Sharply-defined optical filters and dispersionless delay lines based on loop-coupled resonators and "negative" coupling

Miloš A. Popović
Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, Massachusetts 02139
mpopovic@alum.mit.edu

Abstract: Coupled-optical-microcavity geometries incorporating non-adjacent-cavity coupling and "negative" ("inductive") coupling are proposed. These enable new compact, quasi-elliptic microring filters, and can circumvent Kramers-Kronig causality constraints to support square-amplitude and linear-phase response over >80% of the passband.

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Notwithstanding advances in microphotonic resonant structures [1-4], there is a continuing need to develop both highly spectrally efficient (sharp amplitude responses and linear phase) and compact-footprint resonant structures, motivated in part by emerging applications like photonic networks on a microprocessor. Slow-wave structures for optical delay lines and nonlinear applications also require high bandwidth utilization to permit the greatest delay in pulse lengths and enhancement. For both scenarios, series-coupled-cavity filters [1] give suboptimal, all-pole flat-top responses, and are highly dispersive over much of the passband as limited fundamentally by the Kramers-Kronig constraint (for filters, remedied by adding dispersion compensator cavities [2,4]). Another architecture [2] allows optimally sharp (elliptic) passbands, but its extinction is sensitive to achieving broadband 3dB directional couplers.

In this paper, new optical coupled-cavity geometries are proposed that allow the sharpest fundamentally achievable passbands, for a given number of used resonances, in a very compact footprint. They are also shown to support an optimal flat-top and linear-phase response, in the sense defined by Rhodes [5], over >80% of the passband, without compensators and with lower (minimal) filter order – responses not demonstrated previously, to the author's knowledge, in any optical device. The new salient features of these structures are: (1) loop-coupling of resonators (Fig. 1a-b), (2) phase-sensitive (negative) coupling achieved through geometrical configuration and use of high-order resonances (Fig. 1b), (3) optional (weak) direct coupling between the input and output waveguides, (4) existence of a direct mapping of optical parameters to synthesis of linear-phase flat-top passbands in [5]. Analogs of these devices are known in circuit theory and microwave design [5,6], but these concepts have not yet been utilized in optics, including the different approach for flattening dispersion (than all-pass stages) discussed in [5].

In metallic microwave cavities, "positive" or "negative" coupling is possible due to opposite signs of effective polarizabilities of coupling apertures placed at electric and magnetic field maxima [7]. Magnetic coupling is not possible in high-Q dielectric optical resonators for the lack of good metals and a substantial magnetic response in dielectrics at optical frequencies. However, it is still possible to achieve effective negative (inductive) coupling of optical cavities. It is proposed here to use higher-order resonant modes (at least 1 node in the electric field mode pattern), with a geometry that couples cavities in a loop, as shown in Fig. 1(a,b). This is not a disadvantage since optical cavities often operate at high order to achieve high Q (e.g. microrings). In Fig. 1(a), four traveling-wave

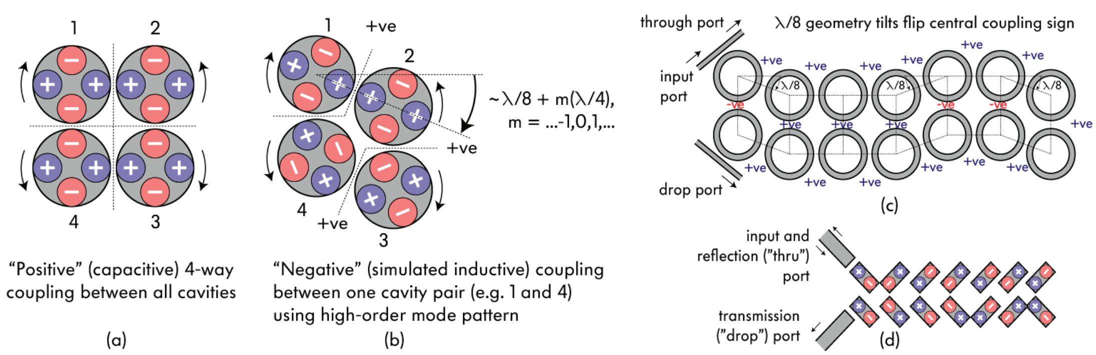

Fig. 1. New loop-coupled ring-resonator structures (coupled: 1-2, 2-3, 3-4 and 4-1): (a) standard positive couplings, and (b) phase-reversed, "negative" coupling created by a λ/8 shearing rotation of the coupling axis geometry. Cavity modes that have at least 1 node in the electric field pattern are used. (c) One geometry of a bandpass optical filter or coupled-resonator optical delay line formed using coupling of non-adjacent resonators in (a-b). (d) General single-mode standing wave (e.g. photonic crystal) cavity structure that could provide equivalent couplings and behaviour to the ring structure in (c).

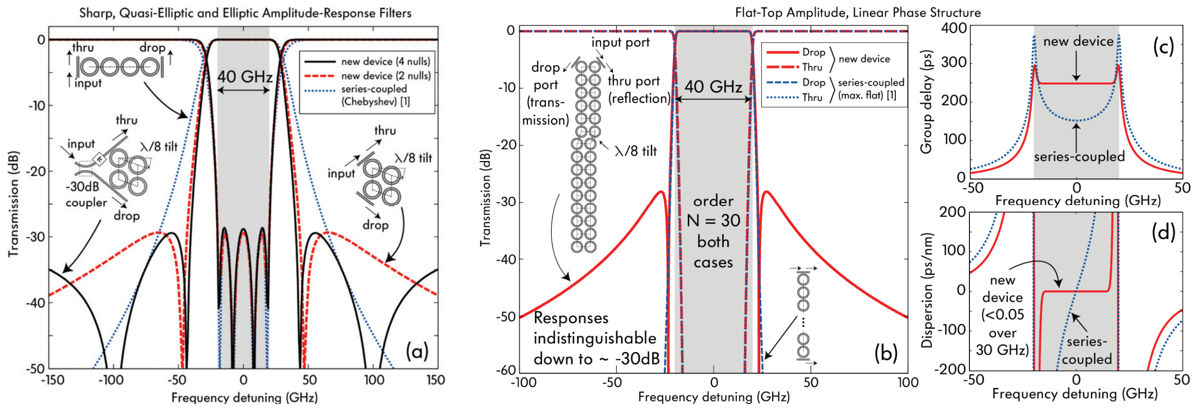

Fig. 2. (a) Compact 4^{th}-order resonant filter with "negative" coupling between ring 1 and 4 allows realization of the sharpest achievable responses for a given number of used resonances (designed for 30dB stopband, compared with series-cavity [1]); (b-d) Coupled-resonator optical delay line that is nearly dispersionless in transmission, and a standard series-coupled cavity [1], each using N = 30 cavities. The new structure can delay a pulse by over 15 pulse lengths with negligible dispersion, while simultaneously maintaining a flat, high-efficiency amplitude transmission in the resonant passband.

(microring) resonators are coupled, each to two neighbors, arranged in a square, showing all positive couplings (by inspection of overlap integrals). By tilting this geometry by ~$1/8^{th}$ of the guided wavelength, fields in cavity 1 and 4 are phase-aligned so that one negative coupling is achieved (Fig. 1(b)). Loop coupling and negative coupling sign have nontrivial consequences for the range of realizable spectral responses [5,6] – nulls and non-minimum-phase.

One implementation of a structure based on multiple, phase-sensitive coupling in Fig. 1(a) is shown in Fig. 1(c), with two rows of resonators coupled horizontally as well as vertically. With non-zero vertical couplings, a generalization of series-coupled cavities [1] is obtained that is not subject to Kramers-Kronig. This structure is extremely useful and optimal in the sense that it supports the most selective (quasi-elliptic) amplitude responses given a resonance order. Fig. 1(d) shows how an equivalent implementation based on single-mode (non-traveling-wave), such as photonic crystal, cavities can be constructed. One 4th-order filter example in Fig. 2(a), based on Fig. 1(a), shows a quasi-elliptic response (with 2 transmission zeros) compared to a series-cavity [1]. To achieve the sharpest possible (elliptic) transition band (here with 4 nulls), it suffices to add a properly phased, weak directional coupler directly between the input and drop waveguides, at the level of the stopband ripple (e.g. -30dB in Fig. 2(a)).

Furthermore, Fig. 1(c) can directly implement an "equidistant linear-phase polynomial" response function, proposed in [5], which simultaneously provides optimally flattened amplitude and group-delay responses. This is generally done with fewer resonators than required in an equivalent cascade of an all-pole filter followed by an all-pass dispersion compensator. A second use may be for slow-light optical delay lines. It was shown by Khurgin that adding side-coupled cavities to a series-cavity structure can cancel the lowest-order dispersion term [4]. The present structure provides optimally flattened dispersion to high order in the sense of the minimizing polynomial [5], and uses no extra resonators (see Fig. 2(b-d)). Fig. 1(b) compares the new optical structure (ripple A = 1, see [5]) with a typical maximally-flat series-coupled-cavity filter [1], both of order N = 30 rings. The passband flatness and rolloff is the same. However, the new structure using the prototype in [5] sacrifices rolloff beyond 30dB extinction, in this case, to allow optimally flattened dispersion. The difference is enormous – dispersion is <20 ps/nm (typical telecom requirement) over 6% of the bandwidth in the standard design, and over 80% of the bandwidth in the new structure (and less than 0.05 ps/nm over 75% bandwidth!). A 20ps pulse is delayed by ~15 pulse widths, with no substantial dispersion. An exact mapping of Rhodes' prototype circuit [5] to a coupled-mode theory in time (CMT) model of this optical structure was found (used in Fig. 2b) that makes the synthesis of this type of optical device immediately accessible to practitioners: $\mu_{n,n+1}^2 = \mu_{N-n,N-n+1}^2 = 1/(C_n C_{n+1})$, $1/\tau_{in} = 1/\tau_{out} = 1/C_n$, $\mu_{n,N-n+1} = K_n/C_n$, for n = 1..N/2.

In this presentation, the goal will be to give a physically intuitive explanation of the principles described and their result – non-adjacent cavity coupling and negative coupling coefficients, input-output waveguide coupling, and the unique way in which dispersion flattening is achieved [5]; as well as other implementations and applications.

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