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Hollow fiber taper with a silver micro-sphere used as refractive index sensor

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ABSTRACT

We have experimentally studied the plasmon resonance phenomenon of a silver micro-sphere with a diameter of 2.3 μm in taper-shaped air cavity of a hollow fiber taper. To take insight into the plasmon resonance phenomenon, we move the micro-sphere along the fiber and observe the significant shift of the resonance peak. To explore this configuration as a sensor, we analyze the reflected optical spectrum changes as a function of the external refractive index by finite difference time domain method. The results show that this device can be used for a bio-chemical sensor to monitor the refractive index around it from 1.6 to 2.0. The further study supports that the variation was much more significantly for using the S polarized light as the incident source than P polarized light.

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1. Introduction

Surface plasmon resonance (SPR) is the charge density oscillation stimulated by electromagnetic wave and decays evanescently at the metal–dielectric interface. In recent decades, SPR have been an important method in analyzing the biological and chemical reactions due to its convenient and efficient characteristics. In recent years, researchers have dedicated to studying the impact of regular and random metal particles arrangements on the light signal [1–3]. It is well known that the small changes, derived from arrangement, configuration and sizes of the metal particles, can affect the phase or amplitude of the light signal [4,5]. The metal particles in random arrangement can produce interesting effects on the light signal, but the manipulation is difficult actually [6]. That is, the experimental repeatability cannot be guaranteed. Meanwhile, the regular arrangement of metal particles relies on the ion beam etching [7] or lithography technology, resulting in a very complex preparation process for the samples [8,9]. How to control the nano-scale metal particles effectively is becoming a hot study topic in recent years [10]. The light tweezers or waveguide is an effective control method to limit the distribution of the metal particles, such as a fiber [11,12]. Recent studies also indicate that the treated fiber has many potential applications. With the optical coupling between the fiber taper and micro sphere, a lot of interesting experimental results have been reported [13–17]. The transmitted light is very sensitive to the surrounding environment, which is used to monitor changes of temperature (as a part of Fabry–Perot interferometer) and RI [18] (as a part of Mach–Zehnder interferometer). Although these structures can be realized as the optical sensor with high sensitivity, high accuracy and real-time measurement, their stability and usability are limited by micro and nanometer manufacturing process or arbitrary spatial position of spheres and fibers. In this paper, we studied the optical properties of a hollow tapered fiber. The hollow fiber [19,20] or photonic crystal fiber (PCF) [21] can be used as a pulse compressor. However, PCF has a core and a muti-layer photonic cladding with increasing cell radius, in which the optical field is very complex. At the same time, its production and structure is very complicated. In contrast, the hollow fiber is only a hollow tube, in which the light properties analysis will be much clearer and meaningful when it is used as an optical sensor. In this paper, we produced the metal microspheres quartz fiber structure by external forces operation. Therefore, we can get the specific structure with respect to the conventional random doping technology.

2. Sample preparation

The fiber taper was obtained from a silica capillary with an air core of 100 μm diameter and an external diameter of about 165 μm. First, the coating (about 12 μm in thickness) of the silica capillary was melt away by a Bunsen burner (by controlling the

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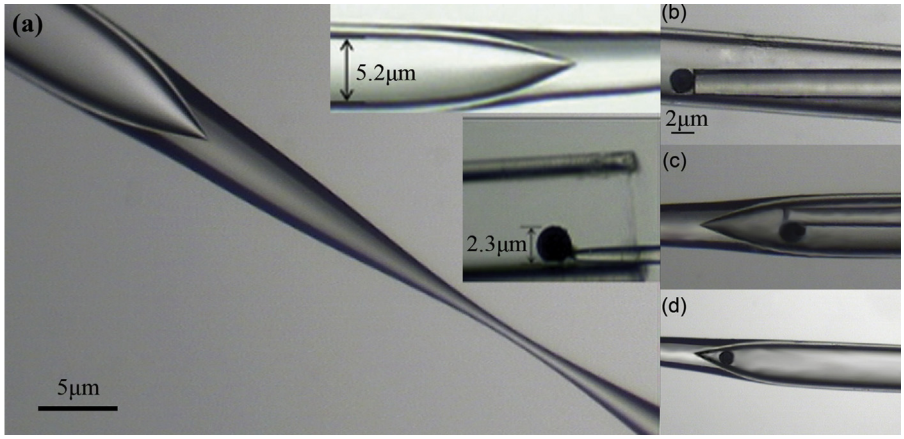

Fig. 1. The preparation of the experimental configuration. (a) The micrograph of the fiber taper with a taper-shaped air chamber; Inset: The size of the hollow fiber and silver microspheres. (b) the propelling fiber and the micro-silver sphere in the direct-part of the fiber taper; (c) the propelling fiber and the silver micro-sphere near the air taper of the fiber taper; (d) 2.3 μm silver sphere in the fiber taper.

flame temperature of the Bunsen burner and the stretching speed, one can get the micron hollow fiber tapers with different diameters and obtain different transmission spectra); Then, the transparent hollow fiber, similar to the glass capillary except the smaller diameter, was further stretched to 5.8 μm in diameter. The diameter of the air hole is about 5.2 μm. Finally, the micron hollow fiber was pushed into a fiber taper with a taper-shaped air chamber, as shown in Fig. 1(a). The end of the fiber taper turned into solid due to high temperature and the stretching force. We have measured and marked the size of the hollow fiber and silver microspheres by using the microscope measurement software, as shown in the insets.

It is difficult to precisely manipulate an object with several micrometers under the microscope. In this paper, we put a 2.3 μm silver sphere in the taper-shaped air cavity of the fiber taper with a fine fiber of 2.5 μm in diameter. Fig. 1(b)–(d) provides the microscope images of the operating process. First, a single-mode fiber with 125 μm in diameter is stretched into a fine fiber with a diameter of 2.5 μm, slightly larger than the diameter of the silver micro-sphere. Next, the fine fiber (used as a push rod) was used to push a 2.3 μm silver micro-sphere into the conical cavity of the fiber taper, as provided in Fig. 1(b). In this way, one can push the silver micro-sphere into the taper-shaped air cavity under the microscope, as shown in Fig. 1(c). Eventually, the fine fiber is withdrawn out from the fiber taper, leaving the 2.3 μm silver sphere, refer to Fig. 1(d). At the moment, the silver micro-sphere has been placed in the fiber taper successfully.

3. Experiment setup and related theory

The schematic of the experimental setup is illustrated in Fig. 2. A light source centered at 1550 nm was used in the experiment, its spectrum ranged from 1530 nm to 1560 nm, as shown in Fig. 3(a). The three-color LED hybrid light source results non-flat spectral characteristics. The spectral broadening on its both side is about 5 nm, which ranges from 1525 nm to 1566 nm. The fibers used for transmitting incident and detecting light were clamped by the fiber clips, which were fixed on the three-dimensional adjustments (XYZ Translation stage with a resolution of 0.1 μm). In this way, we could precisely move the fibers to align the two fibers with the hollow fiber taper, as the enlarge part of the diagram evinced. The entire operation must be precisely controlled under the microscope. The fibers were placed on a piece of MgF_2 crystal to reduce the loss. The fiber taper with an air taper was chose and placed on the MgF_2 crystal. A microscope was used to observe the

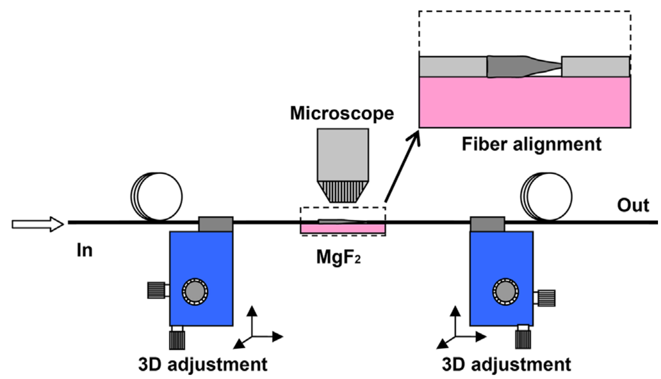

Fig. 2. Schematic diagram of experimental setup. The input fiber and output fiber are fixed by the fiber folders. The position of the fibers can be changed by adjusting the three-dimensional adjustment. The microscope is used for observing optical fiber, which is aligned on an MgF2 chip.

specific position of the fiber probes and the fiber taper. We used a network analyzer (model: Anritsu CMA5000) collecting spectral information, which equipped with a spectrometer (model: OSA400) with the spectral resolution of 0.05 nm. We guided the incident light into the fiber taper and measured the spectra of the light output from the probe fiber by regulating the three-dimensional adjustments.

4. Results and discussions

We experimentally studied the optical response of the hollow fiber taper, as well as the plasmon resonance of the fiber taper filled by a silver micro-sphere. The hollow fiber taper are observed in the spectrum analyzer, as revealed in Fig. 3(b). Two transmission peaks turn up near 1532 nm and 1552 nm, as shown in Fig. 3(b). The selective absorptions depend on the light interference and micro or nano-size effect of the air conical cavity. The result demonstrates that such a fiber optic taper can be used as an optical filter. By using the hollow fiber taper with different geometrical parameters, the specific wavelength can be selected. As we know that the thermomechanical effects play a important role in micro–nano experimental operation using visible light as the source [11]. But the spectrum of the light source in Fig. 2(a) shows that the highest light intensity is less than −60 dBm, which is 10^{-9} W. Therefore, the thermomechanical effects are not the

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