Tunable dual-wavelength absorption switch with graphene based on an asymmetric guided-mode resonance structure

Park, Gyeong Cheol; Park, Kwangwook

Published in:
Optics Express

Link to article, DOI:
10.1364/OE.416394

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Abstract: We propose a tunable dual-wavelength absorption (TDWA) switch based on an asymmetric guided mode resonance (AGMR) structure. A TDWA switch consists of a graphene layer and an AGMR structure sandwiched by cap and slab layers on a buffer/silicon substrate. The AGMR structure adds a smaller grating unit cell next to a larger one, exciting a second resonance close to but distinct from the first resonance. For switching, the TDWA between an absorptive or reflective mode with each on-/off-state, the chemical potential of graphene is tuned from 0.0 eV to 0.6 eV. For the absorptive mode, two absorption peaks of ≥ 96.2% are separated by 23 nm, both having an on-off ratio of ~15.52. For the reflective mode, two reflectance peaks of ≥ 93.8% are separated by 23 nm, having on-off ratios of 15.56 dB and 18.95 dB. The maximum on-off ratios of 39.98 dB and 34.55 dB are achieved near the reflectance peaks. Both the period of the AGMR and the cap thickness alters the two peak wavelengths linearly, while the grating width of the AGMR varies nonlinearly from 17 nm to 28 nm. The buffer excites a weak Fabry-Perot resonance, which interacts with the TDWA structure, the result of which is the two absorption peaks are varied. Finally, as the incidence angle of light increases up to 5.3°, the distance of the two peak wavelengths is tuned from ~22 nm to ~77 nm with ≥ 96% absorption or ≥ 93% reflectance in each mode.

© 2021 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

1. Introduction

Graphene is an attractive electro-optic material which can absorb light over a broad spectrum spanning from the ultraviolet to the terahertz spectral regime due to its gapless nature and its ability to tune the light absorption by controlling the inter-band or intra-band transition [1–5]. For this reason, the graphene has been widely investigated for the use in various photodetector and optical modulator applications [1–6]. Single-layer graphene (SLG), however, has limited absorption of ~2.3% of incident light at the visible and near-infrared (NIR) range. To enhance the absorption efficiency of graphene at specific wavelengths, numerous optical structures have been proposed, including plasmonic structures, optical cavities, and patterned graphene [3–8]. Since surface plasmons on graphene are not easily excited in the NIR wavelength region [9,10], optical cavities or resonance structures such as Fabry-Perot cavities and guided-mode resonance (GMR) structures are widely used to enhance the light-graphene interaction [11–15]. The GMR structures also have been employed for the thin layers other than graphene for second-harmonic generation or resonant absorption application [16–18]. For the applications utilizing the optical absorption, it is always desirable to enhance the light-graphene interaction and attain a perfect absorption by achieving a critical-coupling condition [15,16]. One way to achieve a critical
coupling condition on the cavities is to place a perfect mirror behind the exit region of a two-port cavity [19–22]. This prevents light from being transmitted out and reflects the light back to the incident region [19–22]. Then, both of the leakage rate of the excited mode from the cavity toward the incident region and the absorption rate of graphene can be easily tuned to be the same, and hence a perfect absorption is achieved. However, if the mirrors forming the cavity is made of a metal such as gold (Au), then it will absorb some of the incident light, reducing the absorption efficiency of the graphene [21,22]. Moreover, while Au may be desirable metal for its higher reflectance at the NIR wavelength range, it is poorly suited for use with silicon (Si) due to the unintentional Au doping in Si. For that reason, the dielectric DBRs can be an alternative, though, to achieve a perfect reflectance in the NIR region the DBRs may need to be unsuitably bulky, as they need multiple pairs of high/low-refractive-index layer with a quarter-wavelength thickness.

Furthermore, optical cavities usually support single resonance with high absorption efficiency within a single wavelength band only. On the other hand, since the graphene possesses nearly uniform absorption across the VIS and NIR wavelength region, the multi-band or multi-wavelength photodetectors can be realized with a single absorbing material, the graphene. To achieve absorption in two wavelength bands with high absorption efficiency, a combined resonance structures, either stacked on top of or placed next to each other, is used [14,23–30]. In addition, to obtain dual-wavelength absorption within a single wavelength band, i.e., with a distance between two peak wavelengths of a few tens of nanometers, a resonance structure needs to excite two resonance modes at the same time. However, to absorb light at two different wavelengths using a vertically stacked cavity or a hybrid resonance structure, the fabrication process becomes too complicated; graphene may need to be transferred to the area between each cavity or between the cavity structures [31]. In addition, the interaction between the two cavities deteriorates each critical-coupling condition. As a result, the dual-wavelength absorption within a single wavelength band can hardly be realized. On the other hand, instead of utilizing multiple cavities, if a single cavity can support two resonance modes at the same time with the same quality factor, then the absorption in the graphene layer will be the same at each resonance wavelength.

Symmetry-broken resonance structures offer an alternative means of achieving the dual-wavelength absorption [32,33]. A symmetry-broken structure can excite two resonances and the resonance property can be adjusted by controlling the parameters of the resonance structure. Therefore, if the two leakage rates (γ_{leak}s) of the resonance structure and the two absorption rates (γ_{abs}s) of an absorbing material on the resonance structure are the same, then a critical-coupling condition is achieved [19,20]. We have been recently proposed a dual-guiding-layer resonance structure which can control the leakage rate and absorption rate of the resonance structure with lessen restriction [34]. With this proposed design philosophy, a dual-wavelength resonance structure can be feasible by breaking the symmetry in the grating region. Conventional absorbing materials (III-V compound semiconductors or germanium) are poorly suited to achieving the critical-coupling condition at two target wavelengths simultaneously, as they absorb only a narrow wavelength range with a non-uniform absorption efficiency across a full NIR spectrum. Graphene, however, is a potentially useful material in this regard, as it can be transparent or absorptive over the VIS and NIR region thereby the optical property of the resonance structure can be determined only by changing the chemical potential (µc) of graphene; the dual-wavelength reflector/absorber can be realized with a single resonance structure.

Here, we propose a novel tunable dual-wavelength absorption (TDWA) switch based on an all-dielectric asymmetric guided-mode resonance (AGMR) structure. Graphene absorbs or transmits light uniformly at two wavelengths by controlling its µc, thereby switching the TDWA structure. The AGMR structure is sandwiched between cap and slab layers, followed by a buffer and silicon substrate. The AGMR structure consists of small and large grating unit cells next to each other which excites two resonance modes. In an absorptive mode, there are two absorption
AGMR structure. The SiO₂ weak Fabry-Perot (FP) resonance, which interacts with the TDWA structure and changes the peak wavelengths are linearly redshifted. Contrarily, the grating width of the larger unit cell increases (HfO₂). The TDWA switch mainly consists of single-layer graphene (SLG) as electro-absorption material. The schematic configuration and cross-sectional views of a proposed tunable dual-wavelength absorption (TDWA) switch on a silicon-on-insulator (SOI) are shown in Fig. 1(a) and (b). The TDWA switch mainly consists of single-layer graphene (SLG) as electro-absorption material on top of a thin oxide layer and an asymmetric guided-mode resonance (AGMR) structure sandwiched by a high-refractive-index cladding layer and a slab layer. The AGMR structure is a combined two sub-periodic structure which consists of alternating high-refractive and low-refractive 1D grating bars with two sub-period of Λ₁ and Λ₂, and the sum of Λ₁ and Λ₂ is the period of Λ (Λ = Λ₁ + Λ₂) [35,36]. In particular, to break the symmetry of a guided-mode resonance structure, a sub-periodic structure with Λ₂ is added to the grating structure with a single period of Λ₁. The Λ₂ is smaller than the Λ₁, and the introduced asymmetry can excite a second resonance close to the first [35,36]. The width of each high-refractive-index grating bar is w₁ and w₂ and the ratios of each grating bar width to the Λ are F₁ (w₁/Λ), F₂ ((Λ₁−w₁)/Λ), F₃ (w₂/Λ) and F₄ ((Λ₂−w₂)/Λ). The cap and slab layers surrounding the AGMR structure are high-refractive-index homogeneous layers, which confine, and guide light diffracted by the AGMR structure. The SiO₂ buffer layer (buried oxide; BOX) separates the TDWA structure and the silicon (Si) substrate. The corresponding thickness (t) and material of each layer are shown in Fig. 1(b). Note that the TDWA structure consists of all dielectric layers and no metallic or dielectric back mirror, and it can be fabricated on a SOI platform with CMOS-compatible process. The μₑ of a graphene layer can be controlled by applying electrical gate voltage between the SLG and the cladding layer (doped Si) separated by a high-κ dielectric layer such as hafnium oxide (HfO₂). Furthermore, HfO₂ can reduce chemical doping on the graphene layer and ameliorate the electrical property of the graphene [37]. By applying electrical gate voltage, the complex permittivity of graphene can be tuned and the TDWA switch can selectively absorb or reflect incident light depending on the photon energy (ℏω) [38]. When the SLG is undoped or no gate voltage is applied, the TDWA switch can simultaneously absorb incident light of two separate wavelengths as shown in Fig. 1(c). When the two incident wavelengths are matched with the two resonance wavelengths of the TDWA structure, the absorption increases. If two decay rates at each resonance wavelength are almost same as the absorption rates of the SLG, i.e., a quasi-critical-coupling condition, the absorption becomes near-perfect. Since the structure neither uses a metal nor a distributed Bragg reflector (DBR) bottom mirror, a small amount of light may be transmitted to the exit region at the two resonance wavelengths. With the same structure, but with a different μₑ level higher than the ℏω/2, absorption is suppressed due to Pauli blocking and reflectance is dramatically increased at two resonance wavelengths, as shown in Fig. 1(d) [39]. Therefore, the response to the incident light is similar to the response of a TDWA structure without graphene. Since the TDWA structure is designed to have high reflectance at two resonance wavelengths without graphene, its reflectance will increase dramatically as shown in Fig. 1(d). As a consequence, the TDWA switch can operate as a wavelength-selective mirror at
two resonance wavelengths. By electrically tuning the $\mu_c$ of graphene, its optical properties can be controlled, and therefore, the overall optical response of a TDWA structure can be switched from dual-wavelength absorber to dual-wavelength mirror.

First, to understand the functionality of a TDWA switch using graphene as an electro-absorption material, it is needed to understand the complex permittivity of graphene ($\varepsilon_G$) which depends on $\mu_c$ and wavelength. The optical conductivity of graphene in the NIR wavelength range can be described by the closed formula [40,41]:

$$
\sigma_G = \frac{\sigma_0}{2} \left[ \tanh \left( \frac{\hbar \omega + 2\mu_c}{4k_B T} \right) + \tanh \left( \frac{\hbar \omega - 2\mu_c}{4k_B T} \right) \right]
- i \frac{\alpha_0}{2\pi} \log \left[ \frac{(\hbar \omega + 2\mu_c)^2}{(\hbar \omega - 2\mu_c)^2 + (2k_B T)^2} \right] + \frac{4\sigma_0}{\pi} \frac{\mu_c}{\hbar \omega + i\hbar \gamma}
$$

where $\sigma_0 = q^2/(4\hbar)$ is the universal conductivity for undoped graphene, $q$ is the elementary electron charge, $\hbar$ is the reduced Planck constant, $k_B$ is the Boltzmann constant, $T$ is the temperature, $\omega$ is the angular frequency, $\gamma$ is the intra-band scattering rate, $\hbar \omega$ is photon energy, and $\hbar \gamma$ is the electron relaxation energy. The intra-band scattering rate $\gamma$ is the inverse of the intra-band relaxation time ($\tau$), and it is affected by the quality of graphene. The in-plane complex permittivity of graphene, then, can be calculated from the conductivity as [41]

$$
\varepsilon = 1 + \frac{i\sigma_G}{\omega \varepsilon_0 t_G}
$$

where $\varepsilon_0$ is the vacuum permittivity and $t_G$ is the thickness of a SLG. The $t_G$ of 0.335 nm is used in the calculation [22]. The functionality of the proposed structure can be switched by tuning
the $\mu_c$ of graphene with respect to the energy of incident light. The real and imaginary part of complex permittivity of graphene as a function of wavelength and $\mu_c$ with a relaxation time ($\tau$) of 100 fs are shown in Figs. 2(a) and 2(b), respectively. The sign of the real part ($\varepsilon_1$) of the complex permittivity changes from the positive value to the negative one as $2|\mu_c|$ becomes larger than $\hbar\omega$. The imaginary part ($\varepsilon_2$) starts decreasing as $2|\mu_c|$ approaches to $-\hbar\omega$ and becomes nearly zero when $2|\mu_c|$ is larger than $\hbar\omega$. After transferring graphene to a substrate, the quality of the graphene may be impaired, thus a factor that needs to be accounted for through $\tau$ of Eq. (1).

Figure 2(c) shows $\varepsilon_1$ and $\varepsilon_2$ of graphene at the wavelength of 1.55 $\mu$m with three different $\tau$ as $\mu_c$ increases from 0.0 eV to 1.0 eV. As $\tau$ increases from 10 fs to infinity, the profound difference is found in $\varepsilon_2$ for $\tau$ of 10 fs. When $\mu_c$ is higher than 0.5 eV, two $\varepsilon_2$ for $\tau$ of both 100 fs and infinite become nearly zero. However, for $\tau$ of 10 fs, it results in a significant $\varepsilon_2$ value above the $\mu_c$ of 0.5 eV. When the TDWA switch is set as a dual-wavelength mirror, the reflectance decreases further due to the inherent absorption of graphene even though $\mu_c$ is far above $\hbar\omega/2$. Therefore, the TDWA switching application requires a longer relaxation time in graphene. Accordingly, for the numerical calculation of the proposed structure, otherwise mentioned explicitly, $\tau$ is assumed to be 100 fs. In addition, the value of $\tau$ is experimentally achievable at 300 K [42,43]. To achieve $\tau$ of 100 fs, a thin HfO$_2$ layer is chosen [37]. Depending on the sign of $\varepsilon_1$, graphene can be divided into two regions; a lossy dielectric region and metallic region as indicated by the gray-dotted line reflecting $\mu_c$ of 0.5 eV in Fig. 2(c) [38,43]. At a certain wavelength, the TDWA switch functions as a dual-wavelength absorber in the lossy dielectric region and as a dual-wavelength mirror in the metallic region.

![Fig. 2. Complex permittivity of graphene with a relaxation time ($\tau$) of 100 fs as a function of wavelength and $\mu_c$: (a) real ($\varepsilon_1$) and (b) imaginary part ($\varepsilon_2$). (c) Complex permittivity of graphene as a function of $\mu_c$ at a wavelength of 1550 nm with three different relaxation times (10 fs, 100 fs, $\infty$).](image)

### 3. Results and discussion

To study the absorption and reflectance of a TDWA switch, an in-house rigorous coupled-wave analysis (RCWA) method is employed [44]. The structural parameters of a representative TDWA switch are tailored as $\Lambda = 900$ nm, $\Lambda_1 = 711$ nm, $\Lambda_2 = 189$ nm, $w_1 = 360$ nm, $w_2 = 99$ nm, $t_{\text{oxide}} = 20$ nm, $t_{\text{cladding}} = 72$ nm, $t_{\text{grating}} = 120$ nm, $t_{\text{slab}} = 130$ nm, and $t_{\text{buffer}} = 2410$ nm, and the TDWA switch is designed for transverse-electric (TE) polarization. The dispersion of dielectric permittivity of a SLG is used based on the closed formula of Eq. (1). For the dielectric layers, constant refractive indices are used; $n_{\text{HfO}_2} = 2.07$, $n_{\text{SiO}_2} = 1.45$, and $n_{\text{Si}} = 3.48$. Unless otherwise mentioned, TE polarized light, which is parallel to the gratings, is incident on the TDWA structure with normal incidence.

First, the optical property of the TDWA structure without a SLG is investigated. The TDWA structure with an asymmetric grating structure can excite one more resonance which are closely but distinctively positioned, and two resonance modes are excited. Two reflectance corresponding to the two resonance wavelengths which are simultaneously induced by the guided-mode
resonance can possess almost same peak reflectance and quality factor by adjusting the structural parameters. Figure 3(a) shows the reflectance and transmittance spectra of the representative TDWA structure for TE and transverse-magnetic (TM) polarized light. For TE polarization, there are two reflectance peaks: \( R_{\text{peak},1} \) at the shorter wavelength of \( \lambda_{R,\text{peak},1} \) in the light-blue box and \( R_{\text{peak},2} \) at the longer wavelength of \( \lambda_{R,\text{peak},2} \) in the light-red box. At the \( \lambda_{R,\text{peak},1} \) of 1527.44 nm and \( \lambda_{R,\text{peak},2} \) of 1549.92 nm, the TDWA structure exhibits simultaneously 100% reflectance with a gap of 22.48 nm between the two peak wavelengths (\( \lambda_{R,p} \)). Outside the two peak regions, the background reflectance is \( \geq 85\% \). For TM polarization, the reflectance and transmittance spectra are similar to those of background of TE polarization. Since there is no resonance within the wavelength range, no resonance absorption occurs for TM polarization. Therefore, only TE polarized light is considered. The TDWA structure is not symmetric along the vertical direction relative to the AGMR structure, but reflectance of 100% for TE polarization can be achieved at the resonance wavelength [45]. Note that the TDWA structure is designed to have such high background reflectance, and leakage rates \( \gamma_{\text{leak},1} \) and \( \gamma_{\text{leak},2} \) of the resonance modes toward outside of the resonance structure can be within a wider range than that of a structure with lower background reflectance [45].

As a consequence, the two \( \gamma_{\text{leaks}} \) can be flexibly tuned to match up with the absorption rates (\( \gamma_{\text{abs}} \)) in a SLG. The phase change of reflection coefficient is shown in the bottom row of Figs. 3(a)–3(c). The phase change is much larger in the light-blue and light-red boxes as compared to the ones outside the box, but with a finite slope. The field profiles (\( \text{Re}[E_y] \)) at \( \lambda_{R,\text{peak},1} \) and \( \lambda_{R,\text{peak},2} \) are shown in Fig. 3(d). Unlike the phase spectrum of TE polarization, there is no large change in phase for TM polarization due to the absence of the resonance. Most of the field is concentrated in the cap and slab region, since the two layers resonantly guide two modes initially excited by the AGMR structure. Outside of the structure, an evanescent field extends out of the

---

[Fig. 3. (a, d) Reflectance/transmittance spectrum (upper graph) and phase spectrum (lower graph) of a representative TDWA structure without a SLG and its field profile (\( \text{Re}[E_y] \)) at two peak wavelengths. (solid line: TE polarization, dotted line: TM polarization). Reflectance/transmittance/absorption spectrum (upper graph) and phase spectrum (lower graph) of the TDWA switch with a SLG and its field profiles at two peaks: (b, e) undoped graphene (0.0 eV) and (c, f) doped with 0.6 eV.]
cap and slab layer. When SLG is transferred to the top of the thin HfO$_2$ layer of the TDWA structure, the evanescent field interacts with the SLG. If $\gamma_{\text{abs}}$s in the SLG and $\gamma_{\text{peak}}$s are almost same, then the critical-coupling condition is close to being met. When the SLG is undoped or not electrically gated ($\mu_c = 0$) there are two absorption peaks: ($A_{\text{peak},1}$) of 96.25% at the shorter wavelength ($\lambda_{A,\text{peak},1}$) of 1527.38 nm and ($A_{\text{peak},2}$) of 96.28% at the longer wavelength ($\lambda_{A,\text{peak},2}$) of 1549.76 nm. The reflectance around two resonance wavelengths abruptly drops close to zero, and the transmittance slightly increases from nearly zero to ~3.7% due to the lossy property of graphene [46]. Since the TDWA switch is not backed with any metallic mirror or DBRs, it is impossible to avoid some light transmission through the TDWA structure. However, since the transmittance is quite low around the two peak wavelengths, the absorption of the TDWA switch is slightly lower than perfect absorption. In addition, the TDWA structure consists of all-dielectric material except the SLG, the absorption is solely by the SLG and any loss due to material is not caused by the constituent dielectric layers. The phase changes abruptly as $\sim \pi$ at two peak wavelengths, since the SLG absorbs light with the near-critical-coupling condition [47]. At two $\lambda_{A,\text{peak}}$s, the field intensity decreases to almost half of that without graphene as shown in Fig. 3(e), but the field profile is almost same. When $\mu_c$ is increased up to 0.6 eV, the reflectance and transmittance spectra shown in Fig. 3(c) become very similar to those of the TDWA structure without graphene. However, the reflectance peaks at $\lambda_{R,\text{peak},1}$ of 1526.83 nm and $\lambda_{R,\text{peak},2}$ of 1549.41 nm are reduced to $R_{\text{peak},1}$ of ~93.81% and $R_{\text{peak},2}$ of ~93.91%, and this is because the SLG absorbs 6.17% and 5.99% respectively due to its imperfect quality. Nevertheless, the reflectance peaks are comparable to aluminium mirrors. On the phase spectrum of the bottom row of Figs. 3(a)–3(c), the trend of phase change around the two peak wavelengths proves that the TDWA switch working in the reflective mode is under the over-coupled condition [47]. The slopes near the two peak wavelengths become relaxed and have a finite slope. Here, the $\tau$ of the SLG is assumed to be 100 fs. If the SLG is an ideal one, then the absorption approaches to zero, and the reflectance and transmittance spectra become those of the TDWA structure without graphene. In the case of the field profile at the two $\lambda_{R,\text{peak}}$s in Fig. 3(f), the overall field profile and the maximum and minimum intensities are almost equivalent to those of the TDWA structure without graphene.

To thoroughly reveal the effect of the $\mu_c$ of graphene on the functionality of the TDWA switch, absorption, reflectance, and phase of reflection coefficient ($\angle r$) are calculated as a function of $\mu_c$ and wavelength. As $\mu_c$ increases continuously from 0.0 eV to 0.6 eV, Fig. 4 shows the TDWA switch with SLG switching performance of each operation mode. Firstly, Fig. 4(a) shows an absorption map of the wavelengths between 1510 nm and 1560 nm. There are two distinct absorption peaks, $A_{\text{peak},1}$ and $A_{\text{peak},2}$, around 1527 nm and 1549 nm, respectively, and the $A_{\text{peak}}$s continue as $\mu_c$ increases up to $\sim$0.365 eV and $\sim$0.355 eV. Since $A_{\text{peak},2}$ is corresponding to the longer peak wavelength (1549 nm) having lower photon energy, it starts decreasing slightly earlier than $A_{\text{peak},1}$ which corresponding to the shorter wavelengths (1527 nm). As $\mu_c$ increases further, $A_{\text{peak},1}$ and $A_{\text{peak},2}$ gradually decrease, with the two $A_{\text{peak}}$s falling below $\sim$6.2% at $\mu_c$ of 0.6 eV. Below $\mu_c$ of 0.4 eV, which is comparable to a half of the photon energy of 1550 nm, the TDWA switch works as a dual-wavelength absorber or photodetector with a minimum absorption of $\geq 90\%$. The dual-wavelength absorber can be turned into off-state by shifting $\mu_c$ of $\geq 0.5$ eV. For absorptive mode operation, the on-state (red line) and off-state (blue line) response spectra are shown in Fig. 4(d) together. For the on-state with $\mu_c$ of 0.0 eV, the two $A_{\text{peak}}$s at $\lambda_{A,\text{peak},1}$ of 1527.38 nm and $\lambda_{A,\text{peak},2}$ of 1549.76 nm are $\sim$96.25% and $\sim$96.28% respectively. When it is set as off-state with $\mu_c$ of 0.6 eV, the two $A_{\text{peak}}$s at 1526.76 nm and 1549.16 nm are 6.18% and 6.20%, respectively.

The reflectance map of the same TDWA switch is shown in Fig. 4(b). Below $\mu_c$ of 0.4 eV, two reflectance dips at 1527.38 nm and 1549.74 nm drop down to $\sim$0.01% and $\sim$0.03%, respectively. In between 0.4 and 0.5 eV, the reflectance starts increasing and above 0.5 eV, two $R_{\text{peak}}$s at
Fig. 4. (a) Absorption, (b) reflectance, (c) phase of reflection coefficient map as a function of $\mu_c$ and wavelength. The dotted line at $\mu_c$ of 0.5 eV indicates the boundary of on/off-state of the TDWA switch under each operation mode. (d, e) Response spectra of the TDWA switch depending on the operation mode and its state. (absorptive mode (on-state: 0.0 eV / off-state: 0.6 eV) and reflective mode (on-state: 0.6 eV / off-state: 0.6 eV)) (f) Phase spectra of the reflection coefficient at $\mu_c$ of 0.0 eV and 0.6 eV.

1526.83 nm and 1549.41 nm reach $\sim$93.81% and $\sim$93.91%, respectively. Note that the $\lambda_{A, \text{peak}}$s and $\lambda_{R, \text{peak}}$s are slightly different, since the TDWA structure is in a near-critical-coupling condition not the exact critical-coupling condition. The reflectance spectra at $\mu_c$ of 0.0 and 0.6 eV are shown in Fig. 4(e). At $\mu_c$ of 0.6 eV, the reflective mode of TDWA switch is set in the on-state. If no gate voltage is applied to the SLG-Si cladding, the reflectance at $\lambda_{R, \text{peak}}$s decreases to $\sim$2.69% and $\sim$1.19% due to absorption by the SLG layer. Therefore, the TDWA switch functions as a dual-wavelength absorber or a dual-wavelength mirror, with the option of alternating between the two by changing the $\mu_c$ from 0.0 eV to 0.6 eV. In order to evaluate the on-off performance of the TDWA switch as shown in Figs. 4(d), 4(e), two figures of merits (FOMs) are defined for the absorptive and reflective mode. For the absorptive mode, the FOM$_{abs}$ is defined as $A_{\text{on}}/\max(A_{\text{off}})$ and for the reflective mode, the FOM$_{ref}$ is defined as $10\times \log(R_{\text{on}}/R_{\text{off}})$. At $\lambda_{A, \text{peak1}}$ and $\lambda_{A, \text{peak2}}$, FOM$_{abs}$s are both $\sim$15.52 and the peaks are distinctively separated. The depth between the two peaks and the valley in-between is $\sim$13.7 in terms of FOM$_{abs}$. At the two $\lambda_{R, \text{peak}}$s, FOM$_{ref}$s are 15.56 dB and 18.95 dB. The maximum FOM$_{ref}$s are obtained at the shorter wavelength of 1527.38 nm with $\sim$39.98 dB switching ratio and at the longer wavelength of 1549.75 nm with $\sim$34.55 dB switching ratio. Last, the phase map of the reflection coefficient as a function of $\mu_c$ and wavelength is shown in Fig. 4(c). Around $\lambda_{R, \text{peak}}$, when the $\mu_c$ is below $\sim$0.35 eV, the phase abruptly shifts. The phase change is $\sim \pi$, which indicates that the quasi-critical-coupling condition is satisfied. As $\mu_c$ increases above 0.365 eV for the shorter resonance wavelength and $\sim$0.355 eV for the longer resonance wavelength, the phase change is smoother, as the absorption of the SLG is suppressed, and the $\gamma_{\text{leak}}$s of the resonance modes and $\gamma_{\text{abs}}$s at the two resonance wavelengths are further deviated. At the two resonances, $\gamma_{\text{leak}}$s are larger than $\gamma_{\text{abs}}$s, and the
TDWA switch system is under over-coupled condition [47]. Figure 4(f), which shows the phase spectra at $\mu_c$ of 0.0 eV and 0.6 eV and reflects the distinct difference in phase change around the two resonance wavelengths. At $\mu_c$ of 0.0 eV, the phase change is quite abrupt, which indicates the quasi-critical-coupling condition. At $\mu_c$ of 0.6 eV, however, the phase change is gradual, which shows the over-coupled condition.

Next, the effect of changing AGMR parameters on the distance of two peak wavelengths and on its peak response of a TDWA switch are investigated. Two main grating parameters of $\Lambda$ and $F_1$ are selected. Firstly, when $\Lambda$ is varying, each ratio of grating bars ($F_1/F_2$) is kept constant. Secondly, when $F_1$ is variable, both $\Lambda_1$ and $\Lambda_2$ are not changed. The other parameters except the variable are the same as the representative TDWA structure. The absorption and reflectance map as a function of $\Lambda$ and wavelength are shown in Figs. 5(a), 5(c) with their corresponding on-state. As $\Lambda$ increases from 875 nm to 925 nm, the two bands for $A_{\text{peak}}$ and $R_{\text{peak}}$ are linearly redshifted together. With respect to absorption in Fig. 5(a), $\lambda_{A,\text{peak}} - \lambda_{p,\text{peak}}$ is almost constant as $\sim 22$ nm, and two $A_{\text{peak}}$s are kept as high as $\sim 96\%$. The shorter wavelength band is redshifted with the slope ($\Delta \lambda_{\text{peak}}/\Delta \lambda$) of 0.80 nm/nm as $\Lambda$ increases. For the longer wavelength band, it shifts with the slope of 0.78 nm/nm. With respect to reflective mode, as shown in Fig. 5(c), two $\lambda_{R,\text{peak}}$s shift linearly, with almost the same slope as was apparent in absorptive mode. $\lambda_{R,\text{peak}}$ is $\sim 22$ nm, and $R_{\text{peak}}$s are $\geq 93\%$. As a result, by changing $\Lambda$ of the AGMR structure, the $\lambda_{p,\text{peak}}$ of the absorptive and reflective response of the TDWA switch is easily tuned, while keeping two peak responses for each operation mode. Note that it covers the whole $C$-band wavelength region simply by changing $\Lambda$. In contrast to $\Lambda$, when $F_1$ increases from 0.2 to 0.6, the absorption map shows the nonlinear property of the progress of $\lambda_{A,\text{peak}}$ [as shown in Fig. 5(b)]. At $F_1$ of 0.306, Fig. 5(b) shows the widest $\lambda_{A,\text{peak}}$ of 28 nm, with $\lambda_{A,\text{peak}1}$ of 1514 nm and $\lambda_{A,\text{peak}2}$ of 1542 nm, and two associated $A_{\text{peak}}$s of 96.09% and 94.46%, respectively. At $F_1$ of 0.453, $\lambda_{A,\text{peak}}$ is reduced to the minimum of 17 nm, and the two $A_{\text{peak}}$s are 95.79% at 1536 nm and 95.00% and 1553 nm. For the branch of the longer-wavelength peak, its absorption starts to drop below 90.00% when $F_1$ becomes larger than 0.498. This is because all parameters other than $F_1$ are kept constant, and it is not optimum parametric set to achieve the near-critical coupling condition and hence the absorption drops. When the TDWA switch operates as reflective mode, $\lambda_{R,\text{peak}}$ shows the same nonlinear property as shown in Fig. 5(d). At $F_1$ of 0.306, it shows $R_{\text{peak}1}$ of 95.13% at $\lambda_{R,\text{peak}1}$ of 1513 nm and $R_{\text{peak}2}$ of 94.35% at $\lambda_{R,\text{peak}2}$ of 1541 nm. At $F_1$ of 0.453, it shows $R_{\text{peak}1}$ of 93.7% at $\lambda_{R,\text{peak}1}$ of 1536 nm and $R_{\text{peak}2}$ of 92.91% at $\lambda_{R,\text{peak}2}$ of 1553 nm. When $F_1$ becomes larger than 0.51, $\lambda_{R,\text{peak}}$ starts to drop below 90%. By changing $F_1$, $\lambda_{p,\text{peak}}$ is nonlinearly tuned, while the two distinctive two peaks are preserved. Changing $\Lambda$ and $F_1$ has little effect on the background absorption and reflectance when they are adjusted around their optimum values. Changing these values, however, does affect the two resonance wavelengths, and by extension the coupling condition or absorption efficiency. Consequently, $\lambda_{p,\text{peak}}$ is tunable by adjusting $F_1$, and $\lambda_{\text{peak}}$s are linearly shifted by controlling the $\Delta \lambda$.

In order to understand the effect of the other structural parameters of homogeneous layers on TDWA switch performance, the thickness of cap ($t_{\text{cap}}$) and buffer ($t_{\text{buffer}}$) layers are varied, and subsequent absorption and reflectance maps are analysed. Figure 6 shows the absorption and reflectance map as a function of the thickness of each homogeneous layer and wavelength when each operation mode is on-state. The other homogeneous layers are not considered. The thin oxide layer below a SLG exists to obtain high quality graphene and high-$\kappa$ dielectric. The thickness of this layer will be determined on the basis of the electrical properties of graphene/oxide/cladding capacitor structure that is desired. With respect to the slab layer, its thickness will be determined by that of the grating on the Si device layer of a SOI platform. Moreover, it is impossible to change the slab thickness using post processing, as the remaining homogeneous layer below the grating becomes a slab layer after fabricating the grating on a fixed-thick Si layer. Figure 6(a) shows the effect of $t_{\text{cap}}$ on absorption. As $t_{\text{cap}}$ increases from 65 nm to 75 nm, two $A_{\text{peak}}$s are...
linearly redshifted. The $A_{\text{peak}}$s are $\geq 95\%$ within the simulation domain. The slope of the $\lambda_{\text{peak}}$s ($\Delta \lambda_{\text{peak}} / \Delta \lambda_{\text{cap}}$) are 3.6 nm/nm and 3.2 nm/nm, respectively, with $\lambda_{\text{peak}1}$ shifting slightly faster than $\lambda_{\text{peak}2}$. At $t_{\text{cap}}$ of 65 nm, $\lambda_{\text{peak2}}$ is 25 nm. As $t_{\text{cap}}$ increases to 75 nm, $\lambda_{\text{peak}2}$ slightly decreases to 21 nm. As shown in Fig. 6(c), the reflectance map shows the same slope of the peak wavelength shift as shown in the absorption map. $R_{\text{peak}}$s are more than $\sim 95\%$, and the background reflectance near the two resonance wavelengths is as high as $\geq 85\%$. We conclude that the thickness of the cap layer significantly influences on the two $\lambda_{\text{peak}}$s regardless of the operation mode of the TDWA switch. Next, the effect of the buffer (or BOX) layer which separates the TDWA structure and the bottom high-refractive-index Si substrate is considered. The thick low-refractive-index BOX layer sandwiched by the TDWA and the Si substrate induces a weak Fabry-Perot (FP) resonance. Figures 6(b) and 6(d) show the effect of $t_{\text{buffer}}$ on absorption and reflectance. From Fig. 6(b), it is clear that $A_{\text{peak}}$s change from the minimum of $\sim 81\%$ to the maximum of $\sim 96\%$ as $t_{\text{buffer}}$ increases due to the interaction between the weaker FP resonance and the stronger TDWA resonance, but $\lambda_{\text{peak}}$s are kept at $\sim 1527$ nm and at $\sim 1550$ nm, respectively. The position of two absorption dips or peaks are slightly shifted vertically at the two branches, since the weak FP resonance is excited at different BOX thicknesses. Two $R_{\text{peak}}$s are more than $93\%$, as shown in Fig. 6(d). As $t_{\text{buffer}}$ increases, the buffer layer induces a weak FP effect and appears in the background as a ripple pattern. In addition, the line-width of the two reflectance bands are shrunk and expanded depending on $t_{\text{buffer}}$, but with almost constant $R_{\text{peak}}$s and $\lambda_{\text{R_peak}}$s, as the external weak FP cavity interacts with the TDWA resonance structure, changing $\gamma_{\text{peak}}$s at two resonance wavelengths. When the BOX thickness is deviated from the FP resonance condition, the linewidth of the reflectance spectra becomes narrower. When $t_{\text{buffer}}$ satisfies the FP
resonance condition, the linewidth becomes broader for the current TDWA structure. Clearly, the FP resonance interacts with the TDWA resonance and changes the quality of the overall cavity structure. Comparing Fig. 6(b) and 6(d), it is clear that when the FP resonance peak and the TDWA resonance peak are crossed, \( A_{\text{peak}} \) reaches its maximum. This is because \( \gamma_{\text{peak}} \)s become similar to \( \gamma_{\text{abs}} \)s in the SLG. However, if the quality factor of the TDWA structure increases, \( \gamma_{\text{peak}} \)s are decreased, exacerbating the difference from \( \gamma_{\text{abs}} \)s, and resulting in decreased absorption at the two peaks. Therefore, \( t_{\text{buffer}} \) should be considered carefully to achieve high absorption. Note that the cap layer as a part of the TDWA structure changes the resonance wavelength, but the BOX layer, which excites the external weak resonance while keeps the \( \lambda_{\text{peak}} \)s. Instead, changes the absorption efficiency.

**Fig. 6.** Absorption and reflectance maps as a function of wavelength and a thickness of one of the following homogeneous layers: (a, c) the cap layer and (b, d) the buffer (BOX) layer.

Finally, to study the additional tunability of \( \lambda_{\text{p-p}} \), the angle-dependent absorption and reflectance of the representative TDWA switch are investigated. For the angle-dependent reflectance, only 0\(^{th}\) diffraction order is counted. Figure 7(a) shows the angle-dependent absorption when it is on-state. As the incidence angle increases, the two \( A_{\text{peak}} \)s diverge oppositely. When the incidence angle increases from 0° to 5.3°, \( \lambda_{\text{A,p-p}} \) is widened from \( \sim 22 \text{ nm} \) to \( \sim 77 \text{ nm} \) within the wavelength range. The peak absorption of the two branches below the incident angle of 5.3° is \( \geq 96\% \) for the shorter-wavelength branch and \( \geq 95\% \) for the longer-wavelength branch, respectively. As shown in Fig. 7(b), \( \lambda_{\text{R,p-p}} \) varies from \( \sim 22 \text{ nm} \) to \( \sim 77 \text{ nm} \), and \( R_{\text{peak,1}} \) and \( R_{\text{peak,2}} \) of two branches are \( \geq 93.8\% \) and \( \geq 93.6\% \), respectively. Incidence angle, therefore, has additional potential to mechanically tune \( \lambda_{\text{p-p}} \), while preserving ideal \( A_{\text{peak}} \)s or \( R_{\text{peak}} \)s, by inclining the angle of light relative to the TDWA structure.
4. Conclusion

In conclusion, we proposed and analysed a TDWA switch based on an AGMR structure using single-layer graphene. The TDWA switch operates as an absorber or a reflector at two wavelengths by tuning the chemical potential of graphene. The dual-wavelength resonance has been achieved by adding an additional small grating unit cell to a larger one. By tailoring structural parameters, the TDWA switch has been optimized to achieve a near-critical-coupling condition and a high-reflective condition simultaneously at two resonance wavelengths. The distance of two peak wavelengths $\lambda_{p-p}$ was tuned by changing $F_1$, and the two peak wavelengths were redshifted by increasing the period of the AGMR and the thickness of the cap layer. A thick BOX layer excited a FP resonance that it interacted with the TDWA structure. As a result, modulation of peak absorption and linewidth of reflectance spectrum were observed, while the two peak wavelengths were almost unchanged. When the incident angle of light was increased from $0.0^\circ$ to $5.3^\circ$, $\lambda_{p-p}$ increased from 23 nm to 78 nm while high absorption and reflectance peaks were maintained. Accordingly, this TDWA structure would be useful for graphene-based dual-wavelength NIR image sensors and dual-wavelength on-off optical mirrors.

Funding. Gyeonggi-do; National Research Foundation of Korea (NRF-2020R1F1A1070471).

Acknowledgments. This work was supported by System Semiconductor Development Program funded by Gyeonggi-do. The authors also would like to acknowledge support from National Research Foundation of Korea (NRF) under a grant funded by the Korea government (MSIT) (NRF-2020R1F1A1070471).

Disclosures. The authors declare no conflicts of interest.

References


