Independently Coupled and PZT Controllable Photonic Integrated Three-Resonator Photonic Molecule

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Abstract: We demonstrate an integrated three-resonator photonic molecule with independent buses and PZT controllable 5.11 million Q Si_3N_4 rings. Independent tuning is demonstrated with full control of resonances and splitting and verified with theory and simulation.
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1. Introduction

Photonic molecules (PM) are artificial structures realized by electromagnetic coupling of two or more optical microcavities [1]. The behavior of these structures is analogous to electronic atomic and molecular systems [2] where the microresonator can be treated as a photonic atom, and a collection of mutually coupled microresonators can be designed to act like a photonic molecule in terms of resonances, resonance splitting, bandgaps and supermodes. Realizing tunable photonic molecules can enable a range of functions and physics simulations as well as enabling analog computation. Scaling these molecules to more than two atoms while providing independent bus-coupled access to each photonic atom and independent tuning is a critical next step and fabrication differences can be compensated for using independent low energy tuning of each resonator [3]. However, to date, there has not been demonstration of individually tunable, independent bus-coupled photonic molecules, with more than two cavities.

In this paper we demonstrate for the first time, a photonic molecule composed of three independently tunable microring resonators, coupled to each other and to three independent bus waveguides as shown in Fig. 1(a). This work reports a 5.11 million Q at 1550 nm, the highest Q reported to date for a PZT controlled photonic integrated ring resonator. Using PZT tuning, the holding power for each ring is sub-picowatt, due only to leakage currents. The mutual resonator coupling and independent bus coupling enables a higher degree of resonance tuning freedom and a richer set of molecule resonances than previous designs [4]. Our waveguide structures are designed and fabricated using an ultra-low-loss Si_3N_4 platform [5,6] with a waveguide core dimension of 175 nm × 2.2 um sandwiched between a 15 um thick thermally grown oxide lower cladding and 6 um TEOS-PECVD deposited SiO_2 upper cladding. After upper cladding deposition, the wafer is chemical-mechanical polished (CMP) to remove the bump on top of the waveguide, to planarize the surface for the piezo actuator deposition. A 500 nm thick PZT film is patterned on top of the waveguides and is sandwiched between the top and bottom 100 nm thick Pt layers. The resonators are 580 um radii with a 1.5 um ring-bus coupling gap and the Q is measured via the calibrated unbalanced MZI method [7].

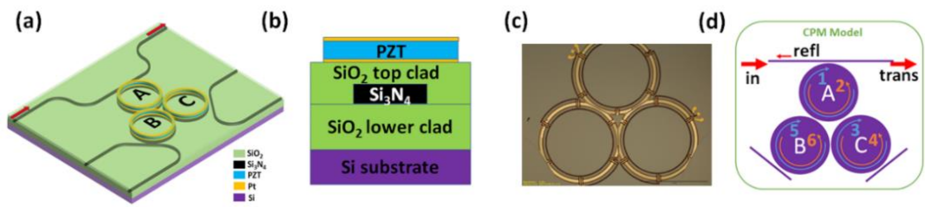

Fig. 1 (a) Three coupled photonic molecules. (b) The device cross-section. (c) The picture of a fabricated device. (d) The CPM model.

2. Modeling and Measurement

In order to understand and predict the behavior of this PM, a coupled photonic molecule (CPM) model is developed based on coupled mode theory (CMT). Each ring resonator has two modes (shown as A_1 and A_2 in Fig. 1(d)) consisting of clockwise (CW) and counterclockwise (CCW) propagating fields. Each photonic atom has two split states with a bonding orbital and an antibonding orbital, similar to the hydrogen molecule model [8] and these states coherently add to generate supermodes. The general CPM transfer matrix is written following [9]. We solve the matrix equations to obtain six eigenvalues that represent the six supermodes. When all the rings are identical and aligned, each atom has the same resonant frequency and the same energy level, yielding 4 supermodes in the transmission spectrum, as shown in Fig. 2(a). The rightmost supermode represents the highest energy level while the leftmost supermode represents the lowest energy level. The four remaining supermodes come in two degenerate pairs [10]. We can break the symmetry by changing the coupling strength between the atoms, or the ring-to-ring coupling coefficient, resulting in a split from the middle two degenerate pairs since mode degeneracy is lifted, as shown in Fig. 2(b). Considering the difference between each resonator introduced during fabrication, resonance frequency and energy level splitting occurs. This splitting may be desirable or undesirable depending on the application, for example engineerable splitting allows a rich dispersion design space. Comparison between experimentally measured and simulated supermodes and splitting is shown in Fig. 2(c) confirming our accurate CPM model prediction.

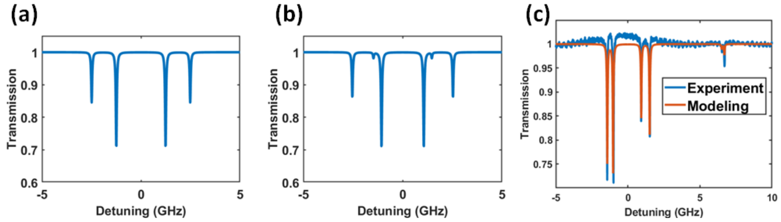

Fig. 2 (a) Transmission spectrum of the aligned case. (b) The non-degenerate case. (c) The measurement and modeling fitting of an actual device.

Next, we demonstrate an independently controllable PM via DC biasing of each PZT actuator on top of each ring resonator. When a DC bias voltage is applied, the PZT film strains due to the piezoelectric effect, and the effective refractive index of the waveguide beneath the actuator is changed through the stress-optic effect. As shown in Fig.3 (a)-(c), as the bias voltage individually applied to each ring is increased, the supermodes are detuned further away. The colored lines indicate the measured transmission spectrums under the DC bias applied to the PZT actuators from 0V to 15V on individual rings. The dashed lines indicate the model fitting by adjusting the resonant frequency of each photonic atom in the matrix, which agrees well with the actual measurements. As shown in Fig.3 (d), the tuning is almost linear, with a tuning sensitivity of 0.161+/-0.031 GHz/V. As a result, we can identify and predict the mode behavior with individual control of each photonic atom via DC biasing with the help of the CPM model. The tuning of the three individual photonic atoms can be further combined and carefully chosen to align the three rings.

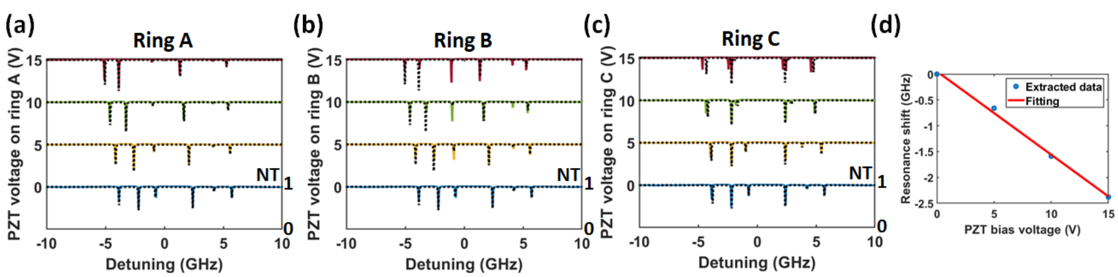

Fig. 3 (a)-(c) Independently DC biasing of ring A, B and C. The colored lines indicate the spectrums under 0 to 15V of DC biasing, and the dashed black lines indicate the CPM model fitting. (d) A linear fit of the DC bias sweep and shifted resonance in frequency range.

3. Conclusion

A mutually coupled, three-ring photonic molecule, with independently PZT controllable 5.11 million Q resonators, and independent bus waveguides to each resonator, has been demonstrated for the first time. The supermode and resonance splitting behavior are measured and accurately predicted using the CPM model. These results can lead to potential applications like a non-magnetic photonic integrated three port circulator/isolator, analog computation, many body physics simulations and the low energy PZT actuation will enable scaling to a large number of coupled photonic atoms and complex photonic molecules.

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