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# Interferometric-type optical biosensor based on exposed core microstructured optical fiber

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ABSTRACT

This work presents a novel biosensor using the multimode interference effect in an exposed core microstructured optical fiber (ECF). In this work biotin molecules are immobilized onto the ECF core surface to serve as the capturing probe for streptavidin, the target molecules. Since each distinct guided mode in the ECF interacts with the surrounding medium differently, the interference between any two specific modes will experience a fringe shift (or phase change) upon a change in the refractive index (RI) of the surrounding medium, or a localized RI change on the surface of the ECF core as a result of a biological binding event. In our experiment, the interferometric sensing platform was realized by splicing a section of ECF with lead-in and lead-out single mode fibers (SMFs). An interference pattern is obtained in the transmission spectrum as the result of multiple excited modes (excited and re-collected at the lead-in and lead-out splicing points) propagating in the ECF with different propagation constants. The interference pattern is non-uniform, indicating that there are more than two modes involved. Fast Fourier transform (FFT) is used to separate individual interference patterns that contribute to this complex spectrum and monitor their phase changes upon RI variation of the surrounding medium. In this way multiple RI sensitivities can be realized because each spatial frequency possesses a distinct sensitivity with respect to the surrounding RI. The operation of this device was validated by measuring the phase changes that occur when the sensing platform was subjected to solutions of different RIs or functionalized with different molecules. A biosensor was demonstrated based on this novel platform using biotin as the capturing probe to specifically detect streptavidin with low non-specific adsorption. The proposed platform is reliable, cost-effective, and offers a potential label-free biosensing alternative to the widely used surface plasmon resonance (SPR) technique.



## 1. Introduction

Cost-effective and stable biosensing platforms are sought after for a wide range of applications such as medicine, agriculture, environmental monitoring, food control, safety, and security monitoring. There have been numerous reviews describing current and potential applications of biosensing devices and the preferred features of such a device [1–6]. Pathogen detection and identification is one such application [7]. This area is important in surveillance and health monitoring and also for diagnostics to facilitate appropriate treatment choices. The motivation for this work is the application of biosensors for pathogen monitoring in agriculture systems. For biosensors to aid in the progression of plant pathology and the increased efficiency of surveillance and/or diagnostic protocols in agriculture, a portable system capable of remote sensing is desired. In-field devices amenable to easy manual use for minimally trained users, or compatible with an autonomous detection system, require an all-in-one sensor-transducer-display arrangement that is not reliant on excessive sample preparation or separation steps. Ideally the biosensor would detect the target (or targets if multiplexed detection is enabled) in an unprocessed sample with high specificity and sensitivity. To minimize sample preparation steps, as well as avoid problems associated with quantum yield losses and

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costs involved in colorimetric and fluorescent tags, a label free sensor platform would be advantageous. Label-free optical biosensors based on various optical effects such as surface plasmon resonance, optical cavities, interferometry, and fiber gratings have been widely investigated to date [8].

Optical interferometry is a well-established technique for analyzing changes in optical thickness or refractive index, and thus is a well-justified option for use in label-free biosensing. Whilst the majority of optical interferometric biosensors have been implemented with optical waveguides [9–11], optical fiber based implementation can offer an important addition as the fibers can be fusion-spliced together, leading to an all-fiber configuration. This eliminates the mechanically-induced errors often associated with optical alignment in bulk-optic systems and thus is particularly attractive for applications requiring portability such as in-field surveillance of pathogens. Optical fibers also offer a great potential for increased sensitivity through long interaction lengths, provided optical losses can be managed [12]. However, to facilitate interaction of the light propagating in the fiber core with the analyte for use in biosensing, chemical etching [13] or tapering [14] typically has to be carried out on the fibers, leading to inferior mechanical properties. More advanced designs of optical fibers such as photonic crystal fiber [15] or suspended core microstructured fiber [12,16] can allow direct interaction of the light in the fiber core with the analyte solution flowing through the air-holes running along the fiber core. However, it is difficult to realize an all-fiber configuration in such cases because the air-holes need to be open to allow the flow of the solution through these holes.

To solve this issue we have developed a special type of optical fiber called exposed-core microstructured optical fiber (ECF) [17–19]. Of its many advantageous characteristics compared with conventional microstructured optical fibers, the most distinctive one is that ECF can be spliced with standard SMFs to form all-fiber configuration [20], while the light propagating in the core still has direct contact with analyte suspended in the surrounding medium thanks to the exposed core. Here we propose and experimentally demonstrate a novel platform for label-free biosensing that utilizes the multimode interference effect in an ECF. We use Fourier analysis to separate the individual interference patterns from the raw complex pattern obtained due to the fact that more than two modes are excited in the ECF, enabling the proposed platform to exhibit multiple and selectable sensitivities with respect to the surrounding refractive index (RI). Due to their very well known strong binding affinity [21], biotin and streptavidin are chosen as the receptor and target molecules to demonstrate the biosensing capability of the platform. The proposed platform is not restricted to just biotin-streptavidin, other types of receptor-target pairs such as cells, cell-surface proteins, enzymes, antibodies, and oligonucleotides could also be used on the proposed platform for developing biosensors for different purposes.

## 2. Methods

### 2.1. Multimode interference in exposed core microstructured optical fiber and the sensor's operational principle

ECF is a special type of microstructured optical fiber whose suspended core is exposed to the surrounding medium thanks to an open side of the ECF cladding [18]. It is typically fabricated by drilling holes along a silica rod [19] to form a suspended core fiber preform. One air hole of the preform is then cut or polished open, exposing the core to the surrounding medium on that side. The preform is then drawn with well-controlled pressure inside the holes into an ECF [20]. In this way, even if the ECF is spliced at both ends, liquid containing analyte can still have direct access to the evanescent field of light propagating along the core. Due to the high numerical aperture of ECF (glass–air or glass–water interfaces) and the difficulty in fabricating the ECF core small enough to support a single mode regime guidance (which requires sub-micrometer core diameters), the ECFs that have been developed to date are multimode fibers.

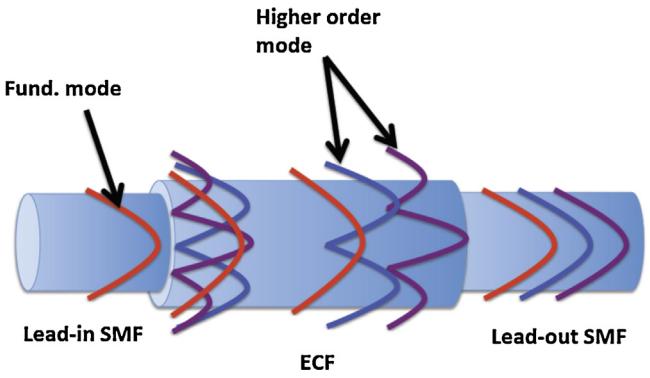


**Fig. 1.** Schematic diagram of the multimode interference that occurs in multimode ECFs. The fundamental mode of the lead-in SMF excites three different modes in the ECF which, after propagating through the ECF, converts again into the fundamental mode of the lead-out SMF but with a certain phase delay between each other. These phase delays result in an interference pattern in the transmission spectrum.

To estimate the number of modes that are supported by the ECF we have performed a simple calculation using a step-index optical fiber model, which we have used previously as an approximation for suspended-core microstructured optical fiber [22]. Using the refractive index values for silica glass as the core, air as the cladding, and a core diameter of 7.5 μm, a step-index fiber can propagate 68 modes. However, only a small subset of these is likely to be involved in the interferometer, depending on the coupling conditions into and out of the ECF.

Each mode propagates in the ECF core with a slightly different group velocity. The principle of operation can therefore be explained by referring to the schematic diagram of the SMF–ECF–SMF configuration in Fig. 1. At the splicing point between the lead-in SMF to the ECF, light from the fundamental mode of the lead-in SMF will be decomposed into different propagation modes of the ECF. After propagating through the ECF, those modes will recouple into the fundamental mode of the lead-out SMF experiencing a phase delay between each other due to different propagation constants. Thus an interference pattern can be formed in the transmission spectrum of the structure. Assuming negligible dispersion over a narrow wavelength bandwidth, the power after propagating the SMF–ECF–SMF structure can be described as:

$$I = \left\{ \sum_{i=1}^{n} \sqrt{I_i} e^{i\beta_i L_{\mathrm{ECF}}} \right\}^2 = \sum_{i=1}^{n} I_i + \sum_{i \neq j=1}^{n} \sqrt{I_i I_j} \cos\left[ \frac{2\pi}{\lambda} \left( n_i^{\mathrm{eff}} - n_j^{\mathrm{eff}} \right) L_{\mathrm{ECF}} \right] \quad (1)$$

where $I_i$ and $n_i^{\mathrm{eff}}$ are the power portion carried in the corresponding $i$th mode of the ECF and its effective index, respectively. $L_{\mathrm{ECF}}$ is the ECF length and $\lambda$ is the wavelength. It can be seen from Eq. (1) that in the general case the resultant interference pattern is a complex spectrum in the wavelength domain as it is the superposition of many individual interferences formed by a specific pair of excited modes $\{i,j\}$ in the ECF. Since $n_i^{\mathrm{eff}}$ is highly sensitive with changes the ECF's cladding index which, in our particular case, is the ambient refractive index on the exposed core side as well as localized RI change on the ECF's core surface due to a biological binding