Single- and Multi-channel Nonlinear Effects in Graphene-enhanced Resonators

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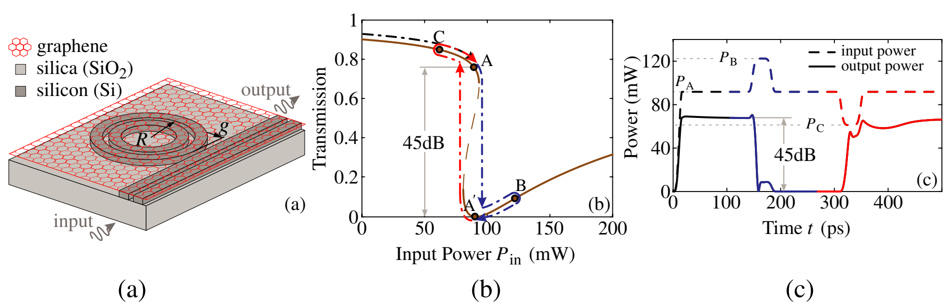
Abstract— We report various graphene-enhanced nonlinear photonic resonators for single- (switching) and multi-channel (wave-mixing) actions. The resonators are analysed with a temporal coupled-mode theory framework to meticulously examine their nonlinear response.

Graphene, the most well-studied and acclaimed 2D material, provides a multitude of promising paths for controlling guided or resonant modes in nanophotonics, both through linear and nonlinear effects, while being technologically compatible with the silicon platform. Electrical biasing induces changes to graphene's chemical potential, which in turn controls its surface conductivity, thus allowing for the impression of amplitude and/or phase changes on the propagating wave. In addition, graphene hosts various nonlinear effects: saturable absorption, responsible for quenching losses at high power levels, together with strong third-order nonlinear response originating from its third-order nonlinear surface conductivity σ_3. The former has been experimentally characterized, indicating saturation intensities as low as 1–10 $\mathrm{MW/cm^2}$, while the latter has been very recently experimentally measured [1] indicating values at least in the order of $10^{-13}\,\mathrm{m^2/W}$ in the NIR (when perceived as an equivalent bulk medium) and even stronger in the THz.

We carefully examine various possibilities of harnessing graphene's nonlinear response in nanophotonic resonators operating in the NIR [e.g., Fig. 1(a)] and in THz resonators. Single-channel effects, such as optical bistability [2] [Figs. 1(b) and (c)], are discussed at first instance and they are subse- quently followed by multi-channel effects, including cross-phase modulation (XPM) and four-wave mixing (FWM) [3]. A systematic mathematical framework based on extensive re-formulations of the Coupled-Mode Theory (CMT) is used to accurately introduce and capture the physics of graphene's nonlinear response in resonators, rigorously considering its 2D nature, together with other nonlin- ear mechanisms taking place, such as Free Carrier Effects. This approach allows for charting the complete map of interrelated nonlinearities, competing or cooperative.



(a) (b) (c)

Figure 1: (a) Graphene-enhanced silicon-slot ring resonator. (b) Nonlinear CW response revealing optical bistability (points A/A′). (c) Nonlinear switching dynamics between bistable states A/A′.

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