Wavelength Conversion in Modulated Dual-Mode Resonators and its Equivalence to a Linear Filter Model

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Abstract: We present a resonant modulation scheme that enables efficient wavelength conversion. The system maps onto linear filter equations that provide straightforward analysis and optimized design. Efficiencies of silicon carrier-plasma modulator implementations are estimated.

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Recent work has utilized the resonantly enhanced sidebands resulting from modulation of a microring’s resonant frequency for RF signal generation [1]. This approach has the limitation that large optical cavities must be used which limits the achievable modulation efficiency due to large capacitance. In this paper, we propose a coupled cavity, dual-mode resonator modulator system as an efficient approach to wavelength conversion and RF signal generation. The system maps onto linear filter equations that provide straightforward analysis and optimized design. Efficiencies of silicon carrier-plasma modulator implementations are estimated.

The CMT equations for two coupled, lossless resonators with resonant frequencies modulated anti-symmetrically are given by

\[
\frac{d}{dt} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = j \begin{pmatrix} \omega_b + \frac{\delta \omega_m}{2} \cos(\omega_m t) & 0 \\ 0 & \omega_b - \frac{\delta \omega_m}{2} \cos(\omega_m t) \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} - j \begin{pmatrix} 0 & \mu \\ \mu & 0 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}
\] (1)

where \( a_1, a_2 \) are the energy amplitudes in resonators 1 and 2, \( \omega_b \) is the uncoupled resonant frequency of resonators 1 and 2, \( \delta \omega_m \) is the amplitude of modulation, \( \omega_m \) is the modulation rate, and \( \mu \) is the coupling between resonators.

By solving for the unmodulated (\( \delta \omega_m = 0 \)) supermodes of Eqn. 1 and rewriting the CMT equations in terms of the supermode amplitudes, we get

\[
\begin{align*}
S_{-1,2} & \quad \omega_b + \frac{\delta \omega_m}{2} \cos(\omega_m t) \\
S_{1,2} & \quad \omega_b - \frac{\delta \omega_m}{2} \cos(\omega_m t)
\end{align*}
\]

Fig. 1: (a) Physical implementation showing two coupled rings that are modulated anti-symmetrically with modulation amplitude \( \delta \omega_m \) and modulation frequency \( \omega_m \). (b) Abstract representation of wavelength conversion where \( b_1 \) and \( b_2 \) are the unmodulated supermode amplitudes of the \( a_1, a_2 \) system. (c) Conceptual figure showing conversion from \( \omega_1 \) to \( \omega_2 \) through the sinusoidal modulation. There is no coupling between adjacent-order FSRs. (d) \( |S_{21}|^2 \) for the system in (b); maximally flat (left), Chebshev (middle), and optimal design with loss (right). (e) Wavelength conversion efficiency as a function of modulation strength normalized to intrinsic bandwidth. The optimal choice of decay rates is used to maximize conversion efficiency.

Our system for wavelength conversion enables efficient wavelength conversion with simplified design, analysis, and implementation compared to previous work.
conversion efficiencies between/shift ranges from $\Delta/\Omega$ and $\Delta\alpha/\Omega\Delta N_{A,D}$ from [4], curves for the achievable resonance shift normalized to the intrinsic linewidth are generated (Fig. 2). The combination of Figs. 1(e) and 2 gives the estimation of conversion efficiency for plasma-dispersion effect resonant modulators in silicon. The maximum normalized frequency shift ranges from $df/df_{3dB} = 3$ to $10$ in Fig. 2. This maps directly to the x-axis in Fig. 1(e) and corresponds to $Q_o=10^5$, 10. We plot the normalized conversion efficiency in Fig. 1(e).

To estimate the conversion efficiency in realistic systems, we consider a symmetric p-n junction carrier plasma-dispersion effect modulator that is widely used in silicon photonics [3]. With this type of modulator, there is a tradeoff between the achievable resonance shift and the broadening of the intrinsic linewidth due to the losses introduced by the implants. Using experimental fits for $\Delta n/\Delta N_{A,D}$ and $\Delta\alpha/\Omega\Delta N_{A,D}$ from [4], curves for the achievable resonance shift normalized to the intrinsic linewidth are generated (Fig. 2). The combination of Figs. 1(e) and 2 gives the estimation of conversion efficiency for plasma-dispersion effect resonant modulators in silicon. The maximum normalized frequency shift ranges from $df/df_{3dB} = 3$ to $10$ in Fig. 2. This maps directly to the x-axis in Fig. 1(e) and corresponds to conversion efficiencies between $-5.4$ dB to $-1.7$ dB. It becomes increasingly difficult to electrically deplete the cavity when using large implant concentrations, so the electrical design must be considered jointly with Fig. 2.

A modulated coupled-resonator system allows controlled coupling of only two wavelengths, permits independent design of wavelength shift (coupling-induced resonance splitting) and the modulation mechanism. We have shown that this class of time-dependent systems maps to linear filters, and leveraging these techniques can bring considerable sophistication to the design of modulator-based photonic systems, especially with the recent progress in complex on-chip electronic photonic systems.

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References