Electrically Tunable Nonlinear Refraction and Absorption in Graphene-covered SiN Waveguides

Koen Alexander¹,², Bart Kuyken¹,², Dries Van Thourhout¹,²

¹Photonics Research Group, INTEC, Ghent University-imec, Ghent B-9000, Belgium
²Center for Nano- and Biophotonics (NB-Photonics), Ghent University, Ghent B-9000, Belgium
koen.alexander@ugent.be

Abstract: The real and imaginary part of the third-order nonlinearity of a gate-tunable graphene-covered SiN waveguide are measured through cross-phase and cross-amplitude modulation. A strong dependence on pump-probe detuning and Fermi energy is demonstrated.

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1. Introduction

Several studies have demonstrated a strong third order nonlinear optical response in graphene [2, 3]. Recently it has been shown that this response is also strongly dependent on the Fermi level ($E_F$), either by measuring the four-wave-mixing (FWM) or third harmonic generation (THG) response in gated graphene [1, 4]. An intrinsic disadvantage of FWM and THG is that they can only be used to measure the magnitude of the third order nonlinear susceptibility ($|\chi^{(3)}|$) (or conductivity $|\sigma^{(3)}|$). However, many potential applications require the knowledge of $\chi^{(3)}$ as a complex parameter.

To assess this, we have integrated graphene on a SiN waveguide and have performed a simultaneous measurement of cross-amplitude and cross-phase modulation (XAM/XPM). We measured, for the first time to our knowledge, the complex value of the waveguide nonlinear parameter $\gamma$ ($\propto \chi^{(3)} \propto i\sigma^{(3)}$) as a function of gating voltage and pump-probe detuning. These measurements uncover an intricate dependence of both the nonlinear absorption and refraction in graphene on these parameters, including strong resonances and sign changes.

2. Experimental results

Sample fabrication and characterization The waveguide design and fabrication were the same as in Ref. [1], Fig. 1(d) shows the cross-section and TE00 mode. Monolayer graphene was transferred to the samples by Graphenea, after which it was patterned and contacted as can be seen on the top-view image in Fig. 1(c). The structures were covered with a polymer electrolyte so that the graphene can be gated using a gate voltage $V_G$ [1]. The resistance over a graphene sheet $R_{DS}$ ($L=800$ $\mu$m) and the waveguide propagation loss $\alpha$ were measured as a function of $V_G$. Both measurements are plotted on Fig. 1(b). Based on this, one can estimate the relation between $V_G$ and $E_F$ in the graphene [1], the estimated $E_F$ is plotted on the top axis of Fig. 1(b).

Fig. 1: (a) Setup for the XAM/XPM experiment. (b) Waveguide loss (blue) and the electrical resistance over the graphene (red) as function of $V_G$. (c) Top-view of the sample. (d) Cross-section of a SiN waveguide with TE00 mode.
One can thus estimate (corresponds to saturable absorption and is known to be strong in graphene. At high doping, |γ| becomes positive right beyond the transparency point (|S1| ≈ |sin(βL/ωF, 1/2 + ∠γ)|) [6], with L being the length and the group velocity dispersion of the fiber. One can thus estimate γ by fitting this relation. Hence the complex value of γ can be derived.

Measurement results Fig. 2 summarizes a measurement of γ of a graphene-covered waveguide (L = 50 μm, waveguide width =1400 nm). In Fig. 2(a), the extracted Reγ and Imγ are plotted as a function of VG, for several probe wavelengths. From these curves it is clear that γ is very dependent on EF. Imγ is negative for low doping, |EF| < hωa/2, this corresponds to saturable absorption and is known to be strong in graphene. At high doping, |EF| > hωa/2, |Imγ| decays due to the decrease of available charge carriers. Interestingly, Reγ becomes positive right beyond the transparency point (|EF| ≳ hωa/2), meaning that the absorption here increases with pump power. The measured Reγ is positive for low doping, goes through a strong resonance and becomes strongly negative around |EF| ≈ hωa/2, after which it decays to zero. In Figs. 2(b,c), Imγ and Reγ are plotted as a function of γprobe, for different gating voltages VG. γ is clearly dependent on wavelength, typically a resonant feature is observed around γprobe ≈ γpump.

3. Conclusion

For the first time to our knowledge, we simultaneously measure the nonlinear phase and amplitude response of graphene for a varying Fermi level. Both the real and imaginary part of the measured nonlinear parameter γ of the graphene-covered waveguide are not only large in absolute terms, they are also strongly dependent on pump-probe detuning and gating voltage. The latter dependence being much more complex than what could be made out from the FWM measurement in Ref. [1]. These results can give new insight into the behavior of graphene as a nonlinear optical material and into how it can be used for tunable nonlinear applications, e.g. electrically controlled all-optical signal processing, modulating γ for quasi phase-matched frequency conversion (as proposed in Ref. [5]), etc.

References