Sensors & Actuators: B. Chemical 275 (2018) 16–24

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Birefringence induced Vernier effect in optical fiber modal interferometers for enhanced sensing

Kaiwei Li[a], Nan Zhang[a,b], Nancy Meng Ying Zhang[a,b], Wenchao Zhou[c], Ting Zhang[a], Ming Chen[d], Lei Wei[a,b,*]

[a] School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore
[b] CINTRA CNRS/NTU/THALES, UMI3288, Research Techno Plaza, 50 Nanyang Drive, 637553, Singapore
[c] State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, 130033, PR China
[d] Center for Photovoltaic Solar Energy Shenzhen Institutes of Advanced Technology Chinese Academy of Sciences, Shenzhen, 518055, PR China

ARTICLE INFO

Keywords:
Optical fiber sensors
Optical microfiber couplers
Biosensors
Vernier effect
Human cardiac troponin T

ABSTRACT

We report a simple and effective method to improve the sensitivities of fiber-optic modal interferometers with birefringence induced Vernier effect. Taking optical microfiber coupler as an example, we study the sensitivity enhancement of a microfiber coupler for refractive index (RI) sensing both theoretically and experimentally in the RI range of 1.33–1.35 where bioassays are typically carried out. Numerical results show that by tracing the wavelength shifts of dips in the envelope formed by the Vernier effect, RI sensitivities can be improved by almost one order of magnitude compared to the sensors without the Vernier effect. Then we experimentally achieve an ultra-high sensitivity of 35,823.3 nm/RIU using a microfiber coupler with a width of 3.2 μm. More importantly, we apply this ultra-sensitive sensor to detect human cardiac troponin, and a limit of detection of 1 ng/mL is achieved. This sensor is simple in configuration andcan serve as a bio-photonic platform for clinical diagnostics environmental monitoring and food safety.

1. Introduction

Fiber-optic biosensors have been widely employed in the fields of clinical diagnosis [1,2] environmental monitoring [3] and food security [4,5] due to the merits of small footprint, short response time, immune to electromagnetic interferences, and capability of remote sensing. Thereinto, label-free fiber-optic biosensors are gaining increasing attention since the sensing procedure is simple, cost-effective, free of laborious labeling chemistry, and more importantly, they offer the capability for real-time monitoring of biochemical reaction [6,7].

Generally, the working principle of label-free optical biosensing is based on the modulation of the optical signals by the refractive index (RI) changes arising from the bio-recognition events at sensor surfaces [8]. Thus, fiber-optic RI sensors are the core element for label-free fiber-optic biosensors. Over the past decades, fiber-optic biosensors with different sensing mechanisms have been proposed and studied. For examples, optical fiber-based surface plasmon resonance (SPR) sensors [9] which are transformed from the golden standard prism-based SPR, have been well studied for both RI sensing and biosensing, and further evolved into several new sensing schemes [10,11]. Moreover, fiber-optic localized surface plasmon resonance (LSPR) biosensors which utilize the collective oscillation of the conduction electrons of nanoparticles, have also been well explored [12,13]. Evanescent wave based fiber-optic biosensor is another large class, which uses the evanescent wave of the guided modes to probe the bio-interactions at the bio-functionalized interfaces. Various sensing schemes such as microfiber interferometers [5,14], optical microfiber couplers (OMCs) [15,16], and long-period fiber gratings [6,17,18] have been adopted for both RI sensing and biosensing. These sensors are simple in structure, cost-effective in fabrication and free of the complicated process of depositing noble metallic films or nanoparticles on the fiber surface.

Although multifarious label-free fiber-optic RI sensors and biosensors have been proposed and studied, the development and further applications of fiber-optic label-free biosensors have been limited by challenges in sensitivity, specificity, reproducibility, etc., while the sensitivity is the most crucial one [19]. In fact, most of the reported fiber-optic label-free biosensors only show limited RI sensitivities of about several-hundred nm per refractive index unit (nm/RIU) to several-thousand nm/RIU [10,16,17,20], which is difficult to meet the required sensing performance in biosensing [21]. To address the challenge of sensitivity, several methods have been developed. For example, the modal dispersion turning points have been discovered in long-

---

[*] Corresponding author.
E-mail address: wei.lei@ntu.edu.sg (L. Wei).

https://doi.org/10.1016/j.snb.2018.08.027
Received 27 January 2018; Received in revised form 29 July 2018; Accepted 6 August 2018

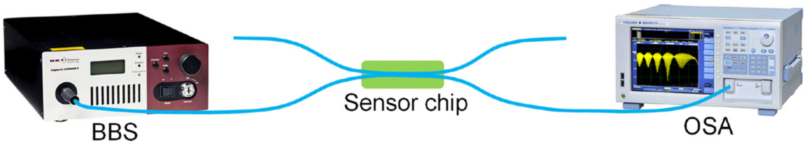

Fig. 1. Experimental setup for optical measurements.

period fiber gratings, optical microfiber interferometers and OMCs, benefiting from which the RI sensitivity can be improved to tens of thousands nm/RIU [15,22–25]. The Vernier effect has also been utilized in a cascaded optical microfiber ring resonator, and thanks to this effect, the RI sensitivity can be further improved [26]. These studies not only offer guidelines for developing ultra-sensitive fiber-optic RI sensors but also reveal the unprecedented potentials of employing such sensors for biosensing applications [27,28].

Though several pioneer studies on sensitivity improvement either by optimizing sensor parameters or by introducing new mechanisms have been reported. The Vernier effect resulted from the superposition of two modal interferences in two orthogonal polarizations in a birefringent optical fiber has not been explored for sensing enhancement. In this study, we take the OMC as an example and study the Vernier effect and sensitivity enhancement both theoretically and experimentally. We also draw a comparison of the sensing performances between the OMCs with and without the Vernier effect. Owing to the Vernier effect, the RI sensitivity can be increased by nearly one order of magnitude. As a proof-of-concept, we implement this OMC sensor into biomarker detection. Here, we employ human cardiac troponin T (cTnT) as a model analyte because it is an acknowledged biomarker for the diagnosis of acute myocardial infarction [29]. Again, we demonstrate that with the help of the Vernier effect, the wavelength shift response induced by biomolecule binding can be amplified and the sensing performance can be significantly improved. Compared with previously reported OMC sensors that can reach the equivalent ultrahigh sensitivities by utilizing the dispersion turning point at single polarization state [15], the required waist width is a bit larger, which make the sensor more robust and stable to use.

2. Experimental

2.1. Reagents and materials

All experiments are performed with reagents of analytical reagent grade. NaOH solution is prepared by dissolving NaOH powder (Alfa Aesar) in deionized water (DI water). Poly (allylamine) (PAA) solution (Mw ~65000, 10 wt. % in H_2O) is purchased from Sigma-Aldrich (Singapore). Phosphate buffered saline (PBS, pH 7.4) solution is purchased from Vivantis (USA). Natural human cTnT protein and cTnT antibody are purchased from Abcam (Cambridge, MA). Bovine serum albumin (BSA) are obtained from Aladdin (Shanghai, China). RI solutions with different RI values are prepared by dissolving sodium chloride (NaCl, Affymetrix, 99 + %) in DI water to different concentrations. The RI values are measured using a digital refractometer (Reichert, USA). Standard single mode optical fibers (SMF-28e) are obtained from Corning Inc. (New York, USA).

2.2. Fabrication of OMCs

The OMCs are fabricated with standard single-mode optical fibers (Corning SMF-28) through a heating and pulling method [30]. Generally, two bare optical fibers are double twisted, along in parallel and fixed onto the elongation stages. A flame is used to heat the fibers and the width of the heating region is ~2 mm. Two electric motors pull the fibers in opposite directions at a controlled speed. To obtain couplers with long uniform waist and desirable length, the flame is scanned by a motor with controlled scanning distances. Thus, the waist width can be controlled by varying the duration of the tapering process. As the optical guiding property of the OMC is very sensitive to the width and length of the waist region, which requires the tapering setup to be quite sophisticated to achieve OMCs with the identical output spectra. Here, we employ an in-line monitoring method to monitor the output spectra in real-time during the fabrication process, which would increase the success rate considerably. To keep the coupler stable and robust, we fix the fabricated OMC inside a fluid channel on a specially designed Teflon sensor chip.

2.3. Experimental system for optical measurement

The experimental setup used for optical measurement is shown in Fig. 1. A supercontinuum white light source (SuperK COMPACT, NKT Photonics) with the wavelength range of 450–2400 nm is used as a broadband source (BBS). The output transmission spectrum at the throughput port is acquired by an optical spectrum analyzer (OSA, Yokogawa AQ6370C) with a wavelength resolution of 0.02 nm.

2.4. Surface modification and antibody immobilization

The process of fiber surface modification and antibody

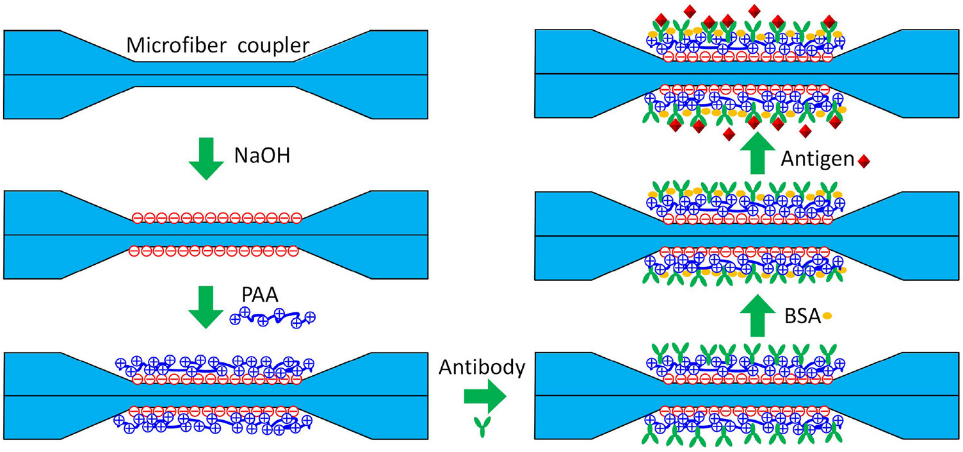

Fig. 2. Schematic diagram of fiber surface modification and antibody immobilization.