Wide-band On-chip Four-Wave Mixing via Coupled Cavity Dispersion Compensation

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Abstract: We demonstrate a dual-cavity resonant structure that employs frequency splitting at one of three resonances to structurally compensate dispersion. We show seeded four-wave mixing across the largest free spectral range to our knowledge of 26nm.

OCIS codes: (190.4380) Nonlinear optics, four-wave mixing, (130.2035) Dispersion compensation devices, (130.3990) Micro-optical devices

On-chip four-wave mixing (FWM) has received much attention recently for applications from wavelength conversion [1] to quantum photonic circuits [2]. FWM is a third-order nonlinear process stemming from the $\chi^{(3)}$ susceptibility where two pump photons are parametrically converted to a signal-idler pair while conserving energy and momentum (phase-matching). Resonant enhancement of both the pump and signal-idler modes has been shown to greatly improve FWM efficiency [3]. Silicon as a nonlinear material has attracted much interest due to a Kerr coefficient over a 100 times that of silica [4] and the ability to fabricate high quality factor Q optical resonators with small mode volumes. In addition to field/Purcell enhancement, resonator modes are also intrinsically momentum matched [1]. Assuming the use of a degenerate pump, this equates the phase-matching condition to three equally spaced (in frequency) resonant modes. A common method is to use adjacent free-spectral ranges (FSRs) of a single cavity for FWM. Here group velocity dispersion (GVD) due to both material and waveguide dispersion often prevents the manifestation of equivalent adjacent FSRs. Careful engineering of dispersion through resonator dimensions and pump wavelength is possible [1,5] but can impose overly strict restrictions on wavelength, mode volume, and FSR while conceding unnecessary fabrication complications such as device thickness. This can also result in multiple adjacent FSRs being energy matched producing a comb of generated signals-idlers [5]. This can be disadvantageous for applications such as heralded single photon sources where additional signals-idlers would result in inefficiencies. Another promising solution is the use of a so-called 'photonic molecule' of three coupled optical cavities and of the triply split resonance modes [6, 7]. The difficulty of obtaining resonant splitting greater than 10 nm without sacrificing Q, due to coupler losses, still provides a need for other dispersion compensating methods.

In this paper, we propose and demonstrate FWM in a dispersion compensating device consisting of two coupled resonators referred to as the 'primary' and 'auxiliary' cavities with different FSRs as illustrated in Fig. 1. The general principle is to use frequency splitting due to mode coupling at a single FSR of the primary cavity to compensate for the inherent frequency mismatch caused by dispersion [Fig. 1(c)]. With strong enough coupling (frequency splitting) and

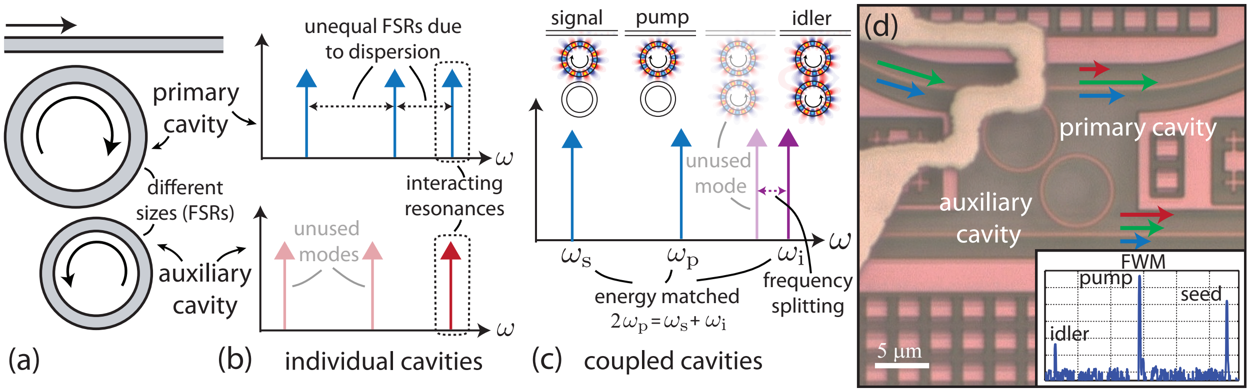

Fig. 1: (a) Proposed resonator geometry of two different sized cavities with (b) uncoupled modes that overlap at one FSR enabling (c) dispersion compensation via frequency splitting. An optical microscope image of cavity with heater for thermal tuning (d) and resulting four-wave mixing (inset).

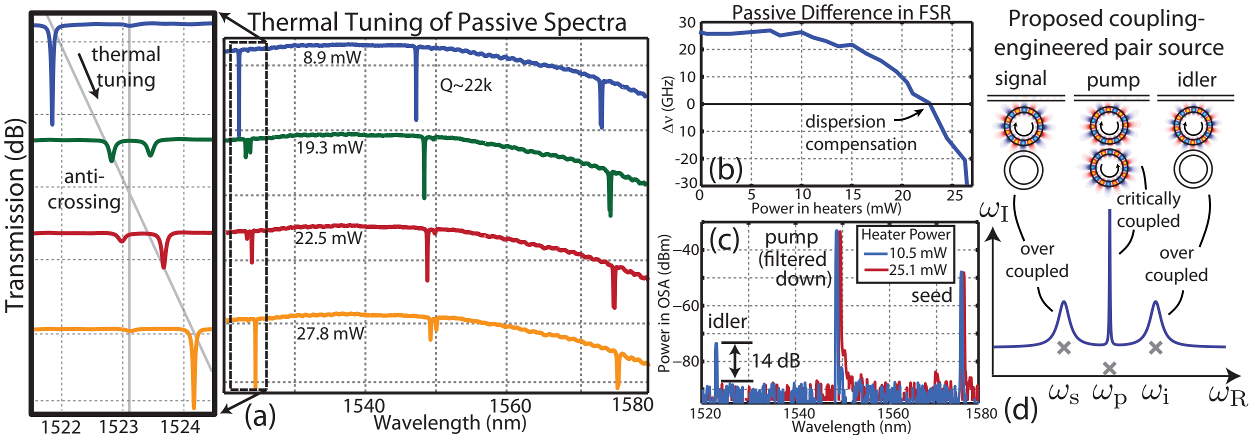

Fig. 2: (a) Passive spectra of cavity with thermal tuning. Note the frequency splitting at 19.3 mW and 22.5 mW. (b) Dispersion compensation as measured by difference in FSR with thermal tuning. (c) Seeded four-wave mixing (blue) spectrum in OSA with filter reduced pump and seed along with no FWM at higher heater power (red) due to dispersion (d) Proposed configuration for engineering a critically coupled pump and over coupled signal/idler to be used for correlated photon pair source.

appropriate tuning of either cavity this creates locally a 4-way resonant system of which three resonances are energy matched and therefore suitable for FWM. At worst (assuming maximally split supermodes are needed), the efficiency is reduced to $\frac{1}{\sqrt{2}}$ $(\frac{1}{2})$ times that of a single dispersion-less cavity using the signal/idler (pump) mode for splitting due to reduced mode overlap, β_{FWM} [8]. This may be a necessary trade-off and small price to pay for small mode volume and large FSRs, enabling broadly separated signal and idler. We note also that the splitting has the additional advantage that it could be used to avoid generating a comb, by splitting only one resonance. On the contrary, where a strong pump's self-phase modulation shifts the pump resonance in an otherwise equispaced comb, splitting of the pump could be used to compensate for this deleterious effect in comb generation. Employing mode splitting at the pump resonance could also allow for a coupling-engineered correlated photon pair source [Fig. 2 (d)]. Since this mode is distributed across both the primary and auxiliary cavities it has half the external coupling of the signal-idler modes, allowing critically coupling of the pump and over coupling of the signal-idler, improving photon pair extraction efficiencies [5].

The device, fabricated in silicon on insulator at IMEC [9], consists of a 3.61 μm radius primary ring and a 3.5 μm auxiliary ring [Fig. 1(d)] with Q factors of 22×10^3 and 9×10^3 respectively. The primary ring displays 25.6 GHz frequency mismatch due to dispersion. The fabricated device includes an additional auxiliary waveguide bus which strongly couples out the generated idler wavelength providing intrinsic filtering of the pump and signal. A resistive heater for thermal tuning was fabricated on the silica overcladding using standard photolithography. In Fig. 2(a) and (b), passive spectra of the through port of the primary ring with thermal tuning show that the frequency splitting provides frequency matched resonances at a heater power of 22.5 mW. Seeded FWM was demonstrated with 10.5 mW of power in the heater with a 1549 nm pump laser and a 1575 nm seed laser with an estimated 5.6 dBm and −13.8 dBm of power respectively in the coupling bus. A 1523 nm idler was generated with −61.1 dBm in the auxiliary bus (−73.3 dBm at the optical spectrum analyzer, OSA) [Fig. 2(c)]. This corresponds to 26 nm between pump and signal-idler wavelengths — to the best of our knowledge the largest FSR in a silicon resonator demonstrated to support FWM. Broader FWM has been achieved but across multiple FSRs [5]. Extracting output coupling losses this corresponds to a device FWM efficiency of −47.3 dB. The reason FWM was maximally efficient at a heater power lower than predicted by the passive spectra is likely due to the additional in-cavity heating of the ring from the pump laser.

In summary, we have demonstrated seeded resonant four-wave mixing across the largest FSR to our knowledge in silicon with a proposed dual-cavity device designed to compensate dispersion through structural degrees of freedom. With improvement in Q's and coupling losses, we believe this can lead to high efficiency, low-power broadly separated FWM and pair generation.

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