Miniaturized Metal-Dielectric-Hybrid Fiber Tip Grating for Refractive Index Sensing

Jun-Long Kou, Sun-Jie Qiu, Fei Xu, Yan-Qing Lu, Ye Yuan, and Gang Zhao

***Abstract*—We fabricate a miniaturized metal-dielectric-hybrid fiber tip grating (FTG) using a focused ion beam (FIB) method with high accuracy for refractive index sensing applications. It is the smallest fiber grating by now (nearly 10 μm in length located at the fiber tip of 3 μm in radius) and it has strong surface corrugations with notches periodically. The grating shows refractive index sensitive [125 nm/refractive index unit (RIU)] and insensitive (nearly zero) properties for reflection channels of different resonant modes by metal-dielectric cladding structure. It can be used as a multichannel sensor for simultaneous refractive index and temperature/pressure measurements. Taking advantage of its flexible design, tiny size, unique modal and spectral characteristics, the metal-dielectric-hybrid FTG has great potential in fast-response detection of ultrasmall objects.**

***Index Terms*—Grating, microfiber, sensor.**

I. Introduction

THE advantages of optical fiber grating sensors are well known as low cost, inherent self-referencing, and multiplexing/demultiplexing capability along a single fiber [1]. Fiber grating sensors have found a broad range of applications and have been widely extolled in the research literatures on refractive index, temperature, pressure measurements, and so on [2]–[7]. Conventional fiber gratings are fabricated by phase-mask-assisted ultraviolet (UV) light writing to generate the periodic refractive index modulation in a typical silica fiber. However, they have the limitations of weak available evanescent field, small index modulation [6], and large size. The evanescent field interacting with the outer environment is important for refractive index sensing. Several approaches have thus been proposed, e.g., polishing the fiber down to the core in the grating region [5], etching the fiber to several micrometers in diameter [2], [8], or employing D-shaped optical fiber [7]. However, the size is still limited by the grating length and fiber diameter. Minimizing the size of a sensor head is a key issue in some applications with special analyte, for example, submicro-size bubbles, particles or droplets detection in ocean, air or bio/chemical solutions. Small size usually also means fast response time. A tapered fiber tip with ultrashort length (tens of micrometers) and ultrasmall head diameter (sub-micrometer or tens of nanometers) is a perfect platform for ultracompact fiber devices, and has been widely used in scanning near field optical microscopy, subwavelength optical source, and sensing [9]–[11].

With the recent advances in micro-machining techniques, tremendous opportunities are shown to develop various micro-devices in thin and small fiber nano-tip, such as notch-like Fabry–Pérot cavity [10], [11] and nano-scale optical source through focused ion beam (FIB) drilling [12]. In this work, we fabricate a miniaturized metal-dielectric-hybrid fiber tip grating (FTG) by FIB for refractive index sensing applications. It is the smallest fiber grating at present according to our knowledge (nearly 10 μm in length located at the fiber tip of 3 μm in radius) and it has strong surface corrugations with notches (650 nm in depth) periodically. In the metal-dielectric-hybrid waveguide exciting multiple modes, the forward-propagating light can be backwardly coupled to several modes simultaneously. Some modes have large evanescent field and high sensitivity to outer environment while some have small evanescent field and are insensitive to outer environment. This kind of grating showing simultaneous refractive index sensitive and insensitive properties for reflection channels of different resonant modes can be used as a multichannel sensor capable of simultaneous refractive index and temperature/pressure measurements. The metal-dielectric-hybrid FTG presents great potential in fast-response submicro-size object detection due to the intriguing properties of flexible design, ultrasmall size, unique modal and spectral characteristics.

II. Fabrication of FTG

The fiber tip is fabricated from Corning SMF-28 using a commercially available pipette puller (Sutter, model P2000). CO_2 laser power and pulling velocity are optimized to achieve an optimum taper profile. The manufactured fiber tip has a long pigtail to allow prompt link to other optical fiber component. The fiber tip is $\sim$2 mm in length and is nonadiabatic. Then the fiber tip is coated with a gold layer with thickness of 30 nm on one side by magnetron sputtering. We choose gold due to its relatively low absorption in the infrared and inertness to oxidation when exposed in air. Then a grating is fabricated by FIB milling at the fiber tip with local radius of $\sim$3 μm. The milling is completed using a Ga-ion-based FEI-201 FIB system in a one-step process. A 30 kV, 58 pA cylindrical-symmetric beam with diameter less than 20 nm is utilized in order to achieve good milling quality. No other treatment is needed to improve the sharpness or accuracy [11]. Fig. 1 shows the scanning electron microscopic (SEM) picture of the periodic structures. The

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The authors are with the College of Engineering and Applied Sciences and National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, China (e-mail: feixu@nju.edu.cn; yqlu@nju.edu.cn).

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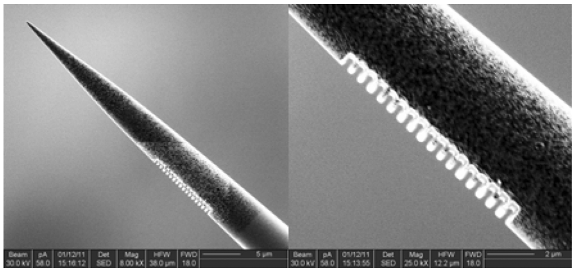

Fig. 1. SEM picture of the metal-dielectric-hybrid fiber tip grating ($\sim$10 μm in length and $\Lambda = 578$ nm). Right: magnified picture of the grating.

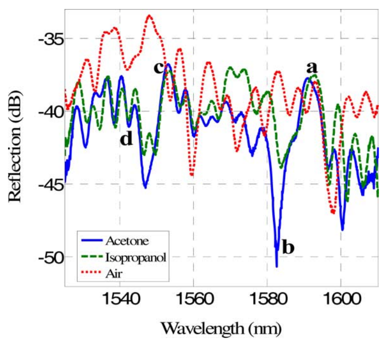

Fig. 2. Measured reflection spectra of the FTG when immersed in air, acetone, and isopropanol.

grating has shallow corrugations of period $\Lambda = 578$ nm with 17 periods. The total length is about 10 μm, which is extremely short.

III. Experiments and Discussion

Optical characterization of the FTG in Fig. 1 is performed using an Ando AQ6317B optical spectrum analyzer (OSA) accompanied by an amplified spontaneous emission (ASE) source (1525–1610 nm) and a fiber-optic circulator. We do not use polarized light to characterize the sensor because the birefringence of the grating is small according to our calculation. The experimental setup is the same as shown in [10].

Fig. 2 shows the reflection spectra of the FTG immersed in air, acetone, and isopropanol, respectively. The spectrum is measured with reference to the light source directly because the taper without grating indicates a reflection of $\sim$90 dB which is nearly negligible [10], [11]. The extinction ratio is about $\sim$10 dB. There are several valleys and peaks with different characteristics in the spectral range of $\sim$100 nm. They shift when the outer environment changes from acetone to isopropanol. However, these valleys and peaks show larger shifts at longer wavelengths, while those at shorter wavelength region shift much less and almost stop at specific wavelengths. This unique response to outer liquid refractive index comes from the fact that the reflected light can be coupled to different modes. In the micrometer-diameter metal-dielectric-hybrid fiber tip, several modes are probably excited with similar propagation constant because of the metal cladding [13], [14]. Some modes are well confined in the tip and have negligible field overlap with the liquid while some modes are not. The different valleys and peaks correspond to the coupling between these different forward and backward propagating modes, with different

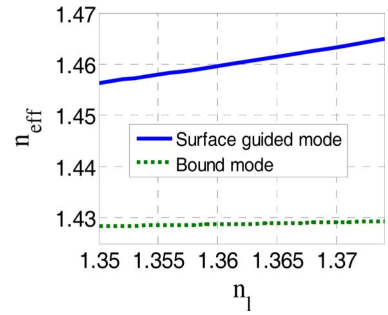

Fig. 3. Calculated effective index of the surface guided mode and bound mode as a function of the outer liquid refractive index n_1. The radius of the fiber tip is assumed to be 3 μm with a golden coating of 20 nm in thickness.

response properties for the outer environment. There is some chirp because of the nonuniform taper. We have measured that the diameter difference is less than 1 μm in the grating region as illustrated in Fig. 1. And according to our calculation, different effective refractive index resulted from the variation of the diameter will induce resonant wavelength shifts of $\sim$4 nm. So some small ripples in Fig. 2 probably come from the chirp.

The reflection resonant condition for the grating is [15]:

$$\frac{2\pi}{\lambda_g}[n_f + n_b] + \frac{k_{fb}}{1} = \frac{2\pi}{\Lambda} \tag{1}$$

where n_f and n_b are the effective indices of the forward and backward modes, respectively. k_{fb} is the coupling coefficient that changes little with respect to the operating wavelength and is proportional to the grating strength. At the same time, the grating length and the grating strength significantly influence the reflectivity. Because the period Λ is the same for all these coupled modes, the reflected mode with larger effective index has a longer resonant wavelength from (1), provided that k_{fb} is a constant and is smaller compared with the reciprocal vector $2\pi/\Lambda$ provided by the grating.

For simplicity, we assume a theoretical model to explain our experimental results which is simple and not perfectly matched with the experiment but can give the fundamental mechanism of the device. Within the model of hybrid metal-cladding dielectric multimode waveguide, the microfiber is 6 μm in diameter with uniform metal cladding (20 nm in thickness). However, the real device is much more complicated, with nonuniform metal cladding and diameter. And if an asymmetrical mode field lies mainly near the grating, leading to a larger modal overlap with the grating, it may result in a higher sensitivity. Fig. 3 shows the calculation on the effective index of the surface guided mode and bound mode (most of the energy is in the dielectric core) as a function of outer liquid refractive index n_l. Due to the existence of the metal layer, the surface guided mode has a larger effective index (corresponding to long resonant wavelength) than that of the bound mode (corresponding to short resonant wavelength) and has a larger overlap with the taper surface and the outside environment, leading to a higher sensitivity to the surrounding medium which is in coincidence with the spectra of Fig. 2.

The performance of resonant refractive index sensors can be evaluated by using sensitivity S, which is defined as the magnitude in shift of the resonant wavelength divided by the change in refractive index of the analyte [16]. In our experiment,

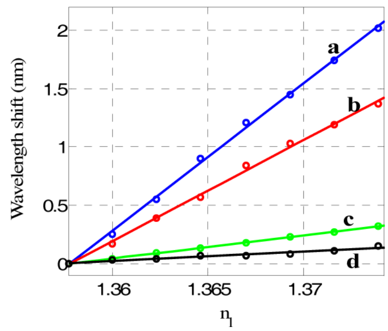

Fig. 4. Dependence of wavelength shift on outer liquid refractive index n_1. The asterisks represent the experimental results with the solid line of linear fitting.

the sensitivity is measured by inserting the sensor in a beaker containing mixtures of isopropanol and acetone, where the isopropanol component has the following ratios: 0, 1/7, 2/7, 3/7, 4/7 5/7, 6/7, and 1. These solutions are chosen with the objective of simulating aqueous solutions, having a refractive index in the region around 1.33 at a wavelength $\lambda = 1.55$ μm. The ratio is increased by adding small calibrated quantities of isopropanol to the solution at a position far from the sensor. The refractive indices of pure isopropanol and acetone at 1.5 μm are 1.3739 and 1.3577, respectively [17].

Fig. 4 displays measured resonant wavelength shifts of several peaks and valleys and fitting of this FTG on the liquid refractive index (a, b, c, d as marked in Fig. 2, (a) and (c) are peaks, (b) and (d) are valleys). As the refractive index increases, the resonant wavelength shifts to longer wavelength. The sensitivities of different modes change severely. It can be as high as 125 nm/RIU (peak a, RIU is the acronym of refractive index unit) or as low as 7 nm/RIU (valley (d)). For peak (a) (or valley (b)), both the resonant wavelength and sensitivity are larger than those of peak (c) (or valley (d)). According to our theoretical calculation, we believe peak (a) (or valley (b)) corresponds to the surface guided mode while peak (c) (or valley (d)) is the bound mode. The smallest sensitivity can be further decreased to nearly zero by optimizing the tip grating profile and metal coating. Because of many different properties on the outer liquid refractive index, the metal-dielectric-hybrid FTG can be applied as a multiparameter sensor and the index-insensitive channel can be used to simultaneously measure temperature, pressure, and so on. In our experiment, we didn't measure the temperature sensitivity and the measurement was taken under room temperature with variation of less than 0.1°C. Conventionally, the temperature sensitivity of the microfiber grating is 10–20 pm/°C [18].

IV. Conclusion

In conclusion, we demonstrate a miniaturized metal-dielectric-hybrid fiber tip grating milled by FIB for refractive index sensing applications. It might be the smallest fiber grating by now. This kind of grating shows refractive index sensitive (125 nm/RIU) and insensitive (nearly zero) properties for different resonant modes from the metal-dielectric-hybrid cladding structure. It can be used as a multichannel sensor with simultaneous refractive index and temperature/pressure measurements. Taking benefit of the flexible design, ultrasmall size, unique modal and spectral characteristics, the metal-dielectric-hybrid FTG has great potentials in fast-response ultrasmall object detection.

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