Loss Engineered High Sensitivity Photonic Crystal Microcavities for Multiplexed Detection of Biomolecules

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Abstract: We experimentally use multi-mode interference (MMI) power splitter with a control sample on the same experiment of L13 photonic crystal microcavity structure to detect different antibodies on each arm. High quality factor Q ~9300 and high sensitivity of 8.8 atto-gram are demonstrated.

OCIS codes: (130.6010) Sensors; (280.1415) Biological sensing and sensors; (050.5298) Photonic crystals

Photonic crystal (PC) microcavities have generated significant interest in label-free bio-sensing. To achieve label-free bio-molecule detection, several groups have investigated platforms based on ring-resonators [1], wire waveguides [2], surface plasmon resonance (SPR) [3]. All the above methods are based on the specific binding of the biomolecule of interest to its conjugate biomolecule receptor bound to the optical device. In addition, microarrays of photonic crystal microcavities provide an unprecedented opportunity for comprehensive concurrent analysis of thousands of biomolecules such as proteins [4], genes, DNA molecules, small molecules or nucleic acids. In this paper, we demonstrated enhanced quality factor and enhanced sensitivities from loss engineered L13-type cavity compared with conventional L3 type cavity. Multiplexing capability of detection was demonstrated by the simultaneous sensing of two antibodies, Rabbit anti-goat IgG and Human IL-10. These two antibodies are used for simultaneous detection of the specific antibody-antibody binding on arms of multimode interference (MMI) power splitter. Thus the multiplexing microarray platform is achieved in our work with high Q and high sensitivity by using photonic crystal L13 type microcavities, which also shows the specific binding of antibodies.

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

$$\frac{1}{Q_T}=\frac{1}{Q_R}+\frac{1}{Q_i} \qquad (1)$$

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:

$$\frac{1}{\tau_R}=\frac{P_R}{W_E} \qquad (2)$$

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. Thus L13 type microcavities are presented in our work.

The structure we design is based on W1 line defect waveguide with lattice constant *a*, where W1 denotes the width of PCW is $\sqrt{3}a$. The air hole diameter is d=0.54a and silicon slab thickness is h=0.58a. PC L-type microcavities with increasing length L13 is fabricated, where L*n* denotes numbers of missing holes inside the cavity along Γ–K direction, which is designed two periods away from the PCW. Fig. 1(a) shows the scanning electron micrograph (SEM) of the device which consists of a 1×4 multi-mode interference (MMI) optical power splitter which splits the input light from a ridge waveguide into four output channels. On each output arm of the 1×4 MMI, photonic crystal (PC) microcavities are arrayed along the length of a single photonic crystal waveguide (PCW).

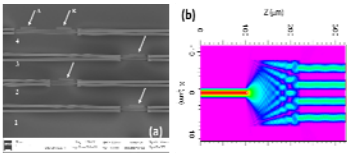

Fig. 1. (a) SEM image of PC devices on the 4 arms of a 1×4 MMI (b) power distribution in the 1×4 MMI.

The resonance spectrum of the L13 PC microcavity was first measured in PBS, functionalized with target receptor antibodies. The transmission spectrum of the PCW with the coupled L13 PC microcavity is shown in Fig. 2(a). The resonance wavelength is at 1578.9nm, near the band edge at 1588nm. A larger wavelength shift is observed in Fig. 2(b) with the probe antibody solution of rat anti-human IL-10 antibodies than goat anti-rabbit IgG antibodies. The difference in wavelength shifts for the two antibodies is related to the lower dissociation constant of rat anti-human IL-10 antibodies (K_d ~10^{-10}M) than goat anti-rabbit IgG (K_d ~10^{-6}M). A sensitivity of 8.8 attograms was achieved.

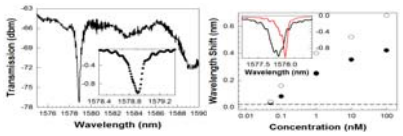

Fig. 2. (a) Transmission spectrum (Inset) shows the normalized transmission (b) Wavelength shift of the resonance shown by arrow in (a) as a function of concentration of probe antibodies, rat anti-Human IL-10 (open circles) and goat anti-rabbit IgG (filled circles). (inset) shows the spectral shift from black to red curve when 0.1nM of probe rat anti-Human IL-10 antibodies is added to a 0nM PBS background. Dashed line indicates detection limit.

In this structure, it has one PC microcavity on three arms. On the fourth arm, two PC microcavities are arrayed along the length of one PCW. The length and width of the MMI were designed as 123μm and 16μm respectively. Each of the input and output waveguide arms is 2.5μm wide and the output waveguides are separated by 1.5μm. On arms #1-#3, the edge air holes are shifted outward [5] in the Γ–K direction by 0.15*a*. On arm #4, both PC microcavities are of the L13 type. In arm #2, rabbit anti-goat IgG antibody is printed and 60μl of 600nM of goat anti-rabbit IgG antibodies in PBS is introduced which causes a resonance wavelength shift. In arm#4 of MMI is also observed with the similar shift. No shift is observed in arm #1 which was printed with human IL-10 antibodies, which is not specific to the introduced probe antibodies or in arms #3 or in the PC microcavity B in arm #4 that was coated with BSA. Next, 60μl of 600nM of rat anti-human IL-10 antibodies in PBS is introduced. A resonance wavelength shift is observed in arm #1 of the MMI that was printed with its specific target conjugate Human IL-10 antibodies. No resonance wavelength shift is observed in the other arms. Fig. 3(d) shows the transmission spectrum of the W1 PCW in arm #4 of the MMI with the two coupled L13 microcavities with slightly different geometry as described earlier. The resonances corresponding to PC microcavities A and B are at 1565nm and 1573nm respectively. Fig. 3(d) shows the resonance wavelength shift observed in the W1 PCW in arm #4 in A at 1565nm when 1nM of goat anti-rabbit IgG antibodies in PBS is added. No shift is observed in B at 1573nm.

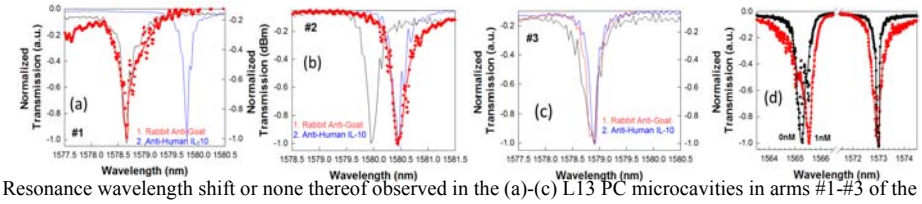

Fig. 3. Resonance wavelength shift or none thereof observed in the (a)-(c) L13 PC microcavities in arms #1-#3 of the 1×4 MMI when probe antibodies goat anti-rabbit IgG in PBS and rat anti-human IL-10 in PBS are added in sequence and (d) arm #4 of the 1×4 MMI with 1nM of probe antibodies of goat anti-rabbit IgG in PBS

In summary, simultaneous detection of two biomolecules was demonstrated by multiplexing the photonic crystal microcavity sensors on two arms of MMI is demonstrated. By utilizing the photonic crystal L13 microcavities on MMI power splitter, the structure with high Q and high sensitivity is achieved, the binding specificity being also determined simultaneously by control measurements performed on other arms of the same MMI.

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