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بررسی کاربرد نانو نوارهای گرافنی به عنوان فلیترهای میانگذر فروسرخ

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چکیده – در این مقاله یک فیلتر میانگذر برای طول‌موج‌های 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 نوارموجبر، ساختار کلی این فیلتر تشکیل می‌شود. نانو نوارهای گرافنی به دلیل قابلیت کنترل پذیرشان در مقید کردن امواج سطحی و هدایت‌شان (در لبه‌های نوار) در طول‌موج‌های فروسرخ، اهمیت فراوانی دارند. با اعمال یک ولتاژ بایاس خارجی، می‌توان طول‌موج‌های 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، طول‌موج فیلتر دچار تغییر آبی (*blue-shift*) شده و کاهش می‌یابد. برخلاف این تغییر، با افزایش طولی تشدیدگر فابری-پرو، طول‌موج فیلتر دچار تغییر قرمز (*red-shift*) شده و افزایش می‌یابد.

کلید واژه- فیلتر میان‌گذر، تشدیدگر فابری پرو، موج تخت، نانو نوارگرافنی

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.

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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 it 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 the GNR-based band-pass filter is displayed in **Fig. 1**. It consists of three 20*nm* 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.

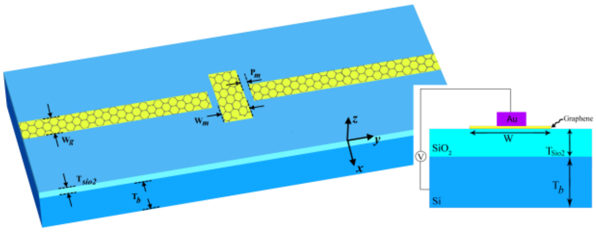

Fig. 1: The three dimensional schematic view of the GNR-based BPF.

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, μ_c, and applied gating voltage, V_{bias}, are related as given [7]:

$$\mu_c = \sqrt{\frac{\pi \varepsilon_0 \varepsilon_r V_{bias}}{et}}, \qquad (1)$$

where ε_0 and ε_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 σ_g, of GNR and its optical properties are related as [7]:

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

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 τ is the relaxation time of charge carriers and T is the temperature. σ_g can be interpreted as a function of V_{bias} and is adjusted via applied voltage. A multilayer stack of $Si/SiO_2/GNR$ is used to form the BPF. The Si and SiO_2 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 (Δ) 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]:

$$\varepsilon_{eq} = \varepsilon_0 + i\,\sigma_g / (\omega\Delta). \qquad (3)$$

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.

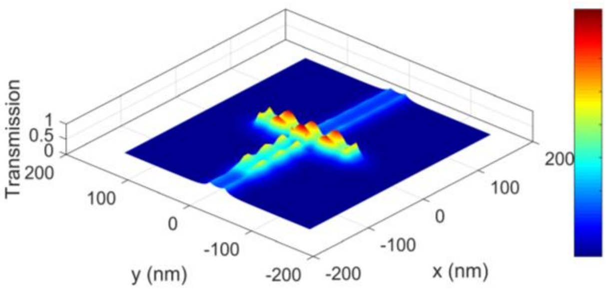

Fig. 2: Representation of the GNR's edge mode.

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 50*nm*), this dependency is correlated to invariant results.

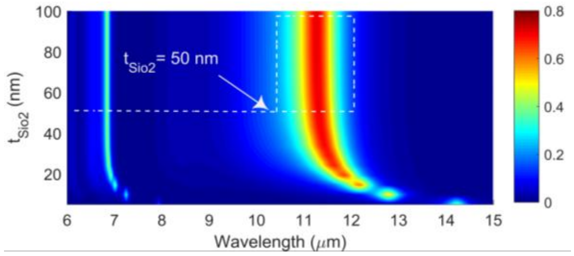

Fig. 3: Study on the GNR's substrate thickness effect versus the transmission spectrum.

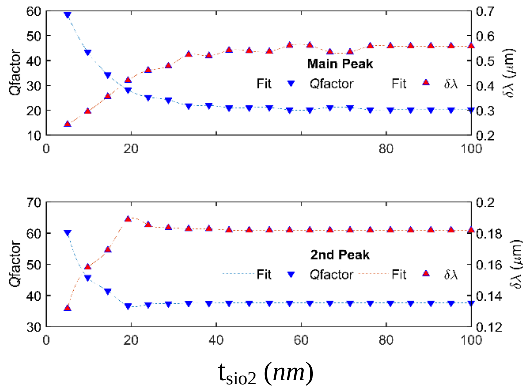

Fig. 4: Left hand side of the figure illustrates Q-factor of the BPF studied versus different t_{sio2} sizes while the right hand side investigates the FWHM ($\delta\lambda$) for: (**a**) larger peak of (**b**) weak peak. μ_c = 0.36 eV. Dashed lines represents the spline fit function applied to discrete points.

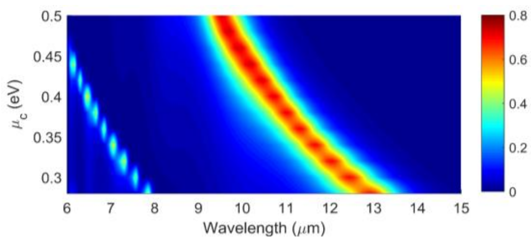

Fig. 5: Study on the GNR's chemical potential effect versus the transmission spectrum.

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 λ_0 around 11-12µm, and weak peak denotes the other one with λ_0 around 7µm. For both peaks, as the FWHM ($\delta\lambda$) increase the amount of Q-factor is decreased. Investigating the chemical potential (μ_c) variation effect on transmission spectrum, it is found that increasing the μ_c - from μ_c=0.3eV to μ_c=0.5eV - 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*nm*). On the other hand, **Fig. 6** shows that increasing the lentgh of FP-resonator - from L_m=120*nm* to L_m=220*nm* - redshifts (upshifts) the peak weavelegnth to higher values.

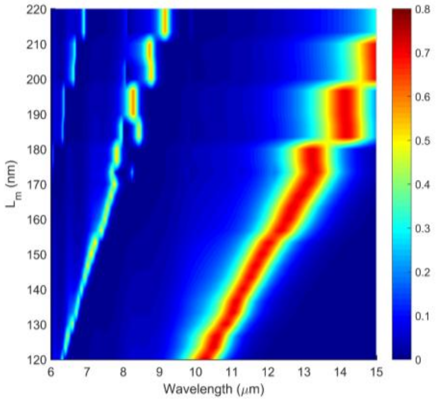

Fig. 6: Study on the GNR's FP-resonator length effect versus the transmission spectrum.

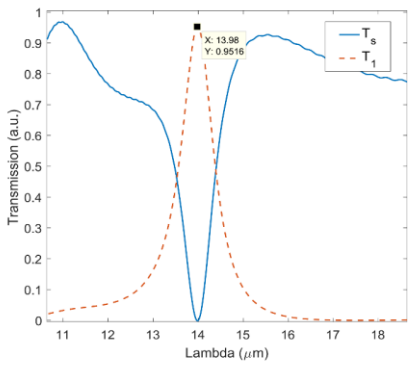

Fig. 7: Transmission and reflection of the proposed BPF when configured according to Table I.

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 λ=13.98μm 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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