Multi-channel Nonlinear Interactions in Practical Graphene Components

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Abstract. Graphene exhibits high third-order nonlinearity in both THz and NIR regimes. It can be exploited in resonant structures to enable elaborate nonlinear functionalities such as frequency generation and all-optical routing. Here, we study multi-channel nonlinear interactions in practical guided-wave resonators comprising graphene. We demonstrate four-wave mixing in the THz with a graphene micro-ribbon standing-wave resonator supporting tightly confined graphene plasmons, and saturable-absorption-based all-optical routing in the NIR with a graphene-covered silicon photonic microdisk. For calculating the nonlinear response, we employ a recently developed perturbation theory/coupled-mode theory framework which is both efficient and accurate. Harnessing the intrinsic nonlinear properties of graphene and following a thorough design process for each component, we demonstrate low power requirements, readily available in real-world systems, and high performance metrics.

INTRODUCTION

In recent years, graphene has attracted considerable interest as a 2D photonic material, since it gathers a wide range of appealing features: it supports strongly localized surface plasmon polaritons in the THz, it can offer wide tunability by means of electric biasing, and it is becoming technologically mature allowing transfer/deposition on different substrates and compatibility with the silicon-on-insulator (SOI) photonic platform. Graphene is particularly interesting for a broad range of nonlinear applications, since it exhibits saturation of the linear losses from low input power levels and high third-order nonlinearity in both NIR and THz regimes; recent measurements [1] indicate values of the equivalent nonlinear refractive index n_2 (when graphene is perceived as an equivalent bulk medium) at least in the order of 10^{-13} m^2/W in the NIR and THz, surpassing conventional nonlinear materials (semiconductors, nonlinear polymers, chalcogenide glasses) by orders of magnitude.

Here, we study multi-channel nonlinear phenomena in guided-wave resonant structures incorporating graphene, in order to propose practical nonlinear components with elaborate functionalities suitable for real-world applications. More specifically, we first demonstrate efficient frequency generation near 5 THz via degenerate four-wave mixing (FWM) in a graphene micro-ribbon standing-wave resonator. Through a comprehensive design process, the conversion efficiency (CE) reaches a very high value of -8.5 dB (14%) with ultra-low input power requirements of approximately 100 μW for both input (signal and pump) waves. Next, we show on-chip all-optical switching/routing

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at near infrared telecom wavelengths by utilizing the saturable absorption (SA) properties of a graphene layer residing on a silicon photonic add-drop microdisk resonator. High-quality switching is achieved with extinction ratios exceeding 10 dB for both ports at a low control power level of only 9 mW.

Overall, the obtained performance metrics highlight the prospect of graphene for *practical* nonlinear components. Importantly, the successful component design process is enabled by a systematic mathematical framework based on perturbation theory and temporal coupled mode theory (CMT) [2], which allows to incorporate all relevant linear and nonlinear phenomena in the analysis, identify their effect, and subsequently propose design solutions.

FOUR WAVE MIXING WITH GRAPHENE STANDING-WAVE RESONATORS IN THE TERAHERTZ

The proposed system is a standing-wave graphene micro-ribbon resonator of length L and width g, fed by a single access waveguide [Fig. 1(a)]. Graphene is modeled as an infinitesimally-thin sheet described by linear and nonlinear surface conductivities [2]. At THz the linear conductivity is dominated by the intraband term and includes loss. We exploit three resonances so as to enhance the conversion efficiency by offering temporal and spatial energy confinement (quantified by their quality factor and effective mode volume, respectively) for all three input and output waves. More specifically, considering a w = 1 μm graphene ribbon for single-mode operation at 5 THz, we find the optimum resonator length L = 24.3 μm, supporting the 7th, 8th, and 9th order modes at f_3 = 4.53 THz, f_1 = 5 THz, and f_2 = 5.45 THz, respectively [3]. The conversion efficiency (CE = $P_{idler}/(P_p+P_s)$) is depicted in Fig. 1(b) as a function of the pump (P_p) and signal (P_s) input power. It reaches -25.8 dB (0.26%) for remarkably low input powers P_p = 127 μW and P_s = 77 μW. This performance, however, is still limited by the deleterious Kerr-induced self and cross frequency shifts that detune the resonant frequencies from the chosen operating wavelengths as the input power increases. It can be greatly improved as revealed by our developed framework [3]. By pre-shifting the operating frequencies to better match the perturbed resonance frequencies, CE can reach extremely high values up to -8.5 dB (14%), as seen in Fig. 1(c) which plots CE as a function of normalized f_1 and f_2 detunings for fixed input power levels.

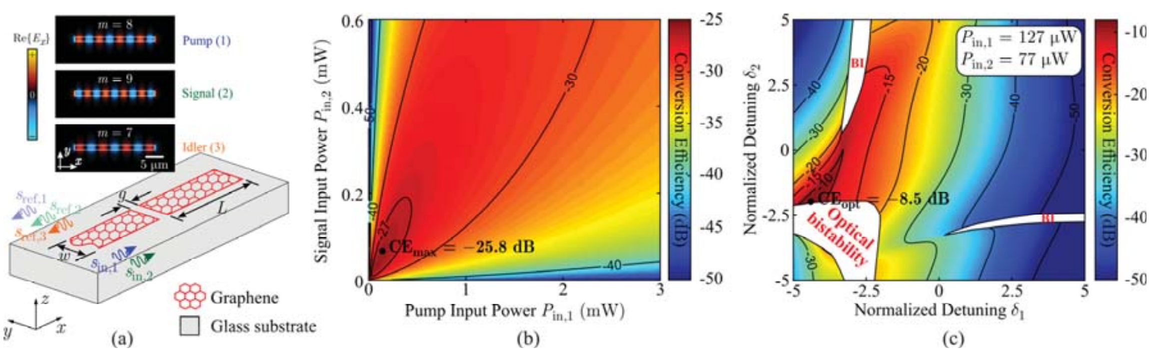

FIGURE 1. (a) Graphene micro-ribbon resonator fed with a single access waveguide. The three resonant modes exploited in the four four-wave mixing process are shown as insets. (b) FWM conversion efficiency as a function of pump and signal wave input powers. A maximum of -25.8 dB (0.26%) is observed for P_p = 127 μW and P_s = 77 μW. (c) FWM conversion efficiency as a function of pump and signal wave detunings, keeping the input power constant. By pre-shifting the operating frequencies, an optimum conversion efficiency of -8.5 dB (14%) is found. Unstable regions where optical bistability manifests are marked and avoided for four-wave mixing operation since they lead to two output states.

SATURABLE ABSORPTION ROUTING WITH GRAPHENE TRAVELLING-WAVE RESONATORS IN THE NEAR INFRARED

Next, a standard, silicon-based travelling-wave disk resonator is examined, enhanced with a graphene sheet placed on top [Fig. 2(a)]. The underlying silicon structure is essential since graphene cannot support plasmons and guide light in the telecom wavelengths (NIR). Graphene is incorporated to contribute its nonlinear properties and mainly the ability to quench its linear losses as the interacting light intensity rises (saturable absorption) [4]. The proposed silica-cladded silicon disk, configured in an add-drop scheme with two access waveguides, has a radius R = 1.503 μm while the waveguide cross-sectional dimensions are w x h = 200 x 340 nm^2 in order to solely support the fundamental TM mode, allowing for efficient interaction with graphene (more than employing the fundamental TE mode). The SA in graphene is exploited in a two-channel routing configuration where the presence of a strong pump wave quenches the resonator losses, steering a weak probe wave to the drop port; in the pump wave absence, light is conventionally led to the through port. A meticulous design process is used to determine the two optimum coupling gaps g_1 = 348 nm and g_2 = 414 nm of the waveguides [5]. The CW performance, as calculated from our multi-channel perturbation theory/coupled-mode theory framework, is depicted in Fig 2(b). As evident, with a moderate pump power of P_{in} = 9 mW, the weak signal is transferred to the drop port, experiencing a 10.5 dB extinction ratio (ER) and almost -3 dB insertion losses (IL) in any of the two output ports. What is more, other nonlinear effects such as self- and cross-phase modulation appear for higher input powers, as seen by comparing solid and dashed curves in Fig. 2(b). Finally, the temporal response of the system is examined in Fig. 2(c): Super-Gaussian pulses are used for the weak probe data as well as for the strong pump wave; the latter should be pre-shifted appropriately in time to forestall graphene nonlinear response [5]. Overall, a bitstream with a rate of 10 Gbps (for scenarios up to 20 Gbps see [5]) is well routed by the proposed resonant element, revealing the possibility of practical exploitation of graphene nonlinear response in telecom wavelengths for all-optical applications.

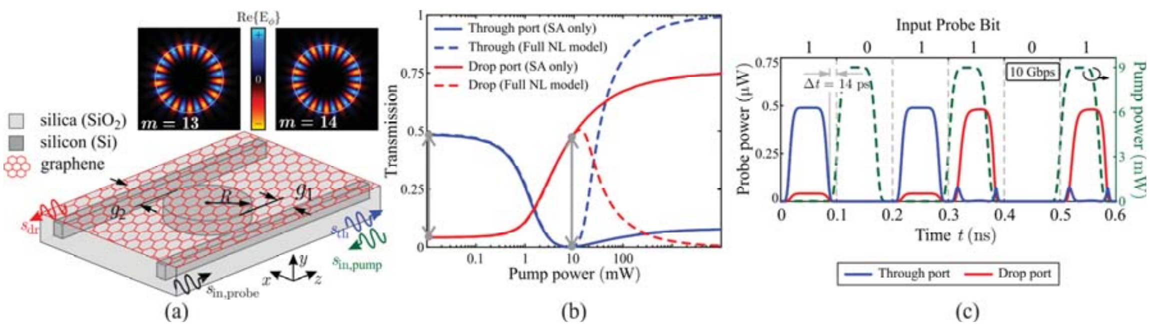

FIGURE 2. (a) Graphene-enhanced silicon disk resonator in add-drop configuration. The two consecutive resonant modes used are shown as insets. (b) Transmission of the probe signal in the through (blue) and the drop (red) port versus pump wave input power. The IL is only -3.2 dB/-3.3 dB in both ports while the respective ER is theoretically infinite for the through and 10.5 dB for the drop port, respectively. (c) Time domain demonstration of successfully routing a 10 Gbps bitstream, revealing the capabilities of the proposed component to handle real-world bitrates.

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