Active Tuning of the Microresonator Coupling Condition with Coupled Rings

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Abstract: We demonstrate a novel approach to actively and continuously tune the coupling condition of microresonators. Our approach allows for wavelength-dependent coupling and dispersion modification after fabrication.

Microresonators are an essential component in integrated photonics for linear and nonlinear applications, including filtering, light modulation, parametric generation, frequency-comb generation, and nonclassical-light generation. The functionality of microresonators depends critically on the cavity-bus coupling condition as it affects the light-transmission and field-enhancement coefficients. Conventional microresonators use evanescent couplers with fixed coupling strengths, which are sensitive to fabrication errors, and thus it would be highly desirable to be able to tune the coupling strength after fabrication. For numerous applications, it is also desirable to vary the coupling condition across closely located resonances. For example, in nonlinear frequency conversion, it is beneficial to have critically coupled pump modes and overcoupled signal and idler modes, whereas in photon-pair generation, the pump mode needs to have a larger linewidth than the signal and idler modes to generate high-fidelity single-mode photons [1].

Here, we propose and demonstrate a new coupling mechanism that has continuously tunable coupling strength after fabrication and can be engineered to exhibit frequency-dependent coupling coefficients. As shown in Fig. 1(a), our system consists of coupled microresonators. Previously, active tuning of coupling conditions has been demonstrated for the cavity connected to the bus while using the cavity farther from the bus as a control unit [2, 3]. However, this approach effectively increases the intrinsic loss of the cavities, which is undesirable for most nonlinear and quantum systems. We address this issue by using the cavity coupled to the bus waveguide as the control unit and using the secondary cavity for the nonlinear interaction. In this configuration, we can view the A, B, C, and D points as the four ports of a beamsplitter, which can be tuned using the control cavity. Critically, we design the device such that the bus-cavity coupling gap is much smaller than the cavity-cavity coupling gap so that the control cavity has a much lower Q than the interaction cavity. In this regime, the control cavity always reaches equilibrium before the field evolves appreciably in the interaction cavity. Mathematically, this corresponds to an adiabatic elimination of the control mode, which yields a dynamical equation for the interaction cavity as,

$$\frac{dA}{dt} = -\frac{\alpha + \alpha'}{2} A - i(\delta + \delta')A + i\kappa'\sqrt{F} A_{in} + \mathrm{NL}(A), \quad (1)$$

where $\alpha' = 4(\alpha_B + \kappa_B)\kappa_A^2/[(\alpha_B + \kappa_B)^2 + 4\delta_B^2]$, $\delta' = 4\delta_B\kappa_A^2/[(\alpha_B + \kappa_B)^2 + 4\delta_B^2]$, $\kappa' = 2\kappa_A\sqrt{\kappa_B}/(\alpha_B + \kappa_B + i2\delta_B)$, A, α, and δ are the field, intrinsic loss, and detuning of the interaction cavity, respectively, α_B and δ_B are the intrinsic loss and detuning of the control cavity, κ_A is the cavity-cavity coupling coefficient, κ_B is the bus-cavity coupling coefficient, F is the free-spectral range (FSR), A_{in} is the input field in the bus, and $\mathrm{NL}(\bullet)$ is any nonlinear interaction function. Notably, when $\kappa_B \gg \alpha_B$, we have $\alpha' = |\kappa'|^2$, which indicates α' being a pure coupling-loss term without introducing any intrinsic loss. A small intrinsic loss is added to mode A when there is a finite intrinsic loss in the control cavity. In addition, the strength of κ' (and correspondingly α') can be tuned with the control-ring detuning δ_B, which provides an effective tuning knob for the coupling condition. Furthermore, we can choose the control and interaction cavities to have different FSRs, which results in varying δ_B and hence α' and δ' over wavelengths. The varying δ' provides additional dispersion that can be used for novel dispersion engineering. The coupled-cavity configuration has been used in fiber cavities where the control cavity is used for power recycling, and an additional drop-port is added to the interaction cavity as the output [4]. It was argued that the configuration drastically lowers the pump-power requirement for nonlinear processes due to power recycling in the control cavity, which we do not observe in our system, as in our system, the control cavity is part of a linear four-port beamsplitter that does not provide additional field enhancement. The control cavity has also been used to only couple the pump mode into the interaction cavity where a drop port is also used for output collection [5]. However, using the control cavity to actively tune the cavity-bus coupling condition, which does not need a drop port, has not been explored.

In our experiment, we use a race-track silicon-nitride microresonator with a cross-section of 730 × 1500 nm^2 and an FSR of ~ 200 GHz. The bus-cavity and cavity-cavity coupling gaps are 250 nm and 850 nm, respectively, with a

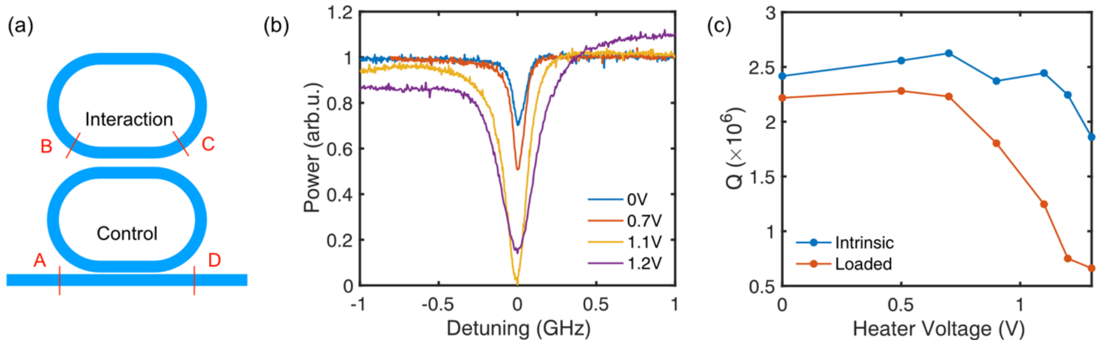

Fig. 1. (a) Schematic of the coupled cavity design for tuning the effective coupling condition for the interaction cavity via the control cavity. A, B, C, and D forms a four-port beamsplitter. The bus-cavity coupling gap is chosen to be much smaller than the cavity-cavity coupling gap. (b) Resonance scans of the interaction cavity as we vary the detuning between the two cavities by changing the voltage on the heater above the interaction cavity in which the interaction cavity is tuned from being undercoupled to overcoupled. (c) Inferred intrinsic and loaded Q of the interaction cavity as the heater voltage is varied.

coupling-region length of ~ 30 μm. We deposit platinum heaters above the silicon-dioxide cladding to thermally tune the resonance frequencies of each cavity. We characterize the cavity resonances by setting the control cavity at 0.9 mV and tuning the voltage of the interaction cavity. We probe the resonance of the interaction cavity, which is shown in Fig. 1(b). The extinction ratio of the resonance changes as the cavities are tuned, where we have shifted the center of the resonances to 0. In the strong-coupling regime, the resonances deviate from the standard Lorentzian due to the finite loss in the control cavity. We fit the resonances and extract the intrinsic and loaded Qs as the coupling conditions are varied. As shown in Fig. 1(c), the intrinsic Q change is very small as the coupling condition varies from under coupling (intrinsic Q < loaded $Q \times 2$) to over coupling (intrinsic Q > loaded $Q \times 2$). The small reduction of intrinsic Q in the overcoupled regime is due to the intrinsic loss of the control cavity, which can be mitigated by further increasing the bus-cavity coupling coefficient.

Next, we show soliton generation and tuning in our coupled-cavity system. We generate the soliton using 296 mW of pump power at 1551 nm. The soliton is generated by thermally tuning the interaction cavity, as shown in [6]. After the soliton generation, we tune the voltage of the control cavity, which actively modifies the soliton-outcoupling efficiency. As shown in Fig. 2, a comb-line power change of up to 3 dB is observed near the pump wavelength. We also observe a change in the dispersive-wave location as the coupling condition is tuned. We attribute this to the dispersion modification accompanying coupling-condition tuning.

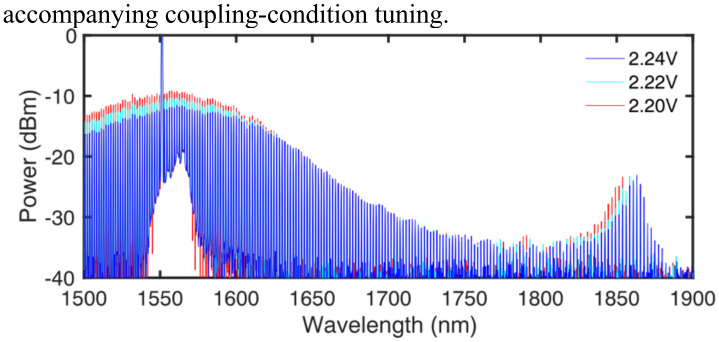

Fig. 2. Soliton spectra as the voltage of the heater above the control cavity are varied. The pump extends beyond 0 dBm.

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