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

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**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. © 2018 The Author(s)

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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).

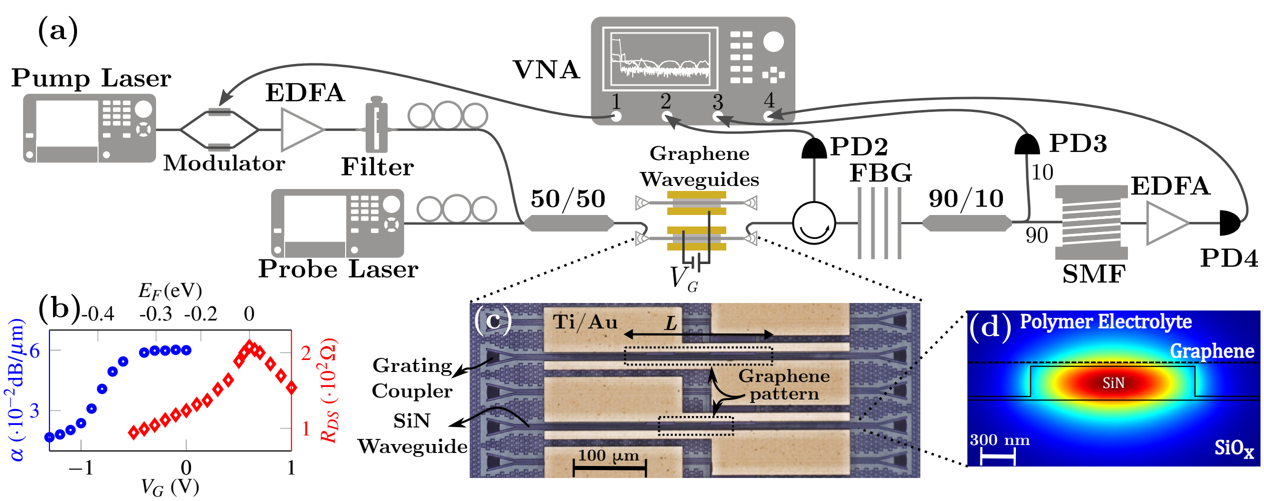


Fig. 1: (a) Setup for the XAM/XPM experiment. (b) Waveguide loss (blue) and the electrical resistance over the graphene (red) as function of $V_G$. (c) Top-view of the sample. (d) Cross-section of a SiN waveguide with TE00 mode.

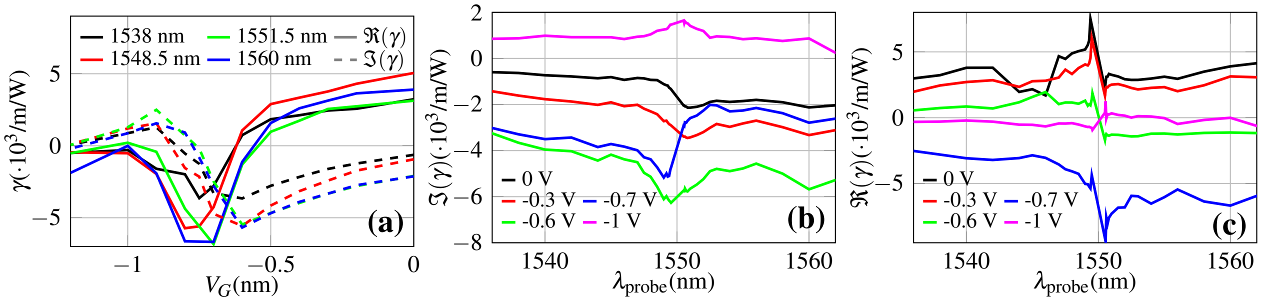


Fig. 2: Experimental results. The waveguide width and height are respectively 1400 nm and 330 nm, the graphene length 50 $\mu$m, $\lambda_{\text{pump}}$=1550.18 nm. (a) $\Re\gamma$ (solid) and $\Im\gamma$ (dashed) as a function of $V_G$, for different values of $\lambda_{\text{probe}}$ (see legend). (b, c) $\Im\gamma$ and $\Re\gamma$ as a function of $\lambda_{\text{probe}}$, for different values of $V_G$ (see legend).

**XAM/XPM measurement** The measurement methodology was partly based on Ref. [6] and the setup is shown in Fig. 1(a). A pump laser ($\lambda_{\text{pump}}$ =1550.18 nm) is modulated using a vector network analyzer (VNA), combined with a weaker CW probe of tunable wavelength $\lambda_{\text{probe}}$ and coupled into the graphene-covered waveguide. The probe field acquires a *complex* phase delay $\gamma P_{\text{pump}} L_{\text{eff}}$ [6], where $L_{\text{eff}} = (1-e^{-\alpha L})/\alpha$ and $\gamma \propto \chi^{(3)}(\omega_{\text{probe}}, \omega_{\text{pump}}, -\omega_{\text{pump}})$. XPM and XAM are thus represented by $\Re\gamma$ and $\Im\gamma$, respectively. After the chip, pump and probe are separated by a circulator and a fiber Bragg grating (FBG) (reflects $\lambda_{\text{pump}}$, transmits $\lambda_{\text{probe}}$). The pump and a fraction of the probe are sent to port 2 and 3 of the VNA, respectively. The remaining probe power is passed through 50 km of single mode fiber and sent to port 4 of the VNA. The voltages measured at port 2 and 3 are directly proportional to the pump and probe powers, respectively. When measuring the electrical S-parameters of the system as a function of modulation frequency $\Omega$ using the VNA, one can prove that $\lim_{\Omega\to 0}\frac{|S_{31}|}{|S_{21}|} \propto |\Im\gamma| L_{\text{eff}}$ and $\lim_{\Omega\to 0}\angle S_{31} - \angle S_{21} = 0\ (=\pi)$ if $\Im\gamma < 0$ ($\Im\gamma > 0$). Furthermore, since the modulated probe propagates through a long dispersive fiber one can prove that $|S_{41}| \propto |\sin(\beta_2 L_{\text{fiber}}\Omega^2/2 + \angle\gamma)|$ [6], with $L_{\text{fiber}}$ and $\beta_2$ the length and the group velocity dispersion of the fiber. One can thus estimate $\angle\gamma$ by fitting this relation. Hence the complex value of $\gamma$ can be derived.

**Measurement results** Fig. 2 summarizes a measurement of $\gamma$ of a graphene-covered waveguide ($L = 50\ \mu$m, waveguide width =1400 nm). In Fig. 2(a), the extracted $\Re\gamma$ and $\Im\gamma$ are plotted as a function of $V_G$, for several probe wavelengths. From these curves it is clear that $\gamma$ is very dependent on $E_F$. $\Im\gamma$ is negative for low doping, $|E_F| \ll \hbar\omega/2$, this corresponds to saturable absorption and is known to be strong in graphene. At high doping, $|E_F| > \hbar\omega/2$, $|\Im\gamma|$ decays due to the decrease of available charge carriers. Interestingly, $\Im\gamma$ becomes positive right beyond the transparency point ($|E_F| \gtrapprox \hbar\omega/2$), meaning that the absorption here *increases* with pump power. The measured $\Re\gamma$ is positive for low doping, goes through a strong resonance and becomes strongly negative around $|E_F| \approx \hbar\omega/2$, after which it decays to zero. In Figs. 2(b,c), $\Im\gamma$ and $\Re\gamma$ are plotted as a function of $\lambda_{\text{probe}}$, for different gating voltages $V_G$. $\gamma$ is clearly dependent on wavelength, typically a resonant feature is observed around $\lambda_{\text{probe}} \approx \lambda_{\text{pump}}$.

## 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 $\gamma$ 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 $\gamma$ for quasi phase-matched frequency conversion (as proposed in Ref. [5]), etc.

## References

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