

Designing a miniaturized photonic crystal based optofluidic biolaser for lab-on-a-chip biosensing applications

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ABSTRACT

Optofluidic biolasers indicate promising potential and properties that make them highly competitive in the development of state-of-the-art biophotonics technologies. One of the bright outlooks and perspectives that could have a profound impact on the current developing situation and trend of such a new found technology is the photonic crystal based optofluidic biolaser. In this article, we theoretically propose a new lab-on-a-chip design of slotted photonic crystal optofluidic biolaser. Within this scheme, the air slot and medial air holes of the miniaturized photonic crystal slab are infiltrated with organic dye solution, acting as the laser gain region. This structure provides a facility for incorporation of the biological molecules in those fluidic gain mediums. Simulations show that, in addition to the proper lasing characteristics, like the spectral linewidth of 0.27 nm and power conversion efficiency of 26%, the proposed device is highly sensitive to the subtle biological changes that may occur in its cavity and shows the sensitivity of 277 nm/RIU.

1. Introduction

Synergic combination of nanophotonic and microfluidics has led to the emergence of a new research area known as optofluidics. Incorporation of optofluidics in a lab-on-a-chip (LOC) system offers a new way of implementing miniaturized devices that can open new frontiers for bioanalytical technologies. In fact, optofluidics LOC devices have a number of particular characteristics and functionalities that give them competitive advantages over the conventional optical biosensing devices. Furthermore, chromatography and electrophoresis as two traditional analytical chemistry technologies have been implemented by use of optofluidic devices [1]. On this basis, a number of optofluidics devices with biomolecular sensing applications has proposed over the past decade [2–5]. They are mainly fluorescence-based biosensors that work on the monitoring of the spectral shifts stemming from the refractive index that is altered by the binding of biomolecular targets to bio-receptors. The major drawbacks of the fluorescence-based biosensing devices are their weak sensing signals, background noise and broad spectra [6]. An effective approach to overcome these drawbacks that have been recently proposed is to use stimulated emission instead of fluorescence in optofluidics sensing devices [7]. In this approach, the target analytes are directly inserted into a laser cavity that provides the

amplification of the sensing signal, improving the sensitivity excessively. Accordingly, a new type of optofluidic devices has emerged recently that is known as optofluidic biolaser. In other words, the optofluidic biolaser is a new class of lasers that arise from the incorporation of biochemical or biological molecules in the fluidic gain medium [6]. Optofluidic biolasers based on microfluidic gain medium [8,9], the cytosol of living cells [10] and interstitial tissue [11] have been proposed in the past couple of years.

Optofluidic biolasers have two main advantages over conventional optical biosensors: (i) the interaction of light with a molecular particle that is placed inside a cavity is enhanced vastly. Hence, the sensing signal derived from varying the light characteristic in response to the light-biomolecule interaction is amplified; (ii) the laser characteristics such as input power thresholds, output power intensities, and spectra are impressionable by the subtle biological changes taking place in the gain medium. Therefore, in these devices, monitoring of the lasing characteristic and its spectral shift can be beneficial. In recent years, a number of optofluidic lasers with various types of optical cavities based on ring resonators [12], distributed feedback (DFB) gratings [13], and Fabry-Perot [14] have been proposed and implemented. Some of them are used in biomolecular analysis [7] and biosensing applications [15]. This biotechnology is in its infancy, now, and one of the bright outlooks

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and technological perspectives that could have a profound impact on the current developing situation and trend of such a new found technology is the photonic crystal (PhC) based optofluidic biolaser [6]. PhC cavities have beneficial characteristics such as high quality (Q)-factor and small mode volume that makes them highly sensitive to environmental changes that may occur in the cavity. Despite the challenges that the design of a PhC-based optical cavity is facing, they are particularly desirable for low-copy-number biosensing [3]. In fact, each individual target pathogen occupies a large portion of the active sensing region, and hence enhancing the device sensitivity. The main challenge in designing and operating these devices is to exploiting fluidic gain medium within the PhC architectures in such a manner that effective excitation of gain medium can be realizable.

In our earlier work reported in Ref. [16], we have presented the design procedure for an optofluidic biolaser, consisting a defect-free Al_2O_3 based PhC whose medial air holes are selectively dye-infiltrated to provide an active heterostructure cavity. The main aim of that work was to enhance the detection limit for a single virus. There, we have shown that the biolaser can detect a sole virus with a radius as small as 13 nm. However, it fails to detect when the virus concentration is high. To overcome this shortcoming, here, we propose a new design considering a slotted PhC waveguide whose medial section is dye-infiltrated adding that is proved to be capable of detecting a high concentration of bioparticles. Within this scheme, the slot and a number of the PhC holes are selectively infiltrated with the organic dye solution that acts as the gain medium of the proposed ultra-compact biolaser. This fluidic gain medium and the LOC structure, facilitate the incorporation of the biomolecules and biorecognition molecules in the gain medium through the chip surface. We simulated the effects of one kind of nanoscale pathogen on the device performance to scrutinize the capabilities of our design in biosensing applications.

2. Materials and methods

2.1. Structure and materials

The structure model of the proposed LOC optofluidic biolaser is schematically depicted in Fig. 1. This biolaser encompasses a slotted 2D PhC structure with a triangular lattice of constant $a = 410$ nm, slot width of $0.32a$ and air holes of radii $r = 140$ nm devised in a 230 nm thick suspended slab of fused silica. Its cross-sectional area is 14 periods ($5.8 \mu\text{m}$) long and 6 periods ($2.6 \mu\text{m}$) wide. An air slot is introduced into this PhC slab by removing the middle row of holes along the Γ -K direction. These geometrical parameters are initially inspired by our previous experimental and theoretical works on PhC slabs [17,18] and then exactly determined by use of particle swarm optimization (PSO) method that is derived from the social behavior of flocks of birds that has been broadly used for various types of advanced design optimization problems as well as nanophotonic designs [19–21]. The slot and midsection holes of this ultra-compact PhC chip are infiltrated with the lasing dye solution, including Rhodamine 6G (Rh 6G) dissolved in Methanol at a concentration of 10^{-4} mol/liter. It is worth noting that, the selective infiltration of PhC slab holes by optofluidics have been experimentally demonstrated in earlier works [22–24]. Pumping the lasing dye is accomplished via a TE polarized optical source with 6 ns pulses of wavelength $\lambda = 532$ nm, placed in close proximity of the chip surface. As far as the coupling an external optical pump into a narrow resonance mode of the PhC slab is concerned, a couple of research groups have demonstrated the possibility of achieving 84% [25], 94% [26] and 98% [27,28] coupling efficiencies, employing the evanescent light coupling between a micro tapered fiber and a PhC slab. Nevertheless, in our simulations, we have used a less demanding efficiency of 85%.

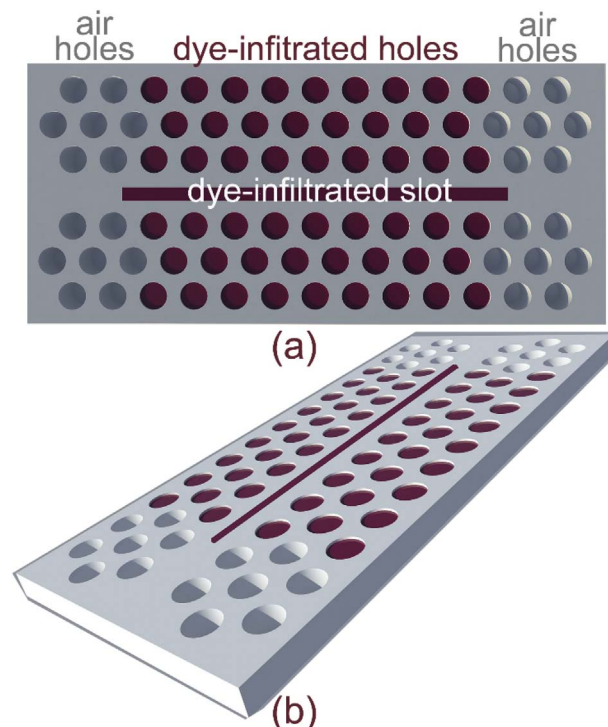


Fig. 1. (a) Schematic top view and (b) 3D perspective of the proposed PhC optofluidic biolaser.

2.2. Operation mechanism

Through dye-infiltration of the slot and medial holes, the midsection effective refractive index becomes greater than those of the adjacent outer regions. Due to this double-heterostructure configuration, the photonic band gap of the midsection differs from that of the two adjacent sections and hence, a particular range of wavelengths can propagate in the medial region that is not permitted to propagate in its neighboring regions. Consequently, the Fabry-pérot-like modes can resonate in the middle section of the designed structure that acts as a Fabry-pérot cavity, if the condition $L = m\lambda_0/2n$ is fulfilled, where λ_0 is the resonance mode wavelength, L is the length of the dye-filled region, n is the medium effective refractive index and $m = 1, 2, 3, \dots$ is an integer. Under these conditions, as illustrated in Fig. 2, the cavity is designed in such a manner that supports two resonant modes in the range of 520–580 nm. This spectrum shows the two possible cavity resonance modes at 532 and 565.7 nm with Q-factors of 5.3×10^4 and 1.7×10^4 . When the gain medium (the organic dye solution) is pumped optically, at the shorter wavelength, the pump light resonates within the cavity and its interaction with the organic dye solution increases

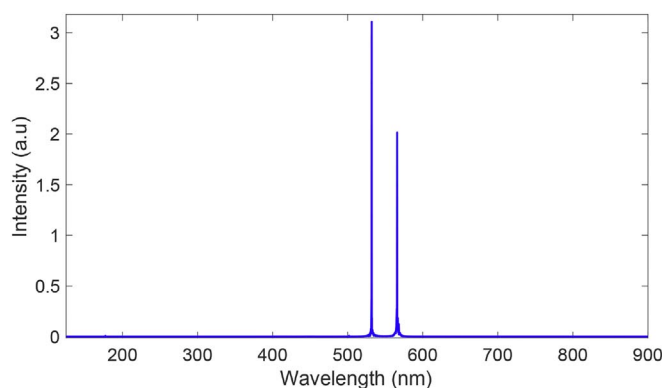


Fig. 2. The spectrum of the cavity resonant modes.

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