Slow Light Waveguide and Enhanced Area Microcavity Engineering for High Sensitivity Photonic Crystal Sensors

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Abstract: We experimentally demonstrate that in photonic crystal sensors with side-coupled cavity-waveguide, group velocity of propagating mode in the coupled waveguide at the resonant mode frequency enhances sensitivity in addition to microcavity mode engineering.

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Amongst all label-free biosensors in integrated optics, photonic crystal (PC) devices provide the unique characteristic of slow light in photonic crystal waveguide (PCW) architectures which effectively enhances light-matter interaction [1], thereby leading to high sensitivities in compact device geometries. The advantage of slow light has been proved in applications such as optical modulator [2], optical infrared absorption sensing of liquid [3] and gaseous contaminants [4]. Highest sensitivity two-dimensional PC biosensors have been demonstrated by our group for chip-integrated microarray applications in proteomics [5]. We demonstrated methods to increase the quality factor (Q) and sensitivity by tailoring the radiation loss and optical mode volume of PC microcavity resonances [5]. Here, we show experimentally that in a PC microcavity coupled PCW system, the magnitude of slow light in the coupling PCW contributes to enhanced sensor sensitivity. Combining slow light engineering with enhanced surface area of PC microcavity promises the potential for extremely high sensitivity biosensors.

Our device is a L13 PC microcavity coupled to a W1 PCW in silicon in a silicon-on-insulator (SOI) platform in which we have previously demonstrated highest biosensing sensitivity among competing optical technologies at a concentration of 0.1μg/ml [5]. Refractive index changes in the vicinity of the PC microcavity leads to a shift in the resonance wavelength. Sensor sensitivity is 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.

Fig. 1 shows that multiple resonances A, B and C of the L13 PC microcavity are dropped from the transmission spectrum of the W1 PCW. (Fig. 1(a) in water, refractive index n=1.33; Fig. 1(b) in glycerol, n=1.46). Fig. 2 plots the dispersion diagram of the PCW in water. At the coupling frequencies of modes A, B and C, group indices of the W1 PCW guided mode are 13.2, 9.8 and 7.9 respectively. The bulk sensitivity is measured in nm/RIU (RIU=refractive index unit) was determined. Mode A has the highest bulk sensitivity of 66nm/RIU.

The total quality factor (Q) of a resonance mode in side-coupled cavity-waveguide architectures is given [5] by:

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

$Q_i=\omega\tau_i$, τ_i denotes the intrinsic cavity loss time constant, $Q_R=\omega\tau_R$, τ_R denotes radiation loss time constant from the microcavity and $Q_{WG}=\omega\tau_{WG}$, τ_{WG} denotes leakage loss time constant from the microcavity to the waveguide. ω denotes the resonance frequency of the PC microcavity.

Higher Q results in light being trapped in the microcavity for a longer duration at the particular resonance frequency which results in enhanced light-matter interaction and thus higher sensitivity. Q of modes A and B are nearly the same within the range of experimental variation of Q. The optical coupling efficiency from W1 PCW of mode A is much higher than that of B. The coupling efficiency η between the cavity and the waveguide is described by

$$\eta \propto \frac{1}{v_g} \quad \text{……..(2)}$$

where v_g denotes the group velocity at the resonance frequency of the corresponding optical mode. v_g is inversely proportional to n_g. Since the coupling strength is inversely proportional to v_g, farther away from the band edge where v_g is high, the coupling strength is low. As a result of the lower optical coupling of incident light into the optical cavity for mode B compared to mode A, light-matter interaction inside the cavity is also reduced which contributes to the lower sensitivity of B compared to A. Similarly, resonance modes A, B and C have decreasing sensitivity, when the L13 PC microcavity is coupled to PCWs W1.025 and W1.05.

To separate the effects of Q_R and Q_{WG}, the coupling of the resonance mode A to the PCW is studied at different propagation group velocities of the PCW. Fig. 3 shows the dispersion diagrams of the W1, W1.025 and W1.05 PCWs in water. The group indices of the W1, W1.025 and W1.05 PCW at the coupling frequency of the resonance mode A of the L13 PCW are 13.2, 12.7 and 10.2 respectively. Fig. 4 shows the results of the sensing experiments for the three waveguides with coupled L13 PC microcavity resonance A, when the device is measured in water and glycerol. Resonance mode A has the highest sensitivity. From Fig. 1, we note that the optical mode overlap of the resonance modes A with the analyte primarily occurs in the first two rows of holes along the periphery of the L13 PC microcavity which is unchanged from W1 to W1.025 and W1.05 since the L13 PC microcavity is located two periods away from the PCW in each case. Hence the additional factor that results in higher sensitivity of resonance mode A in W1 compared to W1.05 PCW is η and thus v_g. Details are covered in ref. [6]

Hence, to achieve the highest sensitivity in PC waveguide coupled biosensors, the resonance mode of the PC microcavity must couple to the PCW at guided wavelengths with highest group index.

In addition, we increased sensitivity of resonance modes by increasing the surface area of the PC microcavity by incorporating nano-holes at the antinodes of the cavity resonance. Nano-holes of gradually increasing size with radii 0.4, 0.5 and 0.6 times the radii of lattice air holes resulted in sensitivities greater than 100nm/RIU compared to L13 PC microcavities without nano-holes. In contrast to previous demonstrations [7], for slow light enhanced sensitivity, the width of the PCW was reduced respectively to W0.95, W0.91 and W0.87 where Wx denotes that the width of the PCW is x times $\sqrt{3}a$ where a is the lattice constant. High Q-factors ~10,000 were observed in measurements in water. Biosensing is currently in progress. In recent results, experimentally detected sensitivity ~50fM was achieved for the binding of avidin to biotin with bulk sensitivity 74nm/RIU [8], it is expected that sub-10fM sensitivities will be achieved in the slow light engineered waveguide coupled to nano-hole engineered microcavities.

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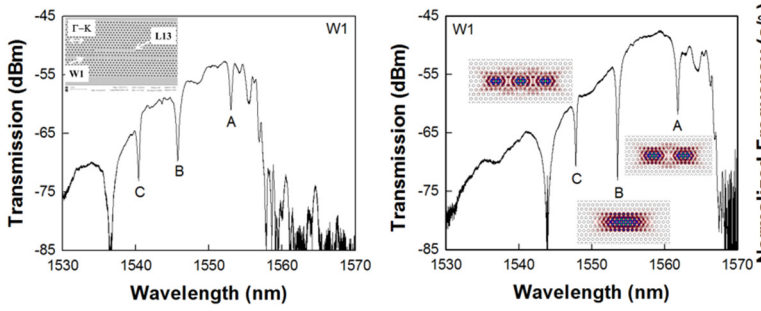

Fig. 1: Transmission spectrum of L13 PC microcavity coupled to W1 PCW in (a) water and (b) glycerol. SEM of device is shown in inset of (a). Mode profiles of resonance modes A, B and C are shown in insets of (b).

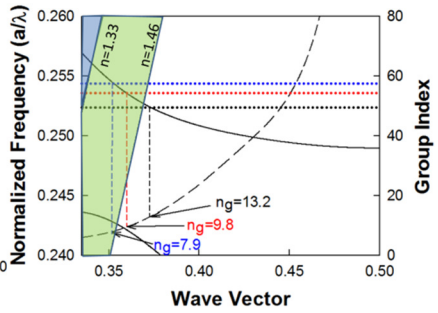

Fig. 2: Dispersion diagram of W1 PCW. Coupling of L13 PC microcavity modes A, B and C are shown.

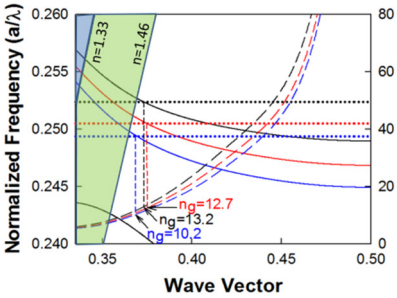

Fig. 3: Dispersion diagram of W1, W1.025 and W1.05 PCW. Coupling of mode A is shown.

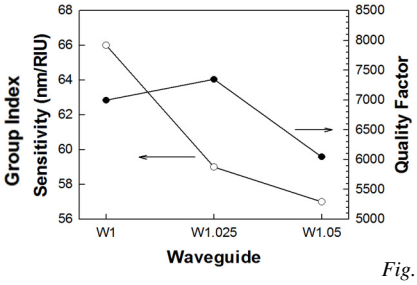

Fig. 4: Quality factor and sensitivity of resonance mode A coupled to W1 PCW

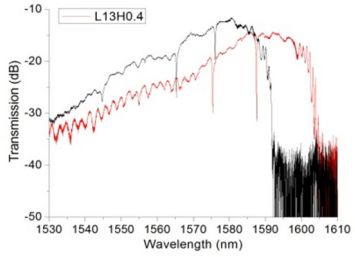

Fig. 5: Transmission spectra in water (black) and glycerol (red) of L13 PC microcavity with nano-holes with radius 0.4×bulk radius showing 11nm resonance shift compared to 9.5nm shift in Fig. 1.

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