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Dynamical Slow Light Cell based on Controlled Far-Field Interference of Microring Resonators

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Abstract: A novel dynamical slow light cell with a tunable group delay, fabricated in silicon-on-insulator, is demonstrated. It provides a tuning range of more than 1 ns, with a usable group delay of about 0-24 ps.

OCIS codes: (130.3120) Integrated optics devices; (200.4490) Optical buffers; (230.5750) Resonators.

1. Introduction

Tunable optical delay lines and optical memory elements will be important building blocks in advanced photonic integrated circuits. "Slow light" (i.e. resonance based propagation delay) photonic devices are interesting structures to build such components, due to the resonantly-enhanced group delay of the propagating light [1,2]. The use of resonant structures also results in small devices, which can easily be integrated with electronics [3] and tuned [4]. Coupled microring resonators have been extensively used to build slow light devices [5-15]. In most common configurations, ring resonators are coupled directly in series [5-9], also known as coupled resonator optical waveguides (CROW), or in parallel, through a common bus [8-13]. All these are coupled through 2×2 directional couplers. Such an arrangement usually means the devices are synthesized from "reactive" coupling of cavities, i.e. from energy exchange between resonators. In this work, we propose, and experimentally demonstrate for the first time, a dynamical slow light cell that makes use of "far field" coupling, i.e. a form of coupling that involves no energy exchange between cavities, but rather affects their lifetime through destructive or constructive interference into the cavities' radiation channel(s). The device here is based on dual-microring resonator configuration with a shared 3×3 coupler. Elsewhere, a 3×3 coupled dual microring resonator configuration [14], similar to that here, has also been used to propose a loadable and erasable optical memory unit, using active microring optical integrators [15]. In our demonstration device, the group delay is controlled by thermo-optically detuning the resonant frequencies of the two rings from each other, by actuating titanium microheaters. In the lossless case, for a zero detuning, there is a slow light state that decouples the ring system from the bus waveguide, corresponding to an infinite external quality factor ($Q_{external}$). In the demonstrated device, usable group delays up to 24 ps are measured, with losses <1 dB. By relaxing this condition and allowing larger losses, larger (and negative) group delays are observed, with a maximum total group delay tuning range of 1 ns. Several cells can be cascaded to increase the group delay, and/or to cover different channels over a band. Furthermore, in an analogous device to the one demonstrated here, fast detuning schemes such as optical pulse excitation or solid-state carrier-plasma generation can be used to affect fast index changes so as to couple light into the slow light state and use the cell to store light for an arbitrary time, limited only by the loss-limited optical cavity lifetime [12,13].

2. Design and Fabrication

The interferometric dual-microring structure used here is illustrated in Fig. 1(a). The device was fabricated in a silicon-on-insulator (SOI) platform with a 3 μm-thick oxide undercladding, from the 105 nm top silicon layer (thinned down from 220 nm), and was then coated with a 1 μm-thick hydrogen silsesquioxane (HSQ) layer [16,17].

Fig. 1. Passive design of the interferometric dual-cavity slow light cell: (a) Illustration and dimensions, and (b) optical micrograph, before the fabrication of the titanium microheaters on top of the HSQ overcladding.

The cross-sections of the ring and bus waveguides are 600×105 nm and 495×105 nm, respectively [18]. The rings' outer diameter is 14 μm and the targeted ring-bus gap is 240 nm, corresponding to about 10% power coupling. Two individual titanium microheaters were fabricated on top of the HSQ for thermo-optic tuning of the resonant frequency of each individual ring [4]. Typical heater-resistance values were between 1 and 2 kΩ. The detuning of the rings changes the group delay because it allows access to the otherwise symmetry-forbidden high-Q antisymmetric state. Fig. 1(b) is an optical micrograph of the fabricated passive structure, before the subsequent fabrication of the microheaters.

3. Experimental Results

The individual rings of this design (and fabricated in this process) typically show intrinsic Q factors of ~250k and ~130k, without and with the titanium heaters [18]. This corresponds to propagation losses of about 2-2.5 dB/cm and 4.5 dB/cm, respectively. The device was tested for wavelengths around 1.5 μm, and the thermal control was performed using a multi-channel digital-to-analog controller, similarly to [19]. The thermal tuning efficiency is ~28 μW/GHz/ring, and the relative tuning range tried in this experiment is ±4 mW, which corresponds to ±140 GHz.

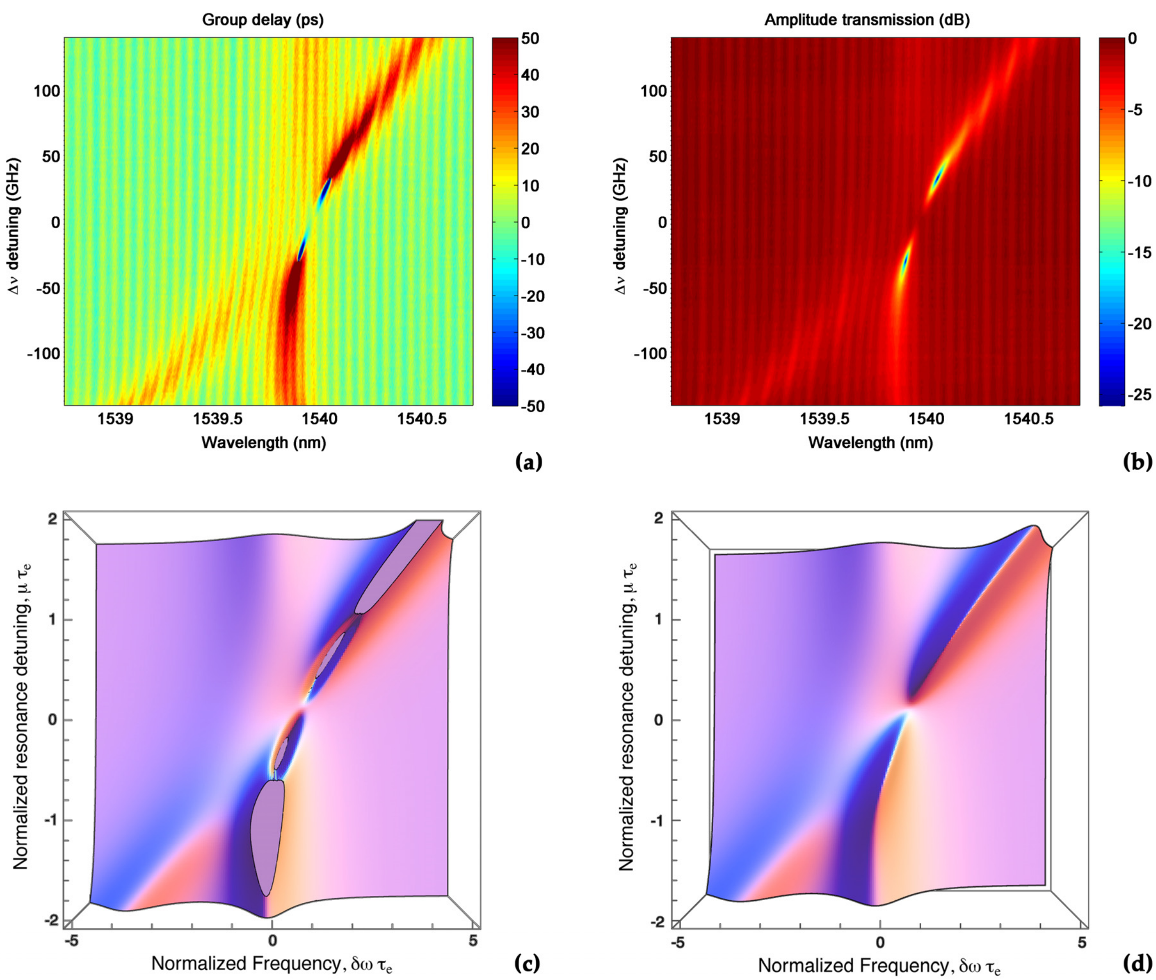

Fig. 2. Device characterization: (a)-(b) experimental results, and (c)-(d) qualitative theoretical predictions based on a coupled-mode theory model; (a) and (c) represent the group delay, (b) the amplitude transmission, and (d) the loss. The range of measured group delays is between -491 ps and +524 ps. For color discrimination purposes, the colorbar scale in plot (a) is limited to ±50 ps.

TE-polarized light is coupled into the bus waveguide using a high-NA lensed fiber, and the transmitted light is collected in a similar way. The slow light cell response is measured using an optical vector analyzer which simultaneously provides the amplitude and phase response. The amplitude response and group delay are measured for different relative detunings between the two rings – Figure 2(a)-(b). When the rings are widely detuned, the resonances are far apart and the system is equivalent to two all-pass filters with different resonant frequencies. The measured total (loaded) Q factors for the rings are ~5k and ~8k, which correspond to external Q factors of ~6k and ~9k. The splitting in the resonances around zero detuning is indication of residual direct coupling between the two ring modes – all the way across the waveguide, which here is an undesirable side-effect. Around a detuning of ±30 GHz, the transmission spectrum shows a large dip, and the group delay exhibits large positive and negative values in this region. This neighborhood shows the high-Q supermode critically coupled, and over and under coupling regimes nearby. The high-Q supermode is nearly decoupled from the bus waveguide via destructive interference of the two rings into the waveguide output. The measured total Q factor is now ~26k, which corresponds to an external Q factor of ~33k. For this state, the maximum (minimum) measured group delay is 524 ps (-491 ps, i.e. 491 ps advance). However, these are the extreme values, for which the losses are large, and do not represent usable delays. For low losses (below 1 dB), delay values are measured between 0 and 24 ps. For losses up to 3 dB, group delays between -13 ps and 44 ps are obtained. If a delay of 100 ps is needed, it can be achieved with a loss of ~9 dB and a bandwidth of a few GHz. This is not a fundamental limitation, and can be improved through fabrication of lower loss cavities. The important aspect of this geometry of slow-light unit cell is that it is an all-pass filter (pass at all wavelengths), and can thus be cascaded into a higher order system to increase the group delay arbitrarily without reducing the operating bandwidth. This is unlike all transmission based slow light systems like atomic gases, or CROW waveguides, which are limited by the Kramers-Kronig relationship, which does not apply to the present system because it is all-pass. Figure 2(c)-(d) shows qualitative theoretical predictions obtained through coupled mode theory, indicating a good agreement with experimental results. They show that the measured characteristics of the fabricated device indicate some resonator loss, some deviation from equal coupling of the two rings to the waveguide, and a small direct coupling of the rings to each other, across the waveguide. The frequency and detuning are normalized to the external coupling (lifetime) of a single ring next to the bus waveguide. The thermal crosstalk between the rings is low and does not affect the performance of the device.

4. Conclusion

We have experimentally demonstrated a dynamical slow light cell based on microring resonators, in an interferometric dual-cavity configuration. The group delay is adjusted by controlling the interference of the decay of the two rings into the common bus waveguide, via thermal frequency detuning of the resonant frequencies of the rings. Usable group delays up to 24 ps are obtained, with less than 1 dB loss. Maximum delays in the range [-491,+524] ps are demonstrated (with large losses). The slow light state responsible for the large delays (and transmission losses) has, by design, an infinite external Q factor. The measured range of external Q factors is ~[6,33]k. Several cells can be cascaded in order to increase the delay range and/or bandwidth of operation. In addition, the slow light state can be used to store light for arbitrary times, limited by the cavity lifetimes, by implementing a fast mechanism for switching between the low-Q and high-Q states (i.e. detuning), in the ps-scale.

5. References

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