Optimum micro-optical parametric oscillators based on third-order nonlinearity

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Abstract: We show that optimum designs of optical parametric oscillators require different pump and signal/idler coupling, suggesting novel microphotonic geometries. Normalized models with linear/nonlinear loss show that Si can oscillate at 1550nm below certain free-carrier-to-cavity-photon-lifetime ratios.

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Microcavity-based optical parametric oscillators (OPOs) based on four-wave mixing (FWM) are a promising approach for on-chip coherent light generation. Previous demonstrations include OPOs based on FWM in silica microtoroids [1], and silica and silicon nitride microring resonators [2]. However, while integrated photonics enables an enormously rich space of possible device geometries [3], OPO models have been limited to conventional laser analogies. It is of interest to investigate the fundamental limits of micro-OPO performance from first principles and to find designs that achieve the best possible performance for given material parameters. Further, because nonlinear loss, including two-photon and free-carrier absorption (TPA, FCA) can be integral to integrated-photonic solid-state realizations of OPOs, such as in silicon microrings in the telecom band, it is of interest to investigate how nonlinear loss enters the problem of optimal OPO design, and to draw general conclusions about thresholds, scaling and optimum design.

In this paper, we summarize the conclusions from a first-principles model of resonant OPOs, illustrated in Fig. 1(a). It is based on temporal coupled mode theory and includes two-photon absorption and free-carrier loss. First, we show that this complex model can be normalized to only a few parameters, enabling the derivation of simple, general results, including 1) the oscillation threshold for systems with TPA and FCA, 2) an upper bound on achievable (pump-to-signal/idler) conversion efficiency, and 3) broadly applicable design curves allowing optimum designs for systems with all possible linear and nonlinear losses to be summarized in a few simple plots. This is important because the models are in general mathematically complex and need to be solved, at least in part, numerically. Second, we show that the optimum design of an OPO, in terms of maximizing conversion efficiency, requires different external coupling to the pump and signal/idler resonances. Unequal coupling is not present in most tabletop OPOs, which use broadband mirrors, or microring/toroid implementations, which rely on broadband evanescent coupling. Our results suggest that optimum OPOs may require a more complex geometry that enables independent control of pump, signal and idler coupling. One such geometry is proposed in Fig. 1(b), where we suggest using interferometric coupling to differentiate the coupling of a waveguide to different resonant modes [4]. A resonator comprising multiple coupled cavities supports supermodes that provide pump, signal and idler frequencies with orthogonal field distributions, to which the interferometric coupling can be matched. Finally, we use our model to provide guidance on the achievable OPO performance in a few common systems including Si and SiN. We show that even in silicon in the telecom band, with TPA and FCA present, 1 mW of pump light can oscillate, and generate about 1 μW of signal light in a microring cavity with intrinsic quality factor of 10^6 and a sufficiently small (but realistic [5]) free carrier lifetime of <60 ps.

We define the OPO efficiency as output signal power divided by input pump power. Previous work [1] has shown that an efficient OPO requires the pump, signal and idler wavelengths to be on resonance with the cavity, to have substantial field overlap, and satisfy energy and momentum conservation. Our results in addition show that the optimum choice of

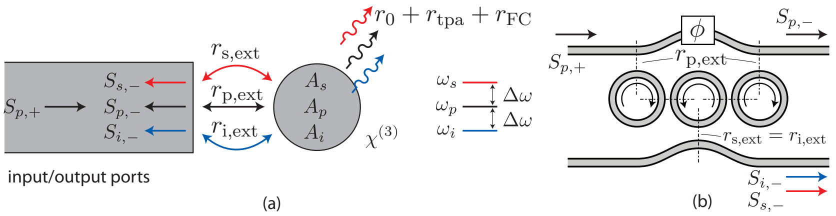

Fig. 1. (a) Model of micro-OPO including a multimode resonator with linear and nonlinear loss; (b) example proposed multimode resonator with unequal pump and signal/idler external coupling, for efficient OPOs [4].

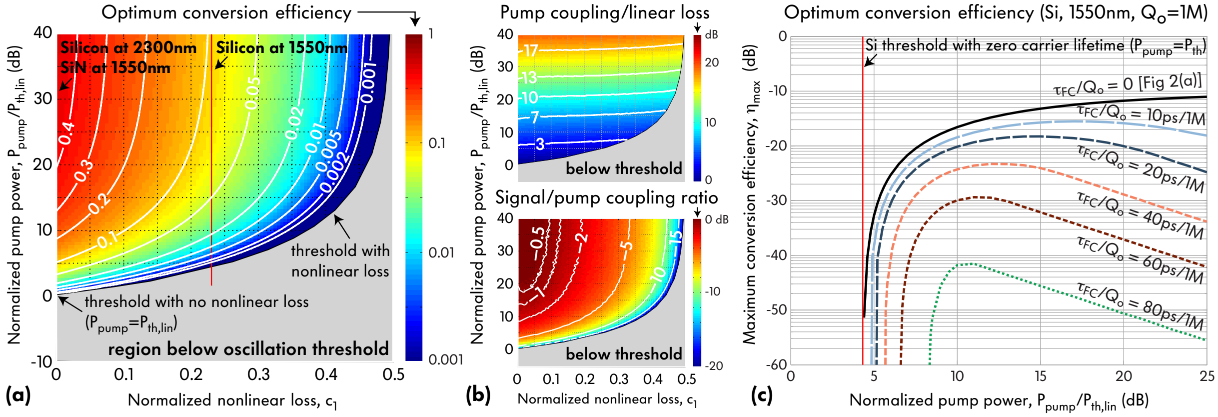

Fig. 2. Normalized design curves for the optimum OPO design: (a) maximum achievable efficiency and threshold for a given pump power (normalized to linear loss), and nonlinear loss (FOM) of material, in limit of zero carrier lifetime; (b) Optimum pump coupling (top) and ratio of signal/pump couplings (bottom); (c) large free-carrier lifetime to cavity photon lifetime (Q) ratio reduces conversion and stops oscillation at high pump power.

Table 1. Examples of oscillation threshold in microring OPOs with/without nonlinear loss (Q = 1M)

Nonlinear material	λ (μm)	n_2 (10^{-5}cm^2/GW)	$\beta_{\rm TPA}$ (cm/GW)	c_1	Width×Height (nm)×(nm)	$R_{\rm out}$ (μm)	$V_{\rm eff}$ (μm^3)	$P_{\rm th}$ (mW)
silicon	1.55	2.41	0.5	0.234 [6]	460×220	3	8.4	0.23*
silicon	2.3	1.2	≈ 0	≈ 0	700×220	8	48	0.64
silicon nitride	1.55	0.24	≈ 0	≈ 0	1500×750	14.5	356	12.2

*Threshold without free-carrier absorption (zero free-carrier lifetime) [see vertical, red line in Fig. 2(c)].

external couplings is asymmetric. Fig. 2(a) shows the maximum efficiency achievable for a given pump power (y-axis) and for a given nonlinear figure of merit (FOM) of the nonlinear material used, where we define $c_1 \equiv \Im[\chi^{(3)}]/\Re[\chi^{(3)}] = 1/(4\pi\,\mathrm{FOM})$. In general, this maximum efficiency is achieved with different pump and signal/idler external couplings, shown in Fig. 2(b). The optimum pump coupling is largely independent of the nonlinear "loss tangent" c_1, while the ratio of signal/idler coupling to pump coupling is largely independent of pump power.

Linear losses do not limit the maximum conversion efficiency, but merely scale the required pump power and optimum choice of external coupling coefficients. On the other hand, nonlinear loss c_1 places an upper limit on the maximum achievable conversion efficiency ($\eta_{\rm max} = 0.5 - c_1$), and increases the threshold and power requirements. For example, silicon can never exceed 26.6% efficiency (out of a maximum 50% to each of the signal and idler).

Our model also provides insight when TPA and FCA are substantial. In Fig 2(c), we show simulation results of OPO efficiency for a silicon microcavity at 1550 nm (see Table 1) versus free-carrier lifetime. The simulation shows that a silicon microring OPO can achieve conversion efficiency of $\sim 0.1\%$ with pump power of 1 mW and a free carrier lifetime of 60 ps, which may be achieved using carrier sweepout via a reverse biased pin diode [5]. The oscillation threshold can be found in closed form as $P_{\rm th} = P_{\rm th,lin} \cdot 4(1-c_1)/\left((1-2c_1)+\sqrt{(1-2c_1)^2-\rho'_{\rm FC}}\right)^2$, where the normalized free-carrier loss $\rho'_{\rm FC} \equiv \left(\frac{c_1\sigma_a n_{\rm nl}^2}{\hbar\omega n_g n_2}\right)\frac{\tau_{\rm FC}}{Q_o}$ depends on only the nonlinear loss parameter c_1, and the ratio of free carrier lifetime $\tau_{\rm FC}$ to cavity photon lifetime (loss Q), Q_o. Efficiency strongly depends on $\tau_{\rm FC}$ and Q_o, and a 5× improvement in either would increase it by >15 dB. We will show examples that illustrate the difference in performance of equal and optimal unequal coupling, designs with linear and nonlinear loss, and performance limits.

We conclude that efficient micro-OPOs can be designed even in the presence of nonlinear losses, but such designs in general call for different external couplings for the pump and signal/idler light. These results have motivated our proposal of both spatial mode and Q engineered multimode resonators for nonlinear FWM applications in Fig. 1(b) [4].

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