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

AUTH-ECE Photonics

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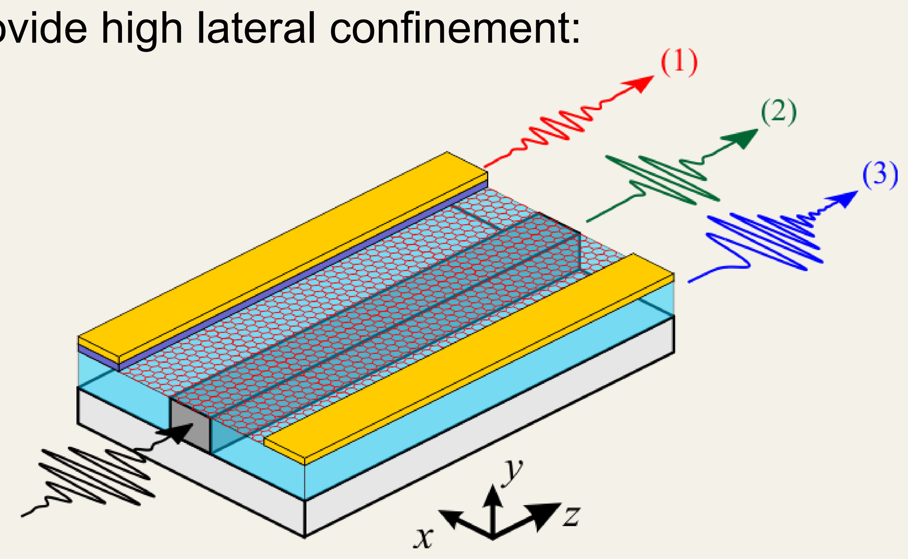
Introduction / Abstract

We present a study of **Kerr microcombs** [1] generated by CW pumping of **graphene-comprising silicon nitride waveguide ring resonators** in the NIR [2]. 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.

Graphene-comprising Si-based Waveguides & Resonators

Silicon-based integrated waveguides provide high lateral confinement:
- ✓ **Miniaturization** of footprint
- ✓ Boosting of **nonlinear (NL) effects**

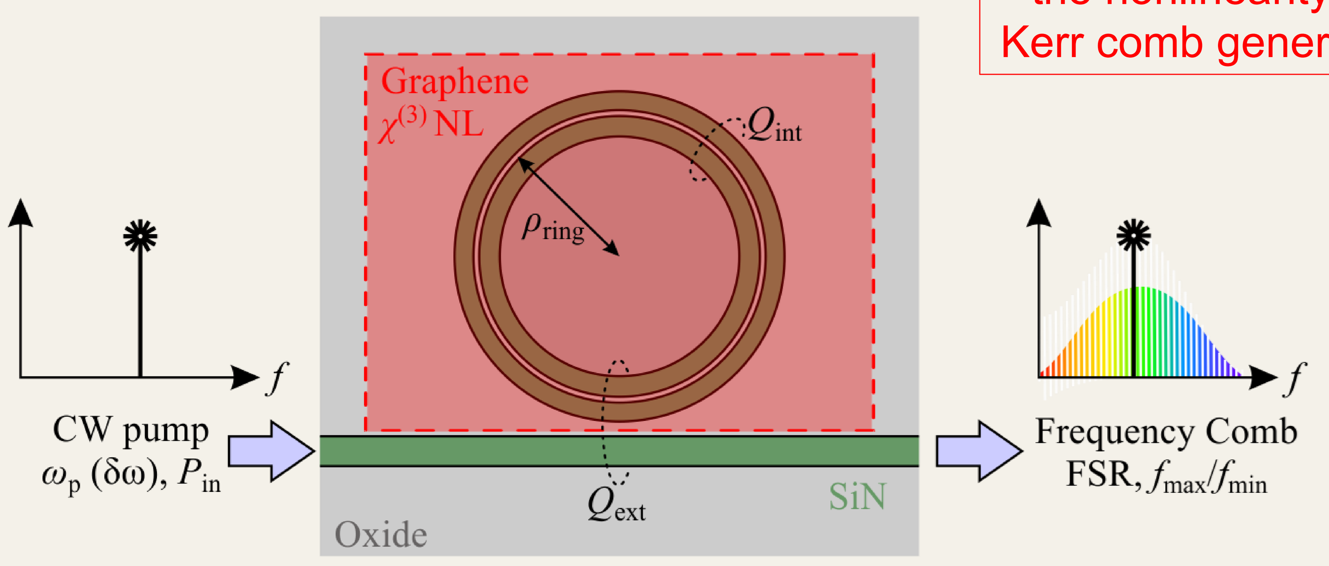


Graphene can be incorporated in such waveguides to enhance them with:
- ✓ Electro-optic tunability
- ✓ Rich and voltage-tunable NL
  - High 3rd-order (Kerr) response
  - Saturable absorption

Ultrafast NL functionalities
- ▶ Waveguide cross-section engineering
- ▶ Graphene quality and electrical tuning via its chemical potential (μ_c)
- ▶ Input pulse: power, duration, shape, chirp

Kerr micro-combs with graphene-comprising waveguide ring resonators (WRR)
- Traveling wave cavity with high 3rd-order nonlinearity
- Low losses (high $Q_{\rm int}$) and critical coupling
- CW pumping with a (slow) frequency tuning

Graphene provides the nonlinearity for Kerr comb generation



Methods

Nonlinear Schrödinger Equation (NLSE)
- ▶ Pulse's slowly varying envelope $A(z,\tau)$ distortion along z-waveguide
- Waveguide effective parameters: $\{\alpha,\beta,\gamma_{\rm NL}\}$ = {absorption, dispersion, Kerr-NL}
- ❖ $\delta_{\rm GNL}(z,\tau)$ = Graphene NL → Free-carrier effects (see GHEM)

$$\frac{\partial A}{\partial z}=\left[-\frac{\alpha}{2}+\left(\sum_{m=2}^{\infty} i^{m+1}\frac{\beta_m}{m!}\frac{\partial}{\partial\tau^m}\right)+i\gamma_{\rm NL}|A|^2-\delta_{\rm GNL}\right]A=F_{\rm NLSE}(z,\tau)A$$

Lugiato-Lefever Equation (LLE)
- ▶ Total field evolution inside a pumped dispersive nonlinear cavity
- $E=E(t_{\rm slow},\tau_{\rm fast})$: two-timescale representation
- Similar to NLSE with $z\to t_{\rm slow}$, but also driven ($\sqrt{\theta}E_{\rm in}$) and detuned ($i\delta_0$)
- Other parameters: roundtrip time (t_R = 1/FSR), cavity length (L),

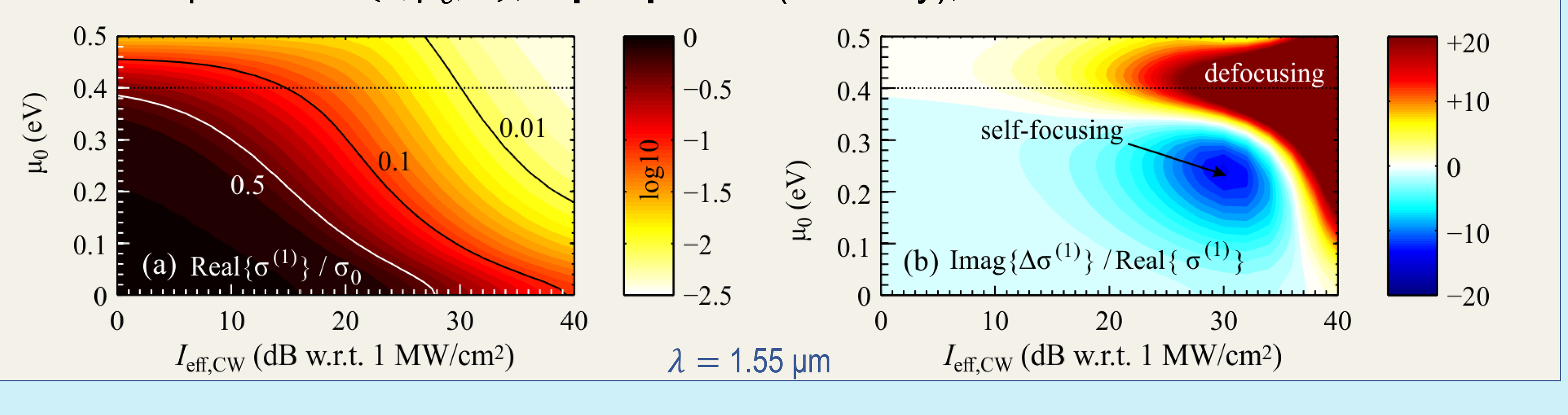
$$t_R\frac{\partial E}{\partial t}=L\,F_{\rm NLSE}(t,\tau)\,E+\left(-0.5\theta-i\delta_0\right)E+\sqrt{\theta}E_{\rm in}$$

Split-step Fourier Method (SSFM)
- ▶ Solve NLSE or LLE: Each "step" in z (NLSE) or $t_{\rm slow}$ (LLE) is split in two
- Spectral (Fourier) domain: Linear terms, e.g., absorption and dispersion
- Time domain: nonlinear terms, Kerr and/or free-carrier effects
- ❖ In-step iterations (typically 2-5) for convergence and stability

Material: Graphene Nonlinearity

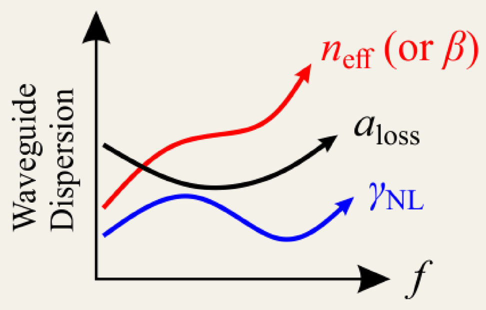
Equilibrium: Carrier temperature = lattice temperature (T)
- Perturbative 3rd order NL response [3] → Computation of $\sigma^{(3)}=\sigma^{(3)}(\lambda,\mu_c,T)$

Non-equilibrium: Graphene "hot electron" model (GHEM) [4]
- Fermi-Dirac electrodynamic microscopic model → Non-perturbative
- Complex photoconductivity $\Delta\sigma^{(1)}=\sigma^{(1)}_{\rm NL}-\sigma^{(1)}_{\rm lin}$: from photogenerated free-carrier (plasma) density and energy, and graphene conductivity (Kubo formulas)
  - ➢ Depends on (λ,μ_c,T), **input power** (intensity), and GHEM lifetimes

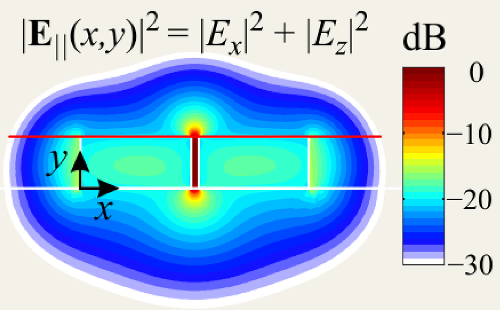


Design: Waveguide for Graphene NL-based Kerr Combs

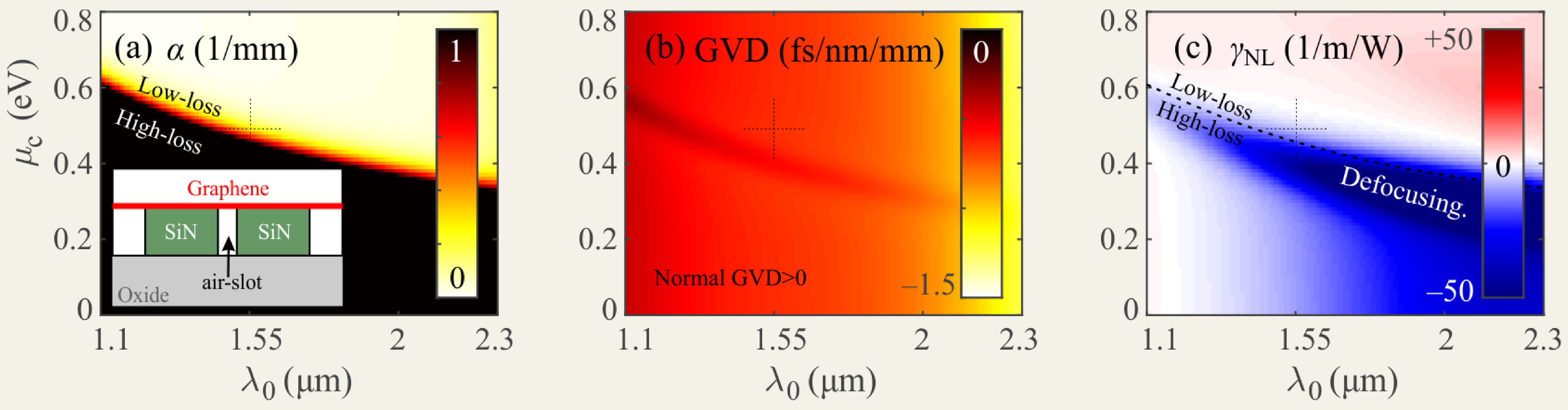
General Methodology
- Maximize overlap of E-field (tangential) with graphene
- Dispersion of $\{\alpha,\beta,\gamma_{\rm NL}\}$ parameters → FEM mode solver
- GHEM [4]: Define effective parameters to relate $\Delta\sigma^{(1)}$ to pulse power and NL refraction and absorption/bleaching.



Graphene-based Kerr comb: The slot-waveguide
- Graphene nonlinearity is defocusing, $\gamma_{\rm NL}<0$
  - ▶ For cavity soliton (Kerr combs): normal GVD<0
- Octave spanning around **1.55 μm** (1.1 to 2.3 μm)
  - ▶ Low-loss (transparency): Si-nitride on insulator
- ❑ Waveguide: 800 nm × 500 nm SiN rails; 50 nm air-slot

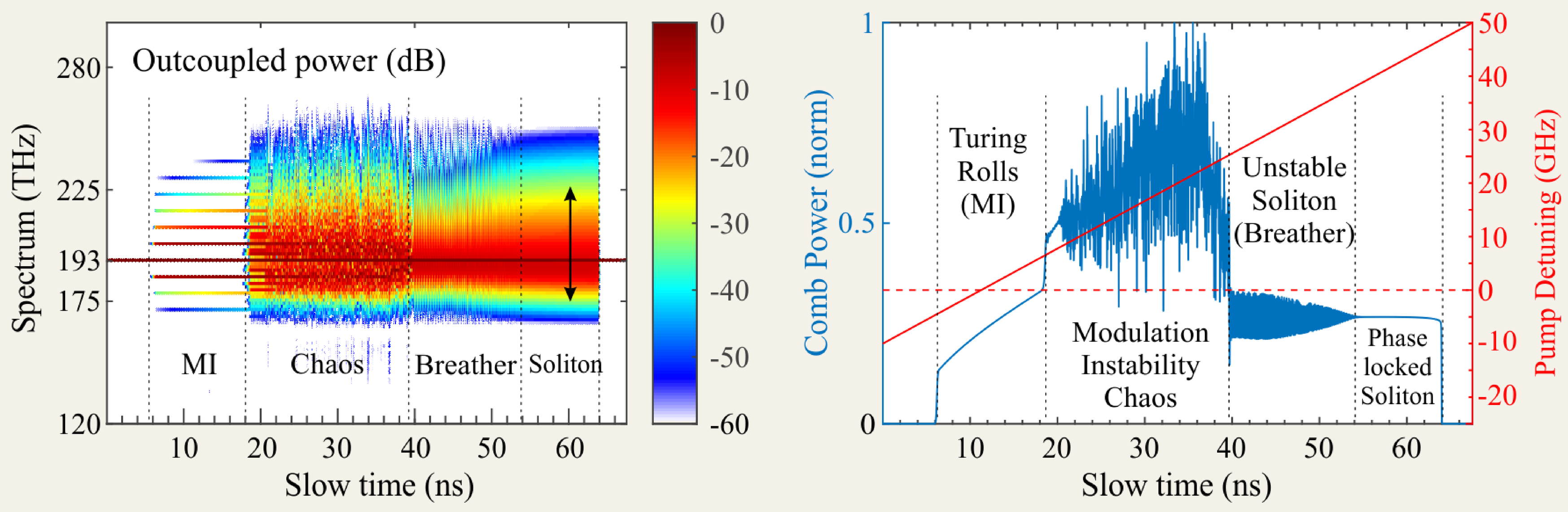


Graphene Tuning
- Identify optimal graphene-monolayer chemical potential (μ_c)
- ▶ Frequency dispersion of w/g parameters $\{\alpha,\beta,\gamma_{\rm NL}\}$ using $\sigma^{(3)}(\lambda,\mu_c,300\text{ K})$ [3]



Simulation Results: Kerr Comb Generation

Waveguide resonator and pumping laser
- CW laser pumping near 193 THz (1.55 μm) resonance
  - ➢ Power: $|E_{\rm in}|^2\approx 10$ W
  - ➢ Detuning range (speed): −10 → +50 GHz (~ 0.9 GHz/ns)
- Cavity length L = 100 μm → Roundtrip time: t_R ~ 0.67 ps → FSR ~ 1.48 THz
- Graphene chemical potential μ_c ~ 0.5 eV for 1.55 μm (see cross in figs above)
- $Q_{\rm ext}$ ~ 3.6 × 10⁴ (no dispersion) for critical coupling near 193 THz



Four regimes: (1) modulation instability [MI] "Turing rolls", (2) MI chaos, (3) unstable soliton "breathers", (4) stable solitons.

Conclusions & Outlook
- ✓ Kerr combs *can* be generated in graphene-comprising WRRs
  - ❖ Stability vs. pump power & detuning and vs. graphene's μ_c
- ✓ Dissipative cavity solitons originate from graphene's nonlinear ${\rm Im}\{\sigma^{(3)}\}$
  - ❖ Full dispersion included, for the perturbative regime [3]
- ✓ **Voltage tuning** on graphene (μ_c) can control the comb through…
  - Absorption: ${\rm Re}\{\sigma^{(1)}\}\to\alpha\to Q_{\rm int}$
  - Refractive NL: ${\rm Im}\{\sigma^{(3)}\}\to\gamma_{\rm NL}$
  - ❖ In [2] graphene voltage tuning affected dispersion, not nonlinearity
- ▶ High cavity powers → graphene non-perturbative NL regime (GHEM) [4]

References

[1] Pasquazi, A., *et al.*, "Micro-combs: A novel generation of optical sources," *Phys. Rep.*, Vol. 729, pp. 1–81, 2018.

[2] Yao, B., *et al.*, "Gate-tunable frequency combs in graphene–nitride microresonators," *Nature*, Vol. 558, No. 7710, pp. 410–414, 2018.

[3] Mikhailov, S. A., "Quantum theory of the third-order nonlinear electrodynamic effects of graphene", *Phys. Rev. B*, Vol. 93, No. 8, 085403, 2016

[4] Pitilakis, A. and E. E. Kriezis, "Ultrafast pulse propagation in graphene-comprising nanophotonic waveguides considering nonperturbative electrodynamic nonlinearity," *JOSA B*, Vol. 39, No. 10, pp. 2723-2734, 2022.

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