Nonlinear Photonic Resonators With Graphene: Saturable Absorption and the Effect of Carrier Diffusion and Finite Relaxation Time

Georgios Nousios,[1] Thomas Christopoulos,[1] Dimitrios Chatzidimitriou,[1] Alexandros Pitilakis,[1] Odysseas Tsilipakos[2] and Emmanouil Kriezis[1]

[1] *School of Electrical and Computer Engineering, Aristotle University of Thessaloniki, GR-54124, Thessaloniki, Greece*

[2] *Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, GR-71110 Heraklion, Crete, Greece*

gnnousios@ece.auth.gr

Abstract: We assess the CW and dynamic nonlinear optical response of microdisc resonators enhanced by graphene saturable absorption, by carefully considering the carrier diffusion and finite relaxation time of graphene photoexcited carriers.

1. Introduction

Graphene is the most prominent two-dimensional (2D) material for nanophotonic applications due to its attractive linear and nonlinear optical properties and almost seamless compatibility with mature commercial silicon-on-insulator (SOI) platforms. A nonlinear effect in graphene, that has only recently attracted attention outside mode locking applications, is saturable absorption (SA): the quenching of absorption with increasing incident power. SA in graphene exhibits a significantly lower power threshold compared to other nonlinear effects (e.g., Kerr effect), and an ultrafast response [1], rendering its exploitation in nonlinear devices highly preferable.

In this work, we introduce a rate equation model incorporating carrier diffusion and finite relaxation time, aiming to describe graphene's SA in an accurate and comprehensive way. In order to demonstrate both the quantitative and qualitative features predicted by the aforementioned model, a graphene-enhanced silicon disk resonator is examined, both in CW and pulsed conditions. This is achieved with a rigorous framework combining temporal coupled mode theory (CMT) and perturbation theory [3], complemented with the proposed rate equation model.

2. Saturable absorption in graphene

First, the employed model of graphene's SA is briefly described. The saturable surface conductivity is considered to depend on the photoexcited carrier density, $N_c(\mathbf{r},t)$, according to the following relation [2]

$$\sigma_{\mathrm{SA}}(N_c) = \sigma_0 \left(1 - \frac{N_c}{2N_{\mathrm{sat}}}\right), \tag{1}$$

where N_{sat} is the saturation carrier density, and σ_0 the linear or low-power conductivity. The carrier density is calculated through a separate spatiotemporal rate equation incorporating both the finite relaxation time as well as the carrier diffusion in the 2D material. It takes the form:

$$\frac{\partial N_c}{\partial t} = \frac{\frac{1}{2}\mathrm{Re}\{\sigma_{\mathrm{SA}}(N_c)\}|\mathbf{E}_{||}|^2}{\hbar\omega_0} - \frac{N_c}{\tau} + D\nabla^2 N_c, \tag{2}$$

where $(1/2)\mathrm{Re}\{\sigma_{\mathrm{SA}}(N_c)\}|\mathbf{E}_{||}|^2$ is the absorbed power density due to the saturable graphene conductivity, τ is the phenomenological SA relaxation time (encompassing the faster carrier-carrier intraband scattering and the slower carrier-phonon scattering or electron-hole recombination) and D is the diffusion coefficient.

3. Graphene-enhanced silicon disk resonator

The structure under study consists of a SOI-based disk resonator in an add-drop configuration, overlaid with a uniform graphene monoatomic layer. A multi-channel excitation scheme is examined, where the output port of the weak probe wave is determined by the presence or absence of the strong control (pump) wave. In the absence of the latter, the probe is transmitted to the through port, whereas in the opposite case the losses are quenched,

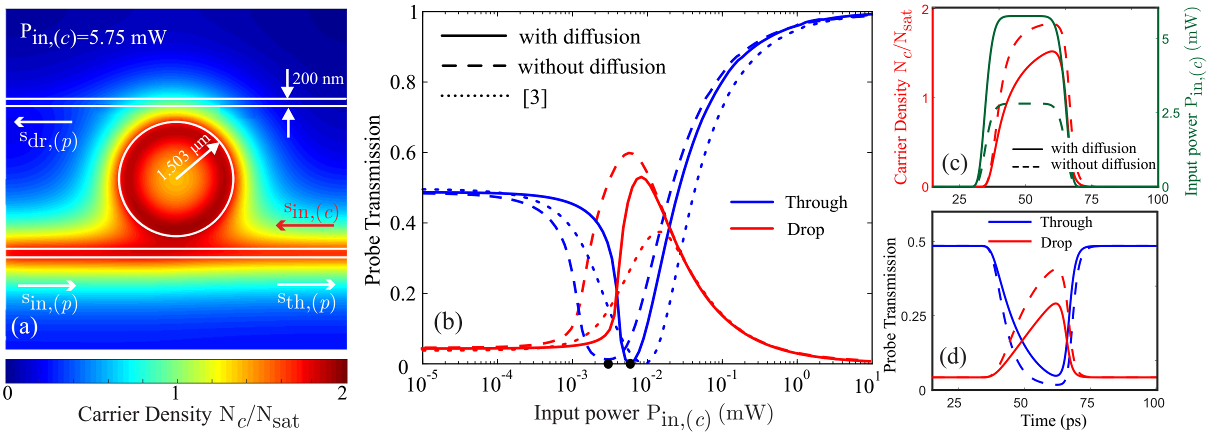

Fig. 1. (a) Carrier distribution on graphene for the control input power required to reach zero-transmission point. The input and output waves are marked with arrows. (b) CW transmission of the probe signal in both trough and drop ports as a function of the control input power, for three different models of SA. (c) Control input power and developed carrier density in the outer boundary of the disk resonator vs time, in both the presence and absence (D is set to zero) of carrier diffusion. In each of the aforementioned cases the control input power is determined according to Fig. 1(b) in order to reach the zero transmission point, as indicated by the black dots. (d) Transmission in both through and drop ports of the probe wave vs time.

the critical coupling condition is satisfied and the probe wave is directed to the drop port. Fig. 1(a) shows the steady-state carrier distribution on graphene for a high power level of the control wave, $P_{\text{in},(c)}$ (the graphene sheet occupies the entire depicted space). As can be seen, due to diffusion the photoexcited carriers are spread across a wide area, extending well beyond the points where they are generated. Employing the nonlinear framework of CMT/perturbation theory we calculate the CW curves of Fig. 1(b). The same procedure is followed with two other SA models, corresponding to the absence of diffusion in Eq. (2) (dashed curves) and the model used in [3] (dotted curves). The calculated responses share the same qualitative features; however important quantitative differences are evidenced (note that the horizontal axis is logarithmic), indicating the importance of incorporating the diffusion effect. Comparing solid and dashed curves, shows that the input power required to reach the zero-transmission point increases when diffusion is taken into account. Furthermore, the model used in [3] leads to an even greater input power requirement, even though carrier diffusion is not considered. Finally, between the different models examined, the SA treatment in this work leads to steeper changes in the transmission curves.

Subsequently, the temporal response of the nonlinear resonator is studied. The diffusion coefficient and the SA relaxation time are chosen to be $D = 5500$ cm^2/s and $\tau = 1.67$ ps, respectively, which are typical values for graphene. The quality factor attributed to unsaturated losses (low-power regime) is $Q_{0,\text{SA}} \cong 1000$. A simple switching scenario is depicted in Fig. 1(c,d) with the use of a single control input pulse with duration of 30 ps (FWHM), while the probe input power is constant. Initially, the diffusion effect is neglected, thus the delay and distortion in the transmitted pulses are attributed to the cavity photon lifetime and the finite SA relaxation time. With the inclusion of the carrier diffusion effect the delay and distortion are even more pronounced. Therefore, both contributions should be evaluated for correctly predicting the achievable switching speed of the component.

Acknowledgement

The research work was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "First Call for H.F.R.I. Research Projects to support Faculty members and Researchers and the procurement of high-cost research equipment grant." (Project Number: HFRI-FM17-2086)

References

1. G. Xing, H. Guo, X. Zhang, T. C. Sum, C. H. A. Huan, "The physics of ultrafast saturable absorption in graphene," Opt. Express **18**, 4564 (2010).
2. D. Chatzidimitriou, E. E. Kriezis, "Light propagation in nanophotonic waveguides considering graphene's saturable absorption", Phys. Rev. A **102**, 053512 (2020).
3. T. Christopoulos, V. G. Ataloglou, E. E. Kriezis, "All-optical nanophotonic resonant element for switching and routing applications exploiting graphene saturable absorption", J. Appl. Phys. **127**, 223102 (2020).