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Modeling of Nonlinear Effects in an InP-Membrane Microring Resonator

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***Abstract*—We present a rate equation-based model for InP membrane microring resonators and we extract the model parameters using a Particle Swarm Optimization scheme. The resulting simulations are compared with experimental data, enabling a detailed understanding of the relationships among the underlying microscopic effects.**

***Index Terms*—Photonic Integrated Circuit, Indium Phosphide, Microring Resonator, Nonlinear Optics, Modeling**

I. Introduction

Microring Resonators (MRRs) are devices used extensively in Photonic Integrated Circuits (PICs) due to their wavelength-selective spectral characteristics and their strong sensitivity to external perturbations [1]. Owing to these rich physical properties, they have emerged as key building blocks in Photonic Neural Networks (PNNs) [2]. Especially when nonlinear effects are desirable, MRRs fabricated on membrane-based platforms can exhibit pronounced nonlinearities induced by strong optical and thermal confinement [3]. However, accurately modeling the complex interplay between these optical and thermal effects remains challenging. In this work, we model the behavior of a MRR integrated on the Indium Phosphide Membrane on Silicon (IMOS) platform [3]. For this sub-μm-thick InP membrane device, we carefully account for the Kerr effect, Two-Photon Absorption (TPA), Free Carrier Dispersion (FCD), Free Carrier Absorption (FCA), and Self-Heating (SH) of the MRR [4], validating our simulations against experimental measurements. Our model defines a set of coupled, time-dependent differential rate equations, while relevant parameters are inferred by employing a Particle Swarm Optimization (PSO) [5] scheme. With this set of physical parameters, we are able to simulate the physics regulating the IMOS MRR behavior, thus allowing us to understand the interplay of effects responsible for its strong nonlinearities.

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II. Model and simulation framework

The nonlinear behavior of the MRR is described with a set of rate equations derived from Coupled Mode Theory (CMT) [6], originally developed for the simulation of ultra-high-Q Si MRRs. The original model contains two rate equations to describe the variation of internal energy inside the ring $u(t)$ and the variation of the density of carriers $N(t)$, in relation to various nonlinear optical effects such as the Kerr effect, TPA, FCA, and FCD. Some of these effects modify the effective refractive index (Kerr and FCD), while others affect the absorption of photons in the MRR (TPA and FCA).

In order to describe the actual operation of an IMOS-based MRR, an additional nonlinear effect must be taken into account: the SH effect. Indeed, when TPA-generated free carriers (e.g., free electrons in the conduction band) absorb photons, they experience intra-band transitions towards higher energy levels. After a given relaxation time, the excited free carriers relax back to lower energy levels with the emission of a phonon (i.e., transfer of heat to the crystal lattice). In order to model this effect, we need to consider an additional rate equation to describe the internal temperature variation $T(t)$ due to the SH effect.

$$\frac{\mathrm{d}u}{\mathrm{d}t} = \left\{ i\left[\Delta\omega - \frac{\omega_0}{n_0}\left(\frac{n_2 c}{n_0 V_\mathrm{K}}|u|^2 - \sigma_r N + \frac{\mathrm{d}n}{\mathrm{d}T}(T-T_0)\right)\right] - \left[\frac{\omega_0}{2Q_L} + \frac{\beta_2 c^2}{2n_0^2 V_\mathrm{TPA}}|u|^2 + \frac{\sigma_\mathrm{FCA} c}{2n_0}N\right]\right\}u + \sqrt{\Gamma_\mathrm{c} P_\mathrm{in}} \quad (1)$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\frac{N}{\tau_\mathrm{car}} + \frac{\beta_2 c^2}{2\hbar\omega_0 n_0^2 V_\mathrm{TPA} V_\mathrm{car}}|u|^4 \quad (2)$$

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{1}{C_\mathrm{th}}\left(P_\mathrm{abs} - \frac{T-T_0}{R_\mathrm{th}}\right) \quad (3)$$

with $\Delta\omega = (\omega_0 - \omega_\mathrm{L})$ detuning between the MRR reference resonance frequency ω_0 and the input laser frequency ω_L, n_0 InP refractive index, n_2 Kerr coefficient, c speed of light in vacuum, $V_\mathrm{K} = V_\mathrm{car} = V_\mathrm{TPA}$ interaction volumes for Kerr, carrier, and TPA effects (assumed to be equivalent to the effective volume due to the high optical confinement provided by the IMOS platform), σ_r FCD empirical coefficient, $\mathrm{d}n/\mathrm{d}T$ thermo-optical coefficient of InP, T_0 ambient temperature, Q_L quality factor, β_2 TPA coefficient, σ_FCA FCA coefficient, Γ_c

TABLE I
COMPARISON OF THE PHYSICAL MODEL PARAMETERS EXTRACTED USING PSO, WITH THE NOMINAL INP WAVEGUIDE ON IMOS

Parameter	Symbol	Unit	PSO	IMOS [3]
Kerr coefficient	n_2	$\mathrm{m^2/W}$	27.6×10^{-18}	27×10^{-18}
TPA coefficient	β_2	$\mathrm{m\,W^{-1}}$	20.9×10^{-11}	$14.2 \times 10^{-11} - 33 \times 10^{-11}$
FCA coefficient	σ_{FCA}	$\mathrm{m^2}$	9.92×10^{-21}	$4 \times 10^{-21} - 7 \times 10^{-21}$
FCD coefficient	σ_{r1}	$\mathrm{m^3}$	3.84×10^{-25}	
Carrier lifetime	τ_{car}	s	0.95×10^{-9}	$< 0.5 \times 10^{-9}$
Quality factor	Q_{L}	–	1516	Device dependent
Thermal resistance	R_{th}	$\mathrm{K\,W^{-1}}$	690.7	Device dependent

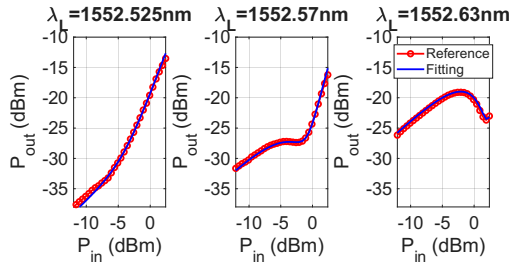

Fig. 1. Comparison between PSO-fitted simulations (blue) and measurements (red) of P_{out}-P_{in} curves at different values of input laser wavelength λ_{L}.

power coupling factor, P_{in} input power, τ_{car} carrier lifetime, C_{th} thermal capacitance, R_{th} thermal resistance.

P_{abs} represents the power absorbed via linear and nonlinear effects, contributing to SH [7]. It is defined as $P_{\mathrm{abs}} = (\alpha_{\mathrm{lin}} + \alpha_{\mathrm{FCA}} N)|u|^2$, where α_{lin} and α_{FCA} are the same absorption contributions present in (1). TPA is excluded from P_{abs} because, although it generates the free carriers responsible for FCA that will cause SH, it does not contribute directly to SH (neglecting the contribution of band-to-band recombination). The complex amplitude of the field on the output bus of the MRR can be written as $b_{\mathrm{out}} = \sqrt{P_{\mathrm{in}}} - \sqrt{\Gamma_{\mathrm{c}}} u$ [6]. This quantity is normalized so that $P_{\mathrm{out}} = |b_{\mathrm{out}}|^2$.

This set of Ordinary Differential Equations (ODEs) is implemented in MATLAB and solved at the steady state with the built-in function `fsolve`.

In order to create a realistic simulation framework, the set of unknown model parameters is inferred from experimental data of a fabricated IMOS racetrack MRR, employing a PSO scheme with the goal of reproducing a set of experimental P_{out}-P_{in} nonlinear curves of the target device measured for different values of input laser wavelength. These curves highlight the nonlinear power behavior of the device, related to the experimentally observed red-shift of the MRR resonance wavelength for increasing values of input power. The fabricated device has radius $R = 20\,\mu\mathrm{m}$, coupling length $L_c = 13.3\,\mu\mathrm{m}$, waveguide cross-section $400\,\mathrm{nm} \times 300\,\mathrm{nm}$ and a spacing $s = 200\,\mathrm{nm}$ between the ring and the bus waveguide.

III. RESULTS

The model parameters extracted with PSO and the comparison with those for the InP waveguide on IMOS are reported in Table I. Fig. 1 shows a comparison between three of the 20 experimental P_{out}-P_{in} curves used as references during the PSO fitting (red circles) and the results of the simulations obtained by employing the parameters of Table I (blue line).

After the PSO-based fitting of the data, we show that further insight into the individual contributions of these effects on the overall resonance shift can be obtained by selectively switching off the physical mechanisms responsible for refractive index changes (i.e., Kerr, FCD, and SH), represented in Fig. 2. When only the Kerr effect is considered, a negligible red-shift is observed, meaning that this term is secondary in the overall resonance shift. When considered in isolation, FCD induces a much stronger blue-shift with respect to the red-shift produced by the Kerr effect alone, and in line with experimental evidence reported in [8]. Finally, the simulated spectra obtained when considering only SH demonstrate that the SH contribution is dominant with respect to both FCD and Kerr effects, and it is therefore responsible for the overall red-shift of the resonances observed experimentally.

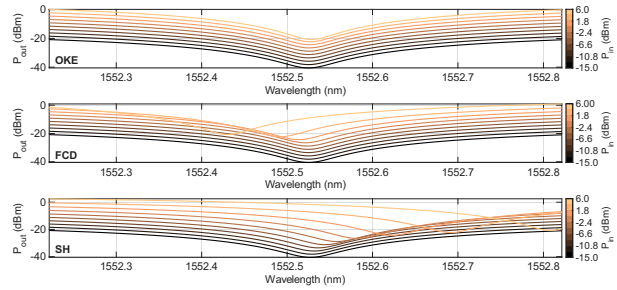

Fig. 2. Output power spectra of the MRR for varying input power levels, obtained by simulating the model with all nonlinear effects turned off, except one at a time.

IV. CONCLUSIONS

In this work, we have presented a detailed model developed for membrane-based MRRs and, using PSO-fitted parameters, confirmed that our simulations can accurately capture the nonlinear response of an IMOS MRR. The specific impact of each microscopic model parameter can be readily simulated and shows good agreement with the experimental observations: by neglecting the SH, the model would have required the Kerr coefficient to be unphysically large to reproduce the measured red-shift. This highlights the relevance of our addition of the SH effects to the nonlinear model of [6] for the description of IMOS-based devices. The numerical values of the extracted parameters and their consistency with prior experimental studies [3], [8] strongly support the validity of the model as an accurate representation of the underlying physical mechanisms.

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