \alpha + e_2 k_1}{i e_1 \alpha - e_2 k_1},$$

$$\gamma_{01} = \frac{e_2 k_1 + e_1 \alpha}{i e_2 k_1 - e_1 \alpha}.$$  

In Eqs. (1)–(5), $\varepsilon_j$ is the relative permittivity ($j = 0, 1, 2, 3$ means the relative permittivity in the bottom BK7 glass prism, Ag layer, air layer, upper Ag layer, and the BK7 glass cylinder), $\alpha = (\beta^2 - k_0^2 \varepsilon_0)^{1/2}$ is the attenuation coefficient of both the upper and bottom Ag layer (for the reason that $\varepsilon_0 = \varepsilon_1$), $k_1 = (k_0^2 \varepsilon_1 - \beta^2)^{1/2}$ is the propagation constant, $\beta = k_0 n_1 \sin \theta_i$, $d_1$ and $d_2$ are the thickness of the hollow core of the chip and the upper Ag layer. The numerical simulation result of the curve of resonance modes is shown in Fig. 2(a). A series of dips in the reflectivity spectrum due to the resonant transfer of energy into guided modes (TM) can be clearly observed. As shown in Figs. 2(b) and 2(c), the two parts of modes curves have been presented. Five ATR dips fall in $0°$–$2°$, and only one SPP mode

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**Fig. 1.** (a) Optofluidic resonator. (b) The excited SPP composed of Ag film and the prism structure of the optofluidic resonator. (c) The bottom three layers of the optofluidic resonator form a SMHW.

**Fig. 2.** (a) Numerical stimulation result of the curve of resonance modes. (b) Five ATR dips of UOMs in a range $0°$–$2°$. (c) SPP mode in the range of $34°$–$36°$. 
is present in 34°–36°, by which the resonance angle can be obtained.

According to the reflected light function, we need to use global variables to define the following parameters. The RI $n_1$ of the BK7 prism, the Ag film dielectric constant $\varepsilon_1$ of SMHW, the thickness $d_1$ of the metal layer in the bottom of the prism, the thickness $d_2$ of the hollow core, and the incident beam wavelength $\lambda$. Meanwhile, we need to define a global variable $e_20$ because the dielectric constant of the waveguide layer within the allowable accuracy range needs to be obtained. Defining these variables facilitates us calculating the reflectance curves for different structural coefficients and determining the resonance angle at which the ATR dips appear. In combination with the reflectivity definition in Eq. (1), the $R$ of the SPP can be written with the incident light based on the three-layer waveguide structure. Through calculation, SPP can provide a RI detection limitation of $5.0 \times 10^{-4}$ RIU. The approximate range of the dielectric constant of the analyte can be calculated in advance using the Matlab program. To obtain highly accurate values of the dielectric constant, we need to redefine the dielectric constant of the waveguide layer when UOMs are excited, which can be set as $\varepsilon_{20}$. This $\varepsilon_{20}$ variable with higher accuracy is what we aim to obtain. The minimum division of $\varepsilon_{20}$ is the accuracy of the required dielectric constant. $\varepsilon_{20}$ falls within the approximate range of the dielectric constant of the analyte determined by SPP, which can be calculated in advance using Matlab. Similarly, the function file $R(\theta)i$ is used to calculate the dip value of the UOMs, which corresponds to each dielectric coefficient indexed in the range of the dielectric coefficient obtained by SPP. With all these values, the exact value of the dielectric coefficient of the analyte can finally be determined. When the accuracy of the angle measurement is reliable, the measured dielectric constant can achieve the RI detection limitation of $1.0 \times 10^{-6}$ RIU.

The experimental arrangement is presented in Fig. 3. To excite the UOMs of SMHW in small incident angles and SPP at large angles simultaneously, a transverse-excitation-polarized laser beam from a 30 mW, 632.8 nm He–Ne laser (MW-SL-632.8/30 mW, Shanghai Optics Engine Inc. Shanghai, China) with a 0.001 mrad divergence (a 1 mm aperture further reduces the divergence) impinges on the prism bottom. The sample solution is pumped through the cell further reduces the divergence) impinges on the prism bottom. The sample solution is pumped through the cell.

In the experimental data, as shown in Fig. 4, we obtain the UOMs and SPP modes when the analyte has been injected into the hollow core, respectively. (c) and (d) UOMs and SPP modes when air has been injected into the hollow core, respectively. (e) and (f) UOMs and SPP modes when the 1 $\times$ 10^{-3} mol/L R6G solution has been injected into the hollow core, respectively.

Fig. 4. Experimental data. (a) and (b) UOMs and SPP modes when analytes with different RIs have been injected into the hollow core, respectively. (c) and (d) UOMs and SPP modes when air has been injected into the hollow core, respectively. (e) and (f) UOMs and SPP modes when the 1 $\times$ 10^{-3} mol/L R6G solution has been injected into the hollow core, respectively.

In summary, this study combines SPR technology and UOMs and successfully creates an optofluidic resonator consisting of an SMHW and prism. This new waveguide can scan for the angles of SPP and UOMs as a whole structure instead of measuring as two parts. Measuring the SPP can roughly figure out the range of the RI and also the thickness of the waveguide. Then, by using the angles of the UOMs, we can figure out the exact value of the RI. By programming with Matlab, this research can automatically calculate the RI of the waveguide.
After numerical simulation and experiments, it comes out that the precision of the RI can reach $1.0 \times 10^{-6}$ RIU as the measurement precision of the angle reaches $1 \times 10^{-4}$ deg.

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### REFERENCES


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