Efficient coupled-cavity electro-optic modulator on silicon for high carrier frequency, narrowband RF signals

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Abstract: We demonstrate a coupled-cavity electro-optic modulator with 5.5 GHz bandwidth centered at 41 GHz. The device, driven with a -5 dBm RF signal, shows -27 dB pump-to-sideband conversion efficiency, a 15 dB improvement over a regular ring modulator.

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Modulation of light by high-carrier-frequency, narrowband RF signals with high conversion efficiency is key to enabling a number of applications such as microwave photonic receivers [1], optical wavelength converters [2], satellite-based millimeter-wave sensors [3,4], and quantum microwave-to-optical converters [5,6]. Resonant modulators that employ multiple optical resonances are particularly suitable for these applications because they can provide maximal optical density of states at the pump and sideband frequencies, without wasting it on the in-between frequency band. In these devices, continuous-wave pump light couples into one of the optical resonances. Modulation by the RF drive signal excites one (two) optical resonances adjacent in frequency to the first resonance and spaced from it by the RF carrier frequency to generate a single (dual) sideband(s). Resonance enhancement of the pump and sideband light maximizes conversion efficiency. Moreover, these modulators do not suffer from the cavity photon-lifetime tradeoff between high carrier frequency ("speed") and conversion efficiency, which is typical to singly-resonant modulators, such as conventional single-ring modulators [7]. The first such devices were whispering-gallery-mode resonator-based modulators with large radii that use several resonant mode orders with their frequency spacing matched to the RF carrier frequency [1,3]. With a free spectral range set equal to the RF carrier frequency, these devices are inherently large in radius (millimeter scale) and thus have a large optical mode volume that limits their conversion efficiency. They may also be unsuitable for application in on-chip integrated photonic or electronic-photonic systems due to their large size. To address these shortcomings, we proposed sideband-resolved coupled-cavity modulators [2,8,9], comprising dual (or triple) coupled microring modulators as schematically shown in Fig. 1(a). Their implementation in a $LiNbO_3$ platform was recently demonstrated by Zhang [10], and their conversion efficiencies for RF photonics applications were studied in [11] and for quantum transduction in [5]. These devices make use of resonant supermodes of the coupled cavity system where supermode frequency splitting, controlled by the coupling strength between the cavities, is set equal to the RF carrier frequency [Fig. 1(a)]. In an alternative approach, two resonant modes of a single-microring modulator cavity with orthogonal polarizations can be used [6] but require a modulation scheme with off-diagonal dielectric tensor perturbation.

In this work, we report the first demonstration of a sideband-resolved coupled-cavity modulator in a silicon photonics platform. We characterize the modulator's conversion efficiency from the optical pump to the sideband. We compare the conversion efficiency to that of a single-ring modulator and show an improvement exceeding 15dB.

The coupled-cavity modulator, shown in Fig. 1(b) [top], consists of two coupled, identical microring cavities, one of which is also coupled to a bus waveguide. The ring-to-ring coupling is designed to produce a frequency splitting of the two supermode resonances equal to the RF carrier frequency, here 40 GHz. For maximum small signal modulation efficiency, the ring-to-bus coupling is designed to meet the critical coupling condition [11]. The measured passive optical transmission is shown in Fig. 1(c). The resonances both have 5.5 GHz linewidth, with a

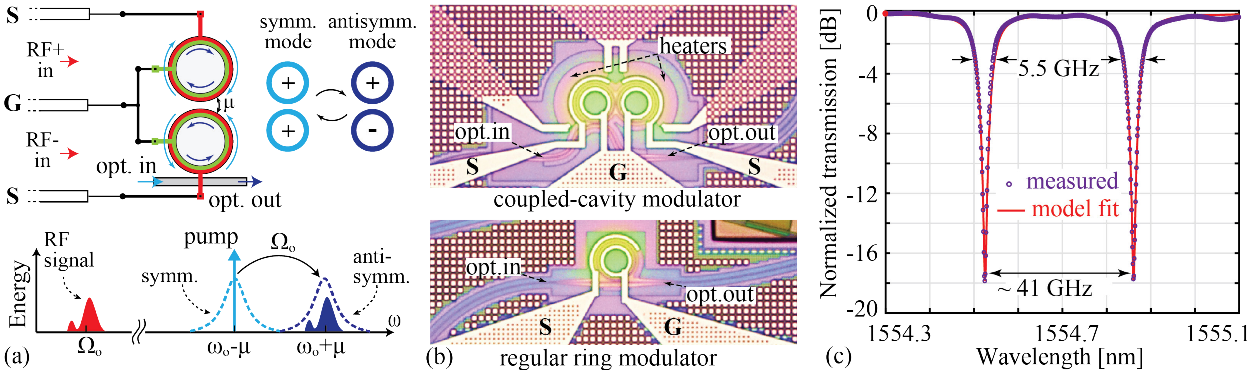

Fig. 1. (a) Schematic of coupled-cavity modulator (top left) and conceptual representation of modulation-induced coupling between resonant supermodes (top right and bottom). (b) Optical micrographs of coupled-cavity (top) and regular microring (bottom) modulators. (c) Normalized optical response of the coupled-cavity modulator showing 5.5 GHz linewidth of supermode resonances and 41 GHz splitting between them.

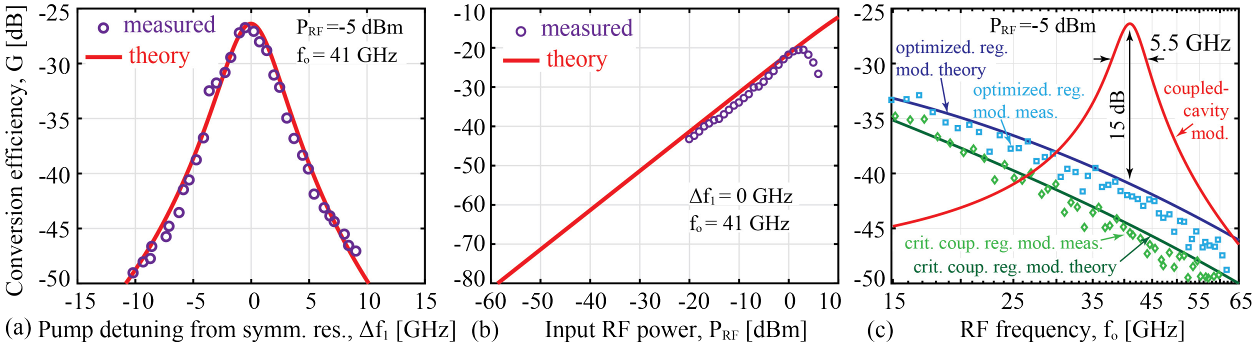

Fig. 2. Dependence of conversion efficiency of coupled-cavity modulator on (a) laser pump detuning from symmetric resonance, and (b) input RF power. (c) Conversion efficiency of coupled-cavity (red), optimized regular microring (blue), and critically coupled regular microring (green) modulators versus frequency of RF drive. In all figures experimental data are shown by markers and theoretical models shown by solid lines.

loaded Q-factor of 35k, and an intrinsic Q (including doping) of 61k. The measured resonance splitting is 41 GHz. The measured shift efficiency of resonance frequency modulation, with the built-in p-n diode phase shifters, is 1.4 GHz/V at 0 V bias. For comparison, a regular single-microring modulator was also implemented. Shown in Fig. 1(b) [bottom], it uses *the same cavity design* as the coupled-cavity device. That ring is over-coupled to the bus with the coupling strength optimized, based on the analysis in [7], to ensure maximum modulation efficiency at 40 GHz.

To measure the conversion efficiency of the coupled-cavity device, laser light, with -15 dBm on-chip power, is coupled to the modulator, a differential RF signal is applied to terminals shown in Figs. 1(a, b), and the output modulated light is detected on an optical spectrum analyzer. First, the RF frequency is set to 41 GHz and the power in the optical sideband is measured versus detuning of the laser frequency from the symmetric resonance [Fig. 2(a)]. As predicted theoretically [11], and shown experimentally here, the pump-to-sideband conversion is most efficient when the laser is aligned with the resonance. A conversion efficiency of -27 dB is achieved with -5 dBm total RF drive power, which corresponds to normalized RF-to-optical photon conversion efficiency of 1.3×10^{-6} per 1mW pump power. Next, with the laser aligned to the symmetric resonance, and the RF frequency set to 41 GHz, the conversion efficiency is measured versus input RF power. The measured efficiency, shown in Fig. 2(b), increases linearly with increasing RF power up to 0 dBm. Beyond this point, the efficiency reaches its maximum and drops as the RF power increases further. At high RF power level, the p-n diode phase shifters, in this case operated at 0V bias, pass forward current, which degrades electrical bandwidth of the modulator and, therefore, results in an efficiency drop. Finally, the frequency response of the modulator is extracted from the efficiency vs. detuning experimental data points in Fig. 2(a), and is shown in Fig. 2(c). The response peaks at 41 GHz and has a bandwidth of 5.5 GHz, which is largely determined by the linewidth of the antisymmetric resonance, as discussed in [11].

The efficiency of the regular single-microring modulator is measured by applying a single ended RF drive and detecting the power in the higher-frequency optical sideband. The conversion efficiencies of optimized and critically coupled designs measured at 41 GHz with -5dBm RF power level are -42 dB and -45 dB [Fig. 2(c)], respectively, 15 dB and 18 dB lower than the efficiency of the coupled-cavity modulator.

In conclusion, we demonstrated a novel modulator concept, suitable for integrated RF/microwave photonic applications, in a silicon photonics platform. The modulator harnesses resonant enhancement of the optical pump and sideband in spatially overlapping resonant states. Unlike a single-ring modulator, it performs efficient modulation even when the RF carrier frequency far exceeds the linewidth of the optical resonances. The modulator, designed for 41 GHz RF carrier frequency, shows 15 dB improvement in conversion efficiency compared to a single-microring modulator designed optimally for the same frequency, and around 18 dB over a conventional critically coupled single-microring modulator using the same technology.

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