# Enhancing SOI Waveguide Nonlinearities via Microring Resonators

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**Abstract:** All-optical devices can exploit a suite of nonlinearities in silicon photonics. We study how microring resonators (MRRs) harness these nonlinearities, with theoretical model and experimental validation. Free-carrier effects will practically always dominate Kerr in MRRs. © 2019 The Author(s)

**OCIS codes:** 190.4390, 070.4340.

## 1. Introduction

Microring resonators (MRRs) are ubiquitously used in silicon photonic integrated circuits (PICs) in a variety of devices: modulators, filters, and multiplexers. Recent improvements in fabrication and packaging of silicon PICS are decreasing coupling- and waveguide loss. This allows the cavity energy inside each resonator to easily reach levels that trigger optical nonlinearities, such as Kerr effect and two-photon absorption [1]. These effects can be exploited to engineer devices for all-optical switching [2], thresholding [3] or self-pulsations [4].

All nonlinear optical effects in single waveguides must be taken into account to correctly model the experimental behavior of MRRs built on silicon-on-insulator (SOI) platforms. These include thermo-optic, free-carrier absorption (FCA), free-carrier dispersion (FCD), two-photon absorption (TPA), and the Kerr effect. Here, we study their relative strengths in a typical SOI electron beam foundry platform. We match a constructed model with coupled-mode theory (CMT) to experimental measurements. Our results suggest that all these effects, except for the thermo-optic, play an important role in altering ultrafast dynamics.

Theoretical papers often propose new optical circuits while ignoring the effect of carriers generated by TPA, focusing instead on nonlinear dispersion caused by Kerr and absorption caused by TPA (e.g. [2,3,5]). The motivation is that Kerr effect is a parametric process that interacts instantaneously with incoming lightwaves. However, it can only be taken advantage of if active measures are taken to sweep away generated free-carriers, such as reverse-biasing a p-i-n junction transversal to the waveguide [1]. Another mitigation technique is to constrain the inputs to strong, short pulses, so that there is no time for carriers to accumulate. But as we show in the next sections, in nonlinear MRRs, free-carrier effects will practically always dominate over Kerr effect for passive MRRs.

## 2. Nonlinear Microring Resonator

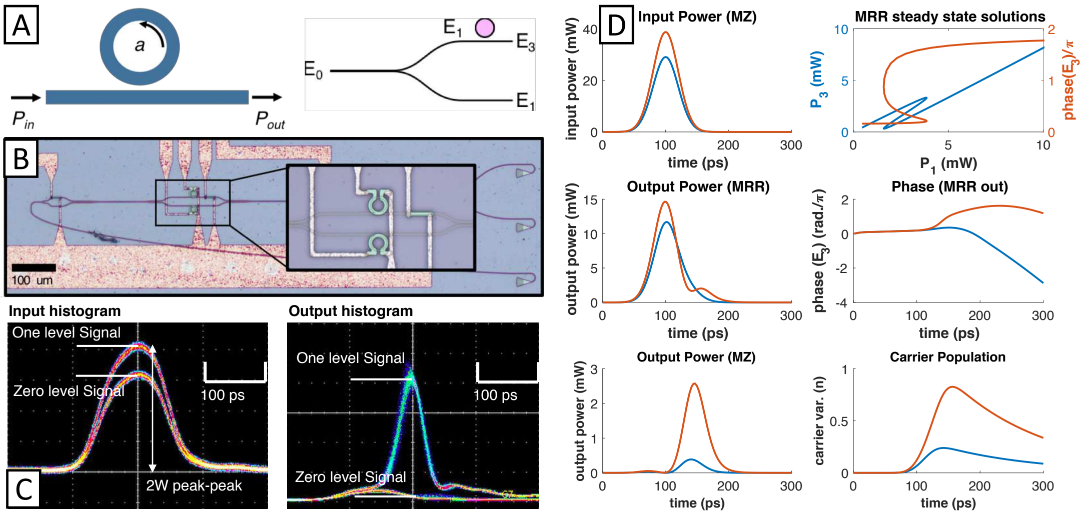

Fig. 1: A. All-pass MRR. B. Micrograph of a ring-loaded Mach-Zehnder interferometer with heater tuning elements. C. Experimental input-output sampled waveforms taken from the sampling oscilloscope in the histogram mode. D. Simulation model based on Eq. 1. Blue and orange lines refer to pulses with different amplitudes (top-left), excepting the top-right plot, which shows the steady-state solutions for $E_3$ in power and phase as a function of $P_1$. All plots have real units except for the bottom-right one.

An all-pass MRR (Fig. 1A) with nonlinearities can be modeled via a CMT method [4]. Its normalized complex amplitude, $a$, and normalized carrier density, $n$, evolve with

$$\partial a/\partial t = i(\delta\omega - n_{\mathrm{Kerr}}|a|^2 + \sigma_{\mathrm{fcd}}\alpha_{\mathrm{tpa}}n)a - (1+\alpha_{\mathrm{tpa}}|a|^2 + \gamma_{\mathrm{fca}}\alpha_{\mathrm{tpa}}n)a + \sqrt{\gamma_p P_{\mathrm{in}}(t)} \tag{1a}$$

$$\partial n/\partial t = |a|^4 - n/\tau, \tag{1b}$$

where $\delta\omega$ is the frequency detuning between the light source and the MRR resonance; $t$ is the time variable normalized with $\Gamma_0^{-1} = 2Q_L/\omega_0$, where $Q_L$ is the total quality factor; $P_{\mathrm{in}}$ is the power input; and $(n_{\mathrm{Kerr}}, \alpha_{\mathrm{tpa}}, \sigma_{\mathrm{fcd}}, \gamma_{\mathrm{fca}}, \gamma_p) \propto (n_2\omega_0, \beta_2, \sigma_{e,h}\omega_0, \sigma_{\mathrm{fca}}, \Gamma_c/\Gamma_0^3)$, are the Kerr, TPA, FCD, FCA, and quality factor coefficients, respectively. This equation was simplified from Ref. [4], and renormalized so that the two-photon absorption only shows up in Eq. (1a). This correctly illustrates that the stronger the TPA, the stronger the free-carrier effects will be. A figure of merit ($F = n_{\mathrm{Kerr}}/\alpha_{\mathrm{tpa}}$) is often introduced when evaluating the nonlinearity of a material (e.g. silicon has $F \approx 0.4$) [1]. The most important feature of Eq. (1) is that Kerr and FCD have opposite consequences on the phase of the cavity waveform—Kerr induces a red shift, while FCD induces a blue shift. Therefore, whichever effect dominates will govern the phase shift induced by the MRR to the incoming lightwave.

To test this model, we fabricated low-quality-factor MRRs with a small radius ($R = 5\,\mu\mathrm{m}$) and high coupling coefficient ($\mathrm{gap} = 100\,\mathrm{nm}, r \approx 0.04$). The device was fabricated with standard $500\,\mathrm{nm} \times 220\,\mathrm{nm}$ ridge waveguide cross-section with silicon oxide cladding. The MRR was placed in one of two Mach-Zehnder interferometer's arms, so that phase shifts would be detected as amplitude differences (Fig. 1B). We sent pulses with varying pulse widths to study the relative effects of Kerr vs. FCD (Fig. 1C). We also built a model from Eq. 1 to understand the different nonlinear dynamics present there.

## 3. Finding a Sweet Spot

Can one find a combination of pulse amplitude, pulse duration, and wavelength detuning that would favor Kerr nonlinearity over FCD for passive MRRs? Our analysis show that it is practically impossible to do so. For example, the ring fabricated in Fig. 1B has low quality factor (about 14,000), which places the photon cavity lifetime at about 180 ps. Short otical pulses would minimize free-carrier effects by not saturating the carrier population built up via TPA (Eq. 1b). In Fig. 1C, we show the output of the ring-loaded balanced MZI from Fig. 1B with two inputs that are 100 ps long, differing by 30% in amplitude. The MRR's resonance wavelength was tuned to the vicinity of the laser input wavelength (around 1551 nm). Many pulses were sent with a repetition period of 10 ns, and collected with a sampling oscilloscope with 20 GHz bandwidth. It can be seen that the frontend of the output pulses follow similar paths, essentially linearly proportional to their input. But the backend of the pulse has very different levels.

This behavior can be explained by FCD, as shown in Fig. 1D, lower-right plot. When the cavity energy hits the maximum in the MRR, the carrier population starts to increase rapidly, causing a permanent phase-shift in at the output port of the top arm of the MZI (Fig. 1D, center-right). This phase difference removes the destructive interference at the output coupler of the MZI so that an amplitude difference emerges (Fig. 1D, lower-left).

With the model confirmed to be valid as we explored pulses with different pulse widths, we make a few asymptotic calculations. Assume that the pulse width is much longer than the carrier recombination rate, $\tau$. Then, the carrier population will always reach its steady state value $n_{ss} = \tau|a|^4$. At this point, it is worth considering the ratio between the dispersion caused by Kerr and FCD, $K = n_{\mathrm{Kerr}}|a|^2/\sigma_{\mathrm{fcd}}\alpha_{\mathrm{tpa}}\tau|a|^4 = F/\sigma_{\mathrm{fcd}}\tau|a|^2$. This means that FCD dominates over Kerr if the cavity energy reaches $|a|^2 > F/\sigma_{\mathrm{fcd}}\tau$. On the other hand, if we assume that the pulse is much shorter than the photon cavity lifetime and has an energy of $E$, we calculate this ratio to be $K = F/\sigma_{\mathrm{fcd}}\gamma_p E$. This means that FCD will dominate over Kerr if this energy is above $F/\sigma_{\mathrm{fcd}}\gamma_p$. However, realistic SOI waveguides require a large optical energy to reach bistability due to optical nonlinearities, excluding the possibility of a Kerr-dominated regime.

## 4. Conclusion

We conclude that to enhance nonlinearities with a silicon MRR, one must necessarily exploit the effects of FCD, which is the strongest in this case. The good news is that passive MRRs *can* be used to create reliable all-optical devices, as long as they are designed and modeled with both Kerr and FCD taken into account.

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