# Design of an Energy Efficient Optical Delay Line Using Graphene in Photonic Crystal Waveguide

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***Abstract*— An energy efficient design of an optical delay line by introducing graphene in the photonic crystal waveguide (PCW) is proposed. It is observed that PCW can slow down the guided light utilizing the unique optical properties of graphene. The proposed device comprises of two designs; in first design Graphene is coated at the core, and in second design at cladding area of PCW respectively. The maximum group delay of 80 picoseconds and 88 picoseconds have been observed in the core and cladding region respectively even at a low power consumption of < ~3 volts. The performance investigation has been carried out using Finite Difference Time Domain (FDTD). Moreover the proposed design has a small footprint (420 µm2), guaranteeing its utility in low- power electrically tunable on-chip delay lines.**

***Keywords*—** *Photonic crystal waveguide, graphene coating, group velocity, delay.*

## I. INTRODUCTION

Recently, tunable delays have attracted great attention in slowing down the velocity of light. The rapid increase in data traffic nowadays has accelerated the development of (Optical Delay Line) ODL technology [1]. Also, delay lines are tremendously useful in optical time division multiplexed (OTDM) systems, optical storage and buffering devices, phased array antennas and optical coherence tomography.

Various approaches including stimulated Brillouin scattering, stimulated Raman scattering, electromagnetically induced transparency, Fabry-Perot cavities, photonic crystals and coupled resonant cavities have been experimentally demonstrated for tunable delays. Khan et al. [2] demonstrated an integrated optical delay line based on apodized fiber gratings. However, the delay cannot be continuously tuned due to the lack of cascading between the waveguides which poses limits on its practical applications. Ju et al. [3] proposed a novel tunable time-delay technique in which fibers of different length were utilized and the phenomenon of the stimulated Brillouin scattering was selectively controlled. Unfortunately, it has limitations too such as pulse broadening due to the limited bandwidth of SBS gain and inaccurate comparison of delays under different gains because of amplification of pulse during SBS process. Chen et al. [4] investigated the effect of crosstalk on the performance of a silicon feed-forward optical delay line consisting of Mach-Zehnder Interferometer (MZI) switches and waveguide delay pairs.

Cao et al. [5] proposed a silicon based tunable optical delay line used for steering millimeter-wave beam. The proposed delay generates the delay time too short for practical applications. Conteduca et al. [6] demonstrated a new design of tunable optical delay line based on two vertically stacked microring resonators coupled to a straight waveguide. However, the delay-bandwidth product is inadequate. Liu et al. [7] analysed characteristics of slow light using ring resonator. The number of rings, length of rings, splitting ratio of couplers were investigated. However, the trade-off between the investigated parameters (number of ring, ring length, splitting ratio of couplers) is difficult to achieve simultaneously. Thind et al. [8] calculated the maximum group delay of 72 ps and 87 ps at the graphene coated core and cladding region of photonic crystal waveguide respectively by electricallty tuning the waveguide by applying 4 volts power. However, the performance (maximum group delay) can further be improved by modifying the lattice constant, length of the waveguide and the position of line defect in the waveguide.

Nowadays, integrated on-chip devices are in huge demand for delay applications. However, the low electro optic coefficient of silicon is not conducive. Dawlattey et al. [9] reported variation in refractive index, Δn = 10-5 due to Franz keldysh effect and Δn =10-8 due to Kerr effect with application of electric field of magnitude 105 V/Cm electric field.

These approaches have limitations such as lack of cascading between waveguides, pulse broadening, small time delay and bulky configuration. Recently, graphene has attracted significant attention research owing to its unique optical and electronic properties such as high mobility, high optical conductivity. Also, the feasibility of using graphene in integrated devices further stimulate the interest in graphene based tunable delay devices.

In this paper, we propose a novel design of an energy efficient optical delay line by introducing FLG in PCW. FLG is coated on the core area and other with graphene on the cladding area respectively. The Fermi level of graphene is electrically tuned at <3 volts resulting to group velocity reduction from 0.061c to 0.027c and from 0.045c to 0.0098c in the core and second cladding region respectively. Maximum group delay of 80 ps and 88 ps is reported in the first and second design respectively using design analysis in FDTD software.

The paper is organized as follows. Section II explains the concept and principle of the proposed ODL device. Section III presents the design of the energy efficient ODL using FLG in PCW. Section IV elaborates the results and discussions of the simulation analysis. Eventually, the conclusions are given in Section V.

## II. CONCEPT AND PRINCIPLE

Thanks to the outstanding properties of graphene that it owes to its unique energy band structure which can be described by a pair of Dirac cones. When voltage is applied, the lower energy cone becomes empty while the upper one starts is full.

The electrical tuning of Fermi-level of graphene causes dynamic variation in the dielectric constant of graphene. The real Kramers-Kronig relation [9-10] can be used to derive expressions for the real and imaginary part of the dielectric constant of graphene

$$\varepsilon'_g(E_f) = 1 + \frac{e^2}{8\pi\varepsilon_0 d}\ln\frac{(E+2|E_f|)^2+\Gamma^2}{(E-2|E_f|)^2+\Gamma^2}\frac{e^2}{\pi\varepsilon_0 d}\frac{|E_f|}{E^2+(\frac{1}{\tau})^2}$$

(1.1)

$$\varepsilon''_g(E_f) = \frac{e^2}{4\pi\varepsilon_0 d}\left[1+\frac{1}{\pi}\left\{tan^{-1}\frac{E-2|E_f|}{\Gamma} - tan^{-1}\frac{E+2E_f}{\Gamma}\right\}\right] + \frac{e^2}{\pi\tau\varepsilon_0 d}\frac{|E_f|}{E^2+(\frac{1}{\tau})^2}$$

(1.2)

$E_f$, $\varepsilon_0$, $d$, $1/\tau$, $\Gamma$ are the Fermi energy, vacuum permittivity and thickness of graphene, carrier scattering rate and interband transition broadening respectively.

The imaginary part ($\varepsilon''_g$) of graphene exhibits monotonic variation with increasing voltage because of inter band transitions. However, the real part of ($\varepsilon'_g$) is a non-monotonic function of the applied voltage. This phenomena is key in the group velocity reduction of light propagating through FLG coated PCW.

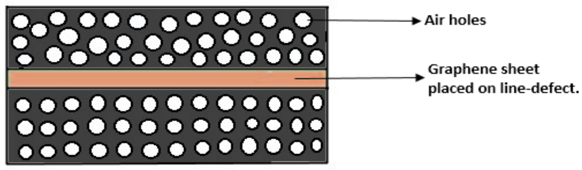
Also the influence of voltage (V) application on the Fermi energy of graphene ($E_f$) and applied voltage (V) can be studied using the following relation [10]

$$E_f = \hbar V_f\sqrt{\left(\pi n_0 + \frac{C|V|}{q}\right)} \qquad (2)$$

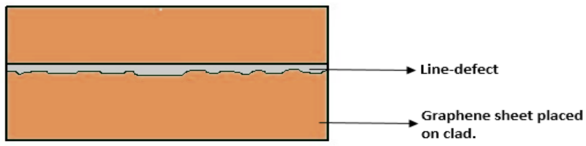
In eq. 2, C , $V_f$ , $h$ are effective capacitance per unit area ,the Fermi velocity of graphene, h is Plank's constant and $n_0$ is the intrinsic carrier concentration.

## III. PROPOSED DEVICE DESIGN

The proposed device consists of two designs (fig. 1) in which FLG is introduced in the core and cladding region of the PCW.




(a)




(b)

Fig. 1. Designs of the proposed device. First with graphene sheet coated at the core region and second at the cladding region respectively of the photonic crystal waveguide.

The design parameters considered during the design of the proposed device are shown in Table I. Graphene having 1.8 refractive index is coated on the silicon photonic waveguide 240 nm high. An important parameter from design point of view, the lattice constant 'a' is chosen to be 400 nm for both directions x and y. The air holes having radius 80 nm are selected for modifying the guiding characteristics of photonic crystal waveguide.

TABLE I

Design Parameters

| **Parameter** | **Value** |
|---|---|
| Refractive index of silicon | 3.48 |
| Refractive index of graphene | 1.8 |
| Slab height | 240 nm |
| Lattice constant | 400 nm |
| Radius of air hole | 80 nm |
| Thickness of graphene sheet | 2 nm |



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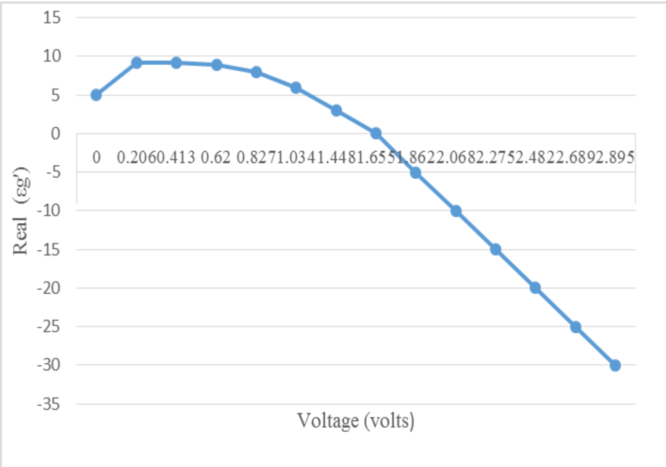
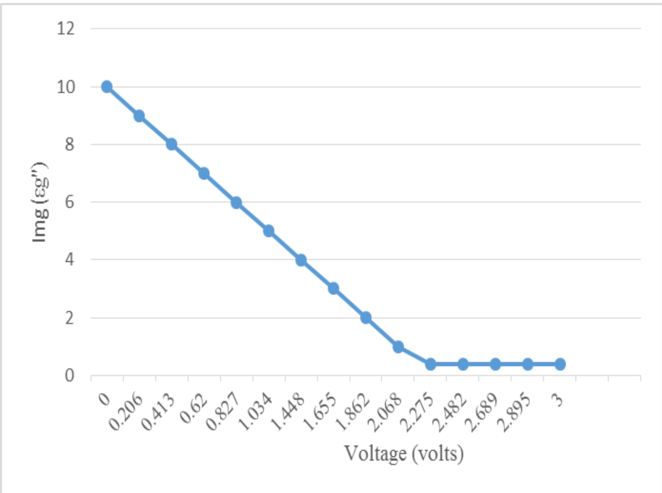
## IV. RESULTS AND DISCUSSIONS

We have electrically tuned the fermi level of both designs by varying the voltage from 1 volt to 3 volts generating tunable time delay. Therefore, complex refractive index of graphene exhibits variation following eq. (1.1-1.2). As shown in fig. 2 (a), it is reported that the real part ($\varepsilon'_g$) of the refractive index is a non-monotonic function of the applied voltage. On the other hand, the imaginary part ($\varepsilon''_g$) decreases monotonically with increasing voltage due to inter band transitions as shown in fig. 2(b).




2(a)




2(B)

Figure 2. Tuning of the complex refractive index of graphene. (a) The real part exhibits non- linear dependence on the applied voltage (b) The imaginary part exhibits linear variation with applied voltage.

We also observed the variation of group velocity in the graphene based PCW with respect to the applied voltage. The good level of group velocity is achieved using the proposed setup which is also suitable for on-chip delay tuning applications. Figure 3 shows the variation in the group velocity of the device with respect to applied voltage.

From this Figure the reduction in group velocity is observed when the applied voltage increases. With no applied voltage at 1550nm a group velocity value of 0.068c is reported. With an applied voltage of 1.5V, group velocity of 0.047c (c is the velocity of light in vacuum) is observed. With an applied voltage of 3V, group velocity of 0.026c is observed at wavelength of 1550nm.

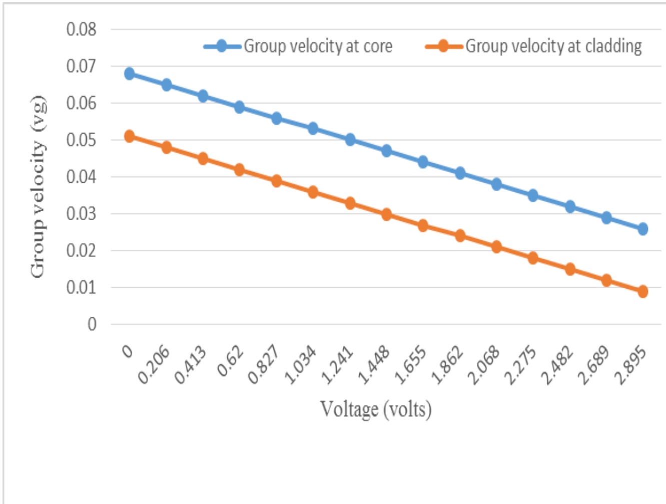



Fig. 3. The tuning of group velocity of light propagating through graphene coated core and cladding area of photonic crystal waveguide respectively.

Also, we calculated the group velocity variation in the graphene based photonic crystal waveguide with the applied electric voltage when graphene is placed on the cladding region, i.e., on the air holes and cladding (line-defect).In our device design, a large group velocity variation (0.068c to 0.03c) is reported with very low applied electric voltage (<3 volts) which is a considerably better performance than the previous work [8] in which group velocity is tuned from 0.0769c to 0.0464c with 4 volts of electric voltage applied.. Figure 3 shows the observed change in the group velocity of the device with variation in applied voltage. It is evident from the figure that applying electric field results in the reduction of group velocity at the cladding. Moreover, increase in applied electric voltage causes reduction in group velocity. Therefore, with reduction in group velocity, there is subsequent increase in the group delay.

## V. CONCLUSION

We proposed two novel designs of an optical delay line by coating the core and the cladding area of photonic crystal waveguide with graphene. Further, we electrically tuned the group velocity (0.061c to 0.027c) and (0.045c to 0.0098c) of guided light in the first (core) and second (cladding) design respectively by applying low power (1Volt-3Volts) Thus, achieving a large tuning of group delay (50ps-88ps) and (58ps-88ps) respectively. The achieved performance of design demonstrates its higher efficiency at lower power consumption, which paves its potential for future all optical networks such as optical buffers, optical storage and optical equalizers.

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