Experimental detection of 1pico-molar concentration from high-Q photonic crystal microcavity biosensors

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***Abstract*—We experimentally demonstrate a photonic crystal microcavity biosensor with 1pM sensitivity. Radiation loss engineering for high Q and increased mode overlap with analyte are combined to achieve the highest sensitivity in silicon-on-insulator platform.**

Keywords-Photonic Crystal Microcavity; Biosensor; Chemical Sensing; Photonic Crystal Waveguide

I. INTRODUCTION

Photonic crystal (PC) microcavities, because of its compact size (of the order of a few square microns in surface area) and high sensitivity, have attracted significant interest in bio-sensing. The working mechanism is based on transducing the specific binding of the biomolecule of interest to its conjugate biomolecule receptor bound to the optical device into an optical signal. Compared to other competitors such as ring-resonators [1, 2], wire waveguides [3] and surface plasmon resonance (SPR) [4], PC microcavities have higher sensitivity due to its slow light effect and a larger optical mode overlap with the analyte within compact optical mode volume. It is possible to design sensors with ultra-small mode volumes [5]. However, when fabricating a microarray, the minimum spacing between resonators in an array when each sensor is coated with a unique biomolecule receptor is determined by the size of the dispensed spot in ink-jet printing or the width of the microfluidic channel in other instances. We recently demonstrated that the size of an ink-jet dispensed spot for coating the target receptor on the specific microcavity is 35μm with a minimum spacing of 50μm. In addition to the above engineering limitation, it is also known that radiation losses increase as the resonator size decreases. We showed recently that slightly increasing the sizes of PC microcavities can enhance the resonance quality factor Q as well enhance the optical mode overlap with the analyte, thereby leading to higher sensitivity [6].

In this letter, we investigated the limits to increasing the device sensitivity within the biomolecule patterning engineering limits. Chemical sensing experiments were done to characterize the device sensing ability, followed by bio-sensing. We experimentally detected sensitivity one order of magnitude lower than our previous results.

II. DEVICE PRINCIPLES AND EXPERIMENTS

A. Device Principles

The device investigated is a L_n type PC microcavity side coupled to a W1 PC waveguide (PCW), where *n* denotes the number of missing air holes along the Γ–K lattice direction in a triangular lattice PC and W1 demotes that the width of the PCW is √3a. A scanning electron micrograph (SEM) of a typical PC microcavity is shown in Fig. 1.

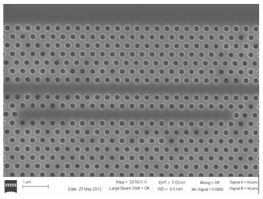

Figure 1. SEM of L21 PC microcavity side coupled to a W1 PCW.

The total quality factor Q_T of the resonance mode of a PC microcavity side coupled to a PCW, which is related to the photon lifetime τ_p, at frequency ω by $Q_T=\omega\tau_p$ is given by

$$\frac{1}{Q_T}=\frac{1}{Q_i}+\frac{1}{Q_R}+\frac{1}{Q_{WG}} \quad \text{..... (1)}$$

where $Q_R=\omega\tau_R$ and $Q_i=\omega\tau_i$, τ_R and τ_i represent the radiation loss and intrinsic cavity loss respectively. τ_R is given by:

$$\frac{1}{\tau_R}=\frac{P_R}{W_E} \quad \text{..... (2)}$$

where P_R denotes the total power radiated by the cavity and W_E denotes the stored energy in the cavity which is proportional to the cavity mode volume. Hence a method that reduces P_R and increases W_E will decrease the radiation loss from the cavity and hence increase the effective Q. A high Q implies that the light is trapped for a longer period of time in the cavity and hence interacts longer with any analyte in the vicinity of the photonic crystal microcavity. In addition, since W_E is proportional to the optical mode volume, a higher W_E leads to potential for larger optical mode overlap with the analyte which also contributes to higher sensitivity. We recently demonstrated 10pM detected sensitivity with L13 PC microcavities. [7] However, a longer cavity leads to increased leakage from the cavity to the PCW leading to lower Q_{WG} which lowers the effective Q_T. A high Q_T is desirable since it enables smaller *changes* in concentration to be detected. Q_{WG} can be increased by moving the PC microcavity more periods away laterally from the PCW. A L21 PC microcavity with 21 missing air holes is being investigated with increasing number of periods between the PCW and the PC microcavity to achieve higher sensitivity as well as high Q_T.

B. *Device Fabrication and Characterization*

The devices were fabricated on SOI wafer with 250nm top silicon layer and 3μm buried oxide. PC waveguides, PC impedance tapers to minimize reflection loss, and strip waveguides are patterned in one step with e-beam lithography followed by reactive ion etching. Devices were tested with transverse electric (TE)-polarized light. The characteristics including resonance Q and bulk sensitivity are first analyzed with water and glycerol (n=1.46) as the ambient medium. Figs. 2 (a) and (b) show experimental transmission spectra from W1 PCWs with coupled L13 and L21 PC microcavities in water. In Figs. 2 (c) and (d), transmission of the resonance closest to the band edge for L13 and L21 PC microcavities in water and in glycerol are shown.

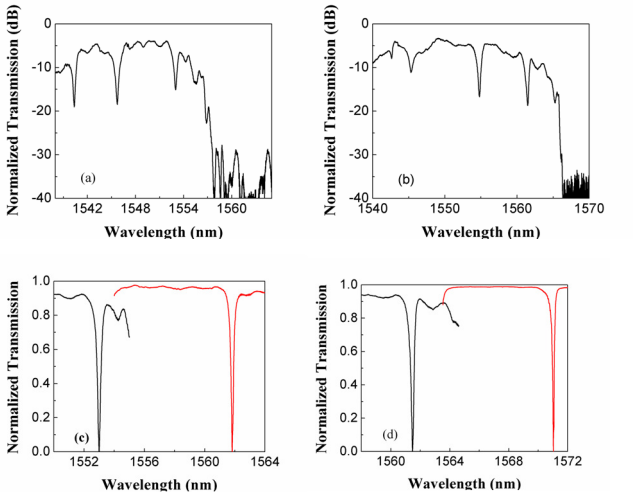

Figure 2. Experimental W1 PCW transmission spectrum in water with coupled (a) L13 and (b) L21 microcavities. Experimental spectra showing shift of resonance mode closest to the band edge in (a) and (b) in (c) and (d) respectively in water (black) versus glycerol (red).

To enable the biosensing experiments, the devices were firstly functionalized by the same process as in ref. [7]. After overnight incubation and washing, the device is coated with bovine serum albumin (BSA) to prevent any non-specific binding and washed 3 times with PBS. Probe protein Avidin (67kDa) solution was directly dispensed from a micro-pipette. During biosensing measurement, after each concentration of probe protein binding, the device is washed three times in PBS.

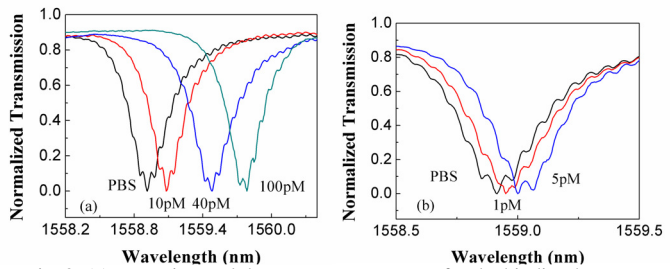

Fig. 3: (a). Experimental drop resonance spectra for the binding between Avidin to Biotin (K_d~10^{-15}M) between 0pM to 100pM and (b) at the lower concentration range between 0pM and 5pM.

Experimental resonance transmission spectra observed when avidin binds to the target biotin is shown in Fig. 3(a). The lowest concentrations are shown separately in Fig. 3(b) for clarity. Fig. 4 plots the resonant wavelength shift $\Delta\lambda$ as a function of concentration.

C. *Discussions*

Compare L13 and L21 PC microcavities, in chemical sensing, the shift for L13 is 8.9nm, (68nm/RIU), while the L21 shift is 9.6nm (74nm/RIU). In integrated nanophotonic structures where the optical mode is very closely confined to the devices surface, the surface sensitivity is the more important parameter. We proved the same in our biosensing experiments where a higher sensitivity is observed in L21 PC microcavities than in L13 PC microcavities. We successfully detected 1pM concentration of avidin which is one order of magnitude lower than previous our results by using L13 device and significantly better than results published elsewhere [7].

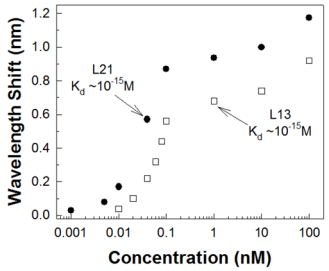

Fig. 4: Experimental spectral shift for various concentrations of avidin binding to biotin in L13 (open squares) and L21 (filled circles) PC microcavities.

In summary, we increased the quality factor of L21 PC microcavities coupled to PC waveguides by microcavity engineering and experimentally detected 1pM concentration of avidin in PBS, one order of magnitude higher sensitivity than our previous demonstration [7]. Device miniaturization is still retained from the context of practical engineering limitations of biomolecule patterning in a biosensing microarray.

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