Four-wave mixing in silicon "photonic molecule" resonators with port-selective, orthogonal supermode excitation

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Abstract: We propose coupled-cavity resonators for four-wave mixing (FWM) that support strong nonlinear interaction between distributed pump, signal and idler modes, yet allow independent coupling of these modes to separate ports. We demonstrate seeded FWM and discuss applications of such orthogonal coupling.

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Optical microcavities such as microrings and photonic crystal cavities provide small mode volumes and high field enhancements that enhance nonlinear optical interaction. In silicon, the large material third-order nonlinearity has motivated their use for four-wave mixing (FWM). Nonlinear photonic circuits on chip may enable important advances in classical applications including optical frequency comb generation, wavelength conversion and optical amplification, as well as quantum information applications such as heralded single photon and correlated photon pair sources.

Critical to nonlinear applications is high conversion efficiency at minimum pump power. Single microring cavities used for FWM place constraints on design that force tradeoffs, e.g. between mitigating dispersion and enhancing nonlinear interaction through mode volume, and constrain the pump/signal/idler wavelengths. Smaller microrings have higher FWM parametric gain due to smaller mode volume, but have larger free spectral range (FSR) along with higher dispersion among different longitudinal modes involved in FWM. Optical frequency combs are typically generated with larger cavities, which mitigate dispersion but do not maximize parametric gain.

Coupled resonators have been investigated for both classical and quantum FWM applications [1–4], enabling independently optimized parametric gain and output wavelengths. In [1,2], we showed that optimum design of a parametric oscillator (OPO) calls for unequal coupling of the waveguide(s) to the three resonances. Also, for example, in optical data stream parametric amplification, to maximally utilize a CW pump a high Q pump resonance should be used, while high bit-rate data streams will require wider bandwidth signal and idler resonances to accommodate the modulation. It is also advantageous in a photon pair generator to have critical coupling for the pump mode while the signal/idler mode may be over-coupled promoting both efficiency and photon time correlation. While controllable mode selective coupling was suggested in [1,2] and demonstrated in [4], the latter work still couples 2 modes to one port and all three to another port. Completely orthogonal control of mode Q's would be an important degree of freedom in design.

In this paper, we propose a coupled-cavity resonator that supports orthogonal coupling of its resonant supermodes to separate bus waveguides (ports), and thus allows independent linewidth control in design as well as isolation of the pump from signal and idler wavelengths (the latter also achieved in [4]). In general, independent orthogonal excitation of all three resonances requires coupling to all three cavities. In this paper, we present a more limited design, suitable to FWM because signal and idler physics are symmetric, where the pump is independently controlled from signal and idler, while the latter are common mode. This device enables breaking the tradeoff between gain and dispersion, as well as achieving wavelengths by design, with independently designable coupling to the resonances. We demonstrate four-wave mixing for the first time in such a device.

Fig. 1(a) shows our "photonic molecule" compound resonator (electron micrograph of fabricated device), with a "pump bus" waveguide for pump resonance excitation and a "signal bus" waveguide for signal/idler resonance coupling. Direct coupling μ of three degenerate cavities, each resonant at ω_o, forms resonant supermodes at $\omega_o - \mu\sqrt{2}$, ω_o, and $\omega_o + \mu\sqrt{2}$. These modes each have fields distributed across the cavities [Fig. 1(b-d)] with ring amplitudes akin to a discrete version of 1, 2 and 3 half-wavelength (three lowest energy) wavefunctions of a particle-in-a-box potential.

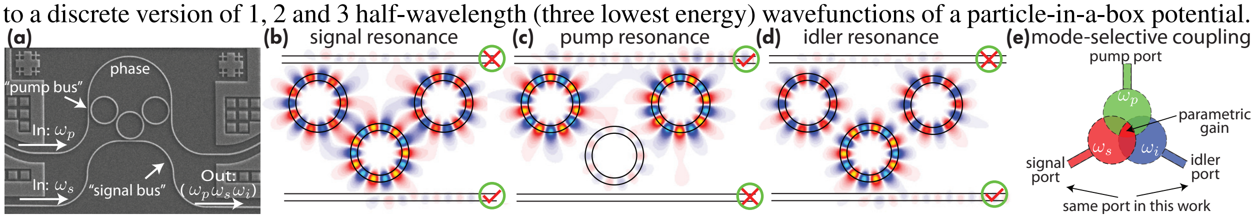

Fig. 1. **Proposed "photonic molecule" resonator with port-selective, orthogonal supermode coupling:** (a) SEM showing "signal bus" coupled to the middle cavity and "pump bus" interferometrically coupled to the outer cavities; (b)–(d) simulated field of signal, pump and idler resonances including decay to ports, showing suppressed coupling of signal bus to pump mode and pump bus to signal/idler modes. (e) Cartoon of port-selective coupling.

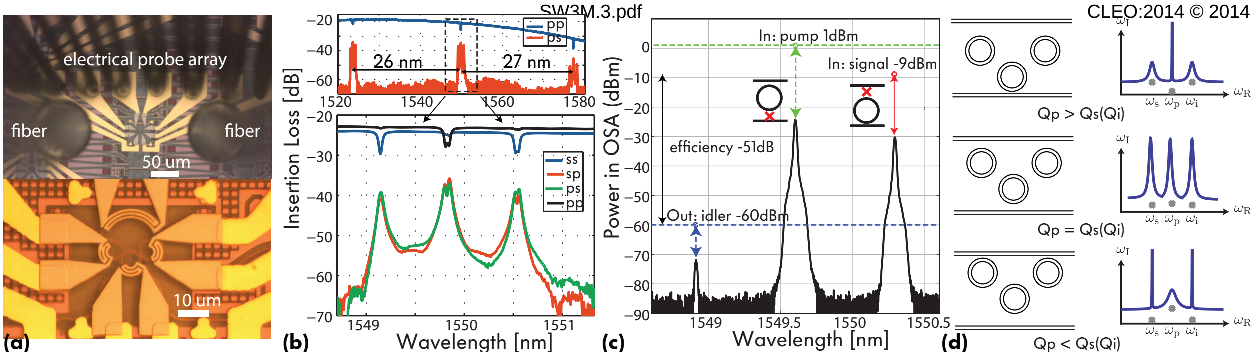

Fig. 2. **Four-wave mixing experiment in silicon 3-ring resonator:** (a) Micrographs of device under test with heaters; (b) optical transmission spectra of four port combinations (legend: "ps"="pump bus" input, "signal bus" output) showing that signal (pump) bus couples weakly to pump (signal/idler) resonance; (c) seeded FWM with efficiency of -51 dB; (d) Proposed orthogonal supermode linewidth engineering by controlling the "pump bus" and "signal bus" gaps.

The overlap of the fields ensures parametric gain enabling three interacting resonance modes (independent of choice of FSR) in the proposed degenerate-pump FWM process. The coupling μ via control of the ring-ring coupling gap controls the frequency separation of the generated wavelengths. The field profiles of such supermodes are illustrated in Fig. 1(b)-(d). We next engineer the coupling of each of two waveguides to the compound resonator's modes in a mode-selective way [Fig. 1(e)]. The pump resonance (with resonance of ω_o) has nearly zero energy in the middle cavity, and thus barely couples to the bottom bus, coupled to the middle cavity. However, the signal and idler resonances have significant field in the middle cavity and couple to the bottom bus (which we call "signal bus"). Next, the pump mode has anti-symmetric field profile about the middle cavity, while the signal and idler resonances are symmetric [see position of red and blue fields in Figs. 1(b-d)]. Therefore, an interferometric bus that couples equally to the two outer cavities can be orthogonalized to the signal and idler resonances with a π phase shift between the two coupling points, while coupling optimally to the pump resonance. The mode coupling for pump and signal/idler is entirely isolated to separate waveguides, and the device in the linear regime is an all-pass filter on each bus – the only source of power transfer from the pump bus to the signal/idler bus is the nonlinear (FWM) coupling.

The triple-ring microcavities were fabricated on standard SOI wafer by IMEC (ePIXfab). A ring radius of 3.5 μm was chosen to minimize mode volume without compromise of quality factor limited by bending loss. In order to have efficient FWM, it is important to resonantly enhance the signal, pump and idler light in the resonator, and satisfy both energy conservation ($2\omega_p = \omega_s + \omega_i$) and phase matching ($2k_p = k_s + k_i$). Due to fabrication errors, the three rings can have different dimensions, resulting in unequal frequency spacing between them ($2\omega_p \neq \omega_s + \omega_i$). Resistive metal heaters were fabricated on top of oxide cladding layer to thermally tune the compound resonator. Specifically, each ring was tuned independently to restore the right supermode, and the interferometric phase in the "pump bus" was tuned to control its coupling to each supermode. Fabricated triple-ring cavities with heaters are shown in Fig. 2(a).

Fig. 2(b) shows passive spectra of a coupled-ring resonator, with unequal FSR induced by dispersion. However the compound resonator has equal splitting within one FSR, enabling FWM near 1550 nm. In the case where light is coupled into the resonator via "pump bus" ("signal bus"), there are no dips of the insertion loss spectra at the signal/idler (pump) resonance, proving that the "signal (pump) bus" couples weakly to the pump (signal/idler) resonance.

After thermally tuning the individual rings and interferometric bus to enable equally-spaced supermodes, and sending in pump and seeding light resonant of the compound cavity, parametric wavelength conversion from FWM was observed at an input pump power of 1 dBm and seeding power of -9 dBm at the "pump bus". Fig. 2(c) shows the power spectrum of output light measured at an optical spectral analyzer (OSA). The generated idler light power at the "signal bus" was estimated by backing out the insertion loss of two fiber-chip couplers. Since the pump light coupled weakly from the triple-ring cavity to the "signal bus" [see Fig. 2(b)], our device works as an effective filter for the strong pump light when detecting generated signal at the "signal bus". The estimated conversion efficiency from signal light at input "pump bus" to generated idler light at the "signal bus" is about -51 dB. Note that this efficiency is with signal inserted into the "pump bus" for simplicity (same fiber as pump), *not* in the signal bus, and the resonator very poorly couples in signal. In future experiments we will launch the pump and seeding light from different ports and expect 10-20 dB higher efficiency based on the coupling extinction.

References

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