Optical modulation based on a graphene-loaded 2D grating

Sare Vatani, Hussein Taleb, Mohammad Kazem Moravvej-Farshi*

Nano Plasmo-Photonic Research Group, Faculty of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran

sare.vatani@modares.ac.ir; h.taleb@modares.ac.ir; *moravvej@modares.ac.ir

Abstract- To design a narrow-band reflective optical modulator with large modulation depth, we have used a graphene-loaded 2D grating in the critical coupling condition, for the first time. The simulation results show that the designed structure can achieve a modulation depth of more than 80% over a ~70 pm bandwidth. Moreover, to study the effects of the possible fabrication errors on the resonant wavelength, we have investigated the effects of minute changes in the grating period (\(\Lambda\)) and its teeth dimensions. The results show that a 1-nm error in the \(\Lambda\) results in an about 1.2 shift in the resonant wavelength. Whereas, the effects of the same errors in the grating teeth dimensions are much less significant. These results can pave the way for obtaining narrow bandwidth optical modulators with high modulation depth for optical communication applications.

Keywords: Optical Modulator, Graphene, Modulation Depth, Insertion Loss

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1. Introduction

A high-speed compact optical modulator serves as a fundamental element for optical communication systems. Depending on how an optical modulator modulates the light signal, it can be classified as amplitude, phase, or polarization modulator. Depending on its operation principle, an optical modulator is categorized as all optical, electro-optical, or thermo-optical. Moreover, an optical modulator can be either reflective or absorptive, depending on the type of light-matter interaction responsible for the modulation [1].

Reflective optical modulators, due to their potential application in high-capacity dense wavelength division multiplexing (DWDM) systems, have attracted much attention. They can be replaced for lasers used at the subscriber-end in most bidirectional optical communication systems. A narrow bandwidth optical modulator can be made more environmentally robust and reliable than the expensive narrowlinewidth lasers [2].

A layer of pristine graphene, with unique electrical and optical properties [3, 4], exhibits a constant optical absorption, \( \alpha = \varepsilon \alpha = \varepsilon^2 / \hbar c \) [5], in which \( \hbar \) is the reduced Planck constant, \( e \) is the elementary electric charge, and \( c \) is the free space light velocity. Moreover, the carrier concentration and optical surface conductivity of graphene can be modulated via modulation of its chemical potential (\( \mu_C \)), through an appropriate electrical gating scheme [6], making it a prominent candidate to be employed in optical applications [7]. Nonetheless, the limited optical absorption of a 0.34-nm thick monolayer of graphene can be enhanced, by integrating it with dielectric resonators, enhancing the light-matter interaction required for the critical coupling condition [8].

In this paper, taking advantage of a graphene-loaded 2D grating, in the critical coupling condition, we have designed a narrow-band high-modulation-depth reflective optical modulator.

2. Modulator Structure and Operation

Figure 1 illustrates the physical structure of the proposed optical modulator, schematically. It consists of a distributed Bragg reflector (DBR) formed by a stack of Si,N,SiO, pairs devise on a Sapphire substrate. In Fig. 1(b), \( h_a \) and \( h_b \) representing the thicknesses of SiO, and Si,N, slabs, respectively, each equals a quarter of the wavelength in the respective material. The top SiO, slab in the DBR is sandwiched between two single layers of graphene. On the top of the upper graphene layer, a 2D grating of pitch \( \Lambda \) is formed by a 2D array of Si rods with square cross-sectional areas.

Each unit cell of the grating with the underlying forms a resonator at the wavelength \( \lambda = 1550 \) nm.

Fig. 1: (a) Schematic of the proposed modulator, (b) side-view of the grating structure.

One can modulate the optical properties of the proposed structure, specifically its reflectance; taking advantage of the tuneable property of the graphene chemical potential (\( \mu_C \)), and hence its optical conductivity via an appropriate electrostatic gating scheme. The graphene sheet optical conductivity (\( \sigma_S \)), is related to its chemical potential via the well-known Kubo formula [9]. Moreover,
we can estimate the relative effective permittivity of a graphene layer sandwiched between two dielectric slabs by \( \varepsilon \approx \varepsilon_{av} + i\sigma_0/\varepsilon_0 \Delta \). where \( \varepsilon_{av} \) is the average effective permittivity of the top and bottom slabs, \( \varepsilon_0 \) is the free space permittivity, and \( \Delta \) is the thickness of the graphene layer. Hence, the effective relative permittivity of the proposed structure is also tuneable. This property lets us modulate the structure reflectance minima and maxima, as desired for the reflective optical modulators.

Consider a transverse electric (TE) polarized plane wave of center \( \lambda_0=1550 \text{ nm} \), incident upon the structure top surface, in the \(-z\)-direction. The periodic elements of an appropriately designed structure can provide necessary phase matching between the incident light and subwavelength structures inherent mode, leading to a near-critical coupling condition required for the emergence of a Guided-mode resonance with near-zero reflectance. For this purpose, we choose the design parameters to achieve the critical coupling for the lowest possible chemical potential (\( \mu_{C1} \)), first. In this condition, the reflectance for the designed structure approaches near zero at a specific wavelength—i.e., the OFF state. Then, we seek for an appropriate chemical potential (\( \mu_{C2} > \mu_{C1} \)), for which the reflectance spectrum exhibits a suitable shift, providing the ON state with the desired modulation depth of greater than 80\%. Notice, the modulation depth for the modulators is determined by the ratio of the minimum to the maximum of the reflectivities for \( \mu_{C1} (R_1) \) and \( \mu_{C2} (R_2) \), — i.e., \( MD(\lambda) = 1 - \min[R_1, R_2]/\max[R_1, R_2] \) [6].

Another important characteristic parameter for an optical modulator is its insertion loss (IL) that equals the optical loss when the light intensity is maximized — i.e., \( IL(\text{dB}) = 10\log R_{\text{min}} \text{ dB} \) [6].

### 3. Results and Discussions

Using the physical parameters and geometrical dimension given in Table I, we have simulated the reflectance spectrum of the proposed structure, in the wavelength range \( 1449 \leq \lambda \leq 1553 \), to characterize the modulator for two values of \( \mu_C = 120 \text{ meV} \) for OFF state and 370 meV for ON state.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Size</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_{\text{Si}} )</td>
<td>Grating height</td>
<td>56</td>
<td>nm</td>
</tr>
<tr>
<td>( W_{\text{Si}} )</td>
<td>Si rods horizontal dimension</td>
<td>842</td>
<td>nm</td>
</tr>
<tr>
<td>( \Lambda )</td>
<td>Grating pitch</td>
<td>998</td>
<td>nm</td>
</tr>
<tr>
<td>( h_a )</td>
<td>SiO(_2) slab thickness</td>
<td>( \lambda/4n_a )</td>
<td>nm</td>
</tr>
<tr>
<td>( h_b )</td>
<td>SiO(_2) slab thickness</td>
<td>( \lambda/4n_b )</td>
<td>nm</td>
</tr>
<tr>
<td>( n_{\text{Si}} )</td>
<td>Si refractive index</td>
<td>3.47</td>
<td>–</td>
</tr>
<tr>
<td>( n_a )</td>
<td>SiO(_2) refractive index</td>
<td>1.45</td>
<td>–</td>
</tr>
<tr>
<td>( n_b )</td>
<td>SiO(_2) refractive index</td>
<td>2.13</td>
<td>–</td>
</tr>
<tr>
<td>( N )</td>
<td>Number of the pairs of SiO(_2)/Si(_3)N(_4) in the DBR</td>
<td>20</td>
<td>–</td>
</tr>
</tbody>
</table>

The dots and solid line in Fig. 2(a) represents the reflectance spectra for \( \mu_{C1} \) and \( \mu_{C2} \), respectively. The dots-dashes in the same figure represent the MD spectrum with a narrow bandwidth of less than 1 nm. Fig 2(b) illustrates the corresponding insertion loss.

Since the resonance wavelength of the modulator is sensitive to the grating pitch that in turn is affected by the unavoidable fabrication errors, we have repeated the simulations for a 1-nm change in the pitch size (i.e., \( \Lambda = 999 \text{ nm} \)), keeping the other dimension fixed. Figures 2(c) and (d), illustrate data similar to those of Fig. 2(a) and 2(b), for the new \( \Lambda \).

A comparison of these two sets of data reveals a redshift of \( \Delta \lambda \approx 1.25 \text{ nm} \) in the resonant wavelength.

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This wavelength shift is due to the fact that the propagation constant of the guided varies as $\beta \propto \Lambda^{-1}$ [10]. In other words, as $\Lambda$ increases, while other grating dimensions are fixed, the effective refractive index and hence the propagation constant of the guided mode decreases, resulting in a redshift in the reflection spectra and hence in the corresponding MD spectrum.

Other grating dimensions ($h_{Si}$ and $W_{Si}$) are also subject to the fabrication process errors, influencing the modulator characteristics. Figures 3(a) and 3(b) compare the MD and IL spectra for $h_{Si}$=56 and 60 nm, while other parameters are the same as those in Table I. This comparison shows that a 2-nm increase in the grating teeth height causes a redshift of $\Delta \lambda \approx 0.7$ nm. This redshift is attributed to an increase of $\sim 0.47\%$ in the grating aspect ratio ($h_{Si}/W_{Si}$) [11]. Figures 3(c) and 3(d) compare the MD and IL spectra for $W_{Si}$=840 and 842 nm, while other parameters are the same as those in Table I. This comparison shows that a 2-nm decrease in $W_{Si}$ causes a redshift of $\Delta \lambda < 0.1$ nm in the modulator resonant wavelength. In fact, to achieve a 0.7-nm redshift we need to decrease $W_{Si}$ by $\sim 56$ nm.

Fig. 3 (a) MD and (b) IL spectra for $h_{Si}$ =56 and 60 nm; (c) and (d) illustrate MD and (b) IL spectra for $W_{Si}$=840 and 842 nm.

4. Conclusion

We have proposed a multi-layered refractive optical modulator that operates based on the guided-mode resonance of Si grating, devised 20 pairs of SiO$_2$/Si$_3$N$_4$ DBR. The top SiO$_2$ is sandwiched between two sheets of graphene. By modulating the graphenes chemical potential between $\mu_C=120$ meV (OFF state) and 370 meV (ON state), we have achieved a modulation depth of $\sim 80\%$ insertion of $\sim 12$ dB over a narrow bandwidth of $<0.1$ nm, at $\lambda \sim 1550$ nm. We have also investigated the effects of the grating geometry on the resonant wavelength of the designed modulator.

References