

Thermo-Optical Modulator Based on VO₂ and Graphene Plasmonics

Sareh Vatani , Vahid Faramarzi , and Jeongwon Park , *Senior Member, IEEE*

Abstract—This paper details the design and theoretical analysis of a novel thermo-optical modulator that leverages the unique phase transition characteristics of vanadium dioxide (VO₂) and the plasmonic properties of graphene. Employing a combination of transmission and reflection mode structures, the study explores four configurations designed to optimize modulation depth and minimize insertion loss. The analysis conducted using COMSOL Multiphysics with the finite element method (FEM) highlights the significant influence of geometrical parameters on the modulator's performance. The specific attention to the interaction between VO₂'s phase transition at critical temperatures and graphene's conductivity adjustment provides insights into the dynamic control of optical signals in the mid-infrared spectrum.

Index Terms—Graphene optical conductivity, modulation depth, surface plasmon resonance (SPR), thermo-optical effect, vanadium dioxide (VO₂).

I. INTRODUCTION

THERMO-OPTICAL (TO) modulators are crucial in modern photonics, offering dynamic control over manipulating light signals [1]. By exploiting the relationship between temperature-induced phase transitions and optical properties, TO modulators facilitate precise modulation of light signals across various spectral ranges [2].

Electro-optic and All-optical modulators offer high modulation speed. Still, they are challenged by low modulation efficiency and considerable size. In contrast, TO modulators and switches present a balanced combination of moderate speed, compactness, and minimal loss, enabling seamless large-scale photonic integration [3]. The convergence of phase-changing materials and innovative modulation techniques has propelled modulators to the forefront of optical device engineering, promising unparalleled versatility and performance in diverse applications [4], [5], [6], [7], [8]

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Sareh Vatani and Jeongwon Park are with the Electrical and Biomedical Engineering Department, University of Nevada, Reno, NV 89557 USA (e-mail: svatani@unr.edu; jepark@unr.edu).

Vahid Faramarzi is with the Department of BioNano Technology, Gachon University, Seongnam 13120, South Korea (e-mail: vahid.fra@gmail.com).

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Graphene plasmons (GPs) can confine electromagnetic fields to very small spatial regions, resulting in shorter wavelengths than incident photons. This property opens up exciting possibilities for manipulating light on the nanoscale and developing advanced photonic devices across various frequency ranges. The mid-IR range is particularly relevant for such applications because it includes the vibrational absorption frequencies of many materials, which are useful for enhancing device performance [9].

Despite their potential, incorporating GPs into practical devices such as thermo-optical modulators remains challenging due to the significant momentum mismatch between GPs and incident photons. To bridge this gap, conventional optical coupling methods, including prisms, gratings, and waveguide couplers, are necessary to convert incident light into propagating GPs. Overcoming this obstacle is crucial for leveraging the benefits of GPs in thermo-optical modulation and other integrated photonic applications [10].

At the heart of TO modulation lies the intricate interplay between temperature-sensitive materials and their response to external stimuli [11]. Among these materials, Vanadium dioxide (VO₂) emerges as a prominent candidate, boasting remarkable thermochromic properties and a characteristic phase transition near 68°C [12]. Below this critical temperature, VO₂ assumes a diamagnetic insulator state characterized by a monoclinic structure. However, surpassing the phase transition threshold transforms VO₂ into a paramagnetic metal, adopting a tetragonal configuration [13]. Such dynamic structural transitions underpin the fundamental principles driving TO modulation, offering a robust platform for tailored light manipulation.

The mid-infrared (mid-IR) wavelength spectrum, ranging from 2 μm to 20 μm , emerges as a fertile domain for exploring the capabilities inherent in TO modulators [14]. VO₂ exhibits notable variations in its optical characteristics within this spectral range, eliciting significant shifts in emission profiles within wavelengths from 5 μm to 13 μm [15]. These inherent optical properties of VO₂ serve as a cornerstone for TO modulation, facilitating precise control over light propagation and modulation. As a result, TO modulators offer a versatile toolkit with broad applications in smart windows [16], [17], sensing [18], [19], and optical signal processing [20], [21]. The advancement of phase-change materials, coupled with novel modulation techniques, has propelled TO modulation into new realms of possibility.

In this paper, our focus lies on employing graphene as a plasmonic material for designing a plasmonic TO modulator, and the advancement of phase-change materials, coupled with

novel modulation techniques, has propelled TO modulation into new realms of possibility. Here, VO₂ assumes significance as the active element, where the transition in temperature below and above the critical temperature induces the OFF and ON states of the modulator. Our theoretical exploration delves into four distinct structures, comprising two transmission modes and two reflection mode configurations. Furthermore, we delve into the impact of various geometrical parameters in the design process. We aim to compare the modulation depth and insertion loss across these structures through a comprehensive analysis to understand their effectiveness and practical usability.

II. METHOD

An optical modulator serves as a tool for adjusting or modulating the fundamental attributes of a light beam as it propagates through free space or within an optical waveguide. These devices can manipulate diverse parameters of the light beam, thereby classifying them as amplitude, phase, or polarization modulators [22]. Optical modulators are subject to characterization based on figure-of-merits, including modulation speed, depth, operation wavelength range, energy consumption, and insertion loss. Modulation speed, a critical parameter, is typically defined as the frequency at which modulation reduces to half its maximum value. The modulation depth, often assessed via the extinction ratio (ER), represents the ratio between maximum and minimum transmittance or reflectance, usually expressed in decibels (dB) for engineering simplicity and calculated as $10 \times \log(T_{\max}/T_{\min})$ or $10 \times \log(R_{\max}/R_{\min})$. High modulation depth (>7 dB) is favored in high data-rate interconnects and high-sensitivity sensing applications. For future energy-efficient optical modulators, the targeted energy consumption is estimated to be around a few femtojoules per bit. Insertion loss, which measures the losses experienced by the light wave in the high-transmission state, should be minimized to enhance the system energy efficiency, typically quantified as the difference between input and output power levels. Thus, considering these parameters and their respective formulas is the basis for evaluating and optimizing optical modulator performance across various applications [23], [24].

We conducted comprehensive optical simulations employing COMSOL Multiphysics, utilizing the finite element method (FEM) to explore the transmission and reflection spectra of two-dimensional (2D) material structures. The Electromagnetic wave module incorporated periodic boundary conditions. The effectiveness and efficiency of the 2D surface conductivity model were demonstrated in simulating graphene-based devices [25]. In our numerical simulations, the graphene layer was included. The thin film Graphene layer thickness is 0.34 nm. The surface conductivity of graphene σ_{Gr} , which directly influences its physical properties, can be mathematically described using the Kubo formula [26] as follows:

$$\sigma_{Gr} = \sigma_{intra}(\omega, \mu_c, \Gamma, T) + \sigma_{inter}(\omega, \mu_c, \Gamma, T) \quad (1)$$

Equation (1), the surface conductivity of graphene is composed of the interband conductivity, denoted as $\sigma_{inter}(\omega, \mu_c, \Gamma, T)$, and the intraband conductivity, denoted as σ_{intra}

$(\omega, \mu_c, \Gamma, T)$. At room temperature and low terahertz frequencies, the Pauli repulsion principle suggests that the σ_{inter} can be considered negligible [27]. Consequently, the surface conductivity of graphene is predominantly influenced by the σ_{intra} .

$$\sigma_{Gr} = (2e) / (\pi \hbar) k_B T_k \times \ln [2 \times \cosh(\mu_c / (2k_B T_k))] / (\omega + i\tau_{Gr}) \quad (2)$$

where ω is the angular frequency, μ_c is the Fermi level, $\tau = \mu\mu_c / ev_f^2$ is the relaxation time, and the electron mobility is $\mu = 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, T represents the prevailing temperature conditions, typically set at 300 K for ambient temperature, $\hbar$, k_B , e are the reduced Planck constant $\hbar = \hbar/2\pi$, the Boltzmann constant, and the electron charge in (2), respectively [28]. Practically, the Fermi level modulation in graphene can be accomplished through chemical doping or manipulating the applied bias voltage. The correlation between the Fermi level of graphene and the external bias voltage is described as $\mu_c = \hbar v_f \sqrt{\pi a_0 V_{bias}}$ where $v_f = 10^6 \text{ ms}^{-1}$ is the Fermi velocity, a_0 is a constant, V_{bias} is the bias voltage [28], [29]. Early investigations into graphene revealed that it is possible to modulate its electronic properties by introducing charge carriers through alternative methods to electrostatic gating, specifically by adsorbing different gases such as NH₃, H₂O, and NO₂ onto the material [30]. Additionally, the effective dielectric constant of the graphene layer can be described using the Drude model, $\varepsilon = \varepsilon_b + i\sigma_{Gr} / \varepsilon_0 \omega \Delta$ where ε_b is the average permittivity of the material surrounding the graphene layer and Δ is the graphene thickness. This model allows us to understand how the graphene's conductivity and effective dielectric constant can be adjusted by altering its chemical potential. Such adjustments provide a versatile framework for tailoring graphene's optical and electrical properties to suit various applications [31].

Expanding upon our exploration of conductivity and optical properties in graphene, we delve into the properties of VO₂, a material distinguished by its unique phase transition attributes. Integrating a VO₂ layer is a critical component in our numerical simulations, complementing the graphene layer and broadening the scope of our study. Subjected to thermal [32], optical [33], or electrical [34] triggers, monophase VO₂ transitions from a relatively transparent insulating state with a monoclinic crystal structure to an alternative metallic phase. Up to now, researchers have showcased free-space optical modulators based on VO₂ at both infrared [35] and visible [36] wavelengths, utilizing local heating to trigger the VO₂ phase transition. When the temperature falls below the phase change threshold, this condition is called the insulating state of VO₂. The complex dielectric function in this state is derived using the Drude-Lorentz model and is elucidated by the following [37]. In the insulating phase, the complex dielectric function of VO₂ is parameterized using a Lorentz model, encapsulated within the first three terms of (3). This formula, rooted in the classical theory of light-matter interaction, is employed to elucidate the frequency-dependent polarization arising from bound charges. The variable ω represents frequency, the constant ε_∞ denotes the high-frequency dielectric constant, ε_s stands for the static dielectric function at

zero frequency, and $(\varepsilon_s - \varepsilon_\infty)$ signifies the strength of the single Lorentz oscillator.

Additionally, Γ_0 (eV) serves as each oscillator's broadening or damping factor, reflecting the damping effect associated with absorption processes during transitions between two states. The parameter ω_t (eV) designates the resonant frequency of the oscillator, aligning with the energy of the absorption peak. The term f_j ($j = 1, 2, \dots, n$) corresponds to the oscillator strength in the expression of multiple Lorentz oscillators. Similarly, ω_{0j} (eV) ($j = 1, 2, \dots, n$) represents the resonant (peak) energy of an oscillator in a collection of several Lorentzian oscillators, and γ_j (eV) ($j = 1, 2, \dots, n$) characterizes the broadening parameter to the peak energy of each oscillator [37].

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty) \cdot \omega_t^2}{\omega_t^2 - \omega^2 + i\Gamma_0 \cdot \omega} + \sum_{j=1}^n \frac{f_j \cdot \omega_{0j}^2}{\omega_{0j}^2 - \omega^2 + i\gamma_j \cdot \omega} + \frac{\omega_p^2}{-\omega^2 + i\Gamma_d \cdot \omega} \quad (3)$$

In the metallic phase of VO₂, an additional term corresponding to the Drude model is incorporated into the dielectric function. This augmentation accounts for VO₂ exhibiting Drude metal behavior with strong absorption characteristics.

III. RESULTS AND DISCUSSIONS

The real and imaginary components of VO₂'s metal and insulator phases are illustrated in Fig. 1. In Fig. 1(a), the real part of VO₂'s phases is depicted, highlighting variations in conductivity, refractive index, and other optical attributes across the metal-insulator transition. Meanwhile, Fig. 1(b) presents the imaginary part, which provides insights into absorption coefficients, extinction coefficients, and related optical phenomena associated with VO₂'s metal and insulator states. These visual representations are derived from the mathematical model outlined in (3) and parameterized using data in Table S1 of the supplementary materials. By examining Fig. 1(a) and (b), we understand how VO₂ behaves optically as it transitions between its metal and insulator phases.

In this investigation, we explore the operational dynamics of thermoelectric optical modulators utilizing VO₂ as the active element. The modulation mechanism relies on the distinctive transition of VO₂ from an insulating phase to a metallic state near its critical temperature. Applying this phase transition, we engineered four unique structures: two operating in reflection mode and two in transmission mode, each offering distinct optical behaviors. We are examining two structures, both adopting the properties of surface plasmon waves in graphene.

The first structure utilizes a grating configuration as an optical element, effectively transforming incoming light into surface plasmon waves on graphene through guided wave resonance within a silicon grating structure.

This mechanism operates based on the optical diffraction theory [38], where the grating compensates for the discrepancy between the wavevectors of the incoming light and the graphene plasmons, thereby stimulating the plasmons [39].

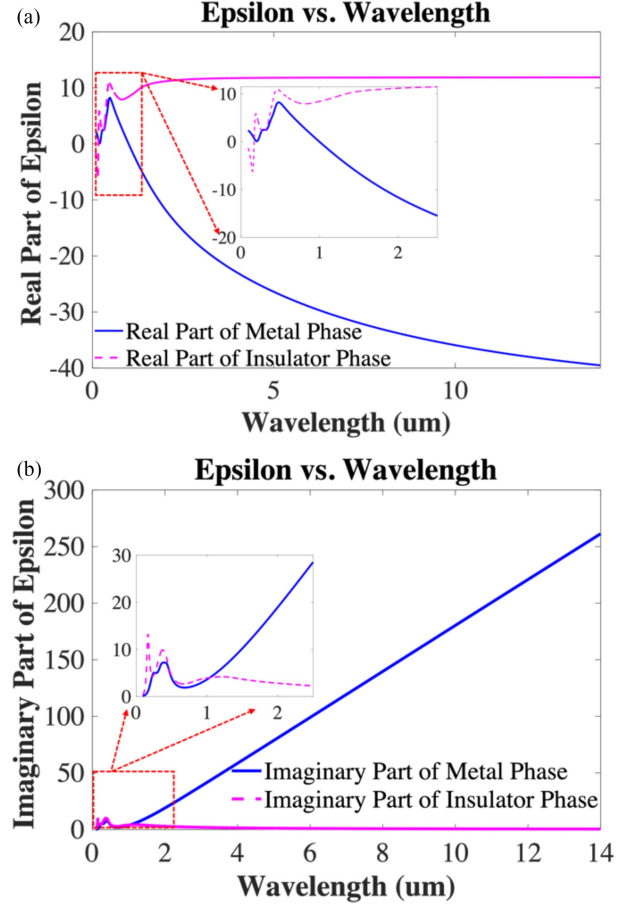


Fig. 1. Optical properties of VO₂ across the metal-insulator transition. (a) Real part and (b) Imaginary part.

In the second structure, involving graphene nanoribbons—predominantly patterned at the nano-scale—the movement of electrons, which are the free charge carriers, becomes constrained, forming what is termed 'bound electrons.' These confined electrons generate resonant oscillatory modes, primarily occurring at the nanoribbon edges, and are excited by perpendicular radiation to the structure [40], [41]. This configuration allows for exploring unique plasmonic behaviors and interactions within the nanostructured graphene, offering potential advancements in nanophotonic applications. During our simulation, the graphene conductivity values, calculated according to (2) with $\mu_c = 0.64$ eV, are imported into its material properties, thus enabling the setting of the graphene material. This approach, utilizing graphene plasmons known for their rapid tunability due to the high carrier mobility and collective oscillations, allows its application as a high-speed optical modulator across a broad spectrum from infrared to terahertz frequencies. Additionally, this capability extends its use as an optical filter or switch, showcasing the versatility and potential of graphene-based plasmonic devices in advanced photonic systems.

A. Transmission Mode

We utilized FEM to calculate theoretical transmission spectra. We must acquire the transmission spectra outlined in the Method

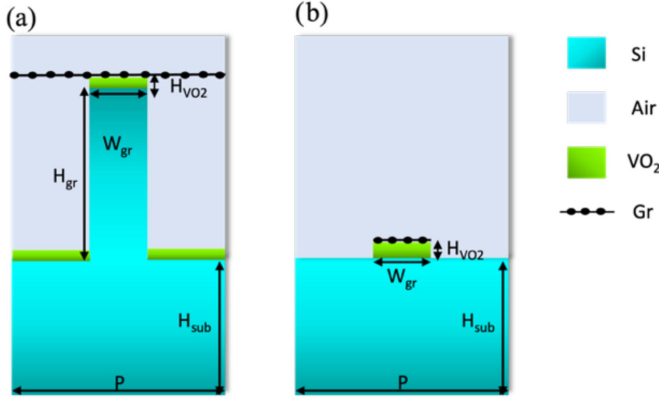


Fig. 2. (a) The schematic unit cell of the grating structure in the transmission mode. (b) The schematic unit cell of the nanoribbon structure in the transmission mode.

section to determine modulation depth and insertion loss. A higher difference between transmission in OFF and ON states yields greater modulation depth. Our primary objective is to provide a design with minimal transmission at the plasmonic wavelength. This approach enables efficient modulation with moderate or low insertion loss. The First structure's unit cell, comprising a silicon substrate with an embedded silicon grating, a VO₂ thin film, and a graphene layer Fig. 2(a), underscores the interplay of geometric parameters in defining optical performance. It includes a silicon substrate with a thickness of $H_{\text{sub}} = 200$ nm, a grating with dimensions $W_{\text{gr}} = 60$ nm and $H_{\text{gr}} = 300$ nm, and the pitch of the unit cell is denoted as $P = 100$ nm. Upon TM light illuminating the graphene layer, plasmons are excited, inducing a discernible dip in the transmission spectrum, as illustrated in Fig. 3. However, as the ambient temperature surpasses the critical threshold, a phase transition in VO₂ occurs, leading to the emergence of metallic behavior.

Consequently, plasmonic behavior diminishes, as evidenced by the absence of characteristic dips at specific wavelengths in the mid-infrared spectrum. By systematically varying parameters such as W_{gr} , H_{gr} , and P , we optimized the structure's optical response. Notably, the grating design profoundly influenced modulation characteristics, with changes in grating dimensions yielding discernible shifts in transmission spectra.

To assess the structure's robustness against fabrication errors, we analyzed variations in geometric parameters and their impact on transmission spectra, modulation depth, and insertion loss. Fig. 3 illustrates transmission spectra obtained by varying the grating width from 40 to 90 nm. As the width of the grating increases by 10 nm, a notable observation is the deepening of the dip in the transmission spectra until 70 nm. Additionally, this dip undergoes a wavelength shift towards longer wavelengths. The correlation between the width of the grating and the characteristics of the transmission spectra, particularly the increasing depth and wavelength shift of the dip, suggests a significant impact of the grating parameters on the optical properties, providing valuable insights into the behavior of light transmission in this structure. The transmission spectra analysis reveals an intriguing trend in the wavelength shift as the grating width varies.

Specifically, the analysis of the transmission spectra indicates that as the grating width ($T_{W_{\text{gr}}}$) increases, there is a notable trend in both the wavelength shift and the depth of the transmission troughs. For grating widths ranging from 40 nm to 70 nm, the depth of the transmission minimum, which represents the strongest light absorption, becomes more pronounced (i.e., the transmission value decreases, indicating less light is transmitted). Beyond a grating width of 70 nm, this trend reverses, and the transmission minimum becomes less deep (i.e., the transmission value increases, indicating more light is transmitted).

A unit cell's effective refractive index (n_{eff}), defined by the filling factor (f), further influences transmission spectra characteristics.

$$n_{\text{eff}} = \sqrt{f \cdot n_{\text{gr}}^2 + (1 - f) \cdot n_{\text{air}}^2} \quad (4)$$

where n_{gr} and n_{air} represent the refractive indices of the grating and the space between the gratings, respectively. The filling factor f is intricately related to the grating parameters and is defined as the ratio of the W_{gr} to the grating period P . According to (4) and the filling factor f , an increase in W_{gr} while keeping P constant leads to an escalation in the filling factor. This heightened filling factor subsequently increases the effective refractive index of the unit cell, consequently causing a redshift in the transmission spectrum [42]. The trend reverses with increasing the width of the grating by more than 70 nm because as f becomes greater, the grating gets closer to the full cover of the surface, and the grating effect will disappear. In the first structure, which has a grating width of 60 nm, the modulation depth reached 6 dB, with an absolute insertion loss value of 2 dB.

In the transmission mode, the unit cell of the second structure in Fig. 2(b) exhibits a silicon substrate thickness H_{sub} of 200 nm and a VO₂ thin film height H_{VO_2} of 1 nm, with a pitch set at 100 nm. Nano ribbons of graphene, serving as the grating, are positioned atop the VO₂ layer. The width of the VO₂ layer matches that of the graphene nanoribbons, ranging from 20 nm to 80 nm with a step of 20 nm. Through systematic variations in the width of the nanoribbons, transmission spectra were obtained for both insulator and metal phases. Notably, as the width of the nanoribbons increases, a discernible shift of the plasmonic dip towards longer wavelengths is observed. For the second structure, featuring a nanoribbon width of 60 nm, the achieved modulation depth is 8.37 dB, alongside an insertion loss of 1.92 dB.

B. Reflection Mode

After exploring the figure-of-merits of the transmission mode, our inquiry now shifts to the reflective properties inherent in the structures under examination. In this subsection, we delve into the Reflection Mode analysis, where we explore the effects of integrating metal mirrors at the terminus of the structures. The Third structure, as depicted in Fig. 5(a), features a gold mirror that effectively impedes light transmission. Comprising a Silicon substrate ($H_{\text{sub}} = 200$ nm), a grating with dimensions $W_{\text{gr}} = 60$ nm and $H_{\text{gr}} = 300$ nm, and a gold layer ($H_{\text{Au}} = 200$ nm), the unit cell's design optimally influences its reflective properties. The pitch of the unit cell, denoted as $p = 100$ nm, plays a pivotal

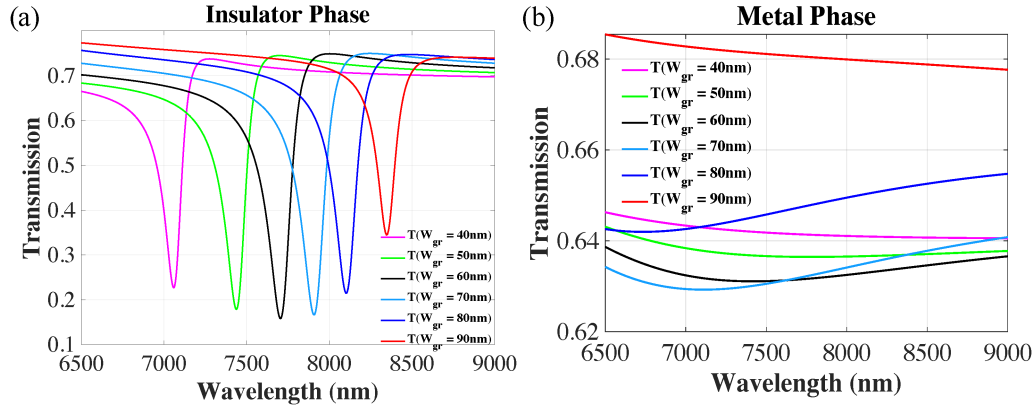


Fig. 3. Dependence of transmission on grating width for (a) insulator phase, (b) metal phase.

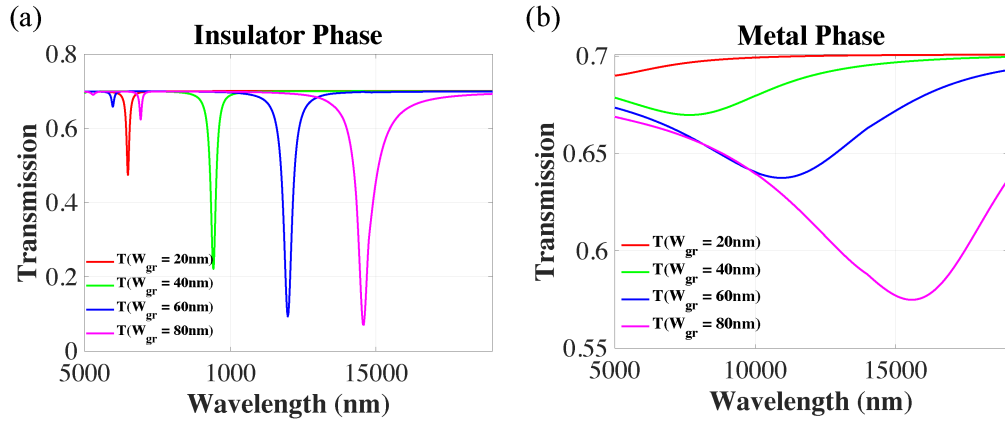


Fig. 4. Dependence of transmission on nanoribbon width for (a) insulator phase, (b) metal phase.

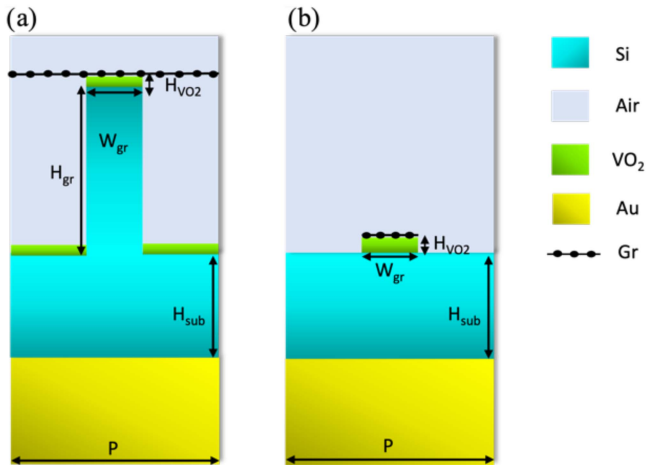


Fig. 5. (a) The schematic unit cell of the grating structure in reflection mode (b) the schematic unit cell of the nanoribbon structure in reflection mode.

role in defining its optical characteristics. Positioned atop the grating and silicon substrate is the VO₂ layer, with a graphene layer overlaying the entire structure. In this structure, as the

transmission is impeded, the reflection spectrum is given by $(\lambda) = 1 - (\lambda)$. Considering the thickness of the bottom gold layer, which exceeds its largest skin depth $\sigma \approx \lambda/2\pi\text{Im}(nAu) \approx 28$ nm at mid-infrared frequencies, the transmittance $T \approx 0$ effectively functions as a mirror [15]. When light is applied to the graphene on top of the grating, plasmons are excited, resulting in a dip in the reflection spectrum of the structure, Fig. 6(a). This dip signifies that light is absorbed to excite plasmonic behavior. Upon elevating the ambient temperature to more than the critical temperature, a phase change in VO₂ occurs, leading to the observation of metallic behavior. As is shown in Fig. 6(b), there is no plasmonic behavior at the specific wavelength in mid-IR.

In our study, we present two significant figures that elucidate the influence of the thickness of VO₂ on the shift of the reflection spectrum, offering crucial insights into the optical behavior of the material. Fig. 7(a) showcases the pronounced impact of VO₂ thickness variation on the reflection spectrum, revealing distinct shifts in spectral features as the thickness of the VO₂ layer is altered. Concurrently, Fig. 7(b), derived from the first, presents a detailed analysis of the dip wavelength and MD and IL in the reflection spectrum against the thickness of the VO₂ layer. Remarkably, our findings indicate a non-linear

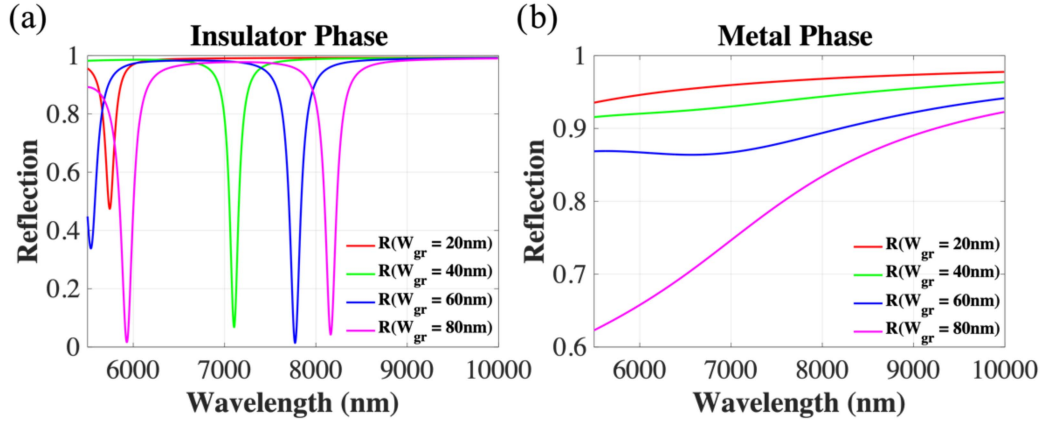


Fig. 6. Dependence of reflection on grating width for (a) insulator phase, (b) metal phase.

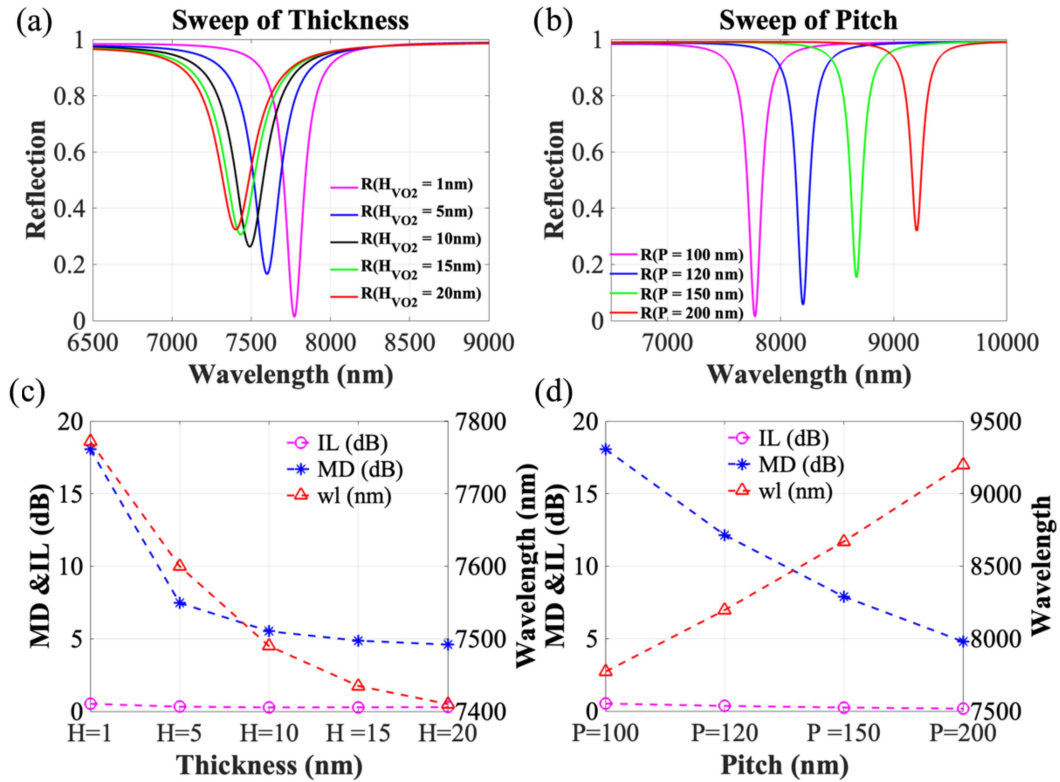


Fig. 7. (a) Dependence of reflection on height of VO_2 , (b) comparison of MD, IL, and wavelength dependency of structure within different VO_2 thicknesses where all other geometrical parameters are constant, (c) dependence of reflection on grating pitch, (d) comparison of MD, IL, and wavelength dependency of structure within different pitch where all other geometrical parameters are constant.

relationship between VO_2 thickness and the observed changes in dip depth, accompanied by a subtle blue shift as the thickness increases. Notably, the most significant dip is observed at a VO_2 thickness of 1 nm, suggesting the critical role of VO_2 thickness in modulating reflection characteristics. These figures offer valuable insights into the intricate optical properties of VO_2 and provide a foundation for further exploration and understanding in the realm of optical metamaterials. For instance, a VO_2 thickness of 1 nm yielded a modulation depth exceeding 18.07 dB, with a nominal insertion loss of 0.52 dB at the corresponding

wavelength. Conversely, a 5 nm VO_2 thickness resulted in an MD of 7.47 dB and IL of 0.32 dB, highlighting the sensitivity of modulation depth to VO_2 thickness variations.

Furthermore, Fig. 7(c) depicts the impact of varying the pitch of the unit cell within the periodic grating structure on the reflection spectrum. The graph displays the reflection intensities across a range of wavelengths, where each curve represents a different pitch from 100 nm to 200 nm. These curves highlight how changes in the pitch significantly alter the position and amplitude of the plasmonic dips, illustrating the direct influence

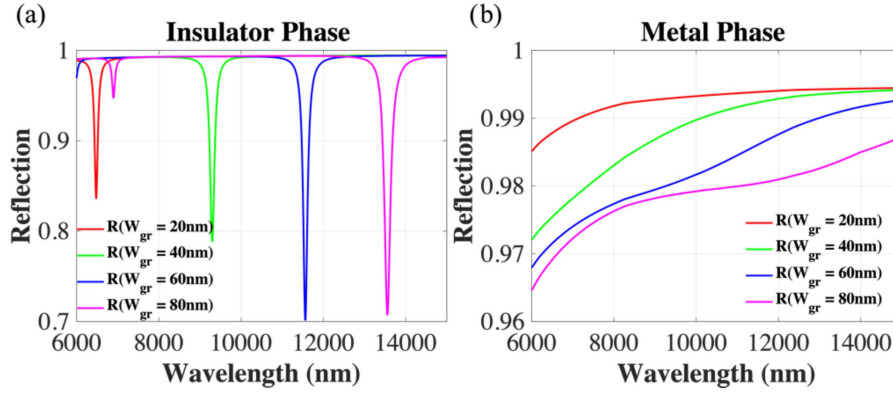


Fig. 8. Dependence of reflection on nanoribbon width for (a) insulator phase, (b) metal phase.

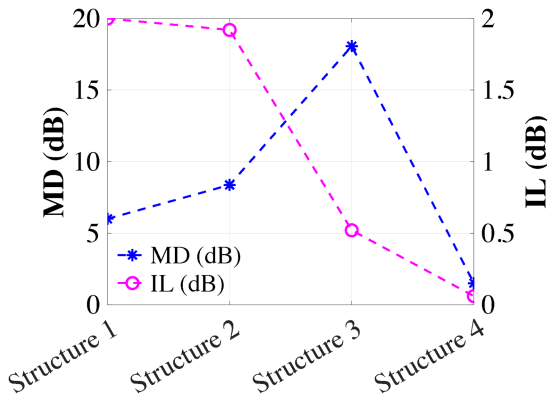


Fig. 9. MD and IL comparison for four different structures in transmission and reflection mode.

of structural periodicity on the optical properties. As the pitch increases, the plasmonic dips exhibit a noticeable shift towards shorter wavelengths, with a corresponding decrease in peak intensity. This demonstrates that adjusting the pitch can finely control the spectral response, optimizing the optical characteristics for specific applications. Similarly, Fig. 7(d), based on the previous figure, provides a comprehensive analysis of the dip wavelength and MD and IL in the reflection mode as a function of the grating pitch.

In reflective mode, the unit cell of the last structure closely resembles that of the second structure in both dimensions and configuration. However, an additional Au substrate is appended to the structure's end as a mirror to reflect incident light. This mirror effectively mitigates reflection losses in transmission mode, enabling the conversion of nearly all input light into output. For instance, in transmission mode, approximately 0.3 incident light is typically lost through reflection, leaving only 0.7 for modulation, as shown in Fig. 8. With the mirror integrated into the structure, the reflected light becomes available for modulation, effectively augmenting the usable light to nearly 1 in the reflection process. It is expected that this strategic addition enhances the efficiency of the structure by minimizing losses and maximizing the modulation capability.

Fig. 9 presents a comparative analysis of the modulation depth (MD) and insertion loss (IL) across four distinct structures, each employing different transmission or reflection mode configurations. Structure 1, which utilizes a grating in transmission mode, notably shows an initial high modulation depth but a moderate insertion loss. In contrast, Structure 2 features nanoribbons in transmission mode and achieves a higher modulation depth and lower insertion loss, demonstrating superior efficiency. Structures 3 and 4, which operate in reflection mode, exhibit a reversal in trends; Structure 3 shows the greatest desirable modulation depth, while Structure 4 offers the lowest insertion loss. This was contrary to expectations, as it did not exhibit a greater modulation depth compared to similar structures without mirrors or those in transmission mode, emphasizing the influence of structural design on optical performance.

IV. CONCLUSION

The findings from this study emphasize the critical role of VO₂'s phase transition and graphene's adjustable electronic properties in enhancing the performance of thermo-optical modulators. The detailed simulation results reveal that strategic manipulation of geometrical configurations, such as grating width and VO₂ thickness, can substantially influence the modulator's efficiency, evidenced by modulation depth and insertion loss variations. Among the configurations tested, the third structure emerged as the most effective, achieving a modulation depth of 18.07 dB, representing a tremendous value and a relatively low insertion loss, making it the best candidate among the four structures evaluated. This superior performance underlines the potential of this design for practical deployment in advanced photonic applications. Future efforts will focus on experimental validation of the theoretical models and further refinement of the designs to enhance their operational parameters and achieve even higher efficiencies in real-world applications.

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