# Design and optimization of graphene-on-silicon nitride integrated waveguide mode filters

*(Student paper)*

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**In this work, we report on the design and optimization of graphene-on-silicon nitride integrated waveguide mode filters for suppressing the spurious propagation of either $TE_0$ or $TE_1$ modes. The integrated waveguide consists of a silicon nitride waveguide partially covered by single layer graphene films. We then compare the efficiency and fabrication tolerance of the devices to those of similar graphene-on-silicon integrated waveguide mode filters.**

***Keywords***: *Mode filter, Graphene, Silicon nitride, Waveguide*

## INTRODUCTION

Given the increase in demands regarding Internet traffic, new multiplexing techniques have been explored. Mode Division Multiplexing (MDM) is a technology that has attracted attention, because it can extend the capacity of a single wavelength channel by taking advantage of higher-order modes. In a traditional MDM system, the fundamental modes generated by the signal sources are individually modulated by separate electro-optic (EO) modulators. Then, they are converted to higher-order modes, and multiplexed into a few-mode fiber. This method suffers from high insertion losses, large device footprint and high costs.

Waveguide mode filters are promising devices in order to overcome those limitations, since they can selectively modulate a certain guided mode [1]. An interesting case are graphene covered waveguide filters [2]–[5], where patterned graphene films are integrated coplanar to the waveguide core. Graphene is a material with a large absorption coefficient and a broad absorption bandwidth [6]. These optical properties allow to make filters with high extinction and selection ratios in a broad bandwidth. In this work, we simulate the efficiency and optimize the design of $TE_0$ and $TE_1$ mode filters based on graphene-on-silicon nitride (SiN) integrated waveguides. Then, we compare our results to the simulated performance of graphene-on-silicon integrated waveguide filters [2].

## RESULTS

The design of the filter is depicted in Fig. 1(a) for the $TE_0$ case. The waveguide consists of a SiN core embedded in a silicon dioxide ($SiO_2$) cladding, and the core of the waveguide is partially covered by a graphene film. Fig. 1(b) shows the profile of the $TE_0$ mode consisting of a single lobe centered on the waveguide core, while Fig. 1(c) shows the $TE_1$ mode having two lobes at both sides of the core, with the peak electric-field intensities displaced from the center. Therefore, if the graphene film is designed to cover only the central area around where the field intensity of the $TE_0$ mode reaches its maximum, then the fundamental mode will be absorbed, while the $TE_1$ mode will be transmitted. Analogously, if two graphene strips are placed over the core, at the sides where the $TE_1$ mode shows the maximum intensity, the fundamental mode will be transmitted and the $TE_1$ mode will be absorbed. Since the graphene film is one-atom thick, it induces a negligible change in the real part of the effective index of the modes, while strongly affecting the imaginary part. Therefore, the mode profiles are not modified by graphene.

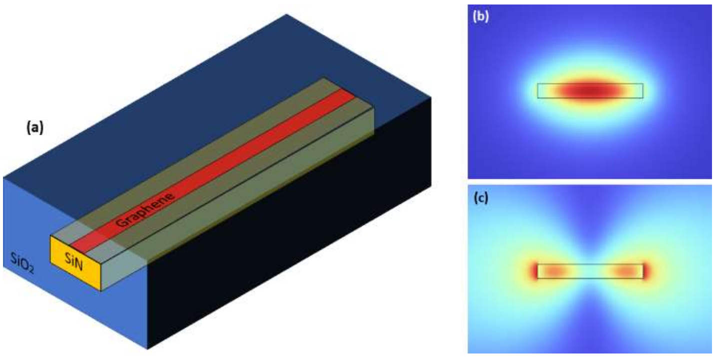


*Fig. 1. (a) Scheme of the $TE_0$ graphene-on-silicon nitride integrated waveguide mode filter. (b) $TE_0$ mode profile. (c) $TE_1$ mode profile.*

In order to assess the efficiency of the mode filter, we use the parameters defined in [2]. The first one is the extinction ratio $ER = \alpha_{stop} - \alpha_{pass}$, and it corresponds to the difference between the absorption coefficient of the stop-mode and the pass-mode. The second one is the selection ratio $SR = ER/\alpha_{pass}$, defined as the extinction ratio divided by the absorption coefficient of the pass-mode.

The length required to obtain a certain contrast $C$ between modes is $L = C/ER$, while the insertion losses of the device are given by $IL = \alpha_{pass} \times L = C/SR$. The goal is to obtain a device with the lowest $L \times IL$ product possible:

$$IL \times L = \frac{C^2}{ER \times SR} \tag{3}$$

Therefore, the figure of merit that needs to be maximized in order to optimize the device is the $ER \times SR$ product.

For each mode, the absorption coefficient can be computed by dividing the power absorbed by the graphene film of width ($w_g$) and the input power ($P_{in}$) as

$$\alpha = 4.34 \times \frac{Re(\sigma_g)/2}{P_{in}} \int_{w_g} \left|E_{\parallel}\right|^2 dx \tag{4}$$

where a conversion factor to dB units is introduced [6]. The real part of the conductivity of graphene ($\sigma_g$) can be extracted from the Kubo formula, which describes the surface conductivity of graphene [7]:

$$\sigma = i\frac{e^2 k_B T}{\pi\hbar^2(\omega + i2\Gamma)}\left(\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\mu_c/k_B T} + 1\right)\right) + \frac{ie^2(\omega + i2\Gamma)}{\pi\hbar^2}\int_0^{\infty}\frac{f_d(-\varepsilon) - f_d(\varepsilon)}{(\omega + i2\Gamma)^2 - 4\left(\frac{\varepsilon}{\hbar}\right)^2}d\varepsilon \tag{5}$$

where $f_d\,(\varepsilon) = 1/(\exp\,[(\varepsilon - \mu_c)/(k_B\,T)] + 1)$ is the Fermi-Dirac distribution function.

In order to optimize the device, we have studied the performance of a $TE_0$ filter and a $TE_1$ filter for a silicon nitride core with dimensions $W = 1500$ nm and $H = 200$ nm, embedded in silicon dioxide. In the case of the $TE_0$ filter (Fig. 2), we have computed the $ER$, $SR$ and $ER \times SR$ parameters for different values of the graphene film width ($w_g$) and the separation between the graphene film and the surface of the core ($h$), while in the case of the $TE_1$ filter (Fig. 3), we varied the width of each film ($w_g$) and the lateral distance between them ($l$). Then, we have compared the results to those presented in [2] for a simulated graphene-on-silicon integrated waveguide mode filter of the exact same core dimensions.

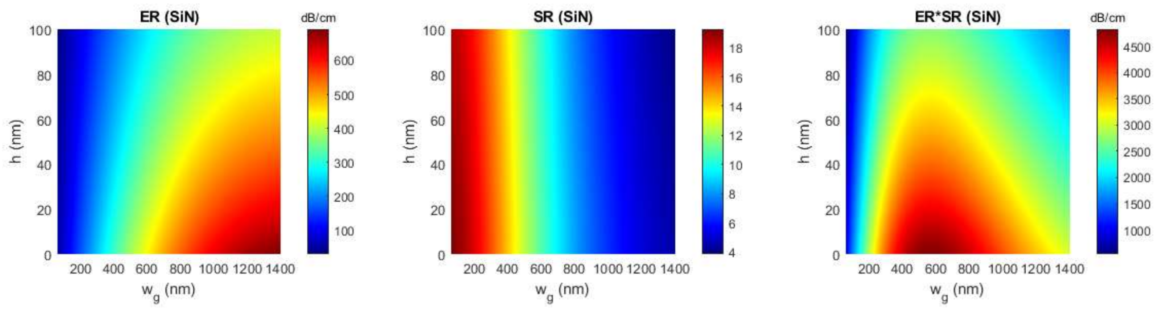


*Fig. 2. ER, SR and ER×SR parameters for a $TE_0$ graphene-SiN filter with respect to graphene film width and vertical separation.*

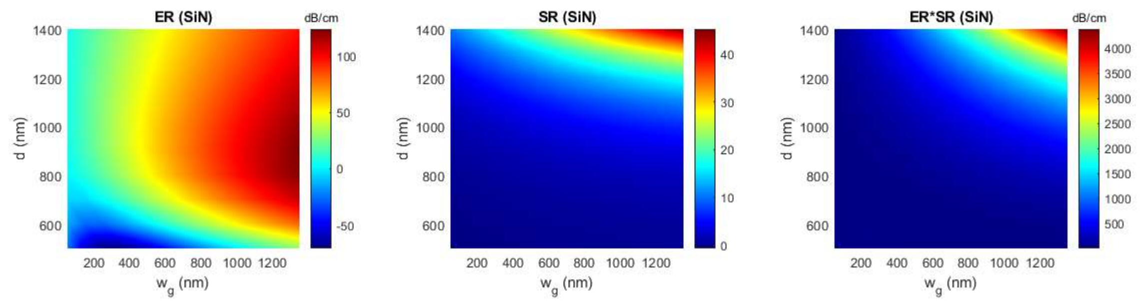


*Fig. 3. ER, SR and ER×SR parameters for a $TE_1$ graphene-SiN filter with respect to graphene film width and lateral separation between films.*

**DISCUSSION**

Fig. 2 shows that it is most effective to deposit graphene on the surface of the core ($h = 0$), due to a stronger interaction between graphene and the evanescent field, which can be assumed to be true for both filters. Compared to the work done by Xing *et al* on graphene-on-silicon mode filters [2], silicon nitride shows a higher extinction and selection ratios for the $TE_0$ filter, as well as a higher figure of merit. In the case of a graphene-on-silicon mode filter, the optimal design consists of a center graphene film of $w_g = 260$ nm with $ER \times SR = 680\ \mathrm{dB/cm}$. Whereas, for the graphene-on-SiN integrated waveguides, the optimal design shows $w_g = 580$ nm with $ER \times SR = 4840\ \mathrm{dB/cm}$. This improvement could be explained by the fact that the $TE_0$ and $TE_1$ modes in the SiN waveguide show less overlapping than those of silicon (Fig. 4). For the $TE_1$ graphene-on-SiN filter, the ER, SR and figure of merit increase with the graphene width ($w_g$). This can be explained when taking into account the intensity profiles for the $TE_0$ and $TE_1$ modes (Fig. 4). In silicon (Fig. 4a) the $TE_1$ mode shows a higher localization than in SiN (Fig. 4b), and therefore enough power can be absorbed with a narrower graphene film. For SiN, ER shows a maximum of 120 dB/cm for a separation between both films of $l$ =900 nm. If the films are separated a longer distance, the fundamental mode losses can be strongly reduced. For this reason, the figure of merit can be optimized for larger $l$ values where graphene is placed away from the surface of the core. However, it must be considered that at a separation of 900 nm, the figure of merit is $ER \times SR = 280$ dB/cm, which is already comparable to the case of silicon.

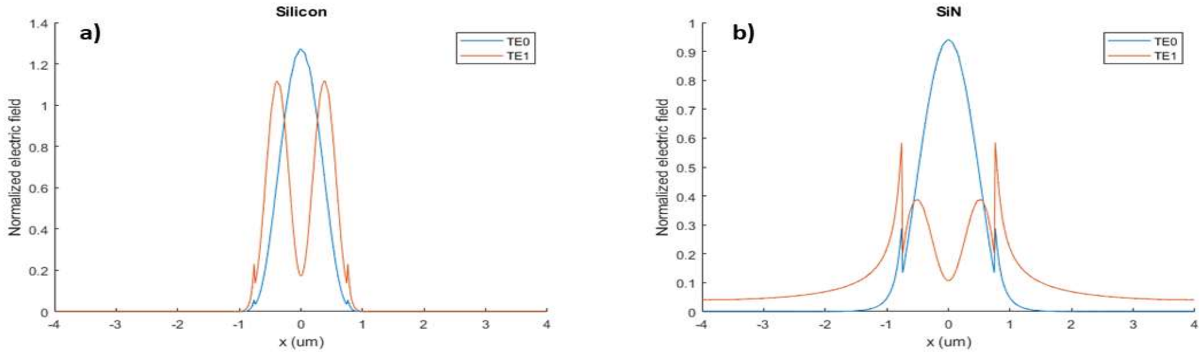


*Fig. 4 Intensity profile for $TE_0$ and $TE_1$ modes in the silicon waveguide and the silicon nitride waveguide.*

The proposed graphene-on-SiN integrated devices would allow to selectively filter the fundamental mode of a waveguide with a figure of merit more than 7 times larger than that of a graphene-on-silicon mode filter. In addition, if we define the fabrication tolerance of the $TE_0$ filter as the range of $w_g$ values in which the $ER \times SR$ product is above 90% of its maximum value, it can be observed that the tolerance for graphene-silicon filters is ±80 nm, while for graphene-SiN it is +180 nm -200 nm. The graphene-on-SiN $TE_1$ filter shows a lower $ER$ than the silicon filter, but it allows a further reduction in the losses suffered by the fundamental mode.

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