A novel surface plasmon resonance (SPR) configuration based on fiber-interface waveguide was proposed and realized by combining the technology of femtosecond laser writing waveguide with SPR effect for measuring refractive index (RI) of analyte. A U-shaped waveguide is inscribed in the coreless fiber and its bottom is very close to the fiber surface, which can produce strong evanescent field being sensitive to ambient media. When the fiber surface is coated with a layer of gold film, the strong evanescent field can excite the SPR effect on the fiber surface. Most importantly, different from some types of fiber SPR sensors with a fragile physical structure, the fiber-interface waveguide SPR sensor exhibits an excellent mechanical strength. Such a SPR sensor exhibits a high sensitivity of $\sim 3352 \text{ nm/RIU}$ at the RI value of $\sim 1.395$, which may have important practical applications in medicine, environmental monitoring, and food safety.

The rapid and sensitive detection of analytes at low concentrations is paramount in many fields, such as medicine, environmental monitoring, and food safety. Surface plasmon resonance fiber sensor is an appealing solution to this problem because the sensing platform is compact and cost-effective (low cost equipment), and it is possible to collect measurements in situ and remotely [1,2]. It is important to note that acquisition of excellent mechanical strength, simple fabrication approaches, and high efficiency of exciting the SPR effect have important practical implications for fiber sensors.

However, one difficulty of the trade-off between the mechanical strength of the fiber and the intensity of evanescent field to excite SPR effect significantly blocks the practical applications of SPR fiber sensor. The commonly used methods to obtain strong evanescent field includes removing all or part of the cladding (via etching, side polishing, or femtosecond laser micromachining) and tapering the fiber to allow the light to escape to the cladding [3–6]. Unfortunately, these SPR fiber sensors are very fragile due to the destroyed physical structure, thus it becomes one of blocks in the practical implications.

To obtain an optical fiber with complete physical structure and strong evanescent field, Guan et al. fabricated one surface-core fiber and coated graphene on it for polarizer use [7,8]. The surface-core fibers make good performance on light guidance, but the structural flexibility is poor. Femtosecond laser direct writing is an effective way for waveguide fabrication in silica [9]. Our team first proposed the fiber-interface waveguide, which is fabricated on the cladding-air interface by femtosecond laser direct writing and produces a strong evanescent field on the fiber surface [10,11]. Compared with the surface-core fiber, the fiber-interface waveguide is much better in structural flexibility and easier to connect with single mode fiber (SMF) system.

In this Letter, we propose a fiber interface waveguide SPR sensor for RI measurement, which is combined the optical fiber sensing with femtosecond laser direct writing waveguide and SPR sensing technology. As is shown in Fig. 1, a U-shaped waveguide (or named interface waveguide) is inscribed in the coreless fiber. To obtain a strong evanescent field, the bottom of U-shaped waveguide is very close to the interface.
of fiber cladding and air. The two ends of U-shaped waveguide are, respectively, connected with two cores of single mode fiber for leading the interface waveguide into optical path. At last, a layer of gold film with 45 nm is evenly coated on the coreless fiber surface. Such a fiber interface-waveguide SPR sensor not only have a high RI sensitivity of 3352 nm/RIU at an RI value of 1.395 but also exhibits a strong mechanical strength with no structural damage, which eases the trade-off between the mechanical strength of the optical fiber and the evanescent field intensity.

The flowchart of device fabrication process is illustrated in Fig. 2.

A section of coreless fiber is spliced with two SMFs (Corning, SMF-28), which supplies a platform for a U-shaped waveguide fabrication.

A U-shaped waveguide is inscribed in the coreless fiber and connected with the cores of two SMFs. Two ends of U-shaped waveguide are stretched into the cores of SMFs with a length of 15 μm aiming to increase the coupling efficiency. The height of the interface-waveguide (h) is designed to be 60 μm, thus the bottom part of the U-shaped waveguide is very close to the surface of the coreless fiber with a strong evanescent field.

To decrease the bending loss of the U-shaped waveguide, the radius of the curved parts (R) is optimized to be 50 mm.

A femtosecond laser (PHAROS, 513 nm/290 fs/200 kHz) is employed to fabricate the waveguide and an oil-immersed objective lens (NA = 1.4) is selected to eliminate the aberration caused by the cylindrical morphology of the fiber. The fixed fiber is translated relative to the focused laser beam by a 3D air-bearing motion stage (Aerotech). The laser pulse energy is optimized to be ∼120 nJ, and the translation velocity of the fiber is set to be 0.2 mm/s. The propagation loss of the interface waveguide at 632 nm is measured to be 1.08 dB/mm by the cutback method.

The surface of the coreless fiber with the interface waveguide is coated with 45 nm-thickness gold film by magnetron sputtering method. The pressure of the vacuum chamber is evacuated to 5 × 10⁻⁴ Pa and then argon fills continuously with a quasi-static pressure of 2 Pa, and the DC current intensity is set to be 40 mA. To obtain a homogeneous gold film, the optical fiber is automatically rotated with a uniform speed during the film coating. When the above processes are all completed, the fiber-interface waveguide SPR configuration is obtained.

The SPR effect can be excited at the interface between the gold film and the dielectric media, when the energy and momentum of the incident light match those of the surface plasmon waves (SPW). The photon energy being coupled to the electrons of gold film achieves a resonant dip in the spectrum. The propagation constant of the SPW strongly depends on the RI of surrounding medium. Therefore, the small RI change of the medium adjacent to gold film will produce a measurable shift of the resonant dip.

The RI distribution of the laser-inscribed waveguide is first studied by a 3D reconstruction system for optical fiber refractive index distribution [12]. The cross-sectional RI distribution of the laser-inscribed waveguide is clearly presented in Fig. 3(a), where it consists of both negative and positive RI modulation segments. As illustrated in Fig. 3(b), the largest magnitude of the negative RI modulation is measured to be ∼4.2 × 10⁻³, and the positive RI modulation is up to ∼8 × 10⁻³, which ensures good confinement of the guided light.

The gold film coated on the fiber surface is analyzed by scanning electron microscope (SEM). As shown in Figs. 4(a) and 4(b), the gold film on the fiber surface is found to be smooth and homogeneous. Figure 4(c) is the cross-sectional profile of the gold film, and we find the thickness uniformity of the gold film is good. All above characteristics supply a pretty resonance platform for SPW. To clearly observe the distance between the bottom of U-shaped waveguide and the cladding interface, the device is cutoff at the middle place of U-shaped waveguide, and its cross-sectional morphology is collected by the optical microscope as shown in Fig. 4(d). The microscope morphology of

![Fig. 2. Flowchart of device fabrication. (a) and (b) Section of coreless fiber (L₁ = 12.9 mm) is spliced between two SMFs. (c) Interface waveguide is inscribed in the coreless fiber. L₂ = 5 mm, b = 60 μm, R = 50 mm. (d) Layer of gold film is evenly coated on the coreless fiber surface. d = 45 nm.](image)

![Fig. 3. (a) Two dimensional and (b) three dimensional cross-sectional RI difference diagrams of the laser-waveguide.](image)
laser waveguide is corresponding to its RI modulation diagrams, the black segment is a negative RI modulation, and the bright segment is a positive RI modulation. The laser modulated area is $\sim 14 \mu m$ in depth and $\sim 3 \mu m$ in width. Moreover, the bottom of U-shaped waveguide, which is very close to the fiber cladding interface, would generate a strong evanescent field at the coreless fiber surface.

The RI response of this SPR sensor is investigated by the specific RI testing system [3]. The input of the device is connected with a Tungsten halogen light source (100 W, LS-3000, Ocean Optics), which supplies a broadband light signal input. The output end is linked to the spectrometer with the operating wavelength range of 300–1100 nm (QE-6500, Ocean spectra). To eliminate the interference of other factors, the tested fiber is fixed between two fiber holders to keep the sensing area to be naturally straightened and all the light path is protected because the intensity and polarization of the transmission light might be affected by the fiber deformation. In room temperature, the SPR sensor is immersed into a series of standard RI liquids (Cargille Labs) with the RI value from 1.305 to 1.395. After each measurement, the sensor is carefully cleaned by alcohol to remove the residual liquid until the spectrum returns to the initial status.

In Fig. 5(a), the normalized transmission spectra of the sensor are obtained from the transmission spectra of the sensor in different RI liquids divided by the one in air, and the resonant dip is resulting from the light coupling from the fiber-interface waveguide mode to the plasmon wave of the gold film. In Fig. 5(b), an exponential fitting method has been employed to reveal the RI response of the traced dip. It is found that as the liquid RI increases the wavelength of the resonant dip exhibits a significant red shift of 144 nm. It is important to note that a high sensitivity of $\sim 3353 \text{ nm/RIU}$ can be achieved at the RI value of $\sim 1.395$. The figure of merit (FOM) of the device, which is calculated with the RI sensitivity divided by the full-width at half-maximum of the resonant dip, is about 30 at the RI value of $\sim 1.395$.

To simulate the mode characteristics of the fiber interface-waveguide SPR sensor, we use the finite element method with perfect match layers (PMLs) boundaries [3], and the simulation is carried out by COMSOL Multiphysics [13]. The simulated model is established based on the device size in Fig. 2(d). According to the definition, the wavelength sensitivity is given by

$$S_\lambda = \frac{\Delta \lambda_{res}}{\Delta n_\alpha},$$  \hspace{1cm} (1)

where $\lambda_{res}$ is the plasmon resonant wavelength of the SPR sensor, and $n_\alpha$ is the liquid RI. The confinement loss can be calculated according to the following equation [3]:

$$\alpha = 8.386 \cdot k_0 \text{Im}[n_{\text{eff}}](\text{dB/m}),$$  \hspace{1cm} (2)

where $k_0 = 2\pi/\lambda$ is the wavenumber in meter scale [13].

The calculated loss spectra of the SPR sensor in different RI liquids are plotted in Fig. 6(a). It can be seen from this figure that the peak wavelength shows an obvious red shift when $n_\alpha$ is increased from 1.305 to 1.395 and the peak intensity stops to grow but begins to decrease when the $n_\alpha$ increases to 1.385.

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**Fig. 4.** (a) and (b) SEM images of the coreless fiber surface coated with gold film. (c) Cross-sectional profile of the gold film. (d) Optical microscope image of the cross-sectional coreless fiber with interface waveguide.

**Fig. 5.** Liquid RI response of the fiber-interface waveguide SPR sensor. (a) Transmission spectra of the fiber-interface waveguide SPR immersed in different RI liquids. (b) Exponential fitting relationship between the wavelength of the traced resonant dip and the RI of liquid.
The simulated results agree well with the experiment. The exponential relationship between the peak wavelength and the liquid RI is illustrated in Fig. 6(b). With an increase of liquid RI from 1.305 to 1.395, the resonant peak exhibits a red shift of 168 nm, and the RI sensitivity is calculated to be 3447 nm/RIU at the RI value of 1.395 from the fitting function. Compared with the experimental results, it can be found that the simulated data has a small difference in the red-shift amount and the sensitivity. This may be caused by the material dispersion of the tested liquids since the RI values of the employed standard liquids are calibrated at 589 nm, different from the sensing wavelength.

In conclusion, a fiber-interface waveguide SPR sensor has been first proposed and fabricated by femtosecond laser direct writing waveguide and film coating methods. Aiming to obtain strong evanescent field, the bottom of the U-shaped waveguide is inscribed very close to the surface of fiber cladding. When the fiber surface is coated with 45nm-thickness gold film, an ideal fiber-interface waveguide SPR sensor is realized and shows a high sensitivity of 3353 nm/RIU at the RI value of 1.395. Different from other fiber SPR sensors with fragile physical structure, our fiber-interface waveguide SPR sensor exhibits an excellent mechanical strength, which may have important practical applications in medicine, environmental monitoring, and food safety.

**Funding.** National Natural Science Foundation of China (NSFC) (61575128); Natural Science Foundation of Guangdong Province (2018B030306003); Science and Technology Innovation Commission of Shenzhen (KQJSCX20170727101953680), (JCYJ20170302152718747).

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