Wide Dynamic Range Sensing in Photonic Crystal Microcavity Biosensors

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Abstract: Typical L-type photonic crystal (PC) microcavities have a dynamic range of approximately 3-4 orders of magnitude in biosensing. We experimentally demonstrated that multiplexing of PC sensors with different geometry can achieve a wide dynamic range covering 6 orders of magnitude with potential for 8 or more orders with suitable optimization.
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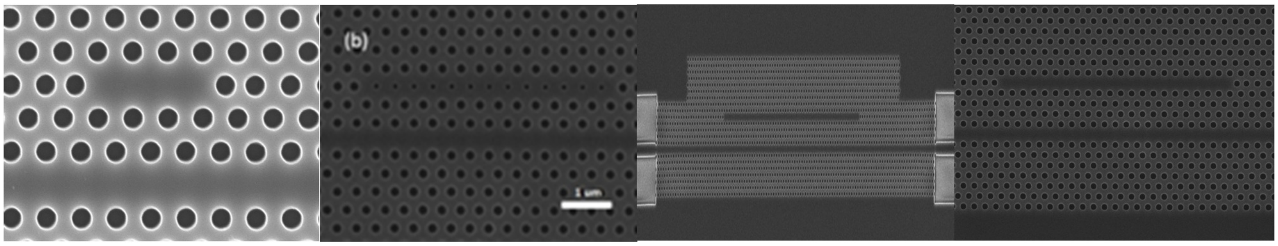
In several applications in biosensing, particularly in drug discovery and therapeutic drug monitoring, it is essential to have sensors that can register concentrations of analytes over a wide dynamic range of at least five orders of magnitude. Recently, numerous optical devices have been investigated for label free detectors, such as ring resonators [1], surface plasmon resonance (SPR) [2], wire waveguides [3], and photonic crystal (PC) microcavities [4] . Among all the label free detectors and optical devices, photonic crystal (PC) has provided the unique characteristics with slow light effect which enhance the interaction between traveling light the analyte. The slow light effect in PC sensors has been investigated by our group in numerous applications such as near-IR absorption chemical and bio-sensing [6], gaseous contaminant detection [7], and two-dimensional PC biosensors for chip-integrated microarray applications in proteomics [8]. However, each PC microcavity sensor in a triangular lattice PC, that we have demonstrated, L3, L13 or L55 where Ln represents that the PC microcavity is formed by removing n air holes in a row along the Γ K direction, the PC cavity being located next to a W1 photonic crystal waveguide (PCW)), have a dynamic range of approximately 4 orders of magnitude, with the linear region of the S-shaped concentration versus wavelength shift curve being linear over just 3 orders of magnitude. Integrated optics however provides the unique ability to multiplex sensors on the same chip that can be measured simultaneously at the same time with the same sample due to the miniature dimensions of the sensors. In this paper, we experimentally demonstrate a novel design for achieving wide dynamic detection range whereby multimode interference (MMI) devices are multiplexed with photonic crystal microcavities of different geometries, each covering a different concentration range and thereby achieving a wide dynamic range of 7-8 orders of magnitude.

We fabricated PCWs on silicon-on-insulator (SOI) devices with a 250nm top silicon layer, a 3μm buried oxide layer. Fig. 1 shows a scanning electron micrograph (SEM) of the individual PC sensors. Four distinct sensors with four different geometries, L3, L13H, L55 and L21 are fabricated where L13H denotes that defect holes that are smaller is size than the radius of the holes in the bulk PC lattice are interrogated. The four PC microcavities are layed on the 4 arms of a 1×4 MMI in designs previously demonstrated [4, 9]. The respective SEMs are shown in Figs. 1(a)-(d). With L3, L55 and L21, the adjacent coupling PCW is of the W1 which indicates that the width of PCW is $\sqrt{3}a$, where a is the lattice constant. For L13H, the width of the coupling PCW is $0.935\sqrt{3}a$. The PC consists of a triangular lattice of air holes with lattice constant a=392.5 nm. The air holes have radius $r=0.277a$. The air hole diameter is $d=0.53a$, and silicon slab thickness is $h=0.63a$. The diameter of defect holes in L13H is $0.4d$ and thus indicated as L13H0.4 in Fig. 1 and Fig. 2.

A typical transmission spectrum of the four different PCWs with PC microcavities of different geometry coupled to the PCW in water is shown in Fig 2(a)-(d). The sensor works on the principle that refractive index changes in the vicinity of the PC microcavities lead to a shift in the resonance wavelength, the sensitivity of the sensor determined by the magnitude of the resonance wavelength change for a given change in refractive index in chemical sensing, or a given change in biomolecule concentration in biosensing. Bio sensing experiments were conducted by selecting biotin as the probe immobilized to the patterned silicon substrate and avidin as target protein. In contrast to our previous demonstrations in lung cancer cell line lysate detection where each PC microcavity on the four arms of the MMI were of the same geometry and were immobilized with different probes to show both sensing and specificity of detection[9], in this paper, all the four PC microcavities on the 4 arms were immobilized with the same probe. The resonance shift as a function of concentration was measured for each individual PC microcavity, as shown in

Fig. 3. The dashed red line indicates the minimum detection limit for each PC microcavity, limited by the wavelength resolution of our optical spectral analyzer of +/- 0.02nm. The detection range is from 10^{-15} to 10^{-9} was achieved by combining the individual ranges from the different PC microcavities.



(a) *(b)* *(c)* *(d)*

Fig 1. SEM image of PC microcavities coupled to PCW in (a) L3 (b)L13H0.4 defect hole cavity (c) L55and (d) L21 PC microcavities

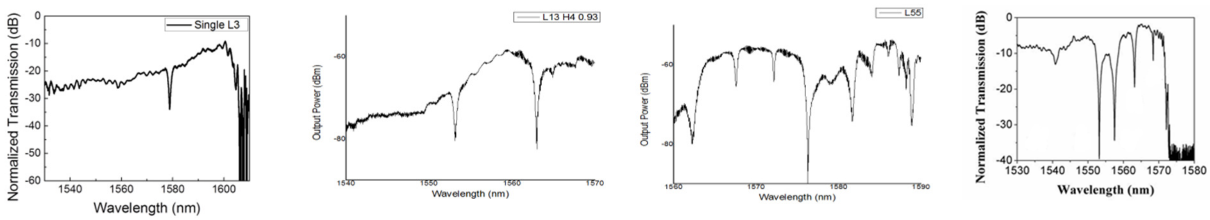


Fig 2. Transmission spectrum of (a) L3 (b) L13H0.4 defect hole cavity (c) L55and (d) L21 PC microcavities

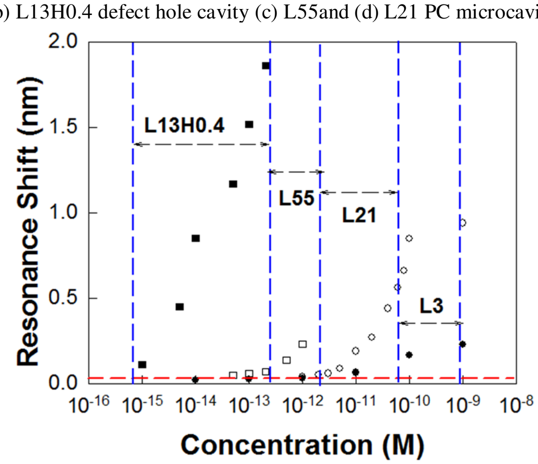


Fig. 3. Bio sensing spectral shifts in L13, L21, L55 and L13 defect holed cavity.

In summary, we demonstrated 6 orders of magnitude dynamic range concentration detection by using PC microcavities of different geometry. Additional methods to increase the dynamic range include increasing the diameter of the defect holes in L13H PC microcavity, increasing the diameter of holes in the bulk lattice as well as reducing the size of the PC microcavity to below L3. Spectral characterization of such PC microcavities has been completed and biosensing data, integrated on a 1×4 MMI will be presented in the future with an anticipated 8 orders of magnitude dynamic range.

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