Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Optical fibers for bio-sensing applications

To cite this article: Wanvisa Talataisong *et al* 2019 *J. Phys.: Conf. Ser.* **1151** 012003

Optical fibers for bio-sensing applications

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Abstract. Here we discuss several different pathways of exploiting optical fibers for sensing applications. We demonstrate that fused optical fiber couplers can operate as a sensitive refractometers and thermometers. Their potential for bio-sensing applications is also discussed. We also discuss application of plastic fibers for accessing mid-IR spectral region for optical sensing.

1. Introduction

Biological sensors based optical fibers can be split into two types: intrinsic and extrinsic. In the former the fiber itself can provide the sensing area, either through its external surface or, in the case of microstructure fiber, through the capillary holes running along its length; the latter requires a functionalization of the external or of the internal fiber surfaces with biological analyte sensing probes, and a mechanism for the transduction of the binding event into an optical signal.

Typically, biosensing involves the modification of the optical fiber surface with so-called probe material, which upon interaction with molecules of interest would generate a physical signal, for instance a refractive index change. In the case of DNA detection, a functionalization process such as a chemical treatment, or derivatization, is needed [1, 2]. Thus, the optically sensitive surface is able to bind to a specific DNA sequence, a phenomenon referred to as DNA hybridization.

The measurement of refractive index and temperature are of particular importance for bio-sensing. Various properties can be indirectly monitored using these two basic parameters: for example cancerous tissues tend to have a higher temperature than surrounding healthy regions [3]. Extremely high sensitivity can be achieved using evanescent fields obtained for instance in total internal reflection configuration. One of the typical approaches is to exploit surface plasmon polaritons. However, the fabrication of optical devices operating on surface plasmon polaritons normally involves expensive and complex fabrication processes. Alternatively, the evanescent field can be obtained using optical fibers. Even a low standard telecom fiber can be modified into a high sensitivity passive optical sensor. In addition, optical fiber simplifies optical sensor interrogation process. Here we discuss fused optical nano-fiber couplers fabricated using standard telecom fibers using the flame brushing technique.

One limitation of telecom optical fibers is the material they are made of. Silica glass has extremely good optical properties in the visible and the near-infrared. However, longer wavelengths are of particular interest for sensing as many different substances exhibit their characteristic absorption bands in the mid-IR. Unfortunately, silicate has strong multiphoton absorption above 2 µm, which in the high optical attenuation for silicate fiber. Thus, the search for optical fiber operating in the mid-IR has focused on the materials that have the high transmittance in the wavelength from 2 - 20 µm such as chalcogenide glasses, heavy metal fluorides, polycrystalline silver halides, sapphire, and tellurium halides [4-6]. However, the fabrication of solid optical fibers with these materials is extremely challenging and requires the novel approaches for achieving low loss propagation.

An alternative to the mid-IR optical fibers are hollow-core fibers (HCF) [7, 8]. The guided light in these fibers is confined within the hollow-core, greatly decreasing the influence of the material on the optical properties of fiber and releasing the optical performance from the limitation of material.

Here, we demonstrate a potential of 3D printing for the fabrication of mid-IR hollow-core optical fibers. The fibers are fabricated using a transparent Polyethylene Terephthalate Glycol (PETG) filament. Although, the PETG has very high material absorption in the mid-IR range, hollow core geometry of the fiber enables light guiding at wavelengths from 3.5 – 5 µm.

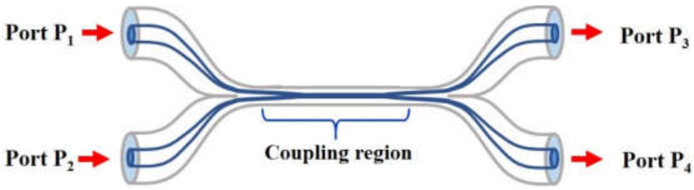

Figure 1. Schematic representation of the fused optical fiber coupler.

2. Optical sensing based on nano-fiber coupler

The fused optical fiber coupler is a passive optical component made by fusing two fibers together (figure 1). The fabrication process is relatively simple and low cost [9]. A typical coupler is composed of two input and two output ports separated with a coupling region. During fabrication the coupling region can be easily controlled by the fusion process. This allows to achieve couplers with various waist diameters. Optical microfiber couplers with a waist diameter smaller than a few microns exhibit a particularly strong evanescent field. The smaller is the diameter of the coupler the larger is the evanescent field in the vicinity of the coupler. In fact, couplers with the waist diameter of few hundred nanometers were successfully fabricated. In such optical element a large part of the electromagnetic field is located outside of the coupler. As a result, the light propagating through the coupler is strongly affected by the environment and its various properties. This feature was applied for various types of sensing.

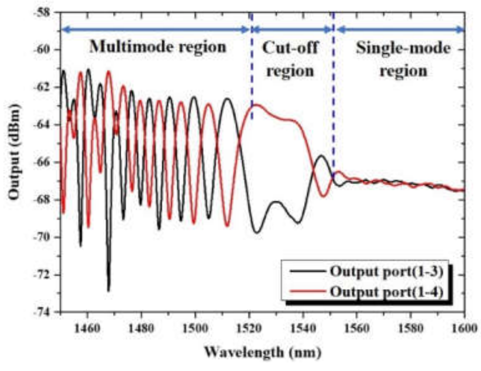

Figure 2. Output spectrum of the optical nanofiber coupler with a waist diameter of 560 nm.

The light propagation in the optical fiber coupler can be explained in terms of supermodes and their mutual interaction. In the coupling region, the supermode beating leads to a continuous change of the power distribution across the coupler resulting in a different power splitting at the output ports (figure

IOP Conf. Series: Journal of Physics: Conf. Series 1151 (2019) 012003 doi:10.1088/1742-6596/1151/1/012003

2). When the waist diameter of the coupler is below 1 micron essentially only two supermodes exist. Their interaction creates beating pattern which can be observed as fringes in optical spectrum. At waist diameter ~ 560 nm only one supermode exist at telecom third window. The modal optical paths depend both on the coupling region length and supermodes effective indices, which in turn are affected by the refractive index of the surrounding medium and by the temperature. That provides this structure its unique sensitivity for both temperature and refractive index changes.

The transition region which occurs before the couplers turns into single mode operation has recently attracted additional attention. One of the supermodes becomes weakly guided. As a result, the difference for the propagation constants of the two supermodes increases eliminating the typical beating pattern. In addition, the weakly guided mode is less efficiently excited and coupler transmission exhibits a plato. Recently it was demonstrated that this transition region from two mode propagation to a single mode propagation can be exploited for high sensitivity measurements of refractive index and temperature.

3. Nano-fiber coupler as a refractometer

The nanofiber coupler was fabricated from two telecom fibers (Corning SMF-28) using the modified flame brushing technique [9]. The fibers were stripped of their acrylic coating over a length of ~50 mm and twisted 1.5 turns around each other. The twisted region was fused together using a resistive ceramic micro-heater at an estimated temperature of ~1450 °C. The length of the uniform waist region was 4 mm with a waist diameter of 560 nm [10].

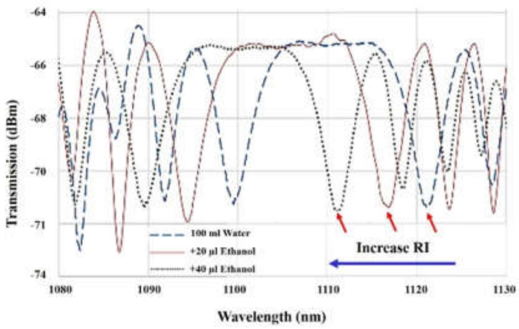

Figure 3. Transmission spectrum at the cut-off region of the NFC at different ethanol concentrations.

For measuring the refractive index of the medium, the waist region of nanofiber coupler was immersed small amount of liquid (around 100 ml). The incoherent white light was launched into one of the two input ports and one of the output ports was connected to an optical spectrum analyzer for monitoring of the transmission spectrum in real time. To demonstrate operation of the sensor we used a mixture of distilled water and ethanol. The ethanol concentration was gradually increased by 20 µL doses at each step (figure 3). In the experiment, the broad peak in the transmission spectrum was monitored with the changing of ambient RI to achieve a large dynamic range. As the ethanol concentration increased the transmission spectrum of the NFC shifted to shorter wavelengths indicating the increase of the ambient refractive index [11]. A record refractive index sensitivity of 4.80×10^5 nm/RIU was obtained. This is the highest reported refractive index sensitivity for all optical fiber-based refractometers.

4. Nano-fiber coupler as a thermometer

Temperature sensing with a nano-fiber coupler was implemented using the same experimental configuration as for the fabrication of this device. The microheater was used for setting different temperature around the coupling region. The exact temperature of the microheater was set by its current.

In our experiments the increase of current from 0.2 A to 1.2A resulted in raising the temperature within the microheater from T=84°C to T=661°C [10] (figure 4). The temperature was stabilized by maintaining the current for 15 min.

To evaluate the sensitivity of the nanofiber coupler thermometer, the three transmission wavelength dips closest to the cut-off region at the lowest temperature (84°C) were monitored. The wavelengths of dip1, dip2, and dip3 were at 1505 nm, 1495 nm, and 1487 nm, respectively (figure 4). When the coupler was heated, the refractive index of silica increased due to the thermo-optic effect and the increasing of coupler diameter and coupler length owing to the thermal expansion. These changes caused the shift of the destructive interference responsible for the dips to longer wavelengths. At the temperature of T= 478°C, dip1 moved into the cut-off region and the weak guidance of the odd supermode resulted in the disappearance of dip1. Similarly, dip2 disappeared at the T= 661°C.

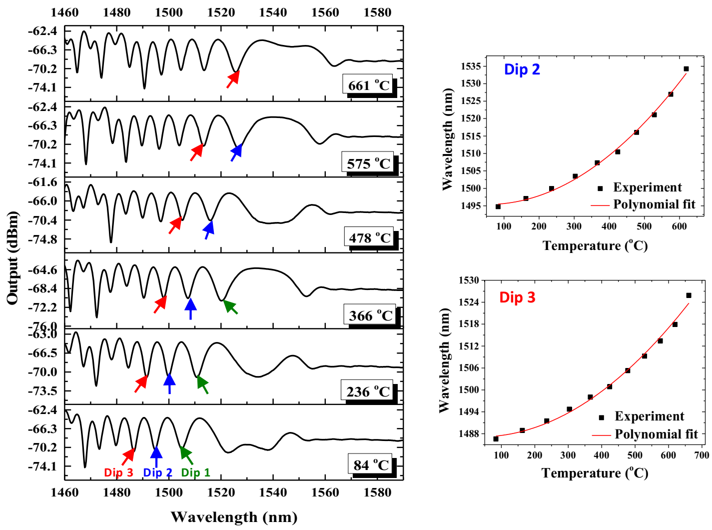

Figure 4. (Left) Optical nanofiber coupler transmission spectrum at different applied temperatures. (Right) Relationship between wavelength and applied temperature for wavelength dip 2 and dip 3.

5. Nano-fiber coupler as a DNA sensor

The change in the surrounding medium of the coupler affects the light guided inside the coupler, and this can be related to the quantity of DNA on the surface. The change in the index is evaluated from the wavelength shift of the coupler transmission fringes in comparison to the input. The ambient refractive index change of MFC produced by depositing the DNA is expected to be relatively large, therefore it is possible that the coupler dynamic range is exceeded. DNA hybridization to functionalize silica yields a refractive index change (Δn) in the range of ~10^{-5}-10^{-2} for DNA concentrations between 0.5–2 µg/mL [12]. By modelling wavelength shift the optimized dimensions of MFC for DNA sensor were found to be 2 µm for coupler diameter and 4 mm for coupling length.

6. 3D printed hollow core fiber for mid-IR

The optical fiber preforms were printed by using the FDM thermal 3D printer [13]. The material used to print the preform in this experiment was the polyethylene terephthalate glycol (PETG). The advantages of this material are its strength and durability compared with polylactic acid (PLA) filament. It is approved for food containers and tools used for food consumption. Thanks to the compatibility with organics materials and non-biodegradable of PETG, plastic hollow-core fiber based on PETG will has a potential for bio-sensing and chemical-sensing.

The manufacturing of the plastic fiber based on 3D printed preform is divided into three stages. The first step is to reduce the size of preform to pre-cane preform to the diameter ~ 30 - 50 mm. The second stage is to produce the fiber cane with the diameter ~ 15 mm. The last step is the pulling stage, the fiber was drawn from the cane (figure 5 (left)).

In order to evaluate the optical guidance properties of the hollow-core fiber in mid-IR, the broad band lamp with the wavelength of 450 -5500 nm (Thorlabs SLS202) was launched in to the fiber (L = 12 cm) using a bare-fiber adapter. The modal image was taken by launching the output light from the fiber into a midwave thermal infrared camera (Onca-MWIR-Insb) using a Znse objective lenses with the focal length of 18 mm (figure 5 (right)). This camera can be used to observe light in the wavelength from 3.5 – 5 µm.

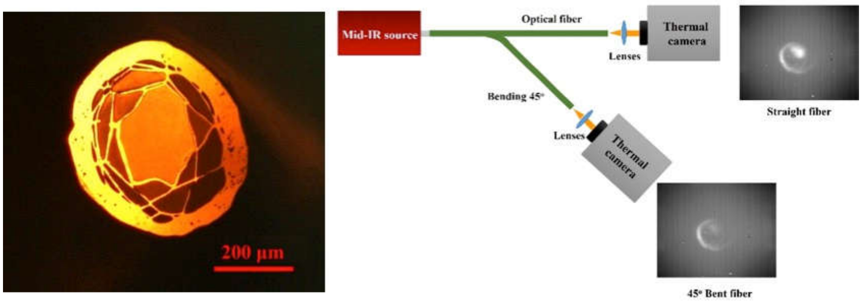

Figure 5. (Left) Cross-section of the produced hollow-core fiber from the 3D printed preform. (Right) Schematic diagram of the experimental setup for mid-IR modal imaging from the hollow-core fiber with different bending angle.

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