Resonant optical modulators beyond conventional energy-efficiency and modulation frequency limitations

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Abstract: Modulator designs are proposed that can employ arbitrarily high-Q resonators to simultaneously achieve high energy efficiency and distortionless modulation at all (low/high) frequencies by completely decoupling optical cavity dynamics from the modulation frequency response.

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Integrated optical modulators have important applications in telecom and datacom [1], future on-chip and inter-chip photonic interconnects for multicore microprocessors and DRAM [2,3], analog signal processing including photonic A/D conversion [4] and sensing. The performance metrics for modulators are high speed [5], high sensitivity/energy efficiency [6], high extinction and compact footprint. Resonant (microcavity, microring) optical modulators enable increased sensitivity (energy efficiency) due to multiple round trips that light makes in the cavity on resonance, and have been demonstrated at Gbps rates [5-7]. However, there is a well-known tradeoff in sensitivity vs. modulation bandwidth in resonant modulators [8-9]: a higher-Q resonator provides higher sensitivity (lower energy switching) due to a narrow linewidth, but the corresponding longer cavity lifetime limits modulation response to low frequencies (smaller than the optical linewidth). This limitation holds for all conventional resonant modulator designs where the cavity resonance frequency (or loss) are modulated. It was shown by Sacher and Poon [10] that this limitation doesn't apply to these same device geometries when the input coupling from the bus waveguide to the resonator is modulated instead of the resonance frequency. In other work, novel modulator geometries have been explored that allow various improvements [11-13]. Nevertheless, all of these designs have modulation response limitations related to the optical resonance, and introduce distortions into either high or low modulation frequencies.

In this paper, new resonator designs are proposed that *completely eliminate the dependence of the modulation response on the optical resonator linewidth*. They can provide a completely flat, distortionless modulation response independent of the resonant cavity enhancement. As a result, arbitrarily high Q cavities can be used to increase sensitivity (energy efficiency) with no detrimental effect on modulation response. This is accomplished by applying simultaneous (complementary) modulation to two couplings at the resonator in such a way that the resonator energy amplitude and phase are constant at all times during the operation of the device. The basic insight is that distortions introduced into the modulation response in all previous designs using a high-Q cavity resulted from the fact that modulation changes the steady-state energy amplitude, which recovers to a new state with a time constant equal to the cavity photon lifetime. By circumventing this limitation, modulators proposed here may permit orders of magnitude improvement in energy efficiency. Two example designs are presented (Fig. 1) to illustrate this concept and explain the operation of the proposed devices, and new tradeoffs are discussed that will be relevant in their design.

Fig. 1(a) illustrates the first proposed design. Coupling from the input waveguide is constant, and two couplings

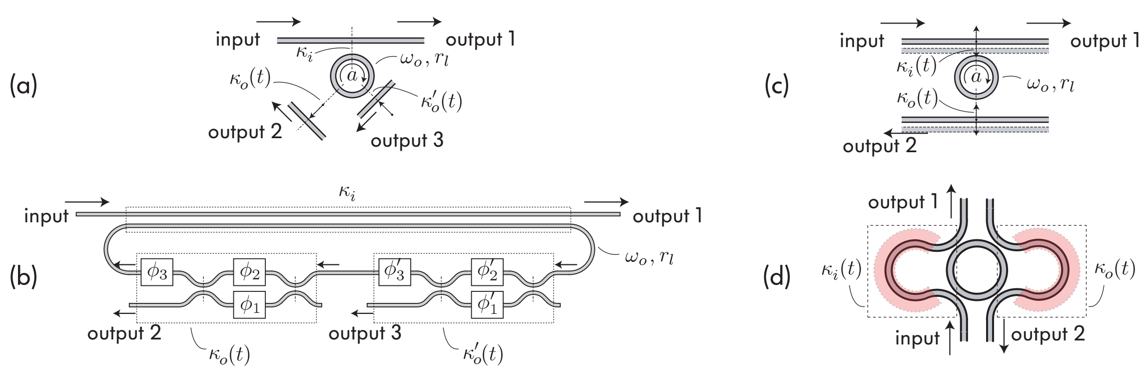

Fig. 1. Proposed "cavity-dynamics-free" resonant modulator designs use push-pull modulation that keeps the cavity photon population constant for all time. This decouples the cavity linewidth (lifetime) from the modulation frequency response, completely eliminating the "sensitivity-bandwidth" product limitation [8], and enables high efficiency with flat modulation response at all frequencies. One proposed design uses constant input coupling and dual modulated output couplings: (a) concept, (b) example implementation. A second design more suitable for WDM cascading uses modulated input and output coupling: (c) concept, (d) example implementation.

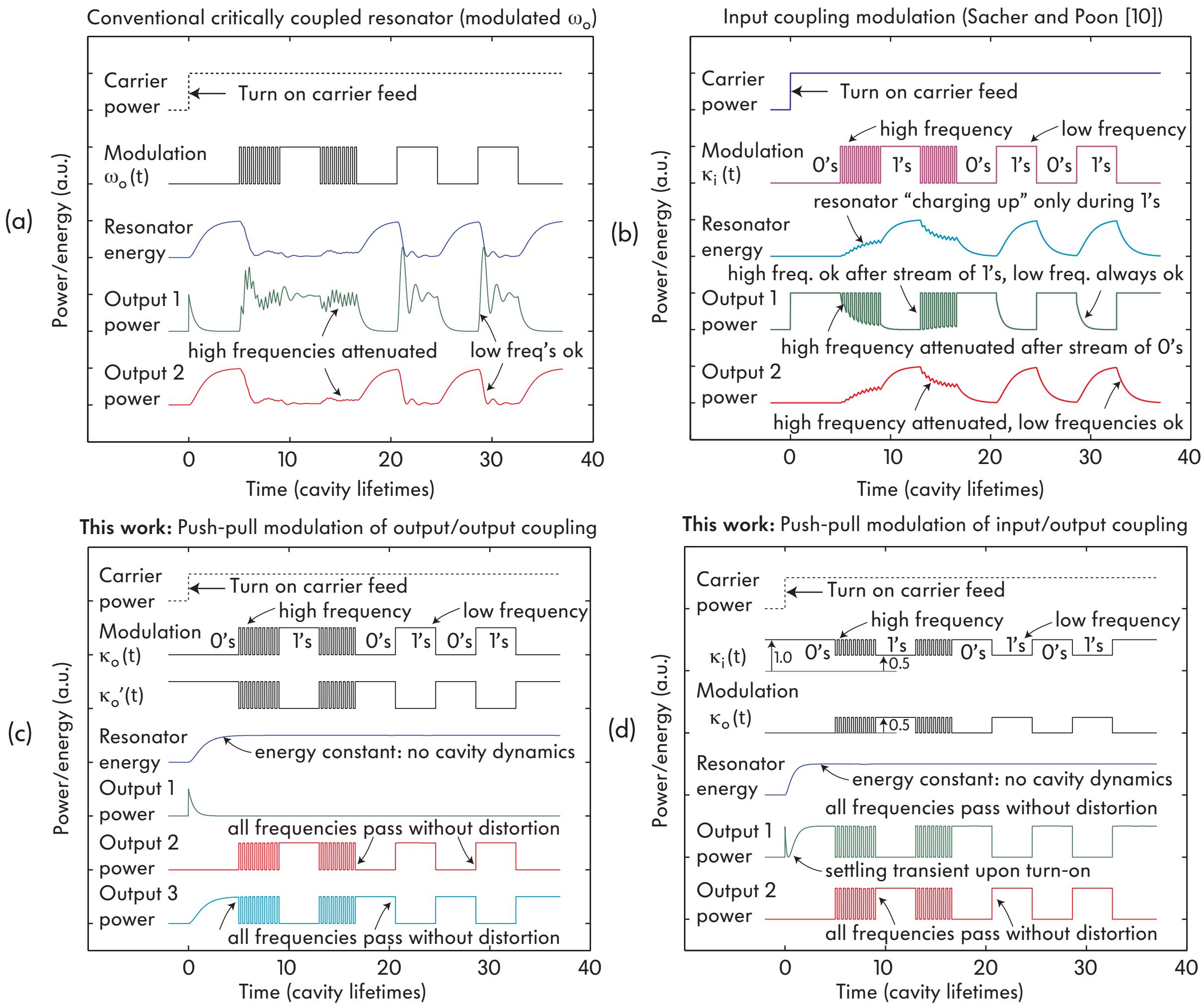

Fig. 2. (a,b) Current state of the art, and (c,d) here proposed cavity-dynamics-free resonant modulators: (a) Conventional resonant modulators are wavelength-drop filters with modulated resonance frequency, and attenuate modulation faster than the cavity lifetime, which limits efficiency or speed; (b) designs [10] where input coupling is modulated, here simulated in critically coupled configuration, allow high frequency modulation faster than the cavity lifetime, but still heavily attenuate high frequencies after long streams of zeros; (c) modulator design proposed here (Fig. 1a,b) uses push-pull modulation of two output couplings and a fixed input coupling to achieve a flat response at all frequencies independent of cavity lifetime; (d) a second design proposed here (Fig. 1c,d), better suited to wavelength-division multiplexing, employs push-pull modulation of the input coupling and one output. Both designs (c,d) can employ ultra-high-Q cavities to approach very low energy operation with no distortion of the high or low frequency modulated data.

to output waveguides are modulated out of phase such that the total rate of energy leakage experienced by the cavity at any point in time is constant. From the input port the device looks like a critically-coupled add-drop filter and fully extracts the CW input carrier at all times, but the energy goes into one, the other or both output waveguides, depending on the modulation signal. Fig. 1(b) is a possible implementation, using Mach-Zehnder interferometers (MZIs) to implement variable coupling. Simulations in Fig. 2(c) show no distortion in the modulation response at frequencies both higher and lower than the resonator linewidth.

This design can be compared to previous work – a resonator with modulated resonance frequency [Figs. 2(a)] and a resonator with modulated input coupling [10] [Fig. 2(b)]. For each design, the corresponding figure shows the power of the input CW carrier to be modulated (it is turned on at t = 0), the input modulation (i.e. modulated parameter of the – resonant frequency, input coupling, output coupling, etc. as noted), the energy in the resonant cavity, and the power in each output port. The cavity lifetime is normalized to 1 here, so the time scale is in units of cavity lifetime, and the sample modulation signal is chosen as a digital waveform with high frequency parts (bits 5 times shorter than cavity lifetime) and a low frequency part (bits 10 times longer than cavity lifetime) to illustrate the large signal modulation response. As intended, the proposed design in Fig. 1(a,b) shows no dynamics in the energy amplitude at all times by design, and shows completely distortion free translation of the modulation signal to optical outputs 2 and 3 [Fig. 2(c)]. By contrast, Fig. 2(a) shows that a conventional resonance frequency-modulated

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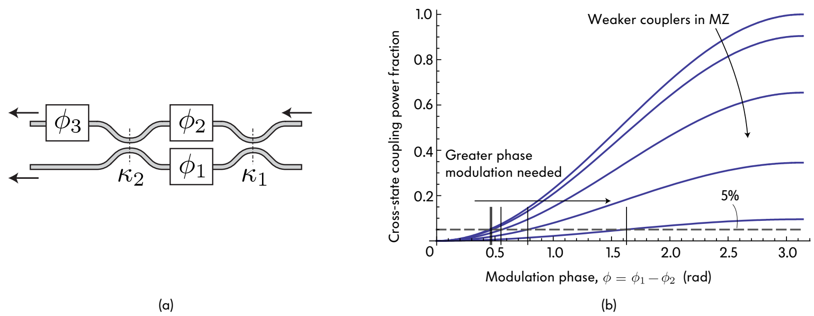

Fig. 3. Practical challenges in approaching extremely high sensitivity / energy efficiency: (a) the input/output couplings may be represented by MZ interferometers. If they make use of 3dB splitters, (b) only a small phase modulation is needed to provide the small coupling modulations needed by presented designs. However, strong directional couplers (near 50%) are also more difficult to design with the small residual losses required here. Alternatively reduced coupler ratios and increased phase modulation to compensate may be used. In practice, there will be an optimum tradeoff depending on implementation details.

device washes out high frequencies completely and rounds the slow signals for the same reason. On the other hand, using coupling modulation [10] [Fig. 2(b)] passes high frequencies most of the time, but still heavily attenuates them after a long stream of zeros. Both of the latter approaches are limited by cavity dynamics. The design proposed here [Fig. 2(c)] enables highly energy efficient and high speed modulators without distortion by eliminating them.

One (minor) down-side of this design is that modulated output goes to the two output waveguides and no signal remains in the through port, which makes inconvenient the cascading of modulators on a waveguide with a wavelength-division multiplexed set of CW carriers. A second design, illustrated in Fig. 1(c,d), provides one modulated output in the through port [Fig. 2(d)], thereby enabling simple WDM cascading. In this design, one input and one output coupling are modulated in such a way that the resonator energy amplitude and phase, again, are fixed for all time during modulation. In order to accomplish this, the input *amplitude coupling* is modulated from a maximum value to half its maximum value, while the output coupling is modulated from half that maximum to zero (i.e. input power coupling is going from 100% to 25%, and output from 25% to 0 of a chosen maximum value). The device state goes between a critically-coupled channel-drop filter and an all-pass filter, while the intracavity power is fixed.

Next, we describe why the presented designs can achieve very high energy efficiencies and/or sensitivities at high speed. Because arbitrarily narrow optical linewidths are permitted in the present designs, the intracavity power is large compared to input signal. The modulated power coupling, which is related to the modulation signal plotted in Fig. 2 can be very small, approaching zero, and still couple substantial modulated signal out of the cavity while the rest is recirculated. As a result of *critical coupling*, full swing 1-to-0 modulation can be produced by modulating the coupling between a small value and zero. In practice, a variable coupling can be implemented using a MZI controlled by a modulated phase shifter. In an MZI using 3dB couplers, only a small phase shift due to modulation is required to shift coupling between zero and a small value, e.g. 5% (Fig. 3). If weaker couplers are used, larger phase modulation is needed. A new tradeoff in design occurs that will be further discussed in the talk.

In conclusion, a general approach has been proposed for the design of efficient resonant modulators by appropriate design of modulation signal applied to two independent ring couplings. The proposed designs completely break the sensitivity-bandwidth limitation [8] by fully decoupling the modulation frequency response from the optical cavity photon lifetime. As a result, very high Q cavities with long lifetimes can be used to achieve high sensitivity (energy efficiency), with no detrimental effect on the modulation speed, enabling distortionless modulation at all frequencies, unlike previous designs [5-10], from 0 to well beyond the optical resonator bandwidth. This should enable a new class of highly efficient modulators and sensors.

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