ABSTRACT: Tunable extraordinary optical transmission (EOT) with graphene is realized using a novel metallic ring–rod nested structure in the terahertz frequency regime. The generated double-enhanced transmission peaks primarily originate from the excitation of localized surface plasmon resonances (LSPRs). On using graphene, the resonating surface plasmon distribution changes in the reaction plane, which disturbs the generation of LSPRs. By regulating the Fermi energy ($E_f$) of the graphene to reach a certain level, an adjustment from bimodal EOT to unimodal EOT is obtained. As the $E_f$ of the graphene integrated beneath the rod increases to 0.5 eV, the transmittance of the peak at 2.42 THz decreases to 6%. Moreover, the transmission peak at 1.77 THz virtually disappears due to the $E_f$ increasing to 0.7 eV when the graphene is placed beneath the ring. The significant tuning capabilities of the bimodal EOT indicate its promising application prospects in frequency-selective surfaces, communication, filtering, and radar.

1. INTRODUCTION

Extraordinary optical transmission (EOT) provides an effective approach to manipulate the propagation of photons in a solid. Ebbesen et al. first discovered the EOT phenomenon in a subwavelength aperture array structure on a silver film, which has since stimulated interest in exploiting this unique optical property. At the interface between a metal and nonmetal, the coupling of external electromagnetic waves and plasmons on the metal surface produces a wave that propagates along the interface. This kind of fluctuating energy quantum is called a surface plasmon polariton (SPP). An SPP propagates on the interface and decays exponentially inside the metal, which overcomes the traditional diffraction limit and manipulates the propagation of light on the subwavelength scale. This is widely regarded as the main mechanism in EOT generation. Localized surface plasmon resonances (LSPRs) from a single aperture or nanoparticle have also been found to result in EOT. To further explain the reasons for changing EOT transmission properties, individuals have extensively studied the effect of aperture size, metal–medium coupling, and aperture shape (e.g., circle, narrow rectangle, split ring) on EOT. Previous work has focused on the visible and near-infrared bands but not on the terahertz (THz) band. Nevertheless, THz research constitutes a very important interdisciplinary field, highly applicable in applications such as imaging, security inspection, communication, and biomedical science. The vast potential for applicability has aroused great interest in THz applications, igniting an upsurge in EOT research in the THz band.

With increasing EOT research, there is a dramatically increasing number of studies on tunable EOT. To improve the transmission properties of EOT, researchers have, for example, appended sophisticated structures to apertures. Xiao et al. added a rodlike structure to a square aperture and numerically proved that the transmission of a transverse electric wave through a metallic film was significantly enhanced. This overcomes the problem of an electromagnetic wave being strongly attenuated as it propagates through a metallic subwavelength aperture. However, with increasing requirements in applications, the double-enhanced transmission peaks can provide more operability in the field of communications. Zhang et al. proposed a tunable plasma metal structure composed of a silver film with two-dimensional cylindrical holes on a quartz substrate, which produced two transmission peaks, one is in the infrared band and the other is in the visible band. However, with limitations in the manufacturing process, such devices cannot provide real-time regulation of the transmission peaks. Moreover, according to evolving requirements in applications, there is an ever-growing desire for adjustable EOT. Intriguingly, the unique tuning properties of graphene in the THz band have captured widespread attention. The Fermi energy of graphene can be...
modulated conveniently by applying an external voltage, which achieves ultrawideband tunability by controlling electromagnetic fields.\textsuperscript{19} Gao et al.\textsuperscript{26} realized high-contrast, terahertz-wave modulation using gated graphene and based on extraneous transmission through ring apertures. Wang et al.\textsuperscript{25} achieved active tuning of the analogue of electromagnetically induced transparency effects by integrating monolayer graphene into all-dielectric metamaterials in THz. Liu et al.\textsuperscript{26} investigated the tuning ability of the incorporated graphene in metamaterials based on the anapole mode. In the THz band, Song et al.\textsuperscript{35} realized enhanced broadband extraordinary transmission using plasmon coupling between metal hemispheres and hole arrays. Although individuals have put forward several theories for and possible structures conducive to EOT,\textsuperscript{27–33} there is a scarcity of work concerning double-peak adjustment in the THz band.

In this article, we propose a ring–rod nested structure in a gold film aperture to realize active modulation of the bimodal EOT. According to numerical simulations, the structure excites two transmission peaks in the THz band, which correspond to the ring and rod modes. LSPR theory and equivalent circuit modeling are used to examine the effect of structural parameters on the transmission peaks, which verifies the sensitivity of the structure to single peak adjustment. To examine how graphene achieved the effect of changing a double peak to one peak, graphene was placed beneath a gold rod. By varying the \( \mu \) from 0 to 0.5 eV, the transmittance of the peak generated by the rod decreased from 70 to 6%, and the physical mechanism behind this phenomenon was thoroughly investigated by examining the electric field intensity distributions of the structure in the \( xoy \) plane. Then, the graphene was placed beneath the gap region, and when the \( \mu \) increased from 0 to 0.7 eV, the transmittance of the corresponding peak decreased from 50 to almost 0%. Our tunable parameter-sensitive structure shows great potential in fields such as frequency-selective surfaces, communication, filtering, and radar.

2. RESULTS AND DISCUSSION

The proposed structure is shown in Figure 1a, which consists of a gold film (yellow part) and a dielectric substrate (blue part). The frequency-dependent permittivity of gold can be described by the Drude model.\textsuperscript{36} The dielectric permittivity of the substrate, which is set to semi-infinite in the numerical simulation, is 1.7. The incident \( E \)-field is along the \( X \)-axis, and specific parameters of the structure are shown in Figure 1b. The lattice period of the array is denoted as \( p \); the height of the Au film is \( h \). The radii of the inner and the outer ring are denoted as \( r \) and \( R \), respectively. And the region between the outer radius of the ring and the edge of the aperture is denoted as the gap. The rod is placed inside the ring; the length of the rod is \( L \), which is along the \( X \)-axis, and the width is \( w \). The transmission spectra and electric field intensity distributions of the proposed structure are calculated using the finite-difference time-domain method (FDTD Solutions, Lumerial Inc., Canada), and the boundary conditions are periodic in the \( X \) and \( Y \)-directions and consist of perfectly matched layers in the \( Z \)-direction. In the remainder of the paper, graphene is processed as a two-dimensional material, and its thickness is set to zero in the numerical simulation. We can grow graphene by chemical vapor deposition and transfer the graphene to the corresponding position through a wet transfer technique. Then, the proposed structure can be obtained by micro- and nanoprocessing technology, such as photoductive, electron beam evaporation, dry etching, etc.

As shown in Figure 2a, the simulated transmission spectrum has two distinct transmission peaks at 1.77 and 2.42 THz. The intensity of the peak at 2.42 THz is slightly higher than that at 1.77 THz, and its FWHM is larger. To explain the corresponding physical mechanism behind each peak, the normalized, electric field intensity distributions are calculated in the \( xoy \) plane at 1.77 and 2.42 THz. There is a considerable enhancement of the local electric field at both ends of the long axis of the rod at 2.42 THz. The electric field of the incident light is parallel to the long axis of the rod, and thus the electrons in the rod oscillate together along the \( X \)-axis. The resonance of the incident light and local surface plasmons excites the LSP mode of the rod, which plays a major role in the enhancement of the local electric field. Because the end of the rod is sufficiently close to the inner ring, the electric field is further confined to both sides of the rod, which can efficiently trap and couple the incident light. This indicates that the excitation of the LSP mode of the rod can be spectrally broadened owing to radiative damping. In addition, the properties of the peak corresponding to the rod will be described using an equivalent circuit model in this paper later. At 1.77 THz, the energy of the electric field is significantly enhanced in the gap between the aperture and the outer ring because of the resonance of the gold surface plasmons with electromagnetic waves in the LSPR mode of the ring. It is worth emphasizing that along the \( Y \)-axis, with increasing electric field intensity along the tangent direction of the ring, the electric field intensity along the radius of the ring, which contributes to resonance, is extremely attenuated, resulting in an attenuation of the enhanced energy. Different from the high-energy electric field coupled closely to the edge of the rod’s long axis, the effective coupling region of the ring to the electric field is relatively large. This indicates the appearance of the ring’s LSP mode, which is weakly damped and spectrally narrowed because more harmonic oscillators participate in the radiation loss.

The influence of \( w \) and gap on the transmission response of EOT was simulated numerically. Figure 3a shows the obtained transmission spectra when varying \( w \) from 2 to 5 \( \mu m \) (gap = 2 \( \mu m \), \( L = 26 \mu m \), \( r = 17 \mu m \), and \( R = 19 \mu m \)). When \( w \) increases from 2 to 5 \( \mu m \), the transmission peak shifts from 2.63 to 2.35 THz. Figure 3c shows an equivalent circuit model of the ring and rod system that elucidates the reason for the red shift of the peak. According to equivalent circuit theory, the frequency

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (a) Three-dimensional schematic diagram of the gold ring–rod nested structure. (b) Unit cell. The geometrical parameters are as follows: \( h = 9 \mu m \), \( w = 4 \mu m \), gap = 2 \( \mu m \), \( L = 26 \mu m \), \( r = 17 \mu m \), and \( R = 19 \mu m \).
At resonance, the frequency \( \omega \) can be represented by
\[
\omega = \frac{1}{\sqrt{(L_1 + L_2)/C}}.
\]
where \( L_1, L_2, \) and \( C \) represent the equivalent inductances and capacitance, respectively. As shown in Figure 2b, because the electric field is mainly concentrated around the rod, the influence of \( L_2 \) can be ignored, relative to \( L_1 \). The value of \( C \) is proportional to \( w \) and inversely proportional to the rod−ring gap in the \( x \)-direction. The value of \( L_1 \) is proportional to \( L_\) and is almost independent of the rod−ring gap because the rod−ring gap \( \ll L \). \( C \) increases when \( w \) increases. From equivalent circuit theory, it is known that the resonant frequency decreases with increasing \( w \) when \( L \) and the rod−ring gap are fixed, which fits well with the results. When \( w \) continues to increase, the trend of the red shift decreases, as the inner ring’s curvature is not negligible, and the impact of the rod−ring gap must be considered. Figure 3b presents the transmission spectra of the structure with different gap sizes. The narrower peak shows an obvious red shift (from 1.79 to 1.66 THz), accompanied by a decrease in intensity as the gap decreases from 2.5 to 1 \( \mu m \). It has been demonstrated that modifying the shape or periodicity of the metal structures can change the resonant frequency of localized surface plasmons. A reduction in the gap size will impair the electric field energy of LSPRs, thus leading to a red shift and attenuation in the intensity of the transmission peak. Based on the above discussion, our proposed structure could play a pivotal role in peak regulation by varying the parameters during the device manufacturing stage.

The effect of double-peak manipulation by graphene is considered in the following discussion. Graphene was placed at the junction of the gold film and substrate, where LSPRs are generated, with initial geometric parameters \( w = 4 \mu m, \text{gap} = 2 \mu m \).
μm, \( L = 26 \mu m \), \( r = 17 \mu m \), and \( R = 19 \mu m \). Importantly, to adjust the transmission peak corresponding to the rod, the graphene was integrated into the inner-aperture region of the gold ring, as shown in Figure 4a. As the \( E_f \) of the graphene increases from 0 to 0.5 eV, the maximum value of the transmission peak decreases from 70% (black line) to 6% (green line), as shown in Figure 4b, with the trend of blue shift. To explain the physical mechanism of this phenomenon, we used the proposed equivalent circuit model. As the Fermi level of graphene increases, its conductivity gradually increases, which means that the permittivity of the medium in the capacitor decreases, and thus, the value of the capacitor decreases. Using the resonant frequency formula, the resonant frequency \( \omega \) increases, and thus, the resonant frequencies blue shift with the Fermi energy increasing. Intriguingly, the peak generated by the gold ring has a transmittance of only 65% when the \( E_f \) is 0, decreasing to 49% when the \( E_f \) is 0.1 eV, increasing to 72% when the \( E_f \) is 0.3 eV, and increasing to 75% when the \( E_f \) is 0.5 eV. The physical mechanism of graphene’s regulation to transmission intensity is detailed in Figure 4c—j. At 0, there is a slight enhancement in the electric field around the inner aperture (Figure 4c,g) caused by the intrinsic absorption of the graphene, which causes a slight decrease in the transmission intensity. When the \( E_f \) increases to 0.1 eV, the light-coupling ability of the graphene improves and the electrons in the graphene are excited by optical resonance with a frequency of 1.77 THz. This leads to an increase in the electric field intensity in the inner region of the ring, as shown in Figure 4h. Because the graphene’s absorption of energy is nonradiative, a decrease in the transmission peak is caused by increasing the \( E_f \). Figure 4d shows the distribution of the electric field around the rod. Due to the energy absorption capacity of graphene, the electric field originally coupled to the end of the rod is now dispersed on the graphene inside the ring. Coupling of the graphene’s resonant absorption and the rod’s LSPR mode results in a blue shift of the transmission peak, resulting in the electric field of light transmission being weakened and thus a decrease in the intensity of the

![Figure 4](image-url)

**Figure 4.** (a) Illustration of the structure with graphene placed beneath the rod. (b) Simulated transmittance spectra when \( E_f = 0 \) (black line), 0.1 (red line), 0.3 (blue line), and 0.5 (green line) eV. Calculated normalized, electric field intensity distributions of each peak in the xoy plane, specifically in (c) \( E_f = 0, 2.56 \) THz, (d) \( E_f = 0.1 \) eV, 2.78 THz, (e) \( E_f = 0.3 \) eV, 3 THz, (f) \( E_f = 0.5 \) eV, 3 THz, (g) \( E_f = 0, 1.77 \) THz, (h) \( E_f = 0.1 \) eV, 1.77 THz, (i) \( E_f = 0.3 \) eV, 1.77 THz, and (j) \( E_f = 0.5 \) eV, 1.77 THz.

![Figure 5](image-url)

**Figure 5.** (a) Schematic diagram of the structure with the graphene placed outside the ring. (b) Simulated transmittance spectra when the \( E_f = 0 \) (black line), 0.3 (red line), 0.5 (blue line), and 0.7 (green line) eV.
transmission peak. This can be attributed to the surface plasmon resonance mode of the structured graphene also being excited in the terahertz band, which is also related to the Fermi level of the graphene.\textsuperscript{40} For 0.3 and 0.5 eV, due to the stronger energy absorption capability of graphene, 1.77 THz light is not sufficient for resonant absorption of the graphene, and the electric field is recoupled to the localized surface plasma of the gap outside the ring (Figure 4i); the transmittance is restored to 75%. Furthermore, as shown in Figure 4ef, with increasing $E_f$, a change in the damping rate causes electromagnetic energy attenuation—the electric field captured by the rod is enormously attenuated. This almost completely destroys the EOT phenomenon, leaving the peak at 1.77 THz in the transmission spectra (green line).

To investigate the tuning effect on the ring’s LSPR mode, the graphene was placed beneath the region outside the ring (Figure 5a). Because the adjustment mechanism of graphene is similar to that discussed in Figure 4, the difference between the two positions of graphene can be elucidated. The transmission response to the $E_f$ of graphene is depicted in Figure 5b; with the $E_f$ increasing from 0 to 0.7 eV, the transmission peak at 1.77 THz disappears. As shown in Figure 2c, the electric field excited by the ring’s LSPR mode is much more extensive than that of the rod’s LSPR mode, which leads to a stronger resonance from localized surface plasmons of the ring with graphene. Thus, the loss rate of transmittance (33.3%) due to the absorption of graphene is greater than that of the rod mode, 11.4% at 0. As discussed above, increasing the $E_f$ leads to a blue shift of the narrower peak, which refers to the coupling of the graphene’s resonant absorption and the ring’s LSPR mode. It is worth noting that at 0.3 eV, the ring’s LSPR mode is affected by the resonance between the graphene and localized surface plasmons, and the frequency of the resonance peak increases to almost 2.42 THz. This leads to a superimposed interference between the LSPR modes of the ring and rod. The coupling of two similar-frequency LSPR modes results in the hybridization of the two transmission peaks (red line). Before the $E_f$ reaches 0.7 eV, with the strong destructive interference between the graphene and LSPR modes, the EOT peak excited by the ring is adjusted to disappear by increasing the $E_f$ of the graphene, leaving the peak at 2.42 THz in the transmission spectra (green line). Therefore, we can adjust the Fermi energy of the graphene according to practical requirements to achieve an active regulation of the bimodal EOT.

3. CONCLUSIONS

Active tuning of double peaks was achieved by incorporating graphene in the proposed ring–rod nested structure based on EOT. Two pronounced transmission peaks corresponding to the LSPR mode of the ring and the rod were observed, and the enhanced transmission behaviors of the structure could be effectively tailored by changing the geometric parameters of the ring and rod—which highlights the pivotal role of our structure in single-peak regulation. Notably, the double peaks were carefully adjusted to form only one peak by modulating the position and $E_f$ value of graphene, which disturbed the resonance mode of the gold film surface plasmon. Graphene with an $E_f$ of 0–0.5 eV was placed beneath the rod with a transmission range of 0.7–0.06; when the graphene was placed beneath the gap, the modulation range of transmittance was 0.5–0 for an $E_f$ value of 0–0.7 eV. The increasing $E_f$ led to destructive interference between the graphene and LSPR modes, which realized the adjustment from bimodal EOT to a unimodal EOT. The powerful tunability of the bimodal EOT with graphene opens up avenues to explore promising applications in frequency-selective surfaces, communication, filtering, and radar.

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**Author Contributions**
The manuscript was written through the contributions of all authors. The primary work was completed by Z.G., and Y.S. provided the core instruction. All authors have given approval to the final version of the manuscript.

**Notes**
The authors declare no competing financial interest.

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**ABBREVIATIONS**
EOT, extraordinary optical transmission; THz, terahertz; SPP, surface plasmon polariton; LSPRs, localized surface plasmon resonances; FWHM, full-width at half-maximum

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