Enhanced fluorescence emission using a photonic crystal coupled to an optical cavity

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Abstract: In this work we report a fundamentally new approach to enhance fluorescence in which surface adsorbed fluorophore-tagged biomolecules are excited on a photonic crystal surface that is coupled to an underlying Fabry-Perot type cavity through a gold mirror reflector beneath the photonic crystal. This approach leads to 6× increase in signal-to-noise ratio of a dye labeled polypeptide compared to ordinary photonic crystal enhanced fluorescence.

OCIS codes: (050.5298) Photonic crystal; (180.2520) Fluorescence microscopy; (110.3960) Nanolithography.

1. Introduction

Coupling of multiple resonators can lead to interesting optical properties like increase in Q, changes in electric fields, or modification of the far-field reflection properties, that can improve detection in sensing applications[1-3]. In this paper we demonstrate such a coupled-cavity photonic crystal structure. The structure operates by coupling one-dimensional (1D) photonic cavity (PC) modes to the modes of an underlying Fabry-Perot type optical cavity. This coupling of the two modes results in even higher evanescent fields on the surface of the PC when compared to the fields when the light is resonantly coupled to a PC without an underlying cavity coupled to it.

2. PC design and fabrication

Figure 1 (a-b) compares the structure of the cavity-coupled PC biosensor to the solitary PC. Adding a layer of gold under the PC at a specific distance forms the cavity-coupled PC structure. The PC structure is comprised of a periodic linear grating structure (Λ=360 nm, depth, d=60 nm) that is patterned in SU8 resist by solvent-assisted soft imprint lithography. A blanket deposition of a TiO_2 film (thickness, t=120 nm) is applied by sputtering on top of the imprinted structure. In previous work, we have shown that an optimal design for PC enhanced fluorescence utilizes transverse magnetic (TM) polarized light (polarization perpendicular to grating direction) for normal excitation and transverse-electric (TE) polarized light (polarization parallel to grating direction) for extraction of the emitted fluorescence signal[4]. Therefore, the PC resonance was designed to be at normal-incidence excitation ($\theta = 0°$) for TM polarized light from a $\lambda = 632.8$ nm, He-Ne laser for fluorescence excitation. The geometry of the structure and the indices of the surrounding dielectric media determine the resonance wavelength of the PC. The optical cavity strongly modifies these PC resonances. Here a 1D-PC, formed by a linear grating structure in low refractive index (RI) polymer with high RI TiO_2 on top, optically couples constructively or destructively to the modes of the underlying optical cavity formed between the PC and the gold layer that acts as a mirror underneath the PC. Figure 1c shows a large area optical image of the cavity-coupled PC fabricated on a 2 inch silicon wafer. Figure 1d shows a cross-sectional scanning electron microscope (SEM) image of the fabricated device with the underlying cavity.

Figure 3a plots the measured far-field reflection for the cavity-coupled PC for the cavity length of 750 nm and the solitary PC with the incidence angle of the white light at $\theta = 0°$. The measured spectra indicates that the presence of the cavity beneath the PC results in an inversion of the resonance characteristic from a reflective maxima to a reflective minima, as predicted by the RCWA model (Figure 2(a-d)).

3. Detection of dye labeled polypeptide

In order to demonstrate the enhancement in the SNR detection of surface attached fluorophores on the cavity-coupled PC surface, a detection experiment using a dye-labeled protein was performed. 0.7 µl volume of the dye-labeled polypeptide, Alexa 647-Poly-Phe-Lysine (PPL-Alexa 647) was applied using a pipette at a concentration of 30 µM on a cavity-coupled PC with resonance cavity length of 750 nm, a cavity-coupled PC with a non-resonant cavity length of 650 nm, and the solitary PC surface. After overnight incubation, the devices were washed by gently

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dipping them in deionized water for 60 sec. Each spot of fluorophore-tagged protein has a diameter of approximately 4 mm. Fluorescent images of the labeled protein spots were obtained using a commercially available confocal laser scanner (Tecan, LS-Reloaded) equipped with a TM polarized λ = 632.8 nm He-Ne laser. The angle of incidence of the laser can be tuned from θ = 0° to θ = 25°. Figure 3b plots the intensity cross section through the dye-labeled protein spot on each device structure. The angle of incidence for the laser was θ = 0° to correspond with the resonance coupling angle of the PC. The fluorescence intensity on the cavity-coupled PC is higher than both the solitary PC and the PC with underlying off-resonance cavity length, showing that the increase in the evanescent fields due to the coupling of the two modes gives rise to the enhancement. From the intensity plot, the increase in the signal to noise ratio for the dye labeled polypeptide on the cavity-coupled PC was calculated as 6× when compared to the solitary PC, and 10× when compared to the off-resonant cavity PC. The noise here is defined as the standard deviation in the background intensity around the spot.

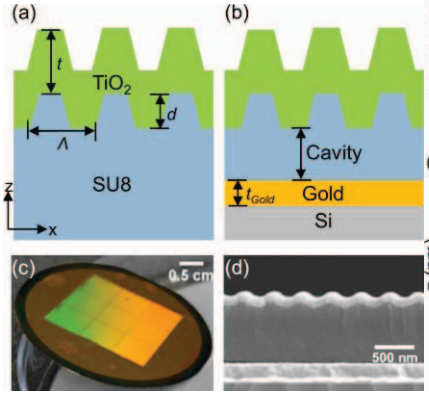

Fig. 1. (a-b) Cross-sectional schematic (not to scale) of the PC compared to the cavity-coupled PC. (c) Large area optical image of the cavity-coupled PC. (d) Cross-sectional SEM image of the cavity-coupled PC showing 1D grating in SU8 coated with TiO_2, SU8 cavity and gold layer on a Si substrate.

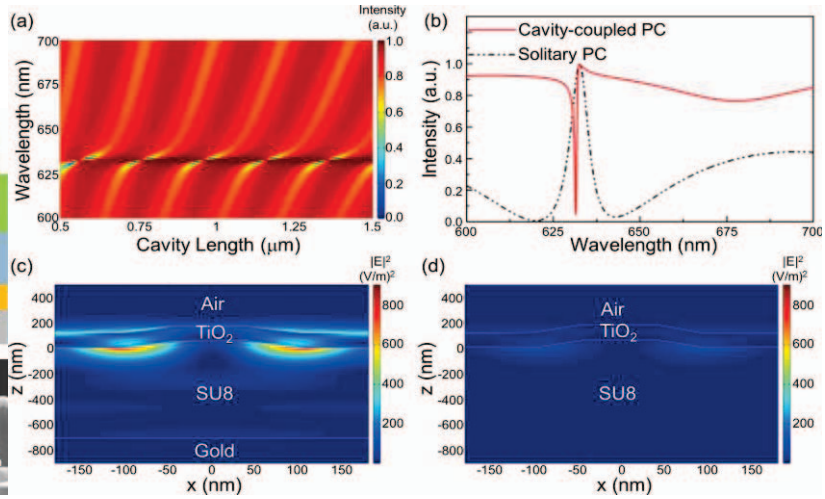

Fig. 2. RCWA simulated data for one period of the PC (a) Far-field reflection of the cavity-coupled PC for various cavity lengths. The incidence angle is θ = 0°, which corresponds to the resonance angle of the PC (b) Far-field reflection spectrum for one of the cavity lengths (740 nm) showing the coupling compared to that of the solitary PC (c-d) Near-field electric field distribution for the cavity-coupled PC and the solitary PC at the resonance wavelength showing enhanced fields for the case of the coupled modes.

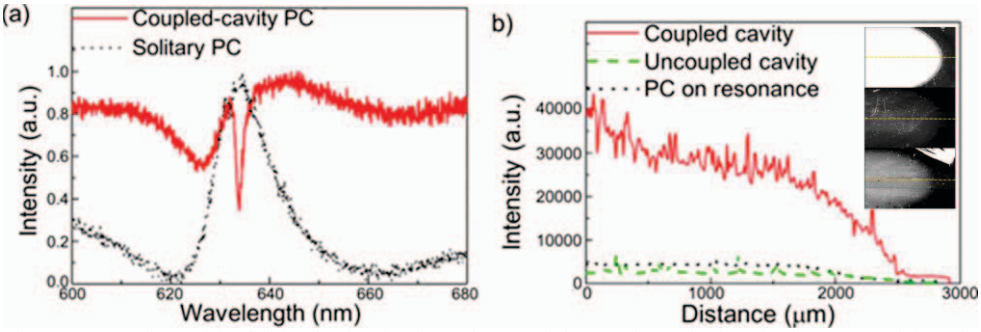

Fig. 3. (a) Experimental far-field reflection for the cavity-coupled PC at the cavity length of 750 nm and the solitary PC. The incidence angle for the laser is θ = 0° which corresponds to the resonance angle of the PC (b) Intensity profile for PPL-Alexa 647 dye for the 3 devices (inset shown in same color scale): Cavity-coupled PC with the cavity length of 750 nm, uncoupled cavity and the PC for the cavity length of 650 nm and the solitary PC.

4. References

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