Electrically Tunable Optical Nonlinearity of Graphene-covered SiN waveguides

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Abstract: Electrical tunability of the optical nonlinearity of graphene is demonstrated on a SiN platform using four-wave mixing. The nonlinearity γ of the graphene-covered waveguide more than doubles when tuning E_F to the vicinity of $-\hbar\omega/2$.

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1. Introduction

In recent years, there has been increasing interest in the nonlinear optical properties of graphene. Both theoretical predictions [1,6] and experimental studies [4,5] have indicated that graphene has a strong and broadband third order susceptibility $\chi^{(3)}$. This effect is also expected to be tunable, as it was suggested that the dependence on Fermi level E_F can be remarkably strong [1,6]. Here we provide, for the first time to our knowledge, experimental verification of the latter claim. We have integrated graphene with SiN waveguides, and have characterized the nonlinearity through four-wave mixing (FWM). Electrical tuning of E_F (gating) is done by using a polymer electrolyte [2].

2. Experimental results

Device fabrication A set of straight SiN waveguides (made in a CMOS pilot line) of different widths and lengths was prepared. Fig. 1a shows the waveguide cross-section. Fig. 1b shows the fundamental TE-mode. Subsequently, CVD-grown (Chemical Vapor Deposition) single layer graphene was transferred to the samples by Graphenea. The graphene layer was patterned so that patches of varying lengths cover the waveguides, metallic contacts were applied at both sides of the waveguides. The structures were covered with an polymer electrolyte consisting of $LiClO_4$ and PEO with a weight ratio of 0.1:1. Fig. 1c shows a sketch of the cross-section. V_{GS} is applied to gate the graphene on the tested waveguide [2]. V_{DS} is only applied when measuring the resistance of the graphene (see below).

Experimental setup Fig. 1d shows a sketch of the setup. A pump and signal laser are combined and coupled (using grating couplers) into a graphene-covered waveguide. At the end of the waveguide, pump light is filtered out by a fiber Bragg grating (FBG) and the signal and idler are collected and measured with an optical spectrum analyser (OSA).

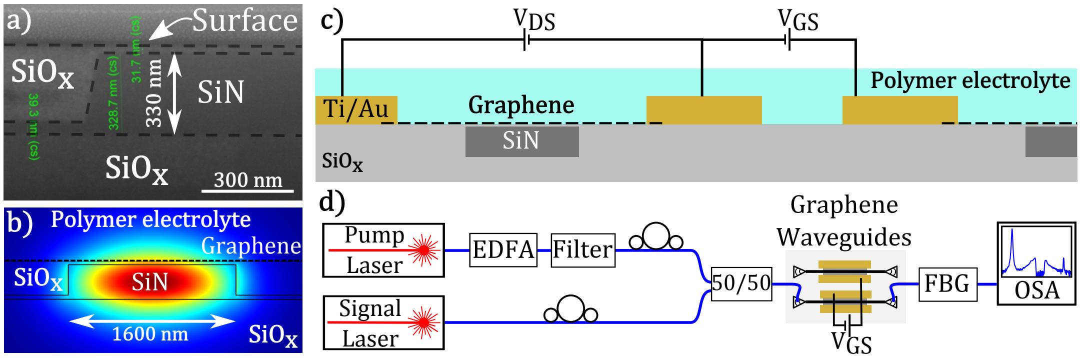
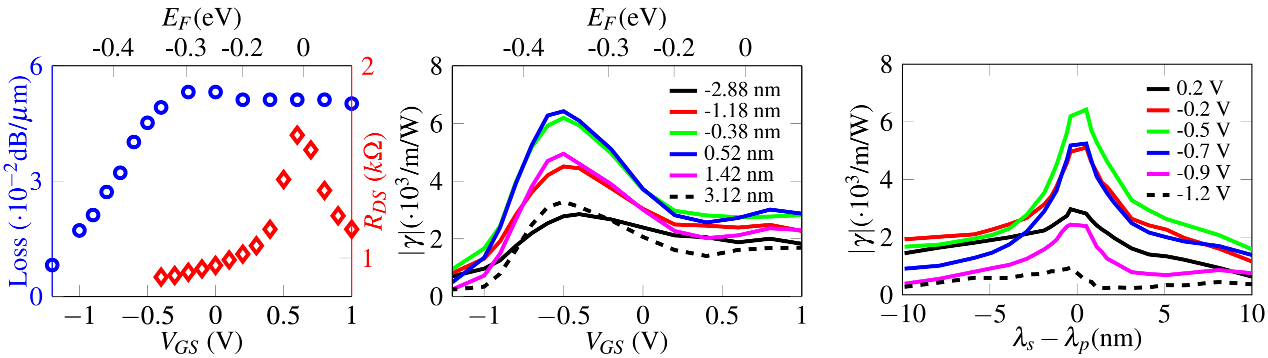


Fig. 1: a) SEM image of the cross-section of a SiN waveguide. b) TE mode profile. The wavelength is 1550 nm. c) Sketch of the gating scheme used. d) Experimental setup used for the FWM experiments.



(a) Waveguide loss (blue) and the electrical resistance over the graphene (red) as function of V_{GS}.

(b) Estimated nonlinear parameter $|\gamma|$ as function of the applied voltage V_{GS}, for different signal detunings $\lambda_s - \lambda_p$.

(c) Estimated nonlinear parameter $|\gamma|$ as function of the signal detuning, for different applied voltages V_{GS}.

Fig. 2: Experimental results. The waveguide width and heigth are respectively 1600 nm and 330 nm, the graphene length 100 μm, λ_p=1550.18 nm and $P_{pump}(0)$=10.5 dBm.

Resistance and linear loss The resistance over the graphene sheet R_{DS} and the propagation loss of the waveguide were measured as a function V_{GS}. Both measurements are plotted on Fig. 2a. Based on this data, it is possible to estimate the relationship between the voltage V_{GS} and the Fermi level E_F in the graphene [2], E_F is plotted on the top axis.
Four-wave mixing In the FWM experiments the phase mismatch is negligible ($L\beta_2\Delta\omega^2 << 1$) due to the short interaction length with the graphene ($L = 100$ μm). For this case the conversion efficiency η, defined as the ratio of the idler output power to the signal output power, has a quadratic dependence on the nonlinear parameter of the waveguide γ: $\eta = P_{idler}(L)/P_{signal}(L) = \left(|\gamma|P_{pump}(0)(1-e^{-\alpha L})/\alpha\right)^2$ [3]. η was measured for a range of gate voltages V_{GS} and idler wavelengths λ_s, for a fixed pump wavelength $\lambda_p \approx 1550.18$ nm. The waveguide width and height are respectively 1600 nm and 330 nm. In Fig. 2b, the extracted $|\gamma|$ is plotted as a function of V_{GS} (or E_F), for several different signal detunings ($\lambda_s - \lambda_p$). From these curves it is clear that the nonlinearity is very dependent on E_F, it increases sharply when tuning the graphene from intrinsic ($E_F \approx 0$) to p-doped ($E_F < 0$). $|\gamma|$ reaches a maximum in the vicinity of $E_F \approx -\hbar\omega/2 = -0.4$ eV and drops drastically when the E_F goes below this value. Finally, in Fig. 2c, $|\gamma|$ is plotted as a function of detuning, for different gating voltages V_{GS}. It is clear that the strength of the four-wave mixing process is significantly stronger over a narrow band around the pump wavelength, with a bandwidth on the order of several nm.

3. Conclusion

For the first time to our knowledge, we have experimentally investigated the nonlinear response of a graphene covered SiN waveguide through four-wave mixing. A first conclusion is that the measured nonlinear parameter $|\gamma|$ can be as high as 6000 /m/W. However, a second conclusion is that this nonlinearity is only high in a narrow wavelength band (≈ 5 nm) around the pump. The third conclusion is that $|\gamma|$ is strongly tunable by electrical gating. For small detunings, more than a two-fold improvement of $|\gamma|$ was observed when tuning the Fermi level, reaching a peak around of $E_F \gtrsim -\hbar\omega/2$. The existence of this resonance has been theoretically predicted [1,6].

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