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Towards Graphene-comprising Waveguide Resonators for Kerr Comb Generation in the Non-Perturbative Electrodynamic Nonlinearity Regime

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Abstract: We present a study of Kerr microcombs generated by CW pumping of graphene-comprising silicon nitride waveguide ring resonators in the NIR. Our resonator is designed to access the dissipative cavity soliton regime under the combined effect of defocusing nonlinearity from graphene and normal group velocity dispersion (GVD) from a slot waveguide, properly accounting for the wideband dispersion of all waveguide parameters. We then proceed to study the effect of non-perturbative graphene nonlinearity on comb formation and efficiency.

Optical frequency combs can be efficiently generated in small travelling wave resonators made of dispersive materials with third order (Kerr-like) nonlinearity [1]. The most frequently used resonators are bulk whispering-galleries (e.g., magnesium fluoride micropillars) designed for very high Q-factors and critically coupled to optical fibers. As practical applications shift towards integrated optics, waveguide ring resonator (WRR) Kerr combs have also appeared, underpinned by the same principles but also requiring for redesign to exploit the stronger light-matter interaction in integrated nanophotonics. To that end, graphene is a novel optical material that can enrich integrated WRR Kerr combs with its electro-optic tunability of its dispersion [2] and nonlinearity [3], controlled by tuning its chemical potential μ_c. Recent studies have shown that when graphene interacts with high electric field intensities, like the ones that can develop in high-Q photonic resonators, its nonlinearity transcends from a perturbative third order to a non-perturbative photoconductivity regime [3]; the latter is characterized by both self-focusing or defocusing refraction, depending on μ_c, and a deep saturation of its absorption as intensity increases. In this work, we investigate these features, i.e., the intensity- and μ_c-dependent electrodynamic nonlinearity, and exploit them for Kerr comb formation, while rigorously accounting for the frequency dispersion of all properties.

To model the Kerr comb formation, we use the Lugiato-Lefever equation (LLE) framework, in the two-timescale arrangement, that monitors the total electric field inside the cavity. The LLE can be considered as a driven, damped, and detuned variant of the nonlinear Schrödinger equation (NLSE) typically used to model pulse propagation along nonlinear waveguides [3]. The LLE, following the variable notation of [1], is:

$$t_R \frac{\partial E(t,\tau)}{\partial t} = L\left[-\frac{\alpha}{2} + i\sum_{n\geq 2}\frac{\beta_n}{n!}\left(i\frac{\partial}{\partial\tau}\right)^n + i\gamma|E|^2\right]E(t,\tau) + \left(-\frac{\theta}{2} - i\delta_0\right)E(t,\tau) + \sqrt{\theta}E_{in}, \quad (1)$$

where $E(t,\tau)$ is the E-field amplitude inside the resonator (fast-time: τ) as the slow-time (t) progresses. The dispersion of the two Q-factors (α and θ), the nonlinear parameter (γ), and β, are incorporated in the LLE.

For the WRR, we consider a graphene monolayer-clad air-slot design, formed by two rails of silicon nitride on insulator (SNOI), transparent down to the visible range; the slot design was chosen for its normal GVD, a prerequisite for soliton formation under the defocusing nonlinearity of graphene in the μ_c range considered. The waveguide cross-section, inset of Fig. 1(a) [800 nm × 500 nm SNOI rails separated by a 50 nm slot], was tuned for operation in $\lambda_0 = [1.1,2.3]$ μm, i.e., in an octave span around 1.55 μm. The frequency and μ_c dispersion of the waveguide parameters is depicted in Fig. 1(a)-(c); for this preliminary study, we used standard linear and third-order surface conductivity formulas for graphene, at room temperature and assuming regular quality samples

(τ_{intra} = 20 fs). We tune graphene at $\mu_c =$ 0.5 eV, as an optimal compromise between attenuation and nonlinearity, and set the WRR round-trip at $L =$ 100 μm for a pump power $|E_{in}|^2 =$ 10 W. Using the LLE, we slowly detune the pump frequency through the 1.55 μm resonance, from -10 to +50 GHz, acquiring a 50 THz (quarter octave) comb, Fig. 1(d). Due to the non-negligible high-order dispersion of the waveguide, the produced soliton is stable but highly dispersive in the fast time frame. Nevertheless, all the Kerr comb regimes are traversed, Fig. 1(d)-(e): modulation instability (MI), chaos, unstable/breather solitons, and stable phase-locked cavity solitons.

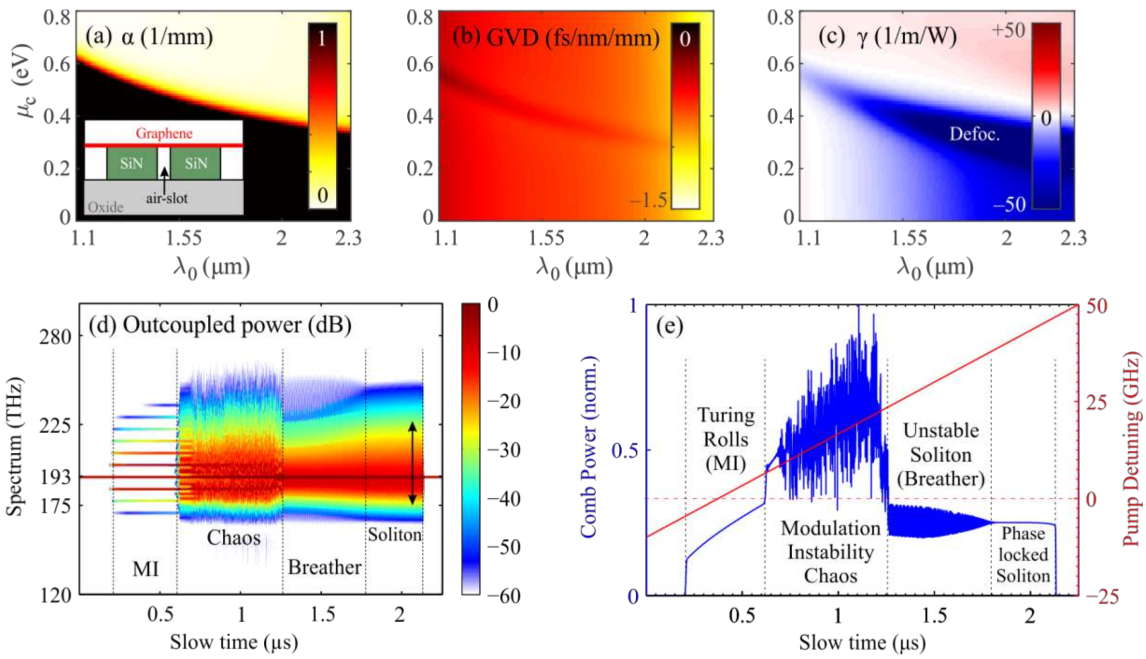

Figure 1. Frequency and μ_c dispersion of the waveguide (a) attenuation, (b) GVD, and (c) nonlinear parameter. The FSR=1.48 THz Kerr comb's (d) outcoupled spectrum and (e) total power, as the pump frequency is detuned.

These results provide encouraging evidence that graphene-comprising WRRs can indeed produce adequately wide Kerr combs in the NIR whereas graphene's tunability can be used not only to control the dispersion [2] but also the nonlinearity and intrinsic Q-factor in a non-trivial way. Our next endeavor will be to study Kerr comb formation under graphene's non-perturbative electrodynamic nonlinearity [3], that could potentially offer improved efficiency owing to the combination of saturable absorption and high nonlinear refraction.

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