Transverse electric/magnetic switchable absorption ring modulator based on graphene

Feng Zhou 1 | Chen Liang 2

1College of Media Engineering, Communication University of Zhejiang, Hangzhou, China
2Department of Computer Science & Engineering, SUNY Buffalo, Buffalo, New York, USA

Abstract
We propose a transverse electric (TE)/transverse magnetic (TM) switchable absorption ring modulator based on graphene that can operate in either the TE or the TM mode. By adjusting the applied voltages onto the graphene layers in horizontal and perpendicular directions, either a TE or a TM absorption ring modulator can be configured, as has been previously reported. The simulation results show that a TE or TM modulator can be configured with a large extinction ratio and wide waveband from 1300 to 2000 nm. Specifically, the modulation bandwidth can be enlarged to over 130 GHz, which is rarely seen in conventional ring modulators. Also investigated is the possibility of extending the resonance wavelength shift to more than 5 nm by replacing the monolayer graphene structure with a quadrilayer graphene structure.

1 | INTRODUCTION

Ring resonator modulators have recently been extensively investigated in various fields owing to their unique structures [1–8]; however, conventional ring modulators usually suffer from narrow modulation bandwidths that greatly hinder their potential applications. In addition, resonance wavelength shifts of ring modulators are usually limited to the order of 0.1 nm [4]. Graphene, due to its extraordinary optical and electronic properties, has been extensively studied in optoelectronics, and different kinds of optoelectronic devices have benefited from graphene to achieve better performance, such as modulators [9–11], photodetectors [12, 13], polarisers [14,15] and so forth. The performance gain can also be extended to ring modulators. In fact, by introducing the 2-D anisotropic material graphene, the resonance wavelength shifts of ring modulators can be enhanced by orders of magnitude compared with enhancement through traditional silicon ring modulators, and the modulation bandwidth can be also enlarged [7, 8].

Most ring modulators, however, no matter whether they are traditional ring modulators or graphene-based ring modulators, normally work on a single polarised light, namely, either the transverse magnetic (TM) or the transverse electric (TE) mode, and are not capable of switching between different polarisation states. Because graphene exhibits the potential to tune the modulation or polarisation in either the TM or the TE mode, it follows naturally that by elaborately design of the ring structure, light polarisation can be manipulated, and a graphene-based TE/TM switchable ring modulator can be configured. On the other hand, compared with electro-refraction modulators, electro-absorption modulators usually possess the advantages of lower driving voltage, smaller footprint and higher modulation efficiency [16–18], and thus a TE/TM switchable absorption ring modulator would be highly appreciated in future modulators. Moreover, to further enhance the light–matter interaction and resonance wavelength shift of the proposed absorption ring modulator, the few-layer graphene structure is also investigated, for it is much easier to transfer and fabricate in practical experimentation than the monolayer graphene structure is.

In this paper, a TE/TM switchable graphene-based absorption ring modulator is demonstrated that can work in either the TE or the TM mode by specifically adjusting the chemical potentials of graphene layers on the horizontal and perpendicular sides of the ring modulator. The proposed ring modulator exhibits a large modulation bandwidth and extinction ratio for both the TE and the TM mode. Another finding is that the resonance wavelength shift is extended to 9 and 5 nm for the TE and TM mode, respectively, simply by replacing the monolayer graphene structure with a quadrilayer graphene structure, which provides a dynamic and convenient way to increase the tunability of the proposed ring modulator.
PRINCIPLES AND DEVICE STRUCTURES

From the ring resonator structure shown in Figure 1a, it can be seen that incident light passes through the bus waveguide from input to output by coupling the ring structure [19]. $t$ and $k$ are the respective self-coupling and cross-coupling coefficients of the ring resonator. It is revealed here that the enlarged variations of $n_{\text{eff}}$ of the hybrid waveguide can be utilised to achieve light modulation. As shown in Figure 1a, the input light from the left side of the straight bus waveguide is coupled to the ring resonator, and the output light is obtained through the right side. The amplitude of the output can be deduced as [20]

$$b_1 = \frac{t - \alpha \, e^{-i \varphi}}{1 - \alpha \, e^{-i \varphi} \, a_1} \quad (1)$$

where $\alpha = e^{-\pi/2 \text{Im}(n_{\text{eff}})/l}$ is the attenuation factor of the ring waveguide, $l = 2\pi r$ is the perimeter of the ring waveguide, $\varphi$ is the phase shift of the ring waveguide and $\lambda$ is the input incident wavelength.

From Equation (1), it can be seen that when $\alpha = t$, the transmission reduces to 0 at the resonant points. At the resonance state, the resonance wavelength is calculated as $\varphi = 2\pi m$, and the transmission curve is simplified as

$$T = \frac{|b_1|^2}{|a_1|^2} = \frac{(\alpha - |t|)^2}{(1 - |t|)^2} \quad (2)$$

In this situation, the ring modulator works on the resonant wavelength, and through tuning it with external voltage, the transmission changes according to different chemical potentials. By utilising this property, optical modulation can be achieved.

Based on this, the structure of the proposed TM/TE switchable graphene-based absorption ring modulator is schematically displayed in Figure 1b. The proposed ring modulator is built on a silicon substrate, the bus waveguide is made of silicon by which the input light passes, and the ring resonator structure has a radius of 5 $\mu$m. Graphene layers are placed on the horizontal and perpendicular sides of the ring resonator structure, while electrodes are positioned to connect the graphene layers and the silicon. In practical fabrication, the bottom graphene layer is first transferred to the silicon substrate, and the alumina transition layer is placed on the surface of the bottom graphene layer to stabilise the structure. The silicon ring structure is then constructed on the bottom layer of graphene and the alumina layer. With the same method, the top layers of alumina and graphene can accordingly be transferred to the top surface of the silicon ring structure. After the horizontal sides of the ring structure are built, the perpendicular sides, including the outer and inner sides of the silicon ring structure, are deposited accordingly with graphene and alumina layers. It should be noted that the four sides of the graphene and alumina layers should be separated from one another. After the structure has been completed, electrodes composed of Au and Pt are connected to the extended graphene layers from four sides, and by simply adjusting the external voltage, the corresponding transmission properties of the proposed ring modulator can be obtained. Figure 1c,d represents the electrical field distributions of the TM and TE modes, respectively, for the proposed graphene-based absorption ring modulator.

Variations of the effective mode index $n_{\text{eff}}$ for both the TE and the TM mode, induced by tuning the chemical potential of graphene on the horizontal and perpendicular sides of the ring modulator, are investigated. At first, graphene layers on the horizontal sides of the ring modulator are studied; the results are shown in Figure 2a. It can be seen that variations of Re($n_{\text{eff}}$) and Im($n_{\text{eff}}$) for the TM mode are much more significant than those of the TE mode, which indicates that TM modulation is realised more favourably by simply tuning the graphene on the horizontal sides. With the same method, graphene layers on the perpendicular sides of the ring modulator are also investigated; variations are displayed in Figure 2b. In this case, variations of Re($n_{\text{eff}}$) and Im($n_{\text{eff}}$) for the TE mode are much more evident than those of the TM mode, and it can be inferred that TE modulation is realised more favourably by simply tuning the graphene on the perpendicular sides of the ring modulator.
For both conditions shown in Figure 2a,b, it is interesting to find that two points exist where Re($n_{\text{eff}}$) are nearly the same while Im($n_{\text{eff}}$) differ greatly, which are much appreciated for realising absorption modulation with a large extinction ratio. To be more specific, we can fix the chemical potential of the perpendicular sides of the ring modulator at 0.7 eV to keep the loss of the whole structure at a relatively low level as shown in Figure 2a, and by choosing the chemical potential of graphene on the horizontal sides as $\mu_e = 0.2$ and 0.48 eV, an absorption TM modulator with a large extinction ratio can be constructed. Similarly, according to Figure 2b, by fixing the chemical potential of graphene on the horizontal sides at 0.7 eV to reduce loss to the maximum extent and choosing the chemical potential of graphene on the perpendicular sides as $\mu_e = 0.2$ and 0.48 eV, an absorption TE modulator with a large extinction ratio can be configured accordingly. Based on the foregoing analysis, either a TM or a TE absorption modulator can be built in the proposed ring resonator structure by specifically adjusting the applied voltages to the graphene layers on the horizontal and perpendicular sides.

To demonstrate this in detail, the corresponding transmission curves are illustrated in Figure 3a,b, where chemical potentials of 0.2 and 0.48 eV are selected for both the TM and the TE modulator. The transmission property depends on cross-coupling coefficient $k$ and self-coupling coefficient $t$, which are expressed as $k^2 + t^2 = 1$ [19]. In our proposed ring modulator, $k$ is chosen as 0.34. As for the TM modulator, as shown in Figure 3a, it can be seen that at the resonance wavelength of 1509 nm, there exists a large gap between 0.2 and 0.48 eV, while Re($n_{\text{eff}}$) is 1.489 for both chemical potentials. Thus, in this case, an absorption TM modulator can be constructed with a large extinction ratio of over 10 dB. Meanwhile, when it is switched as a TE modulator, as displayed in Figure 3b, a large discrepancy between 0.2 and 0.48 eV can be obtained at the resonance wavelength of 1502 nm, while Re($n_{\text{eff}}$) is 1.817 for both chemical potentials, which indicates that an absorption TE modulator with a large extinction ratio of over 20 dB can be configured. Considering both conditions, the absorption ring modulator with large extinction ratios of more than 10 and 20 dB can be constructed for the TM and the TE mode, respectively.

3 | SIMULATION RESULTS AND DISCUSSIONS

3.1 | Modulation bandwidth

Modulation bandwidth has always been a big issue to consider for ring modulators. Conventional ring modulators usually suffer from low modulation bandwidth that hinders their future application. However, for our proposed graphene-based
TM/TE switchable ring modulator, modulation bandwidth is significantly improved as a result of the extraordinary properties of graphene. When it is operating as a TM modulator, shown as Figure 3a, the 3-dB modulation bandwidth can be calculated as about 2.5 nm from 1507.8 to 1510.3 nm, which indicates that a large modulation bandwidth of 312.5 GHz has been achieved. When it is working as a TE modulator, shown as Figure 3b, the 3-dB modulation bandwidth is around 1.6 nm from 1501.2 to 1502.8 nm, which equates to a large modulation bandwidth of 200 GHz. Therefore, it can be concluded that for both the TM and the TE modulator, modulation bandwidth can be expanded to over 200 GHz, a result that is rarely found in conventional ring modulators.

RC restrictions of modulation bandwidth are also considered in our proposed absorption ring modulator, which depends on the equivalent resistance $R$ and capacitance $C$ decided by several factors. As for the equivalent capacitance $C$, the quantum capacitance $C_Q$ is included with the aim to evaluate the result more precisely. $C_Q$ depends on the Planck constant, $\hbar$, and Fermi velocity, $v_F$, and can be estimated approximately as $C_Q = \frac{4\pi e^2}{h^2}$ [21]. By combining the parallel plate model of capacitance and $C_Q$, the equivalent capacitance $C$ can be estimated as 8 fF in our proposed absorption ring modulator. On the other hand, the equivalent resistance $R$ is composed of graphene resistance and contact resistance, which are both decided by the effective length and width of the graphene layers. The graphene resistance is usually chosen to be from 100 to 300 $\Omega$/sq [22], and thus it can be calculated that the total value of the equivalent resistance $R$ is around 200 $\Omega$. Therefore, the 3-dB modulation bandwidth limited by RC restrictions is calculated to be around 133 GHz. Combined with the foregoing calculations, it can be concluded that for both the TM and the TE absorption ring modulator, the main restriction of modulation bandwidth is the $RC$ constant. However, compared with conventional ring modulators, the modulation bandwidth has already been significantly improved.

### 3.2 Operating wavelength

To investigate the operating wavelength for the proposed absorption ring modulator, we have studied the relationship between the wavelength and $n_{\text{eff}}$ when $\nu_c = 0.2$ and 0.48 eV, respectively. Figure 4a represents the relationship when the modulator is configured as a TM absorption ring modulator, and it can be found that from 1300 to 2000 nm, $\text{Re}(n_{\text{eff}})$ for 0.2 and 0.48 eV are almost the same with variations of less than 0.03%, as shown in Figure 4c, while a large discrepancy of $\text{Im}(n_{\text{eff}})$ always exists between 0.2 and 0.48 eV, and the ratio of $\text{Im}(n_{\text{eff}})$ between 0.48 and 0.2 eV varies with the incident wavelength and exhibits a gradual drop from 7 to 3. By comparison, when it is configured as a TE absorption ring modulator, as shown in Figure 4b,d, it is also found that from 1300 to 2000 nm, $\text{Re}(n_{\text{eff}})$ for 0.2 and 0.48 eV are almost the same with variations of no more than 0.03%; however, as shown in Figure 4d, the large gap of $\text{Im}(n_{\text{eff}})$ between 0.2 and 0.48 eV can be found throughout the waveband, and the ratio of $\text{Im}(n_{\text{eff}})$ between 0.48 and 0.2 eV also experiences a corresponding gradual drop from 7 to 4. Thus, considering both conditions, it can be concluded that for both the TM and the TE modulator...
within the operating wavelength from 1300 to 2000 nm, it is feasible to achieve absorption modulation when \( \mu_c \) is selected to be 0.2 and 0.48 eV, respectively.

3.3 | Switching voltage

Switching voltage is another important parameter in measuring the performance of electro-optic modulators, and small switching voltage is in high demand for future optical modulators. As for our proposed absorption ring modulator, the large extinction ratio is achieved by tuning the chemical potential of graphene, and the relationship between \( \mu_c \) and the applied voltage can be expressed as \( \mu_c = \frac{h}{\eta} \sqrt{\eta \pi \left| \frac{V_D - V_0}{V_D} \right|} \), where \( V_D \) is the offset value, which is usually set as 0.8 V [23], and \( \eta \) can be calculated by introducing the parallel plate capacitor model \( \eta = \frac{\epsilon_0 d}{\epsilon} \), which is independent of the dielectric constant of the alumina layer and the gap distance between the two plates in the model. Therefore, it is calculated that only a switching voltage of 1.76 V is requested when \( \mu_c \) switches from 0.2 to 0.48 eV, which is highly appreciated in configuring the absorption ring modulator in practical applications.
3.4 The properties of few-layer graphene

Apart from monolayer graphene, the few-layer graphene absorption ring modulator is also studied. In a practical sense, few-layer graphene structures are much more convenient to construct than monolayer graphene structures, and as experimentally demonstrated in reference [24], the multiband influence caused by few-layer graphene can be neglected. In this case, by tuning the chemical potential of graphene from 0 to 1 eV, we investigated the variations of Re(\(n_{\text{eff}}\)) and Im(\(n_{\text{eff}}\)) for both the TM and the TE modulator when the number of graphene layers varies from one to four; results are shown in Figure 5a–d.

Figure 5a,b illustrates the variations among Re(\(n_{\text{eff}}\)) and Im(\(n_{\text{eff}}\)) from monolayer to quadrilayer for the TM modulator, while Figure 5c,d illustrates those for the TE modulator. It can be found that for both the TM and the TE modulator, with an increase in graphene layers, the interaction between graphene and light is linearly enhanced, and the variation of Im(\(n_{\text{eff}}\)) for quadrilayer graphene is almost four times that of monolayer graphene. To be more specific, for the TM modulator, when \(\mu_c\) is chosen as 0.2 and 0.48 eV, the largest variations of Im(\(n_{\text{eff}}\)) are 0.009, 0.018, 0.027 and 0.036 for the mono-, bi-, tri- and quadrilayer, respectively. For the TE modulator when \(\mu_c\) = 0.2 and 0.48 eV, the largest variations of Im(\(n_{\text{eff}}\)) are 0.0064, 0.013, 0.019 and 0.025 for the mono-, bi-, tri- and quadrilayer, respectively.

3.5 Tunability of the proposed modulator

By investigating monolayer to quadrilayer graphene, it occurs to us that the resonance wavelength shift can be obtained by placing different numbers of graphene layers because the transmission curves vary with different numbers of graphene layers. When \(\mu_c\) is chosen as 0.2 and 0.48 eV, the transmission curves for the mono-, bi-, tri- and quadrilayer TM and TE absorption ring modulators are illustrated as Figure 6a,b, respectively. As for the TM modulator shown in Figure 6a, the extinction ratios for the mono-, bi-, tri- and quadrilayer graphene structures are calculated to be 10, 3.8, 2.4 and 1.8 dB, respectively, and the resonance wavelength experiences a shift of 5 nm when the monolayer graphene structure is replaced by the quadrilayer graphene structure. Meanwhile, when it is switched as a TE modulator, as shown in Figure 6b, the extinction ratios for the mono-, bi-, tri- and quadrilayer graphene structure are calculated as 20.8, 9.3, 5.7 and 4 dB, respectively, and a resonance wavelength shift of 9 nm is achieved when the monolayer graphene structure is replaced by the quadrilayer graphene structure. Compared with conventional ring modulators whose resonance wavelength shifts are usually limited to around 0.1 nm, tunability of the proposed absorption ring modulator has been greatly improved regardless of whether the TM or the TE mode is used.

4 CONCLUSION

A TE/TM switchable broadband absorption ring modulator is proposed that can work as either a TM or a TE modulator by specifically adjusting the applied voltages onto the graphene layers in horizontal and perpendicular directions. Results show that large extinction ratios of over 10 dB for the TM modulator and 20 dB for the TE modulator can be achieved, respectively, as a result. The proposed absorption ring modulator also features the advantages of a large modulation bandwidth, broad operating band and small switching voltage. In addition, few-layer graphene structures are also studied, and results show that by utilising different numbers of graphene layers, 5 and 9 nm maximum values for resonance wavelength shifts are realised for the TM and the TE modulator, respectively. All of these findings and advantages may find great potential use in future optical communications.

ACKNOWLEDGEMENT

This work is supported by Zhejiang Province Science Foundation for Youth under Grant No LQ19F050001.

REFERENCES

1. Dong, P., et al.: Wavelength-tunable silicon microring modulator. Opt. Express. 18(11), 10941–10946 (2011). https://doi.org/10.1364/OE.18.010941
2. Yu, M., et al.: Silicon dual-ring modulator driven by differential signal. Opt. Lett. 39(22), 6379–6382 (2014). https://doi.org/10.1364/OL.39.006379
3. de Valicourt, G., et al.: Integrated hybrid wavelength-tunable III–V/silicon transmitter based on a ring-assisted Mach–Zehnder interferometer modulator. J. Light. Technol. 36(2), 204–209 (2017). https://doi.org/10.1109/JLT.2017.2787763
4. Gould, M., et al.: Silicon-polymer hybrid slot waveguide ring-resonator modulator. Opt. Express. 19(5), 3952–3961 (2011). https://doi.org/10.1364/OE.19.003952
5. Chen, L., et al.: Highly linear ring modulator from hybrid silicon and lithium niobate. Opt. Express. 23(10), 13255–13264 (2015). https://doi.org/10.1364/OE.23.013255
6. Wang, J., et al.: Optical absorption in graphene-on-silicon nitride microring resonators. IEEE Photon Technol. Lett. 27(16), 1765–1767 (2015). https://doi.org/10.1109/LPT.2015.2443051
7. Zhou, F., et al.: Highly tunable and broadband graphene ring modulator. J. Nanophoton. 13(1), 016008 (2019). https://doi.org/10.1117/1.JNP.13.016008
8. Zhou, F., et al.: The absorption ring modulator based on few-layer graphene. J. Opt. 21(4), 045801 (2019). https://doi.org/10.1088/2040-8986/ab0b35
9. Soriano, V., et al.: Graphene–silicon phase modulators with gigahertz bandwidth. Nat. Photon. 12(1), 40–44 (2018). https://doi.org/10.1038/s41566-017-0071-6
10. Shu, H., et al.: Significantly high modulation efficiency of compact graphene modulator based on silicon waveguide. Sci. Rep. 8, 991 (2018). https://doi.org/10.1038/s41598-018-19171-z
11. Liao, Y., et al.: Ultra-broadband all-optical graphene modulator. IEEE Photon. Technol. Lett. 30(8), 661–664 (2018). https://doi.org/10.1109/LPT.2018.2800769
12. Guo, X., et al.: High-performance graphene photodetector using interfacial gating. Optica. 3(10), 1066–1070 (2016). https://doi.org/10.1364/OPTICA.3.001066
13. Schuler, S., et al.: Controlled generation of a p–n junction in a waveguide integrated graphene photodetector. Nano Lett. 16(11), 7107–7112 (2016). https://doi.org/10.1021/acs.nanolett.6b03374
14. Farmani, A., et al.: Design of a high extinction ratio tunable graphene on white graphene polariser. IEEE Photon. Technol. Lett. 30(2), 153–156 (2017). https://doi.org/10.1109/LPT.2017.2779160
15. Zhang, H., et al.: Graphene-based fibre polariser with PVB-enhanced light interaction. J. Lightw. Technol. 34(15), 3563–3567 (2016). https://doi.org/10.1109/JLT.2016.2581315
16. Phare, C.T., et al.: Graphene electro-optic modulator with 30 GHz bandwidth. Nat. Photon. 9, 511–514 (2015). https://doi.org/10.1038/nphoton.2015.122
17. Amin, R., et al.: Waveguide-based electro-absorption modulator performance: comparative analysis. Opt. Express. 26(12), 15445–15470. https://doi.org/10.1364/OE.26.015445
18. Hu, Y., Pantouvaki, M., Van Campenhout, J.: Broadband 10 Gb/s operation of graphene electro-absorption modulator on silicon. Laser Photon. Rev. 10(2), 307–316 (2016). https://doi.org/10.1002/lpor.201500250
19. Yariv, A.: Critical coupling and its control in optical waveguide-ring resonator systems. IEEE Photon. Technol. Lett. 14(4), 483–485 (2002). https://doi.org/10.1109/68.992585
20. Ellis, S.C., et al.: Photonic ring resonator filters for astronomical OH suppression. Opt. Express. 25(14), 15868–15889 (2017). https://doi.org/10.1364/OE.25015868
21. Koester, S.J., et al.: Switching energy limits of waveguide-coupled graphene-on-graphene optical modulators. Opt. Express. 20(18), 20330–20341 (2012). https://doi.org/10.1364/OE.20.020330
22. Abdollahi, S.L., Van Thourhout, D.: Graphene modulators and switches integrated on silicon and silicon nitride waveguide. IEEE J. Sel. Top. Quant. 23(1), 3600107 (2017). https://doi.org/10.1109/JSTQE.2016.2586458
23. Zhou, S.Y., et al.: First direct observation of Dirac fermions in graphite. Nat. Phys. 2, 595–599 (2006). https://doi.org/10.1038/nphys393
24. Bao, Q., et al.: Broadband graphene polariser. Nat. Photon. 5, 411–415 (2011). https://doi.org/10.1038/nphoton.2011.102

How to cite this article: Zhou, F., Liang, C.: Transverse electric/magnetic switchable absorption ring modulator based on graphene. IET Optoelectron. 15(4), 178–184 (2021). https://doi.org/10.1049/ote2.12032