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# Saturable absorption of nonlinear graphene coated $\text{Si}_3\text{N}_4$ waveguides

Pierre Demongodin<sup>1</sup>, Houssein El Dirani<sup>2</sup>, Jérémy Lhuillier<sup>1</sup>, Malik Kemiche<sup>1</sup>, Thomas Wood<sup>1</sup>, Ségolène Callard<sup>1</sup>, Pedro Rojo-Romeo<sup>1</sup>, Corrado Sciancalepore<sup>2</sup>, Christian Grillet<sup>1</sup>, Christelle Monat<sup>1</sup>

<sup>1</sup>Université de Lyon, Institut des Nanotechnologies de Lyon (INL), CNRS, UMR 5270, École Centrale de Lyon, 69134 Écully, France

<sup>2</sup>University Grenoble Alpes, CEA-LETI, Minatec, Optics and Photonics Division, 17 rue des Martyrs, F-38054 Grenoble, France  
pierre.demongodin@ec-lyon.fr

**Abstract:** We investigate the saturable absorption of hybrid graphene/ silicon-nitride waveguides at telecom wavelengths. By measuring the power dependent transmission of picosecond and sub-picosecond pulses, we clarify the temporal dynamics of photo-excited carriers in graphene. © 2019 The Author(s)

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The unique properties of graphene, related to its low dimensionality and Dirac-cone dispersion, make it an attractive candidate for electronic and photonic devices [1]. Its planar geometry facilitates its integration onto chip-based photonic devices, which is key to enhance the otherwise poor light-matter interaction with this monolayer thick material. Among its relevant properties, the graphene nonlinear optical response includes both  $\chi^{(3)}$  processes and saturable absorption. Although nonlinear properties have been widely studied through four-wave mixing or third-harmonic generation measurements, there is still a great disparity in the extracted nonlinear parameters of graphene [2]. In particular, most graphene nonlinear studies that exploited integrated optics used the mature silicon on insulator waveguide platform [3]. However, both high values of the silicon nonlinearity and its two-photon absorption render the characterization of graphene more difficult, and its nonlinear response harder to unambiguously extract from measurements.

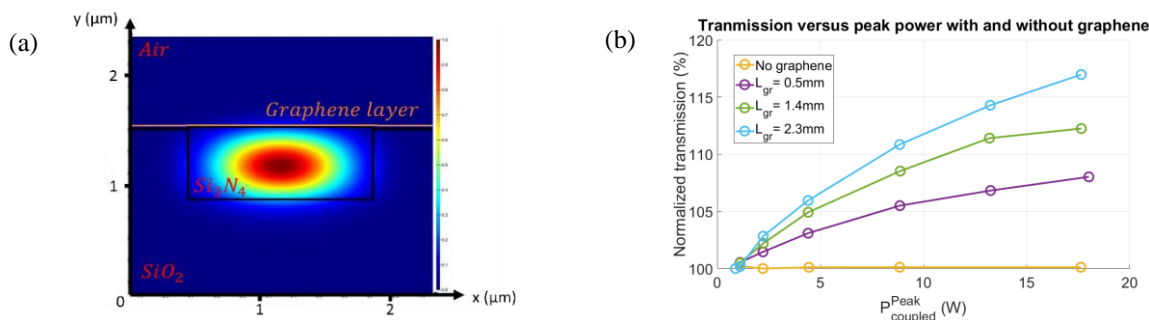


Figure 1. (a) Simulated fundamental TE mode of a  $\text{Si}_3\text{N}_4$  waveguide covered with graphene. (b) Normalized transmission versus coupled peak power of 1.6ps pulses at 1547nm for different interaction lengths with graphene. The transmission is normalized for each waveguide with respect to its related low power (linear) transmission.

Here, we study graphene integrated onto chip-based  $\text{Si}_3\text{N}_4$  waveguides. This very robust platform exhibits low propagation losses, while maintaining a linear optical response for a wide range of input powers. In addition, the large electronic gap energy (around 5eV) forbids the generation of free carriers under optical excitation at telecom wavelengths ( $\hbar\omega = 0.8\text{eV}$ ). The fabrication process [4][5] of our  $\text{Si}_3\text{N}_4$  waveguides embedded in silica includes, as a final step, chemical-mechanical planarization so as to remove the silica top cladding (see Figure 1a). The final  $\text{Si}_3\text{N}_4$  devices exhibit, after removing the cladding, propagation losses for the fundamental TE mode of 3dB/cm (at 1550nm). The planar geometry of the unclad waveguide is suitable for integration with commercial graphene (Trivial Transfer ACS Materials) that is mechanically transferred onto their surface, while allowing for graphene to efficiently interact with the fundamental  $\text{Si}_3\text{N}_4$  waveguide mode. From linear transmission measurements performed on waveguides with various graphene coating lengths, we estimated the propagation losses of our hybrid graphene/ $\text{Si}_3\text{N}_4$  waveguides to be around 130dB/cm at 1550nm.

We investigate the nonlinear response of these hybrid waveguides by focusing here on graphene saturable absorption. This signature has been widely used in single-pass fiber based mode-locked lasers (with graphene coated on the fiber end-facet) but has not been investigated in detail on an integrated platform so far. In addition to providing valuable

spatially averaged information on graphene nonlinear properties at the millimeter scale, so as to diminish the impact of graphene local variations and inhomogeneity, this opens the way to nonlinear applications of hybrid graphene chip-based devices, such as integrated mode-locked lasers or all-optical information processing on a chip.

We performed power dependent transmission measurements of 1.6ps long pulses at 1547nm launched into the fundamental TE mode of a series of four  $\text{Si}_3\text{N}_4$  waveguides that are covered by graphene with different lengths from 0 to 2.3mm. The normalized transmission of each device (with respect to its related low power transmission) is plotted on figure 1.b as a function of coupled peak power. The transmission increases with power, whenever graphene is present, and the relative rise increases for waveguides with longer graphene coating. We attribute these observations to the pulse-induced saturation of absorption in graphene along the covered waveguides.

The saturation of graphene absorption is directly linked to Pauli blocking of photo-excited carriers in the upper band of the Dirac cone. We can thus indirectly probe the excited carrier dynamics by varying the excitation pulse in the time-domain. Figure 2 plots the normalized transmission as a function of the input pulse duration (between 0.2ps and 2ps), for different values of pulse energy coupled to the waveguide. For a fixed number of excitation photons per pulse, we observe a strong increase in the waveguide transmission for shorter pulse duration, indicating that our pulse duration is comparable to the carrier relaxation timescale in graphene. We develop a model to simulate the propagation of picosecond pulses in a nonlinear waveguide by adapting the nonlinear Schrödinger equation solved with the split step Fourier method. We include in this equation a power dependent absorption loss, which accounts for graphene saturable absorption. For each step, we compute this loss contribution from the local density of carriers excited in graphene and account for a decreased absorption probability as the carrier density approaches a saturation density value  $N_{\text{sat}}$ . Relaxation phenomena are also included through an average relaxation time  $\tau_c$  of free carriers in the upper band of graphene. The comparison with our measurements allows us to extract some values for these phenomenological parameters:  $\tau_c \sim 150\text{fs}$  and the saturation density of carriers  $\sim 1.8 \times 10^{10}\text{m}^{-2}$ , being consistent with values found in the literature when taking into account the width of the waveguide.

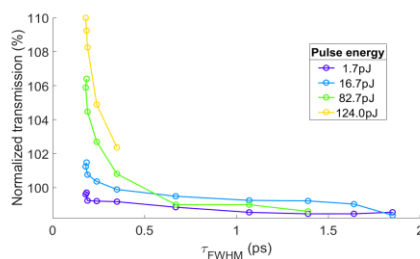


Figure 2: Normalized transmission as a function of the input pulse duration of a  $\text{Si}_3\text{N}_4$  waveguides covered by 2.3mm long graphene. The different colors correspond to different (fixed) values of the pulse energy.

In conclusion, we demonstrated that  $\text{Si}_3\text{N}_4$  waveguides could be used as a reliable platform for probing and exploiting graphene nonlinear properties at telecom wavelengths. Our experimental and simulation work allowed us to extract some valuable information on millimeter scale commercial graphene integrated onto photonic chips. We studied in particular the dynamics of saturable absorption in hybrid graphene/ $\text{Si}_3\text{N}_4$  waveguides which could be relevant for integrated mode-locked lasers and more generally for chip-based all-optical information processing devices.

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