Optimally efficient resonance-tuned optical modulators

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Abstract: Based on a first-principles, physically-intuitive design approach, I propose novel resonance-tuned intensity modulators with optimal modulation efficiency and extinction, even for lossy modulation mechanisms, including higher-order designs cascadable on wavelength-division multiplexed (WDM) signal waveguides.

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Telecom and datacom applications, including future on-chip and inter-chip photonic interconnects for multicore microprocessors, call for channelized integrated optical modulators that are high-speed, energy-efficient, high-extinction and compact. Microcavity and microring-resonator modulators enable increased sensitivity due to the multiple round trips that light makes in the cavity on resonance (up to a well-known sensitivity-bandwidth limitation [1]), and have been demonstrated at Gbps rates [2,3]. However, there are a number of drawbacks to the conventional geometries that modulate a Lorentzian cavity response back and forth in frequency. Modulating the resonance by one optical bandwidth (=half the cavity lifetime) is energy efficient yet it means that one can achieve high extinction ratio (a good zero), but large on-state loss (fundamentally ~1dB), or low-loss on-state transmission but poor extinction ratio, not both. Alternatively, to obtain near 100% to 0 swing (both low loss and high extinction) requires shifting the resonance by many bandwidths, which is energy inefficient. Conventional resonant modulators are thus fundamentally limited. Designs with asymmetric line shapes have been suggested to provide higher modulation efficiency [4,5]. These are also not optimal, and are not cascadeable on a WDM bus. Further, that modulation mechanisms (such as the carrier plasma effect) can introduce added absorption associated with the phase modulation has not been sufficiently addressed in design. There is no systematic theory and design approach to synthesize optimal resonant modulators, to my knowledge, nor an indication of what optimal architectures might be and why. But there have been proposals to use modulation of cavity resonance, cavity loss [6] or coupling strength [7].

In this paper, I summarize a new general, first-principles-based and physically intuitive approach to the synthesis of resonant optical intensity modulators, covering the case where the cavity resonance is tuned by index or loss [6]. I show briefly how the physical parameters are optimally chosen using a graphical representation of a general model, and describe example novel resonant modulator designs that address all of the presented issues. These designs allow (i) full 100%-to-0 output swing with minimum possible modulation (one 3dB optical bandwidth), even for modulation mechanisms that are lossy (if the cavity is low-loss in the off state), and (ii) full passing of off-resonant channels in the through port allowing WDM cascading.

First, optimal modulation at the signal wavelength is addressed. Fig. 1(a) illustrates the general structure of an intensity modulator that can achieve the sharpest (most efficient) possible modulation for a single modulated resonance (the second output port, q', may be a port or a loss mechanism). Optimal design requires full manipulation of

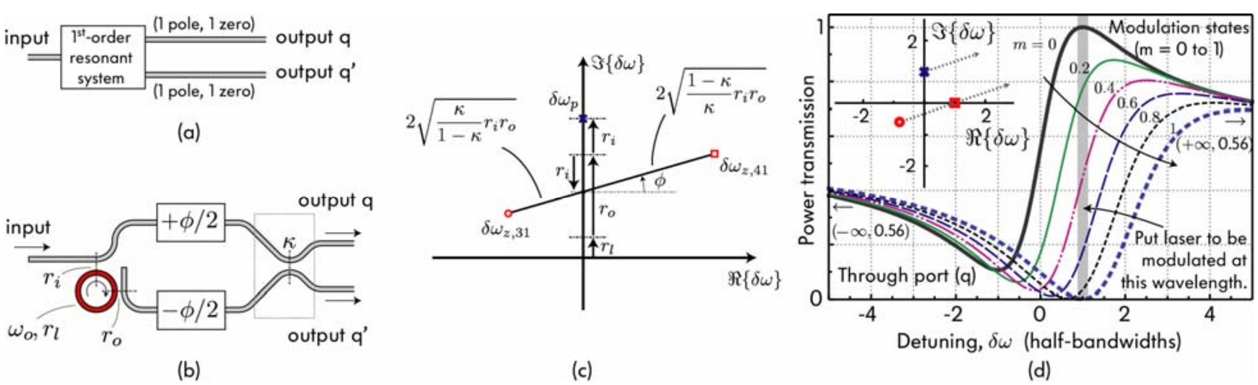

Fig. 1. (a) Optimally efficient single-cavity modulator designs require a finite-detuning transmission zero into each output port, as realized for example by (b) a microring resonator whose dual outputs are re-interfered in a directional coupler. (c) The poles and zeros have a simple graphical representation allowing physically guided optimal design. (d) Such designs not only allow the highest achievable sensitivity (efficiency) for a given photon lifetime, but also allow full 100% to 0% modulation even when using loss-adding modulation mechanisms like carrier injection, as shown by the modulation curves (inset: motion of pole-zero constellation).

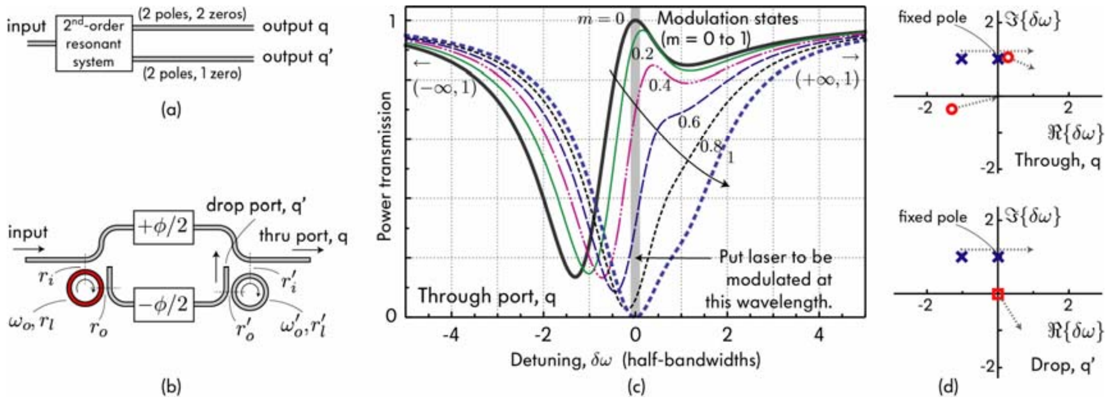

Fig. 2. (a) Wavelength-selective modulators need at least 1 zero in the through port (q), but 1 less zero in the drop port than the number of poles for wavelength rolloff. (b) A microring-based implementation allows (c) full 1-to-0 modulation (no loss, full extinction) with modulation by 1 optical bandwidth, and rolloff off-resonance to fully pass non-resonant channels.

the common pole and the zeros of both transmission functions. This requires a resonator and a direct coupling, κ, connecting the two output ports, as shown in the microring implementation in Fig. 1(b). Fig. 1(c) shows a simple geometrical representation of the pole and zero positions in the complex frequency plane, as related to the six device parameters. Modulation shifts the pole zero plot in the complex plane, and if a zero is at the signal wavelength (on the real axis), that output is zero. The basic, and general, idea for design then is to design the pole-zero constellation so that the pole gives the desired photon lifetime (speed), and modulation runs the system such that the two zeros (one belonging to each port) alternate in being located at the signal wavelength. Then, in one state the through port is 0, and in the other state the drop port is 0, i.e. the through port is 1. This picture shows a number of results. If the modulation is refractive (poles/zeros move left-right), choosing a critically coupled (lossy or lossless) resonator, and setting the phase shifter to 0 puts the zeros on the real axis; modulation efficiency is maximized with a 3dB coupler (κ = 0.5). This works because we are interfering the two outputs of the resonator in the directional coupler and converting their resonant phase to additional amplitude modulation. This design has the largest modulation slope (larger by 54% than a Lorentzian) and efficiency achievable with a single tuned cavity system, lossy or lossless [6]. Another result is that full 100% to 0 extinction can be obtained even if the modulation introduces increased absorption in addition to index change, as is the case with the carrier plasma effect. Modulation moves the pole-zero constellation diagonally in the complex plane, so an optimal design [Fig. 1(d)] takes that into account, and can still achieve full 100%-to-0 modulation. This is because dynamic absorption is only present in one modulation state.

Next, design of off-resonant behavior is addressed. A problem with the design in Fig. 1 is that all off resonance wavelengths are split (by κ) between the outputs. Such devices cannot be directly cascaded on a multiwavelength (WDM) bus. For WDM, a design is required that has 1 less zero than the number of poles in the drop port, so that it rolls off to 0 with detuning, hence the through port approaches 100% off resonance – this requires a second-order resonant design. Fig. 2(a,b) shows a design that replaces the 3dB directional coupler with a resonator that drops 50% of the signal on resonance. Phase ϕ is now 90°, but this design, as shown in Fig. 2(c) provides full 100%-to-0 modulation on-resonance (optimally, with one-bandwidth of modulation), and rolls off to passing all channels off resonance. In Fig. 2(d), the more complex pole-zero plots of the two response functions show non-parallel motion with modulation because only one resonator is modulated. Here, as desired, one response function has a zero at the signal in the off state, and the other in the on state [Fig. 2(d)].

In conclusion, a general approach has been proposed for design of efficient resonant modulators based on cavity modulation, and example designs proposed including I believe the first example of an efficient (half-photon-lifetime modulation), full-swing (1-to-0), cascadable resonant modulator. This work should enable demonstration of devices reaching higher efficiency and signal performance limits. A comparison to coupling-based designs will be given.

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