Effective absorption coefficient of a graphene atop of silicon nitride nanophotonic circuit

S Komrakova\textsuperscript{1,2}, V Kovalyuk\textsuperscript{1,3}, P An\textsuperscript{1,3}, A Golikov\textsuperscript{1,3,4}, M Rybin\textsuperscript{4,5}, E Obraztsova\textsuperscript{4,5}, G Goltsman\textsuperscript{1,2,3}

\textsuperscript{1}Department of Physics, Moscow State Pedagogical University, 119992, Russia
\textsuperscript{2}National Research University Higher School of Economics, Moscow 101000, Russia
\textsuperscript{3}Zavoisky Physical-Technical Institute of the Russian Academy of Sciences, Kazan 420029, Russia
\textsuperscript{4}Moscow Institute of Physics and Technology (State University), 141700, Russia
\textsuperscript{5}Prokhorov General Physics Institute of the Russian Academy of Sciences, 38 Vavilov st., Moscow 119991, Russia

Abstract. In this paper, we demonstrate the results of a study of the optical absorption properties of graphene integrated with silicon nitride O-ring resonator. We fabricated an array of O-ring resonators with different graphene coverage area atop. By measuring the transmission spectra of nanophotonic devices with and without graphene, we calculated the effective absorption coefficient of the graphene on a rib silicon nitride waveguide.

1. Introduction
The combination of the unique electronic and optical properties of graphene makes it an ideal candidate for use in nanophotonic devices [1]. Due to some of the graphene properties: electroabsorption and electrorefraction, it can be used for modulators and switches, as well as photothermoelectric devices [2]. In addition, graphene can be easily integrated on various passive photonic platforms, such as silicon-on-insulator (SOI), silicon nitride (Si\textsubscript{3}N\textsubscript{4}) and doped silica [2].

We chose silicon nitride as a platform for the integration with graphene, since the waveguides from this material can operate both in the visible and in the infrared wavelength range, have good mechanical properties and are compatible with CMOS fabrication processing.

In this article, we integrated graphene with silicon nitride O-ring resonators and investigated its absorption properties on its length.

2. Simulation
When the light falls on graphene normally, the light-matter interaction is weak and only \(\approx 2.3\) % of the light is absorbed by a single layer. To increase interaction with light, we placed graphene on a silicon nitride waveguide. Due to evanescent mode coupling and the travelling wave geometry of nanophotonic devices, the light interacts with graphene throughout the entire longitudinal path, and graphene absorption is substantially increased.

We simulated the cross-section of the waveguide with graphene atop to calculate its effective absorption coefficient. The simulation was performed using The Finite Element Method (FEM), realized in COMSOL Multiphysics software. The mode profile of the TE-like mode for the half etched waveguides of 2.7, 2, and 1 \(\mu\)m widths are shown in Figure 1(a-c). In our simulation, the height of the half etched waveguide equals to 450 nm, and the width was varied from 0.5 \(\mu\)m to 3.08 \(\mu\)m. The height of graphene in the model is equal to 0.34 nm and corresponds to the graphite interlayer distance. Graphene also covers the lateral sides of the waveguide and its refractive index was taken from [3].

\textsuperscript{3} Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow 119991, Russia
\textsuperscript{4} Moscow Institute of Physics and Technology (State University), 141700, Russia
\textsuperscript{5} Prokhorov General Physics Institute of the Russian Academy of Sciences, 38 Vavilov st., Moscow 119991, Russia
Dependence of the effective absorption coefficient on the waveguide width is shown in Figure 1(d). With the increase of the waveguide width, graphene absorption increases as well, due to increasing the graphene covered area and increasing evanescent mode coupling. We obtained values of the effective refractive index in a range of 0.01 dB/μm to 0.028 dB/μm for the waveguide width in a range of 0.6 μm to 3 μm. Saturation at wider waveguides may be affected by decreasing the evanescent mode simultaneously with increasing the graphene covered area. These data mean that for the O-ring waveguide width of 2.7 μm (blue dashed line in Figure 1(d)), to absorb 99% (20 dB), the graphene length should be 20 / 0.028 ≈ 714 μm.

3. Device design and fabrication
For the device fabrication, we used commercial available 540 μm thickness silicon wafers with 2.6 μm thermally oxidized and low-pressure chemical vapor deposited (LPCVD) 450 nm layer Si₃N₄ atop (Figure 2(d)). Nanophotonic devices were fabricated by e-beam lithography (Crestec, CABL-9050C) using a positive resist ZEP 520A as a sensitive layer. After development, resist was used as a protective mask for the reactive ion etching (RIE) in CHF₃ atmosphere and removing of Si₃N₄ with a thickness of 225 μm inside the resist windows. To finalized fabrication, the rests of resist were removed in acetone.

Graphene was synthesized by cold-wall chemical vapor deposition method on copper foil from a gas mixture of methane, hydrogen and argon with pressure 100 mbar and at temperature 850°C using original equipment from RUSGRAPHENE company. The synthesized on copper foil graphene was transferred onto the device by standard “wet” transfer using PMMA as a support layer and etching copper foil in ammonium persulfate solution. To form rectangular areas of graphene with variable dimensions, optical lithography with AZ1505 resist was used. The width of the graphene areas varied from 10 to 70 μm with a step of 10 μm. Afterwards unprotected graphene was removed by O₂ plasma etching. SEM images of fabricated devices are shown in Figure 2(a-b).

The single device consisted of single-mode bus waveguide, connected with two focusing grating coupler for input/output light and separated by the O-ring with a gap (Figure 2(c)). For the experimental verification of the absorption properties of graphene-based devices, we designed a 2D array of such nanophotonic circuits, consisted of 144 devices (12 rows × 12 columns). In the horizontal direction of circuits in the 2D array, the width of O-ring waveguide was varied from 1.7 μm to 3.08 μm. In the vertical direction, the gap of O-ring waveguide was varied from 0.69 nm to 2.52 μm.
4. Experimental setup and results

4.1. Experimental setup
To obtain the effective absorption coefficient of graphene, we measured the transmission spectra of O-ring resonators before and after graphene deposition on the following scheme (Figure 3(a)). The light from the tunable laser source (NewFocus TLB-6600 with tune range 1510-1620 nm) passed through the polarization controller and fiber array to be collected by the first focusing grating coupler (FGC) on the chip [4]. The second FGC was used to output light from O-ring resonators to the next optofiber in the array. For data digitization, a fast photodetector, as well as a fast analog-to-digital converter were used. The sketch-up of the experimental setup for optical transmission measurements in Figure 3(b) is shown.

Figure 2 (a-d). (a) Enlarged SEM image of the O-ring waveguide with graphene atop, graphene is the black rectangle area with the length equals 10 µm. (b) SEM image of the fabricated 2D array of O-ring resonators with graphene atop. (c) Optical micrograph of one of the fabricated O-ring resonator. The single device consisted on single-mode bus waveguide, connected with two focusing grating coupler for input/output light and separated by the O-ring with a gap. (d) Schematic overview of fabrication processes (not to scale).

4.2. Analytical study of the graphene effective absorption coefficient
To extract the effective refractive index of graphene from experimental data, we assumed that the light is absorbed all the way in the ring, according to the Behr-Lambert-Bouguer law.
On the one hand, we can divide the entire path of light in the O-ring (Figure 2(c)) into three sections: the first waveguide region, the waveguide-graphene region and the second waveguide region. Before graphene transfer, the output O-ring power, except the waveguide in the graphene region, is equal to:

$$P_{\text{in}}^{\text{gr}} = P_{\text{in}} e^{-\alpha_b \frac{2 \pi R - l}{2}}. \quad (1)$$

where $\alpha_b$ is the absorption coefficient of the waveguide, $P_{\text{in}}$ is the input power of light entering into the first waveguide region, $R$ is the O-ring radius, $l$ is graphene cell length. The output power after the graphene cell ($P_{\text{out}}^{\text{gr}}$) can be written as:

$$P_{\text{out}}^{\text{gr}} = P_{\text{in}}^{\text{gr}} e^{-\alpha_{\text{eff}} l}. \quad (2)$$

Then the output power of light coming out of the second waveguide region ($P_{\text{out}}$) from the O-ring, except the waveguide in the graphene region is equal to:

$$P_{\text{out}} = P_{\text{in}}^{\text{gr}} e^{-\alpha_b \frac{2 \pi R - l}{2}}. \quad (3)$$

The output power can be expressed in terms of the effective absorption coefficient of the ring after graphene transfer ($\alpha_a$):

$$P_{\text{out}} = P_{\text{in}} e^{-\alpha_a 2 \pi R}. \quad (4)$$

Then we can obtain a total absorption coefficient, as a sum of coefficient at different O-ring regions:

$$\alpha_a 2 \pi R = \alpha_b (2 \pi R - l) + \alpha_{\text{eff}} l. \quad (5)$$

Assuming $2 \pi R \gg l$:

$$2 \pi R (\alpha_a - \alpha_b) = \alpha_{\text{eff}} l. \quad (6)$$

On the other hand, the absorption coefficient of the O-ring resonator is inversely proportional to the measured Q-factor:

$$\alpha = \frac{2 \pi n_g}{Q \lambda_0}, \quad (7)$$

where $n_g$ is group refractive index and $\lambda_0$ is the wavelength in vacuum. Then the difference in absorption indices before and after graphene deposition, expressed through the O-ring Q-factor, can be expressed as:

\[ \text{Figure 3 (a-b). (a) Normalized transmission spectrum of O-ring resonator. (b) Sketch-up of experimental setup.} \]
\[ \alpha_a - \alpha_b = \frac{2m_g}{\lambda_0} \left( \frac{1}{Q_a} - \frac{1}{Q_b} \right). \] (8)

where \( Q_b \) and \( Q_a \) are Q-factors before and after graphene transfer, respectively.

After substitution equation (8) into (6), we can obtain graphene effective absorption coefficient \( \alpha_{\text{eff}} \) [dB/\( \mu m \)]:

\[ \alpha_{\text{eff}} = 10 \log_{10} e^{4\pi^2 R n_g \lambda_0 l \left( \frac{1}{Q_a} - \frac{1}{Q_b} \right)}. \] (9)

5. Discussion
To find the Q-factor from the measured experimental transmission spectra (Figure 4(a)), we first found the minimum of interesting pick (\( \lambda_0 \)), the full width at half maximum (\( \Delta \lambda \)) using the Lorentz fit (Figure 4(b)), then using the formula:

\[ Q = \frac{\lambda_0}{\Delta \lambda} \] (10)

the Q-factor can be obtained.

Figure 4 (a-d). (a) Part of the normalized transmission spectrum of a ring resonator with graphene (purple line) and without (red line). The graphene width is 10 \( \mu m \). The figure shows deeper resonant peaks for a resonator without graphene. (b) Single resonance peak (c) Dependence of the resonator Q factor on the graphene length. (d) Graphene absorption on different graphene lengths. The red line is a linear fit, showing the absorption rate of graphene.

The transmission spectrum of the O-ring with graphene has less deep resonant peaks, and as a result, a lower Q-factor. With increasing graphene length, the Q-factor of the O-rings decreases demonstrated more efficient absorption (Figure 4(c)).
After we found of FSR ($\approx 1.6$ nm) from experimental spectra, calculation experimental group index:

$$n_\text{g} = \frac{\lambda_0^2}{2\pi R \text{FSR}} \quad (11)$$

and substitution of extracted data into equation (9), we obtained the graphene effective absorption coefficient. For clarity, in Figure 4(d) shown the dependence of graphene absorption on a waveguide width of 2.7 $\mu$m versus its length, where the effective absorption coefficient is simply defined as the slope. The linear fit and extrapolation of this data allow us to find the absorption coefficient per unit of graphene covering length $\alpha_{\text{eff}} = 0.037\pm0.003$ dB/µm. In comparison with the expected value from the simulation of 0.028 dB/µm, we obtained a higher absorption coefficient. To absorb 99% (20 dB) of the transmitted light the graphene length should be $20 / 0.037 \approx 540 \mu$m.

We attribute the difference between observed and calculated absorption coefficients with some dust lying on the resonator, occurred after graphene transfer, which also can absorb and scatter the light.

In comparison with other articles, where $\alpha_{\text{eff}} = 0.067\pm0.004$ dB/µm [5] and 1.26 dB/µm [6] we have a lower coefficient value. We associate this with a wider and higher waveguide, as well as using lower contrast photonic platform used here.

6. Conclusion
In this work we fabricated O-ring nanophotonic devices based on graphene atop and characterized its optical absorption. Using numerical simulation and experimental study of optical transmission fabricated devices, we found the graphene effective absorption coefficient equals $\alpha_{\text{eff}} = 0.037\pm0.003$ dB/µm. These results can be used for the design and fabrication of hybrid nanophotonic devices with graphene on a silicon nitride platform.

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