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Side-channel photonic crystal fiber for surface enhanced Raman scattering sensing

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ABSTRACT

A side-channel photonic crystal fiber (SC-PCF) is proposed and fabricated to serve as a high sensitivity surface enhanced Raman scattering (SERS) sensing platform. The SC-PCF has a solid core with triangular lattice cladding structure, and one third of the cladding is removed intentionally to enable fast liquid infiltration and enlarge effective interaction area between liquid samples and the fiber core guided lightwave. The geometry of the SC-PCF is designed to obtain high evanescent field power in cladding side-channel, high free space coupling efficiency and low transmission loss at the excitation wavelength of 632.8 nm. Rhodamine 6G (R6G) solutions mixed with gold nanoparticles (AuNPs) are used to test the SERS performance of the proposed platform. A low detection limit of 50 fM R6G solution is achieved. Moreover, an accumulative effect of SERS signal along the SERS-active fiber length is demonstrated experimentally, and a numerical–analytical model for backward scattering scheme is developed to investigate the dependence of Raman intensity on fiber length.

1. Introduction

Surface enhanced Raman scattering (SERS) has been acting as a powerful tool for label-free molecular detection with high sensitivity [1–3], and it is even able to trace single molecule with the presence of noble metals by increasing the effective Raman scattering cross section [4–6]. SERS reveals the "finger print" information of a molecule, which makes it promising in sensing applications. In SERS, Raman scattering is enhanced predominantly by the enhancement of the local electrical field close to the surface of the metallic substrates due to the excitation of localized surface plasmons [7,8]. Owing to the unique properties of SERS, plenty of work on the development of SERS-active substrates has been reported [9–12].

Optical fiber based SERS sensing platforms have many advantages over SERS substrate platforms, such as compactness, flexibility and capability of remote sensing [13–19]. However, the applications of conventional optical fiber based SERS sensing platforms are limited either by the small amount of SERS active particles in active regions or by the low electromagnetic power in sensing areas. Photonic crystal fibers (PCFs), which consist of hollow cores or holey cladding structures, are inherent optofluidic sensing platforms [20–30]. Guided by the advanced development of fabrication, PCFs provide flexible design of optical waveguide properties, by which the light power in sensing area can be enlarged for a specific range of wavelength appropriately. In addition, their

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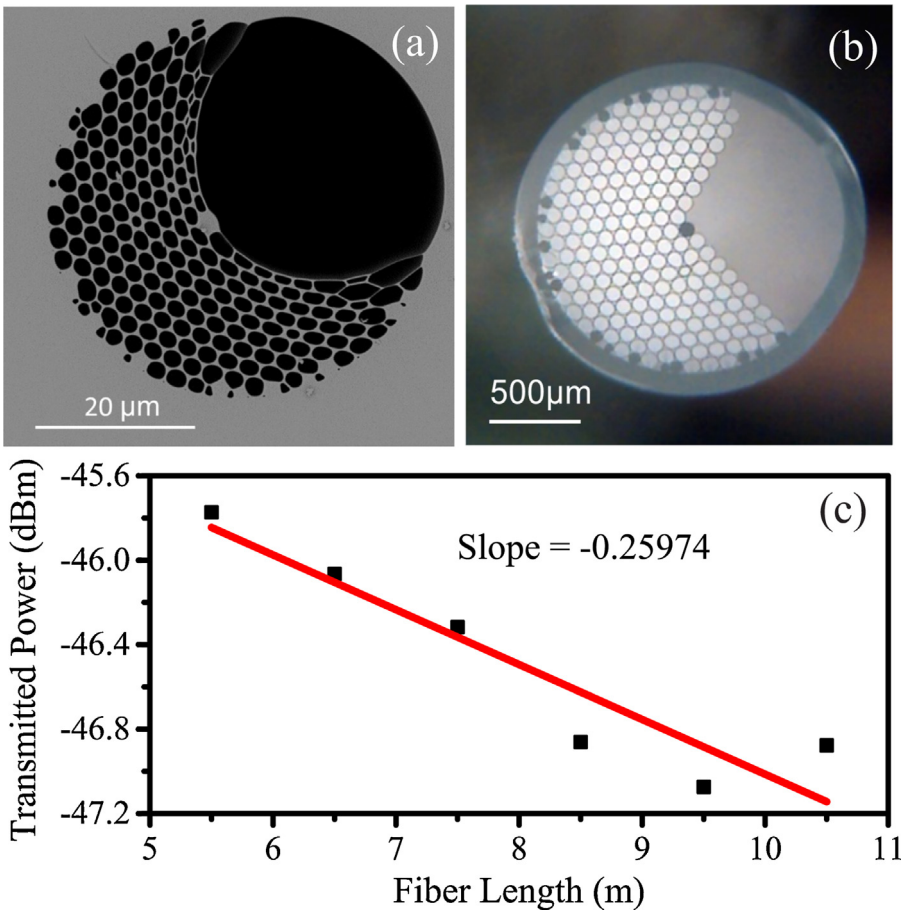

Fig. 1. (a) SEM image of the cross section of SC-PCF. (b) Microscope image of the cane. (c) Transmitted power at 632.8 nm as a function of fiber length. The black squares represent experimental data, and the red straight line is fitted to the experimental data (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

unique ability of transmitting gas or liquid samples in the air channels running along the entire fiber length enables unprecedented long interaction path between the liquid sample and the light, which helps to extend the active sensing area intensely. By synergistically combining flexible design of optical waveguide properties and liquid transmission of air channels in a single fiber, both bandgap-guiding and index-guiding PCFs have been investigated to construct high sensitivity, high performance and versatile SERS sensing systems [31–38]. The bandgap-guiding hollow-core PCFs enable direct interaction between sample and excitation light, while the index-guiding solid-core PCFs generate SERS signal through the interaction with evanescent field in cladding channels. However, the performance of PCF-based SERS sensors has been restricted either by the large attenuation caused by strong absorption and scattering in liquid sample or by the weak Raman signal induced by low evanescent field in air channels. Therefore, in this Letter, we propose and fabricate a solid core side-channel PCF (SC-PCF) which has the properties of low transmission loss, high evanescent power, and single mode propagation at the excitation wavelength of 632.8 nm for building up high sensitivity SERS sensing platforms. Moreover, one third of the holy cladding is removed intentionally to form a cavity which enables fast liquid infiltration for real-time measurement and enlarges effective interaction area between liquid samples and the guided lightwave within fiber core. An ultra-low detection limit of 50 fM Rhodamine 6G (R6G) solution is achieved with our SC-PCF platform and an accumulative effect is investigated for the purpose of further enhancing its sensitivity.

2. Side channel photonic crystal fiber

2.1. Fiber design and fabrication

SC-PCF in our design composes of a solid core and photonic crystal cladding with air holes arranged in triangle-lattice. The scanning electron microscope (SEM) image of the fabricated fiber and the microscope image of the preform are shown in Fig. 1(a) and (b), respectively. Through running simulation with finite element method (FEM) based software COMSOL, we find that the fraction of evanescent power in the side-channel can be increased if the pitch (distance between two adjacent air holes) is decreased or the ratio of the diameter of air hole to pitch increases. To enhance evanescent power, effective methods are to reduce the sizes of fiber core and the pitch, and to increase the air filling ratio. Compromising light coupling efficiency, the size of pitch and the diameter of the air hole are chosen to be 3 μm and 2.1 μm, respectively. SC-PCF is fabricated through the stack-and-draw process, and temperature, pressure and vacuum need to be well controlled to keep the shape of the side-channel during the drawing process. Moreover, the fiber drawing tower provides great stability during drawing process. Thus, good consistence in the dimensions of fiber geometry is obtained with the variation less than 1 μm.

2.2. Fiber characterization

After the drawing, the core diameter of the fabricated fiber is around 2.8 μm. The size of side-channel is about 25 μm