Coupled Photonic Crystal Microcavities for High-Q sensing

Zheng Wang,[1, 2] Hai Yan[2], Swapnajit Chakravarty,[3] D.L. Fan[1, 4] and Ray T. Chen[1, 2, 3]
[1]*Materials Science and Engineering Program, Texas Materials Institute, The University of Texas at Austin, Austin, Texas 78712, USA*
[2]*Department of Electrical and Computer Engineering, The University of Texas at Austin, 10100 Burnet Rd., MER 160, Austin, Texas 78758, USA*
[3]*Omega Optics, Inc., 8500 Shoal Creek Blvd., Bldg. 4, Suite 200, Austin, TX 78757, USA*
[4]*Department of Mechanical Engineering, University of Texas at Austin, Austin, Texas 78712, USA*
Author e-mail address: wangzheng@utexas.edu, swapnajit.chakravarty@omegaoptics.com, raychen@uts.cc.utexas.edu

Abstract: We experimentally demonstrate that resonances in a system of coupled L0-type photonic crystal microcavities can have higher quality factor (Q~15,000) than an uncoupled cavity (Q~4,000), which is critical for sensing applications. We study theoretically the origins of higher Q with respect to bonding and anti-bonding states of coupled photonic molecules.

OCIS codes: (230.5298) Photonic crystals; (130.5296); Photonic crystal waveguides;

Coupled optical microcavities are also called photonic molecules. Photonic molecules consisting of two or more coupled optical microcavities have been implemented in several applications such as chemical and biological sensors [1], optical memory [2] and in the generation of slow light [3]. The photonic crystal (PC) provides a unique platform to study the behavior of one or more coupled photonic molecules, compared to other platforms such as ring resonators due to the unique capability of PCs to confine and guide light on length scales of the wavelength of light. Various research in the literature have investigated the coupling of such structures to semiconductor quantum dots to enable novel quantum confined systems with confinement for both electrons and photons within a small mode volume [4]. We previously demonstrated [5] that when coupled PC molecules are coupled to a photonic crystal waveguide (PCW), the coupled resonance behavior together with the unique dispersion characteristics of PCWs give rise to broad resonance dips with $\Delta\lambda$~6nm, which were then successfully implemented into a compact and high-performance thermo-optic (TO) gate switch. In this paper, we investigate the effect of coupling on the resonance drop transmission characteristics of a coupled PC microcavity system, and its implications in chip based optical sensing.

The smallest PC microcavity, denoted variously as L0 or H0 PC microcavity, is formed by simply displacing two adjacent holes in the PC lattice. Our L0 microcavity is formed by shifting two edge air holes by 0.2a where a is the lattice constant. Since optical sensing benefits from having the maximum overlap integral between the optical mode and the analyte, we introduce a nanoholes of radius r=0.5R at the anti-node position of the resonance, at the center of the L0 PC microcavity. R is the radius of the bulk lattice. Fig. 1(a) shows the magnetic field (Hy) component of the resonance in the aforementioned isolated L0-type PC microcavity with a center nanoholes. W1 indicates that the width of the photonic crystal waveguide is $\sqrt{3}a$. Fig. 1(b) shows the magnetic field (Hy) component of the resonance mode in a coupled system of two (2) nanohole centered L0 PC microcavities, separated by two lattice periods.

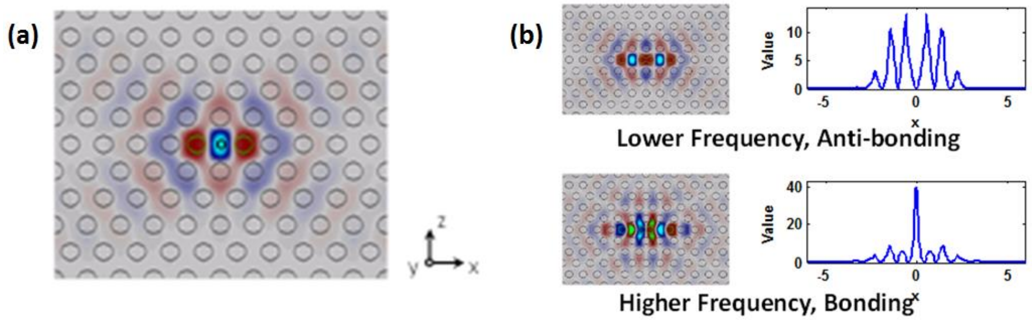

Fig.1(a) Simulated out-of-plane magnetic field (Hy) component of a TE confined resonant mode in an isolated L0-type PC microcavity. (b) Simulated out-of-plane magnetic field component for TE confined bonding and anti-bonding resonance states of the two coupled L0-type PC microcavities separated by 2 periods. The blue curves show the in-plane confined transverse electric field intensity of the modes at the cross-section along the line passing through the two microcavities.

Coupling between identical localized photonic modes in our identical L0-type PC microcavities or L0-type homo-atomic molecules give rise to a frequency splitting into a bonding state and an anti-bonding state. Fig. 1(b) shows the simulated magnetic field component for bonding and anti-bonding states of the split resonances in our isolated coupled L0-type PC microcavities, separated by 2 periods. A detailed simulation study of the bonding and anti-bonding states, for the specific case of optical sensing in water ambient is currently in progress. We have observed previously that in our system of coupled L0-type PC microcavities aligned at 0 degrees, the lower frequency ground state changes from bonding to anti-bonding by varying the distance between the PC microcavities. When the photonic molecules are coupled to a W1 PCW, the transmission drop spectrum is a function of both the resonance spacing and the dispersion of the guided mode of the W1 PCW. In quantum mechanics, the molecular ground state is expected to be a bonding state and the first excited state is expected to be an anti-bonding state. However, due to the oscillating nature of the evanescent waves in the photonic band gaps, as observed in other photonic systems [6, 7], and also in electronic systems [8], we also observed such oscillatory behavior.

Devices were fabricated in a silicon-on-insulator (SOI) substrate following established techniques of ebeam lithography and reactive ion etching. The lattice constants were chosen appropriately so that the resonance dips could be observed in the 1550nm transmission range. Fig. 2(a) and (b) show the transmission drop spectra for a single and dual coupled nanoholes centered L0-type PC microcavity coupled to a W1 PCW. When the L0 PC microcavity is coupled to a W1 PCW, a single broad resonance dip is observed in the transmission spectrum in Fig. 2(a). When the coupled system in Fig. 1(b) is coupled to a W1 PCW, the transmission resonance dip becomes sharper as seen from the simulated transmission profile in Fig. 2(b). We had previously shown that a L0 type PC microcavity can increase the analyte overlap integral to nearly 25% compared to 10-11% in the L13 and L55 PC microcavities [9]. Measurements were made in water and glycerol. We observe experimentally that the bulk resonance wavelength sensitivity is 125nm/RIU, for both the uncoupled L0 and the coupled L0 PC microcavities. However, the resonance quality factor of increases from ~4,000 in water for the uncoupled system to ~15,000 for the coupled system. The higher Q will thus enable smaller changes in refractive index to be sensed and thereby result in sensing with lower detection limits. As the separation between the coupled molecules increases, the separation between the bonding and anti-bonding resonances decreases as observed in Fig. 2(c). Detailed theoretical studies will be presented.

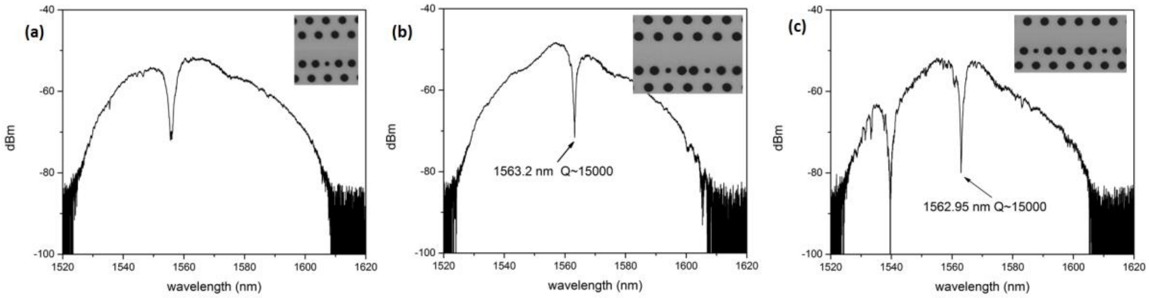

Fig. 2: Transmission drop resonance spectra of (a) uncoupled and (b, c) dual coupled L0-type PC microcavities with center nanohole. The L0-type PC photonic molecules are separated by 2 lattice holes in (b) and 4 periods in (c)

In summary, we demonstrated that a coupled system of L0-type PC microcavities results in a higher Q of the resonance dip in the transmission spectrum than an uncoupled system. The observation has important implications in sensing applications where a higher quality factor implies that small changes in concentration of the target analyte can be detected, thereby lowering the observable minimum detection limits.

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The authors acknowledge the DOE for supporting this work under SBIR Grant #DE-SC0013177.