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Reflection based extraordinary optical transmission fiber optic probe for refractive index sensing

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ABSTRACT

Fiber optic probes for chemical sensing based on the extraordinary optical transmission (EOT) phenomenon are designed and fabricated by perforating subwavelength hole arrays on the gold film coated optical fiber endface. The device exhibits a red shift in response to the surrounding refractive index increases with high sensitivity, enabling a reflection-based refractive index sensor with a compact and simple configuration. By choosing the period of hole arrays, the sensor can be designed to operate in the near infrared telecommunication wavelength range, where the abundant sources and detectors are available for easy instrumentation. The new sensor probe is demonstrated for refractive index measurement using refractive index matching fluids. The sensitivity reaches 573 nm/RIU in the 1.333–1.430 refractive index range.

1. Introduction

The optical transmission through thin metal surface perforated with subwavelength holes is a rather interesting topic, and has received much attention since the extraordinary optical transmission (EOT) was first observed in 1998 [1]. In such systems, the zero-order transmission can be larger than unity when normalized to the areas of the holes. Many experimental and theoretical works have been initiated and devoted to understanding the physics of this effect. It is generally believed that the surface plasmon polariton (SPP) modes originating from coupling of light to collective oscillation of electrons play a key role [2–4]. Later on, the Bloch-mode theory was developed to describe the enhanced evanescent field at the hole apertures and the transmitted light funneling through the hole arrays macroscopically; a comprehensive model involving the SPP mode and an additional field with a quasi-cylindrical wave was built to explain the physical origin of the Bloch mode microscopically [5–11]. In spite of the complexity of the mechanism behind the EOT phenomenon, the structure-enhanced transmission has a wide range of potential applications, e.g., in subwavelength optics [12,13], optoelectronic devices [14,15], and chemical sensing [16–18].

The specific dependence of EOT resonance wavelength on the refractive index (RI) of the surrounding environment suggests the subwavelength arrays are good platforms for chemical sensing. As the surrounding RI varies, the effective index at the metal interface will change to produce a wavelength shift that can be monitored for RI measurement [17]. As such, an EOT structure device can work as a label free chemical sensor. For example, a gold thin film EOT device has been demonstrated for chem/bio molecules detection with high selectivity by monitoring the molecular binding/interaction process in real time [16,18]. Compared with the well-established surface plasmone resonance (SPR) analytical method, the EOT structure provides a number of advantages. For instance, the EOT structure has a small footprint (on the order of micrometers). Consequently, the signal can be generated by a smaller number of molecules and the device has better spatial resolution. Another advantage is easy optical alignment for device implementation. The combination of these features makes the EOT structure a good candidate for the development of compact chemical/biological sensors and parallel diagnostic arrays integrated with lab-on-chip devices [18].

The EOT structure can also be integrated with fiber optics to form an optical fiber probe by fabricating the perforated subwavelength metal holes directly on the endface of an optical fiber. Compared with the extensively studied fiber optic SPR sensors in which a section of the fiber core is partially exposed by polishing or etching, the EOT fiber sensor has better spatial resolution and robustness. As a fact, subwavelength nanoholes arrays have been fabricated on

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metal film coated optical fiber endface using focused ion beam (FIB) milling to demonstrate the EOT enhanced transmission [19]. An EOT based multimode optical fiber device has also been investigated with transmission configuration for refractive index sensing using a light source in the visible range [20]. However, all the reported devices operate in transmission mode, where the optical source and detector are separated at the two ends, making it difficult for in situ monitoring applications.

In this paper, we report a reflection based EOT fiber optic probe by FIB milling subwavelength hole arrays on a gold thin film coated fiber endface. The transmission and reflection spectra of the fabricated probes are investigated. The probes are also studied for in situ measurement of refractive index (RI) variations. Compared to a transmission-based sensor, a reflection-based probe has the advantage of easy installation during applications. A reflection-based probe can access the test environment through a single point of insertion while a transmission-based probe needs to have two access ports, one for input and the other for output. By choosing the period of the hole arrays, the sensor can be designed to operate in near infrared telecommunication band where abundant opto-electronic components (e.g., optical fiber and semiconductor based optical sources, power detectors, etc.) are available for easy instrumentation.

2. Experiments

The fiber optic EOT probes were fabricated by patterning of periodic subwavelength hole arrays on gold thin film coated optical fiber endfaces using FIB milling technique. The single mode fiber employed in this paper is Corning SMF 28e with a core diameter of 8.2 μm and a cladding diameter of 125 μm. A sputtering system (Denton DESK V) was used to coat a gold thin film with a thickness of about 150 nm on the cleaved optical fiber endface.

A Helios FIB milling machine (Nano Lab 600) with a gallium ion source was used to fabricate the periodic subwavelength EOT structure. The hole-perforating area was 20 μm × 20 μm covering the core region of the optical fiber. Computer generated patterns were imported into the FIBs milling machine to fabricate the hole arrays. The periods of the hole arrays ranged from 912 to 1056 nm and the size of the holes varied from 522 to 605 nm. During hole milling, we found that the vibration and bending of the fiber tip could cause deviations of the parameters from the preset values. The fabrication precision could be further improved by more stable installation of the fiber onto the FIBs milling machine. Fig. 1 shows the scanning electron microscope (SEM) images of the hole arrays with the periodicity of 960 nm and hole diameter of 550 nm, which was used in the later RI measurements. Fig. 1(a) shows the whole fiber probe with the EOT pattern and Fig. 1(b) depicts the zoom-in image of the hole arrays on the fiber endface. As shown in Fig. 1, the EOT pattern covered the entire region of the fiber core.

Fig. 2(a) and (b) illustrate the setup for characterizations of transmission and reflection spectra of the fabricated EOT fiber probe, respectively. The EOT probe was excited using an unpolarized broadband light source. To obtain the desired information, light sources of different bandwidths were used to excite the plasmon in the experiments. A quartz halogen white light source (WLS100-X) with the power of 100 W and spectrum range of 350–2500 nm was used to study the EOT transmission spectrum in a wide spectrum range. A super luminescent diode (SLD) source (Agilent 83437A) with the power of ~500 nW/nm and spectrum range of 1250–1650 nm was used to study the Wood's anomaly. An Erbium doped fiber amplified spontaneous emission (ASE) source of with the power of ~0.1 mW/nm and wavelength range of 1520–1620 nm was used to acquire the EOT reflection spectrum and test the device for RI measurement in the reflection configuration for a high signal-to-noise ratio.

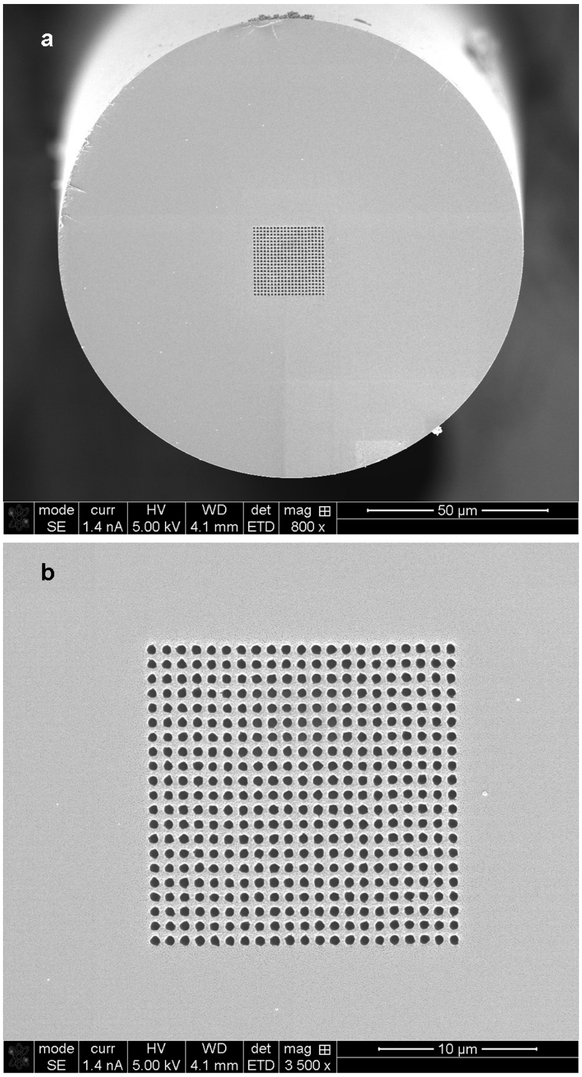

Fig. 1. SEM images of the EOT fiber optic probe. (a) Overview of the EOT structure on the fiber endface; and (b) zoom-in image of the EOT hole arrays.

As shown in Fig. 2(a), during transmission spectrum measurement, the bare fiber with fabricated probe was backwards inserted into an optical fiber FC-type connector so that the fabricated probe did not touch the connector during insertion process. The transmission spectrum was directly collected by an optical spectrum analyzer (OSA, Yokogawa 6370C). To acquire the reflection spectrum, a single mode fiber circulator (Thorlabs 6015-3) was employed. Before the measurements, the loss spectrum of the circulator was measured and calibrated in the extended wavelength range of the optical source used. As shown in Fig. 2(b), the broadband light source, fiber probe and OSA were connected to the Port 1, 2 and 3 of the fiber circulator, respectively. Reference spectra were collected to normalize the transmission and reflection signals. For the transmission configuration, the reference spectrum was directly taken using a fiber patchcord. For the reflection configuration, the reflection spectrum from a freshly cleaved singlemode fiber at Port 2 was captured as the reference.

3. Results and discussions

The transmission spectrum from the fiber EOT structure with an array period of 960 nm and hole diameter of 550 nm is shown