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Dynamical Systems in Nanophotonics: from Energy Efficient Modulators to Light Forces and Optomechanics

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Abstract: We demonstrate novel device concepts based on rigorous design of the dynamics of resonant nanophotonic systems, such as dispersionless resonant switches and energy-efficient modulator architectures, slow-light cells, and nanomechanical photonic devices based on light forces.

Nanophotonic devices and circuits are enabling high-fidelity on-chip optical signal processing scalable to large bandwidth and complexity in a small footprint. Dynamical (time-variant) photonic systems, in which time-dependent actuation is employed to vary resonance frequencies, Q’s, phase shifts or coupling ratios, offer a rich design space for potential applications, from energy-efficient switches and modulators of importance for on-chip interconnects and telecom/datacom applications, through resonant delay lines and dynamical slow light devices, to new light-force based nanomechanical photonics with numerous potential applications and novel functions.

In the work reviewed here, we describe novel device concepts based on first-principles synthesis of dynamical photonic systems, founded on the manipulation of resonances and interference. Dynamical manipulation of poles and zeros of transmission requires control of the resonance frequency (real frequency) and of the Q (imaginary frequency) of resonances [1]. One important telecom problem addressable by designs that make the judicious use of both is hitless (dispersivelss) wavelength tuning of reconfigurable tunable channel add-drop filters [1]. A challenge with tunable add-drop filters has been that switching off filters through resonance frequency detuning has large remaining dispersion that incurs signal degradation. Through dynamical tuning of a resonator into a minimum-phase off state (that results in pole-zero cancellation), we demonstrated a resonant switchable-tunable add-drop filter concept (Fig. 1) that simultaneously turns off both the amplitude and the phase response [1]. This concept can be applied more generally in static and dynamical resonant system design to fully suppress a resonance.

Modulator design, where design goals are energy efficiency and speed, has also leveraged resonant structures. Considerable recent work in the field has shown improved efficiency of resonant over broadband designs. We propose a first-principles design approach, based on pole-zero synthesis of dynamical systems, and show new modulator topologies that simultaneously have several optimal properties (Fig. 2). For designs where resonance frequency is modulated, pole-zero modulators [2] allow the highest sensitivity (energy efficiency), at the same time as perfect extinction by design. Furthermore, the proposed designs show that even modulators that use lossy modulation (like the carrier plasma effect in semiconductors, where refraction is accompanied by absorption) can be designed to provide “lossless”, fully 100%-to-0 modulation, in principle [2]. Generalization to higher-order dynamical resonators is shown, along with their utility for more advanced functions [2].

We have based the design of switches on design of minimum-phase resonance dynamics (which minimizes resonant group delay). Equally important applications may be derived through the synthesis of maximum-phase resonant responses, in particular in resonant delay lines, dispersion compensating filters, and on-chip slow-light structures. For example, we have proposed [3] and experimentally demonstrated [4] loop-coupled resonant cavities and the synthesis of transmission response zeros through control of their geometry. Through engineering of the response zeros, we demonstrated optimally sharp resonant filters [3,4]. In addition, filters with square amplitude response, and linear phase over more than 80% of the passband can be designed [3], hence circumventing the Kramers-Kronig constraint that implies an amplitude-dispersion tradeoff in conventional coupled-cavity filters.

Design of dynamical photonic systems is also central to a new class of nanophotonic devices based on light forces [8]. Combining nanomechanics and nanophotonics, optical forces resulting from interacting optical resonators can scale to large values as optical modes shrink to nanometer-scale dimensions, and cause motion of the nanomechanical parts with accompanying optical effects using modest laser excitation. Such forces can be harnessed in fundamentally new ways when optical elements are free to move and adapt to them through exchange of optical and mechanical energy [6]. Recent work (Povinelli et al., 2005; etc.) has pointed out substantial forces in evanescently coupled waveguides and resonators. We proposed an approach to obtain very strong optical forces, by combining strong confinement found in high index contrast waveguides with high-Q resonant enhancement in nanophotonic resonators through strongly coupled dual-cavity resonators [6]. This approach predicted microNewton
level forces with small laser powers [6], recently confirmed experimentally by a number of research groups. We describe an array of novel functionalities from low-energy switching and tuning [5,6] to self-adaptive photonics based on intrinsic feedback control [6,7] for temperature and dimensional-error insensitive nanophotonic circuits.

Fig. 1. Dynamical nanophotonic systems based on pole-zero manipulation: (a-b) dispersionless (truly hitless) tunable wavelength switch based on microrings [1]; (c) flat-top, dispersionless filters circumvent Kramers-Kronig amplitude-dispersion tradeoff using loop-coupled resonators [3].

Fig. 2. Energy efficient modulator architectures based on rigorous pole-zero design of dynamical systems [2]. (a) Pole-zero modulator topology and (b) schematic, enabling (c) full 1-to-0 modulation at the same time as WDM cascadability, and minimal resonance shift; (d) pole-zero plot.

Fig. 3. Nanomechanical photonics based on light forces in resonators: (a) dual-resonator structure and gradient light forces enable large (micro-Newton) forces [6], ultrawide tuning [6-7], and optomechanical “memory”. (b) Light forces also enable a new class of self-adaptive photonics with physics-based intrinsic feedback control [6-7] that may alleviate extremely large dimensional and thermal sensitivities of nanophotonics.

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References