Optical Fiber Technology 36 (2017) 187–194

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

Compact 3D photonic crystals sensing platform with 45 degree angle polished fibers

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ARTICLE INFO

Article history:
Received 10 November 2016
Revised 8 March 2017
Accepted 25 March 2017

Keywords:
Angle polished optical fiber
Photonic crystals
Inverse opal film
Refractive index sensing

ABSTRACT

Three dimensional photonic crystals are a kind of promising sensing materials in biology and chemistry. A compact structure, consists of planner colloidal crystals and 45 degree angle polished fiber, is proposed as a platform for accurate, fast, reliable three dimensional photonic crystals sensing in practice. This structure show advantages in compact size for integration and it is ease for large scale manufacture. Reflectivity of the 45 degree angle polished surface with and without a layer of Ag film are simulated by FDTD simulation. Refractive index sensing properties as well as mode distribution of this structure consists of both polystyrene opal and silica inverse opal film is investigated, and an experimental demonstration of silica inverse opal film is performed, which shows a sensitivity of 733 nm/RIU. Different kinds of three dimensional photonic crystals can also be applied in this structure for particular purpose.

1. Introduction

Three dimensional photonic crystals (3D PCs) are one kind of materials possess photonic band gaps attributed to their periodic structures in three dimensions. In the past decades, PCs are widely explored as sensing media in biology, chemistry, food safety and environmental detection [1–8]. A versatile of applications have been demonstrated, for example: relative humidity (RH) sensing based on TiO2 inverse opals fabricated by glancing angle deposition [9,10], chemical vapor detection by opals [11–13], independent multifunctional detection by wettability controlled inverse opal hydrogels [14], PH value sensor [15,16] and NH3-HCl detection by polyaniline-infiltrated TiO2 inverse opal film [17]. When 3D PCs are applied in sensing, signals containing sensing information are usually collected and analyzed by an optical spectrum analyzer (OSA) or naked human eyes. It is an essential requirement to measure the optical characters of 3D PCs precisely in practical sensing applications so as to obtain accurate result. Colloidal crystals (CCs), sub-micrometer spheres close packed in face-centered-cubic, are one kind of the most commonly used 3D photonic crystals with band gaps located in visible and infrared range, which largely attributed to ease of fabrication by self-assembly technique.

However, area of high quality CCs produced by self-assembly method is limited. Defects will decrease the band width and band gap wavelength reflectivity of CCs and thus decrease the sensing sensitivity. Furthermore, band gaps of 3D PCs are sensitive to incident light angle. Reliable optical spectrum detection configurations that can eliminate above problems are required for CCs applied in practice. In addition, reduced size and high detection capacity is also desired for bio-sensing [18]. Previously, to overcome the shortage of colloidal crystals and measure their optical response reliably, our group demonstrated a scheme that to produce colloidal crystals on an optical fiber end facet [19]. As relative placement of the fiber and PCs are constant in this configuration, as well as incident light angle, area of high quality PCs required in sensing is only slightly larger than the optical fiber core area.

45 degree angle polished optical fibers have been widely investigated [20–22] and applied to many applications such as pressure sensor [23], passive Q switching [24] and gas sensing [25]. In this paper, a structure consists of planner colloidal crystals and 45 degree angle polished fiber is introduced. Compared to deposition colloidal crystals directly on an optical end facet, planner colloidal crystals could be prepared in large scale with low cost and efficiency. And most importantly, this structure is compact in size and has potential to be integrated on a micro-flow chip. As a platform, this design has great potential to be applied to bio- and chemical analyst.

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http://dx.doi.org/10.1016/j.yofte.2017.03.014
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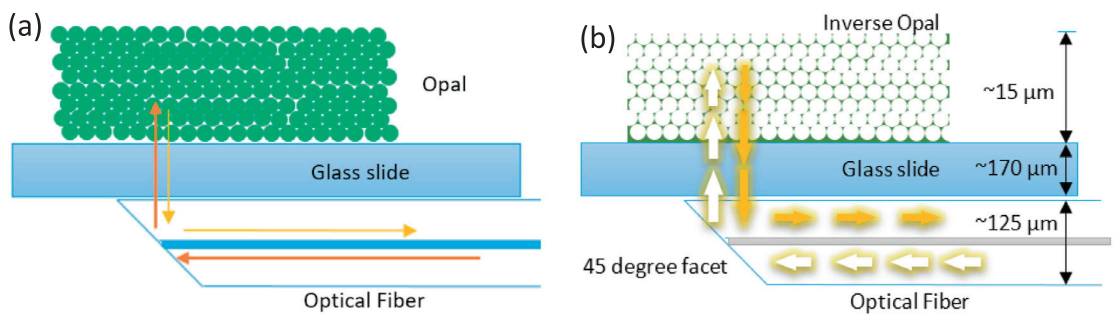

Fig. 1. Schematic diagram of a compact 3D PCs sensing platform with opal (a) and inverse opal (b).

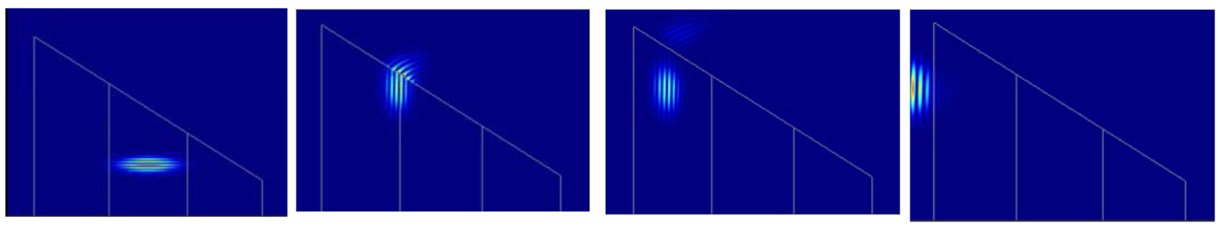

Fig. 2. Electric field distribution on the longitudinal cross section of the 45 degree angle polished fiber at different time when a pulse transmitted through it.

2. Principle of design and fabrication

As illustrated in Fig. 1, a 45 degree angle polished optical fiber was closely attached and glued on a thin glass slab, light transmitted from the optical fiber firstly reflected by the 45 degree polished facet, and then partially reflected by a layer of 3D PCs assembled on the other side of the slab. Light reflected by 3D PCs is partially coupled back to the 45 degree fiber again and transmitted through the fiber to be analyzed by an OSA from the other end of the fiber. A peak in measured reflection spectrum represented the band gap of 3D PCs that is sensitive to surrounding environment refractive index change. A small refractive index change will result in a wavelength shift of the peak in the spectrum.

To verify the performance of this design, a FDTD simulation (FDTD solution) that calculate the light path, reflectivity of this structure and electric field intensity distribution in the proposed structure was conducted. Firstly, light propagate in a 45 degree angle polished single mode optical fiber was simulated. Light transmitted in the fiber core was reflected by the 45 degree polished surface and propagated outside the optical fiber through the cladding layer, as illustrated in Fig. 2. To decrease simulation complexity, fiber core is set as 9 μm while cladding is 25 μm. According to simulation results, cladding with outer diameter of 25 μm is large enough to guide the light in the fiber. In the proposed structure, incident lights will be reflected twice at the 45 degree interface before they come back to be detected. A part of energy loss caused by refraction at the 45 degree interface can be viewed in the simulation. Thus, if energy loss caused by this interface was eliminated, reflected light intensity will increase. An optically thick Ag film ~300 nm was sputtered on the 45 degree face to increase reflectivity at the interface. This Ag film functions as a refractive index match layer to increase the reflectivity of this 45 degree side polished facet when the sensor was used in liquids whose refractive index close to the optical fiber core of 1.46. Other materials with similar optical properties can also be used as coating layer, such as Al and high refractive index dielectric materials. Ratios of transmitted light from side curved surface and reflected light at the incident fiber end are plotted in Fig. 3. Compared to

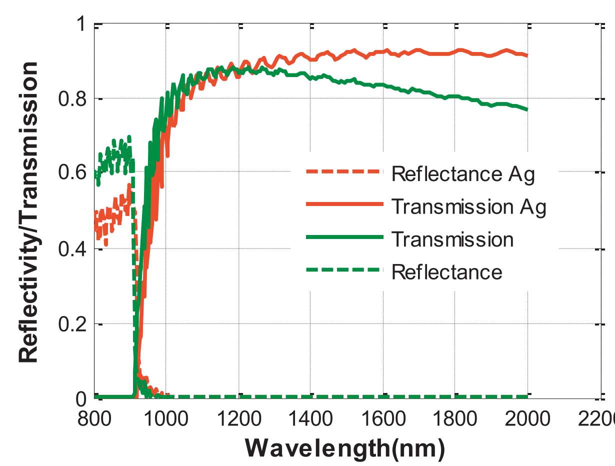

Fig. 3. Reflectivity and transmission of the 45 degree angle polished surface with and without coating a layer of 300 nm thick Ag film.

the case without Ag film, transmission increases obviously at wavelengths larger than 1200 nm, up to 13% around 2000 nm.

Electric field patterns of light transmitted out of the curved side surface of fibers with and without Ag film coated on the 45 degree angle polished surface were record and displayed in Fig. 4 (a) and (b). For Ag coating case, the light electric field pattern is round with Gauss distribution while it is rectangular like for bare fiber case. Both light patterns are good for our design. It is worthy to note that no light transmitted out of the fiber at around 800 nm is caused by diffraction in the simulation due to large mesh grid size of 100 nm in x, y direction, as evidenced in Fig. 4(c). This situation will not occur in experiments since the polished surface is flat with roughness less than 10 nm. No refraction light can be viewed when deposited a layer of Ag film on the angle polished fiber (Fig. 4 (d)).

Band-gaps of CCs are dependent on diameter of spheres and dielectric constants of both spheres and materials in their gaps. Also band-gaps of CCs are dependent on the incident light angle.