

## بررسی کاربرد نانو نوارهای گرافنی به عنوان فلیترهای میانگذر فروسرخ

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چکیده - در این مقاله یک فلیتر میانگذر برای طول موج های باند فروسرخ و با استفاده از نانو نوارهای گرافنی پیشنهاد شده است. با قرار دادن یک نانو نوار (به عنوان تشدیدگر فابری-پرو) مابین دو نانو نوار موجبر، ساختار کلی این فلیتر تشکیل می شود. نانو نوارهای گرافنی به دلیل قابلیت کنترل پذیرشان در مقید کردن امواج سطحی و هدایت شان (در لبه های نوار) در طول موج های فروسرخ، اهمیت فراوانی دارند. با اعمال یک ولتاژ بایاس خارجی، می توان طول موج های مورد نظر را به صورت آنی و تنظیم پذیر کنترل کرد. اثبات خواهیم کرد با تغییر ضخامت ماده بستر گرافن، و همچنین با افزایش پتانسیل شیمیایی، طول موج فلیتر دچار تغییر آبی (blue-shift) شده و کاهش می یابد. برخلاف این تغییر، با افزایش طولی تشدیدگر فابری-پرو، طول موج فلیتر دچار تغییر قرمز (red-shift) شده و افزایش می یابد.

کلید واژه- فلیتر میان گذر، تشدیدگر فابری پرو، موج تخت، نانو نوار گرافنی

## Graphene Nano-Ribbon Assisted Fabry-Pérot Resonator Based Mid-Infrared Bandpass Filter

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**Abstract-** in this study, an ultra-compact optoelectronic band-pass filter is proposed. A single piece of graphene nano-ribbon (GNR) is placed in between of two input-output GNRs to form a Fabry-Perot-like cavity. The GNR - as mid-infrared surface waveguide - enhances the compatibility with complementary metal oxide-semiconductor processing technologies. By modulation of surface charge carrier density -simply changing the bias voltage applied on the GNR cavity- the transmission characteristics of band pass filter are tuned (Other than conventional means such as cavity material or scale modifications) and thus a room temperature tunable filter is achieved. It is found that increasing the gate voltage as well as increasing the silica substrate thickness, the max peak of filter's transmission spectra alters toward smaller wavelengths (blue shift). In contrast, increasing the middle GNR length redshifts max peak of filter toward longer wavelengths.

**Keywords:** Band-pass filter, Fabry-Perot cavity, Graphene Nano-Ribbon, Surface wave.

# Graphene Nano-Ribbon Assisted Fabry–Pérot Resonator Based Mid-Infrared Bandpass Filter

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## 1 Introduction

Since its advent, terahertz devices have attracted enormous attention of researchers [1-3]. Graphene is an important material for this domain because of its fascinating optical, electrical, and thermal characteristics [4].

Graphene is formed in a two dimensional honeycomb lattice of single layer carbon atoms. By electrostatic excitation of electron-hole pairs and/or chemical doping injection and due to high dopant injection, its Ohmic losses decrease and its conductivity change. Unlike metals, graphene electrical conductivity can be modified which in turn results in refractive index variations, thus tuning is not limited to design and fabrication process steps. Using graphene, numerous structures have already been designed such as optical switches [5, 6], filters [7], tuneable antennas [8], and so on.

Here, an ultra-compact graphene nano-ribbon (GNR) based filter is proposed and simulated. It can be tuned in a manner that its transmission spectrum resonant peak can easily be tuned in real time.

In the following section, the theoretical assumptions, simulation methodology, and design considerations are fully discussed. Section 3 presents the result and is followed by discussions about spectral behaviour of the filter due to chemical potential variations and/or geometrical dimension tuning. In the end, Section 4 concludes the paper.

## 2 Theory and Design

The three dimensional schematic view of the GNR-based band-pass filter is displayed in **Fig. 1**. It consists of three 20nm wide graphene strips acting as input/output and FP-resonator sections and multilayered with a highly-doped silicon slab stacked under a thin layer of silica.

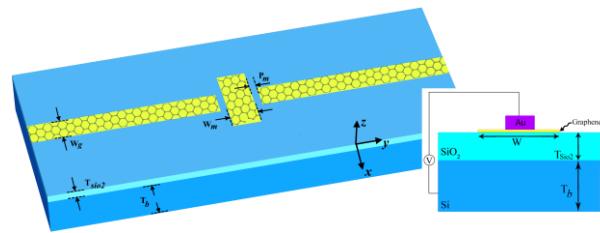


Fig. 1: The three dimensional schematic view of the GNR-based BPF.

If a biasing voltage applies between graphene and silicon slab, graphene's chemical potential modifies, thus if a broadband mid-infrared Gaussian wave comes at the entrance of structure, quasi-SPPs are strongly excited along the edge of graphene layer. Graphene's chemical potential depend on the charge carrier concentration which could be managed by chemical dopant realization and/or electrostatic gating. Chemical potential of the graphene,  $\mu_c$ , and applied gating voltage,  $V_{bias}$ , are related as given [7]:

$$\mu_c = \sqrt{\frac{\pi \epsilon_0 \epsilon_r V_{bias}}{et}}, \quad (1)$$

where  $\epsilon_0$  and  $\epsilon_r$  are permittivity of vacuum and relative permittivity  $SiO_2$ ,  $e$  is the electron charge, and  $t$  is the thickness of Si substrate. According to Kubo's formula, the complex surface conductivity  $\sigma_g$  of GNR and its optical properties are related as [7]:

$$\sigma_g = \frac{2ie^2k_B T}{\pi h^2 [\omega + i\tau^{-1}]} \ln \left[ 2 \cosh \left[ \frac{E_f}{2k_B T} \right] \right] + \frac{ie^2}{4\pi h} \ln \left[ \frac{2E_f - h[\omega + i\tau^{-1}]}{2E_f + h[\omega + i\tau^{-1}]} \right] \quad (2)$$

where the first terms and second term expressions symbolize intra and inter band transitions, respectively. Moreover,  $k_B$  is the Boltzmann constant,  $h$  is the Planck's constant and  $\tau$  is the relaxation time of charge carriers and  $T$  is the temperature.  $\sigma_g$  can be interpreted as a function of  $V_{bias}$  and is adjusted via applied voltage. A multilayer stack of Si/SiO<sub>2</sub>/GNR is used to form the BPF. The Si and SiO<sub>2</sub> are supposed to have refractive indices of 3.45 and 1.44, respectively. To follow the persistence of a reasonable numerical simulation, an equivalent permittivity for GNR is assumed. The thickness ( $\Delta$ ) of such an ultra-thin layer plays an important role in the measurement of its permittivity. Assuming a 1 nm thick GNR, permittivity is [4]:

$$\epsilon_{eq} = \epsilon_0 + i\sigma_g / (\omega\Delta). \quad (3)$$

The simulations are performed using 3D-FDTD with a minimum mesh size of 0.25 nm for 6nm around GNR layer and non-uniform mesh in the rest of simulation region to guarantee the validity of results as well as preserving the time efficiency.

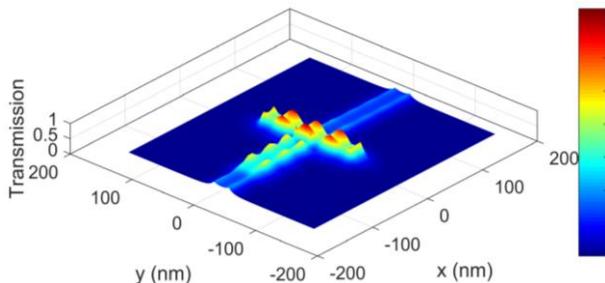


Fig. 2: Representation of the GNR's edge mode.

### 3 Results and Discussions

Graphene strips support both waveguide and edge modes [7]. If the width of the ribbon decreases to fewer than tens of nanometers, edge mode dominates the waveguide mode. Our studies within figure 2 fully confirms the existence of these edge modes for our BPF. Since surrounding media of

the 2D graphene material has direct effect on the obtained results, therefore three dimensional simulations are required. As an example, the thickness of the  $SiO_2$  layer beneath the graphene layer is found to have significant impact on the shift of peak within transmission spectrum. By using higher thicknesses of substrate (at least 50nm), this dependency is correlated to invariant results.

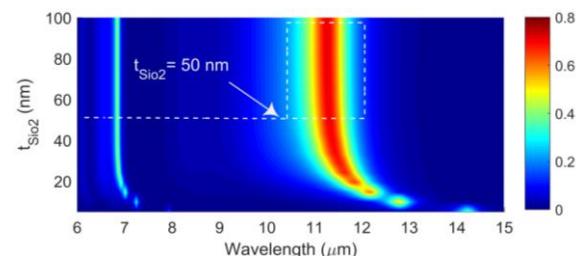


Fig. 3: Study on the GNR's substrate thickness effect versus the transmission spectrum.

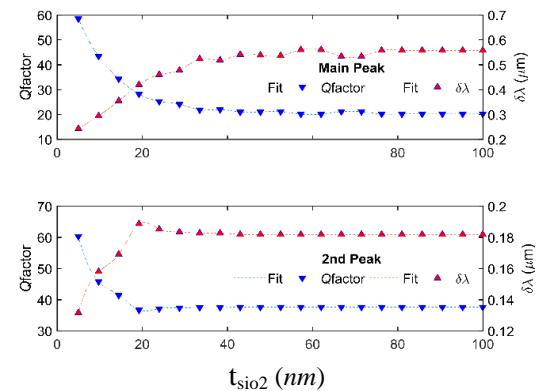


Fig. 4: Left hand side of the figure illustrates  $Q$ -factor of the BPF studied versus different  $t_{SiO_2}$  sizes while the right hand side investigates the FWHM ( $\delta\lambda$ ) for: (a) larger peak or (b) weak peak.  $\mu_c = 0.36$  eV. Dashed lines represents the spline fit function applied to discrete points.

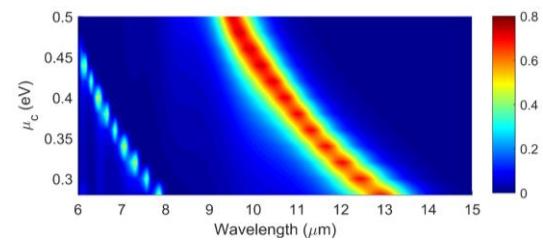


Fig. 5: Study on the GNR's chemical potential effect versus the transmission spectrum.

In **Fig. 4** nominal  $Q$ -factors ( $Q = \lambda/\Delta\lambda$ ) are calculated for both peaks showed **Fig. 3**. Here main peak denotes to larger one with  $\lambda_0$  around 11-12  $\mu\text{m}$ , and weak peak denotes the other one with  $\lambda_0$  around 7  $\mu\text{m}$ . For both peaks, as the FWHM ( $\delta\lambda$ ) increase the amount of  $Q$ -factor is decreased. Investigating the chemical potential ( $\mu_c$ ) variation

effect on transmission spectrum, it is found that increasing the  $\mu_c$  - from  $\mu_c=0.3\text{eV}$  to  $\mu_c=0.5\text{eV}$  - blue shifts (down-shift) the center peak toward lower wavelengths. **Fig. 5** shows the detailed information of this investigation for an arbitrary FP-resonator length ( $L_m=140\text{nm}$ ). On the other hand, **Fig. 6** shows that increasing the length of FP-resonator - from  $L_m=120\text{nm}$  to  $L_m=220\text{nm}$  - redshifts (upshifts) the peak wavelength to higher values.

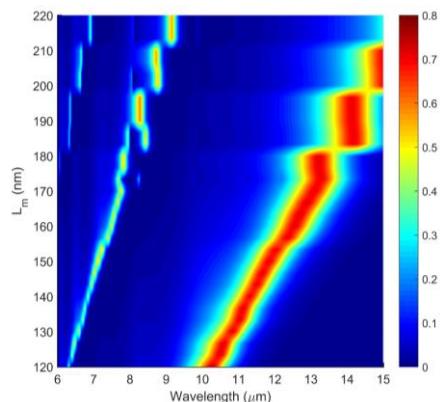


Fig. 6: Study on the GNR's FP-resonator length effect versus the transmission spectrum.

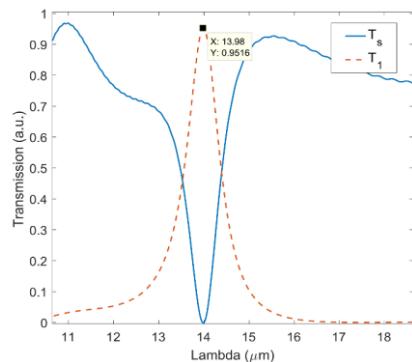


Fig. 7: Transmission and reflection of the proposed BPF when configured according to Table I.

**Table I.** Summarized values of the proposed BPF filter at its optimum operating condition.

Definition	Label	Value (nm)
GNR Spacing	$d$	5
Silicon Thickness	$t_{si}$	1000
Silica Thickness	$t_{sio2}$	50
Width of middle GNR	$W_m$	20
Width of input/output GNR	$W$	20
Length of middle GNR	$L$	140

In addition **Fig. 7** demonstrates the transmission and reflection of the proposed BPF when

configured according to summarized values reported in **Table I**. the peak center is at  $\lambda=13.98\mu\text{m}$  with an amplitude of 95.16%.

## 4 Conclusion

By mean of theoretically well-known resonance wavelength shift dependent parameters, a GNR-assisted BPF based on FP-resonators was designed. The transmission peak was easily tuned by altering the cavity material or scale. In addition, due to real time tune ability of GNR's effective index that occurs by means of introducing tiny variation in surface charge carrier density through applying a gate voltage, dynamic tuning was established for our proposed filter. It was found that increasing the gate voltage as well as increasing the silica substrate thickness or middle GNR width, blue-shifts the maximum peak wavelength of filter toward smaller wavelengths. In contrast to these factors, increasing the middle GNR length redshifted the peak toward longer wavelengths.

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