Graphene-enabled reconfigurable terahertz wavefront modulator based on complete Fermi level modulated phase

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Abstract

Although great achievements have been obtained in metasurfaces so far, the functionalities of these devices are almost static. The dynamically adjustable devices are far less explored. Here we theoretically and numerically demonstrate a veritable reconfigurable terahertz wavefront modulator (TWM). The designed TWM can dynamically shape the wavefront at will via imposing different Fermi levels on the constituent graphene ribbons. By adopting the Dirac brackets and Matrix analysis method, the correlation between the phase shift and Fermi level is theoretically established, which offers a general scheme for designing dynamically switchable devices. As a proof of concept, three different sets of pre-calculated Fermi levels are imposed on the graphene ribbons. The TWM can be dynamically switched among back reflector, varifocal metalens and Airy beam generator, which has never been demonstrated before as far as we know. The proposed reconfigurable TWM owns the capability of dynamically steering terahertz wavefront, indicating great significance for the development of THz reconfigurable devices.

1. Introduction

Metasurfaces, two-dimensional counterparts of metamaterials, have gained tremendous attention due to their unprecedented superiority in manipulating wavefront at sub-wavelength scale. Composed of monolayer artificial meta-atoms, metasurfaces can enforce abrupt changes on amplitude, phase or polarization of the incident electromagnetic wave. The most common way is to modulate the geometry or spatially arrange the meta-atoms [1, 2]. Owing to this specific characteristic, metasurfaces are regarded as the promising candidates to replace the conventional optical components, hence opening up new doors for designing planar optical devices [3, 4]. On the basis of their effectiveness in wavefronts steering at sub-wavelength scale, a wide variety of ultra-thin devices based on metasurfaces have been demonstrated, such as wave plates [5–7], holograms [8–10], metalenses [11–17], vortex beam generators [18–21] and so forth.

Despite great achievements having been obtained in metasurfaces so far, most of the newly demonstrated metasurface-based devices are naturally static. The most important reason is the fixed geometrical dimensions and dispersion relations of the metasurface. The tunability and reconfigurability of the devices, that have emerged as urgent industrial requirements, show vital importance in practical applications like dynamic holography and active focusing. To achieve devices with active tunability, active
materials with adjustable electromagnetic properties in real time under external stimuli are needed. Some materials, such as liquid crystal metasurfaces [22, 23], phase change material [24, 25] and electrically driven carrier accumulation [26–28], have recently been employed to construct the adjustable devices. Graphene, a monolayer material consisting of honeycomb arranged carbon atoms, has been verified to be a promising candidate for dynamic wavefront control at terahertz (THz) and mid-infrared frequencies [29–33]. As we know, the Fermi level and surface conductivity of graphene can be easily tuned by the external stimuli (gate voltage or chemical doping), which can induce a controllable light–matter interaction [34]. Owing to this impressive characteristic, significant efforts have been devoted to investigate dynamically adjustable devices based on graphene or graphene-assisted structures [35–42]. Ding et al proposed a dynamic metafilm constructed of graphene apertures, which possesses the capacity to modulate the focal intensity, length, and bandwidth by changing the graphene’s Fermi level [41]. Liu et al designed a graphene-based grating constructed of graphene ribbons with different widths and obtained a tunable metafilm [42]. Although the previous proposed devices can achieve dynamically switchable wavefront manipulation, almost all of them cannot get rid of restricted tunability by considering its limited phase shift (they cannot achieve phase coverage of 0–2π in response to the external stimulus).

In this paper, we theoretically and numerically demonstrate a veritable reconfigurable terahertz wavefront modulator (TWM) by taking advantage of Fermi level modulated complete phase manipulation. Firstly, the graphene unit cell is optimized to obtain a Fermi level modulated phase coverage of 0–2π, which is the basis of the reconfigurable TWM. Then, by adopting the Dirac brackets and matrix analyze method, the underlying physics of the TWM is investigated. In this process, the relationship between the phase shifts and the Fermi levels is established, providing a general scheme for designing dynamically switchable devices. As a proof of concept, three different sets of pre-calculated Fermi levels are imposed on the graphene ribbons. The TWM can be dynamically switched among back reflector, varifocal metafilm and Airy beam generator. With the capability of dynamically steering the THz wavefront, the proposed TWM will be extended to design other active adjustable devices.

2. Metasurface design and theoretical model

Figure 1 shows the schematic of proposed reconfigurable TWM, which consists of a list of graphene ribbons, a silica spacing layer and an optically thick silver film. As shown in figure 1, the designed TWM exhibits Fermi level modulated reconfigurable functionality: it functions as a metafilm or an Airy beam generator. The inset of figure 1 depicts the unit cell of design, from which one can see the detail parameters (the period along x-axis \(P_x\), the thickness of graphene ribbon \(t\), the thickness of the silver film \(t_z\)), the frequency dependent effective permittivity of silver is considered with the Drude model: \(\varepsilon_0 = 2\pi \times 2.2 \times 10^{15} \text{ rad s}^{-1}, \omega_c = 2\pi \times 4.35 \times 10^{12} \text{ rad s}^{-1}\). The silica space layer (with refractive index of 1.45 and thickness of \(t_1 = 10 \mu m\)) is utilized to function as an FP resonant cavity, aiming at enhancing the reflected phase shift. The silver film at the bottom, which serves as a perfect electromagnetic conductor (PEC), with the thickness be set as \(t_2 = 2 \mu m\). The period of the unit cell along x-axis is \(P_x = 5 \mu m\), and the period along y-axis is infinite. The graphene is modeled as a flat two-dimensional (2D) sheet. Its surface conductivity is dominated by the inter-band contribution in the THz regime: \(\sigma(\omega) = \frac{ie^2E_f}{\hbar\omega}\), where \(e\) is the elementary charge, \(h\) is the Plank’s constant \(h\) divided by 2π. \(E_f\) is the graphene Fermi level, \(\gamma (= 0.11 \text{meV})\) is the intrinsic losses relating to relaxation time \(\tau = \frac{\hbar}{\omega} = \frac{\hbar}{\omega_c} = \frac{\hbar}{\omega} = \frac{\hbar}{\omega_c}\) with carrier mobility [43] \(\mu = 10^4 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}\), Fermi velocity \(v_F \approx c/300\).

In order to obtain a planar device with reconfigurable functionality, the electromagnetic properties of the unit cell should be actively adjustable. For this purpose, the Fermi level modulated characteristic of the unit cell is investigated. The simulated reflected phase shifts and reflectivity of the unit cell as functions of frequency and Fermi level are shown in figures 2(a) and (b). The three-dimensional finite difference time domain (FDTD) method is utilized to characterize the electromagnetic property of the unit cell. In these simulations, periodic boundary conditions and perfectly matched layers are utilized along the x and z directions, respectively. The incident THz wave is x-polarized that normally illuminated on the metasurface along the negative direction of z-axis. The other parameters are the thickness of the silica layer \(t_1 = 10 \mu m\), the width of graphene ribbon \(w = 2 \mu m\), the period of the unit cell \(P_x = 5 \mu m\) and the thickness of the silver film \(t_2 = 2 \mu m\). The simulation results show that, at some certain frequencies (from 2 THz to 6 THz), the reflected phase shifts show active adjustable characteristic, which vary from almost –π to π as the Fermi level ranges from 0 eV to 1 eV. It should be pointed out that this \(E_f\) modulation can be experimentally realized by applying a bias voltage. With this method [44, 45], a pair of ultrathin (e.g. 30 nm) and transparent conductive layers (e.g. doped silicon) as negative back electrode can be proposed upon the graphene grating in our device. The graphene films connect to the positive electrode, and there is a thin
Figure 1. Schematic of the reconfigurable TWM, which exhibits Fermi level modulated dynamically switchable functionality: functions as a metalens or an Airy beam generator. The TWM consists of a list of graphene ribbons placed on a silver film separated by a silica spacer. The inset in the top left shows the unit cell, from which one can see the detail parameters (the period along $P_x$, the width of graphene ribbon $w$, the thickness of spacing layer $t_1$ and the thickness of the silver film $t_2$).

Figure 2. (a) Reflected phase profiles of the unit cell versus Fermi level $E_f$ and frequency $f$ under $x$-polarized incident THz wave. (b) The corresponding reflectivity of (a). (c) and (d) Reflected phase and reflectivity at 5.75 THz as a function of $E_f$. The detail parameters of the unit cell are $t_1 = 10 \mu m$, $t_2 = 2 \mu m$, $P_x = 5 \mu m$ and $w = 2 \mu m$. In these simulations, periodic boundary condition is applied along $x$- and $y$-axes and perfectly matched layers are applied along the $z$-axis.

dielectric layer between the back electrode and the graphene film. As shown in figures 2(c) and (d), the working frequency is selected as $f = 5.75$ THz for its full phase coverage of $2\pi$ and relatively high reflectivity (with average reflectivity over 60%).

The Dirac brackets and Matrix analyze method are adopted to investigate the underlying physics of the Fermi level modulated characteristic of graphene ribbon [46, 47]. For a graphene-based metasurfaces device without external stimuli, the interaction between the incident THz wave and the designed graphene-enabled device (constructed of $n$ graphene ribbons) can be expressed as

$$\left[ \hat{G}_1 \ldots \hat{G}_n \right]^T | L \rangle = \left[ \alpha_1 e^{i\theta_1} \ldots \alpha_n e^{i\theta_n} \right]^T | L \rangle$$

(1)
where $|L\rangle$ is the Dirac bracket of the linearly polarized (LP) light and the operator $\hat{G}_i$ represents the graphene ribbons’ modulation effect on the amplitude and phase of the incident THz wave. $a_i$ and $\psi_j$ represent the amplitude and phase introduced by the $i$th graphene ribbons. Equation (1) also indicates that the reflected light is co-polarized with the incident one (due to the structure symmetry of graphene ribbons). For the device without incident THz wave, the Fermi level’s modulation effect on the graphene ribbons can be expressed as

$$
\begin{bmatrix}
E_{11} & E_{12} & \cdots & E_{1n} \\
E_{21} & E_{22} & \cdots & E_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
E_{m1} & E_{m2} & \cdots & E_{mn}
\end{bmatrix}
\begin{bmatrix}
\hat{G}_1 \\
\hat{G}_2 \\
\vdots \\
\hat{G}_n
\end{bmatrix}
\cdot
\begin{bmatrix}
\sum_{j=1}^{n} b_{ij} e^{i\varphi_{ij}} \\
\sum_{j=1}^{n} b_{ij} e^{i\varphi_{ij}} \\
\vdots \\
\sum_{j=1}^{n} b_{ij} e^{i\varphi_{ij}}
\end{bmatrix}
= |L\rangle
$$

(2)

where $E_{mn}$ represents the imposed Fermi level on the graphene ribbon. $b_{mn}$ and $\varphi_{mn}$ represent the corresponding amplitude and phase changes. The sign $'-$ defined as the Fermi level’s modulation effect on graphene ribbons. Utilizing equations (1) and (2), the total modulation effect can be derived as

$$
\begin{bmatrix}
E_{11} & E_{12} & \cdots & E_{1n} \\
E_{21} & E_{22} & \cdots & E_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
E_{m1} & E_{m2} & \cdots & E_{mn}
\end{bmatrix}
\begin{bmatrix}
\hat{G}_1 \\
\hat{G}_2 \\
\vdots \\
\hat{G}_n
\end{bmatrix}
\cdot
\begin{bmatrix}
\sum_{j=1}^{n} b_{ij} e^{i\varphi_{ij}} + a_{ij} e^{i\psi_{ij}} \\
\sum_{j=1}^{n} b_{ij} e^{i\varphi_{ij}} + a_{ij} e^{i\psi_{ij}} \\
\vdots \\
\sum_{j=1}^{n} b_{ij} e^{i\varphi_{ij}} + a_{ij} e^{i\psi_{ij}}
\end{bmatrix}
= |L\rangle
$$

(3)

Therefore, there is a correspondence relationship between the Fermi level and the phase shifts, namely, a set of imposed Fermi levels would undoubtedly results in a set of modulated phase shifts (see figure S1 in the supporting information) (stacks.iop.org/NJP/22/063054/mmedia). Such a corresponding relationship will give dynamically adjustable phase shifts, providing unprecedented capacity in designing reconfigurable devices.

3. Results and discussion

3.1. Reconfigurable TWM with Fermi level modulated varifocal focusing

As a proof of concept, a reconfigurable TWM constructed of 161 identical graphene ribbons is designed, with a total width of 805 $\mu$m. For the designed TWM, it functions as a back reflector (with the incident THz wave back reflected) without or with identical Fermi levels (see part 2 in the Supporting Information). To function as a dynamically varifocal metalens, the endowed phase shifts should not only fulfill the equal paths principle for focusing but also be independently modulated. The former can be achieved by introducing a parabolic-shaped phase shift and the latter can be achieved by Fermi levels modulation. For a cylindrical metalens, the required phase shifts $\varphi(x)$ along the interface should satisfy

$$
\varphi(x) = -2\pi/\lambda(\sqrt{(x-x_c)^2+f_c^2} - f_c)
$$

(4)

where $\lambda$ is the designed THz wavelength, $x$ is the coordinate of the graphene ribbon and $x_c$ is the coordinate of focusing point on $x$-axis. $f$ represents the vertical distance from the focal point to the metasurface plane and $f_c$ is the focal length which is defined as the distance from metasurface plane to the focal spot and can be calculated as $f_c=(x_c^2+f^2)^{1/2}$. Hence, a dynamically varifocal cylindrical metalens can be designed by linearly arraying the identical graphene ribbons. The varifocal functionality can be achieved by imposing different pre-calculated sets of Fermi levels on the graphene ribbons.

To show that, the TWM is assigned to function as an on-center metalens (with focal length $f_c = 500$ $\mu$m and the coordinate of focal spot on $x$-axis $x_c = 0$). As shown in figure 3(a), the required phase shifts can be endowed by imposing a certain Fermi level on the graphene ribbons. Moreover, the required Fermi levels are almost in the range of 0.0–1.0 eV, which are experimentally attainable. For the Fermi levels go beyond the range in a few small areas, they are approximately set to be 0.0 eV or 1.0 eV in the simulations. Figure 3(b) shows the simulated intensity ($|E|^2$) profile at $x$–$z$ plane, from which one can see clearly that the reflected THz wave is efficiently focused, with a focal spot exhibits at location (0 $\mu$m, 550 $\mu$m). The slight discrepancy between the simulated and designed focal lengths can be attributed to the finite sizes of the constructed unit cells with respect to the incident THz wavelength. The cross section of the focal spots along $x$-axis are depicted in figure 3(c), where the full-width at half-maximum (FWHM) is 54 $\mu$m,
indicating a nearly diffraction-limited focal spot of the designed graphene-based metalens. Figure 3(d) shows the simulated phase profile at $x$–$z$ plane, in which the phase profile exhibits parabolic shape.

As in the above-mentioned discussion, the graphene ribbon exhibits Fermi level modulated phase shift, providing a scheme to rearrange the phase profile of the designed device. Owing to such a characteristic, the designed TWM can be utilized to function as a reconfigurable metalens. Dynamically tuning the on-center focal spot along $y$-axis by Fermi level modulation is demonstrated in figure 4. It can be observed that the focal spot can be actively adjusted to the expected locations. Moreover, the working principle of our designed reconfigurable TWM is also visualized: a certain set of Fermi levels would result in specific phase profiles, and it finally leads to a specific functionality. Using the same strategy, dynamically tuning the off-center focal spot along $x$-axis by Fermi level modulation is also demonstrated and the corresponding results are depicted in figure 5. It can be observed that the focal spot can be dynamically adjust to the expected locations ((−250 μm, 400 μm), (0 μm, 400 μm), (250 μm, 400 μm)) via Fermi level modulation. Therefore, with a proper set of Fermi levels imposed on the proposed TWM, the focal spot can be adjusted at will, indicating more practical applications.

### 3.2. Reconfigurable TWM with its functionality reconstructed from focusing to Airy beam generating

Furthermore, by virtue of Fermi level modulated complete phase manipulation, the proposed reconfigurable TWM capable of switching from one functionality to another. Here the Airy beam generating is chosen as an example due to its unique properties (such as non-diffraction, self-accelerating, and self-healing) and interesting applications in optical micro-manipulation. Such a dynamically switching could be accomplished by imposing a specific Fermi levels on the graphene ribbons, without reconstituting the TWM’s configuration. The amplitude of the 1D Airy beam can be described as follows [48]

$$\psi(x, \theta) = Ai(bx) \exp(ax + i k x \sin \theta),$$  \hspace{1cm} (5)

where $Ai(bx) = \frac{1}{\pi} \int_0^\infty \cos(\frac{t^3}{3} + bxt) \, dt$ is the Airy function with $x$ representing the transverse coordinate and $k$ is the wave number. $a$, $b$, and $\theta$ are performance parameters of Airy beam which represent a positive number to truncate the Airy beam, transverse scale, and bending direction, respectively. The desired phase shift can be calculated as $\varphi(x, \theta) = \arg(\psi(x, \theta))$.

Figures 6(a) and (b) depict the required amplitude and phase shift for the Airy beam, in which the performance parameters are set as $a = 0.004$, $b = 0.021$ and $\theta = 0^\circ$. Here the phase modulated Airy beam is investigated due to the unattainable amplitude variation for our elaborately designed graphene ribbon [49].
Figure 4. Dynamically tuning the on-center focal spot along $y$-axis by Fermi level modulation. (a–c) The required phase shifts and corresponding Fermi levels for on-center focusing ($x_c = 0 \mu m$) with focal length $f = 400 \mu m$, $500 \mu m$ and $600 \mu m$. (d–f) Simulated intensity ($|E|^2$) profiles of the three metalenses in the $x$–$z$ plane at $y = 0$. The incident THz wave is $x$-polarized incident with wavelength $\lambda = 52.2 \mu m$. For these simulations, periodic boundary condition is applied along the $y$-axis and perfectly matched layers are applied along the $x$- and $z$-axes.

Figure 5. Dynamically tuning the off-center focal spot along $x$-axis by Fermi level modulation. (a–c) The required phase shifts and corresponding Fermi levels for off-center focusing with focal length $f = 400 \mu m$ and different displacement on $x$-axis $x_c = -250 \mu m$, $0 \mu m$, and $250 \mu m$. (d–f) Simulated intensity ($|E|^2$) profiles of the three metalenses in the $x$–$z$ plane at $y = 0$. The incident light is $x$-polarized incident with wavelength $\lambda = 52.2 \mu m$. For these simulations, periodic boundary condition is applied along the $y$-axis and perfectly matched layers are applied along the $x$- and $z$-axes.

To fulfill the required phase as shown in figure 6(b), two Fermi levels $E_f = 0.5068 eV$ and $0.3428 eV$ are selected. The two Fermi levels could provide a $\pi$ phase difference along with identical magnitude (see part 3 in the supporting information). By imposing a set of Fermi levels constructed of the two selected ones, the TWM could be reconstructed from focusing to Airy beam generating. Figure 6(c) depicts the simulated electric field distribution ($x$–$z$ plane at $y = 0$) of the TWM, showing clearly non-diffracting and self-bending characteristics. In addition, the self-healing property is investigated as well by placing a PEC obstacle with a size of $85 \mu m \times 85 \mu m$ ($x$–$z$ plane) in front of the main lobe centered (at $x = 5 \mu m$ and $z = 200 \mu m$). The simulated electric field distribution is depicted in figure 6(d). It is obvious that the field distribution can be
locally modified by the obstacle. However, the disturbed beam profiles could be automatically recovered to an Airy beam after passing by the obstacle.

4. Conclusions

In conclusion, we theoretically and numerically demonstrated a graphene-based veritable reconfigurable TMW, which possesses the capacity of dynamically shaping the wavefront of incident THz wave at will. The proposed TWM consists of identical graphene ribbons, which can get rid of the complex parameters design process. Moreover, the graphene ribbon is able to obtain Fermi level modulated phase coverage of 0–2π. By utilizing the Dirac brackets and matrix analyze method, the correlation between the phase and Fermi level is established, provising a general scheme for designing reconfigurable devices. To verify such a strategy, different sets of pre-calculated Fermi levels are imposed on the graphene ribbons. The TWM can exhibit excellent reconfigurability with the functionality can be reconstructed among back reflecting, varifocal focusing and Airy beam generating. With Fermi level modulated full phase manipulation, the proposed reconfigurable TWM will be extended to achieve other dynamically switchable functionalities, opening up new doors for designing reconfigurable devices.

Conflicts of interest

The authors declare no conflict of interest.

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References

[1] Yu N, Genevet P, Kats M A, Aieta F, Tetienne J P, Capasso F et al 2011 Light propagation with phase discontinuities: generalized laws of reflection and refraction Science 334 533–7
[2] Sun S, He Q, Xiao S, Xu Q, Li X and Zhou L 2012 Gradient-index meta-surfaces as a bridge linking propagating waves and surface waves Nat. Mater. 11 426–31
[3] Kildishev A V, Boltasseva A and Shalaev V M 2013 Planar photonics with metasurfaces Science 339 1232009
[4] Yu N and Capasso F 2014 Flat optics with designer metasurfaces Nat. Mater. 13 139–50
[5] Zhao Y and Ali A 2013 Tailoring the dispersion of plasmonic nanorods to realize broadband optical meta-waveplates Nano Lett. 13 1086–91
[6] Zhang X, Kong D, Yuan Y, Mei S, Wang L and Wang G 2020 Broadband and dispersion-free reflective silver metasurfaces as half-wave plate and vortex-beam generator Opt. Commun. 465 125561
[7] Zhao X, Schalch J, Zhang J, Seren H R, Duan G, Averitt R D et al 2018 Electromechanically tunable metasurface transmission waveplate at terahertz frequencies Optica 5 303–10
[8] Wintz D, Genevet P, Ambrosio A, Wooff L and Capasso F 2015 Holomicrol molar metals for switchable focusing of surface plasmons Nano Lett. 15 3585–9
[9] Kamali S M, Arbabi E, Arbabi A, Horie Y, Faraji-Dana M and Faraon A 2017 Angle-multiplexed metasurfaces: Encoding independent wavefronts in a single metasurface under different illumination angles Phys. Rev. X 7 041056
[10] Ren H et al 2019 Metasurface orbital angular momentum holography Nat. Commun. 10 1
[11] Arbabi A, Horie Y, Bull J A, Bagheri M and Faraon A 2015 Subwavelength-thick lenses with high numerical apertures and large efficiency based on high-contrast transmittarrays Nat. Commun. 6 7069
[12] Aieta F, Kats M A, Genevet P and Capasso F 2015 Multiwavelength achromatic metasurfaces by dispersive phase compensation Science 347 1342–5
[13] Khorasaninejad M, Chen W T, Devlin R C, Oh J, Zhu A and Capasso F 2016 Diffraction-limited focusing and subwavelength resolution imaging Science 352 1190–4
[14] Wang S, Wu P C, Su V C, Lai Y C, Chu C H, Chen J W et al 2017 Broadband achromatic optical metasurface devices Nat. Commun. 8 187
[15] Khorasaninejad M, Shi Z, Zhu A Y, Chen W T, Zaidi A and Capasso F 2017 Achromatic metaslens over 60 nm bandwidth in the visible and metaslens with reverse chromatic dispersion Nano Lett. 17 1819–24
[16] Wang S, Wu P C, Su V, Lai Y, Chen M, Kuo H Y et al 2018 A broadband achromatic metals in the visible Nat. Nanotechnol. 13 227
[17] Yang H, Cao G, Ou K, Li G and Chen X 2019 Broadband spin-driven anomalous surface plasmon polariton steering via V-shaped aperture metasurfaces Adv. Theory Simul. 2 1800167
[18] Mehmood M Q, Mei S, Hussain S, Huang K, Siew S Y, Zhang L et al 2016 Visible-frequency metasurface for structuring and spatially multiplexing optical vortices Adv. Mater. 28 2533–9
[19] Yue F, Wen D, Zhang C, Gerardot B D, Wang W, Zhang S et al 2017 Multichannel polarization-controllable superpositions of orbital angular momentum states Adv. Mater. 29 1603838
[20] Zhang Y, Liu W, Gao J and Yang X 2018 Generating focused 3D perfect vortex beams by plasmonic metasurfaces Adv. Opt. Mater. 6 1701228
[21] Yang H, Chen Z, Liu Q, Hu Y and Duan H 2019 Near-field orbital angular momentum generation and detection based on spin–orbit interaction in gold metasurfaces Adv. Theory Simul. 2 1900133
[22] Komar A, Faz A, Bohn J, Sautter J, Decker M, Miroshnichenko A et al 2017 Electrically tunable all-dielectric optical metasurfaces based on liquid crystals Appl. Phys. Lett. 110 071109
[23] Komar A, Panigrahu-Dominguez R, Miroshnichenko A, Yu Y F, Kivshar Y S, Kuznetsov A I et al 2018 Dynamic beam switching by liquid crystal tunable dielectric metasurfaces ACS Photonics 5 1742–8
[24] Wang Q, Rogers E T, Gholipour B, Wang C M, Yuan G et al 2016 Optically reconfigurable metasurfaces and photonic devices based on phase change materials Nat. Photon. 10 60–5
[25] Butakov N A, Valmianski I, Lewi T, Urban C, Ren Z, Mikhailovsky A A et al 2017 Switchable plasmonic–dielectric resonators with metal–insulator transitions ACS Photonics 5 371–7
[26] Huang Y W, Lee H W H, Sokhoyan R, Pala R A, Thyagarajan K, Han S et al 2016 Gate-tunable conducting oxide metasurfaces Nano Lett. 16 5319–25
[27] Park J, Kang J H, Kim S J, Liu X and Brongersma M L 2016 Dynamic reflection phase and polarization control in metasurfaces Nano Lett. 17 407–15
[28] Afridi A, Canet-Ferrer J, Philippet L, Osmond J, Berto P and Quidant R 2018 Electrically driven varifocal silicon metasurfaces ACS Photonics 5 497–503
[29] Geim A K and Novoselov K S 2007 The rise of graphene Nat. Mater. 6 183–91
[30] Chen J, Badioli M, Alonso-González P, Thongrattanasiri S, Huth F, Osmond J et al 2012 Optical nano-imaging of gate-tunable graphene plasmons Nature 487 77–81
[31] Fei Z, Rodin A S, Andreev G O, Bao W, McLeod A S, Wagner M et al 2012 Gate-tuning of graphene plasmons revealed by infrared nano-imaging Nature 487 82–5
Islam M S, Sultana J, Biabanifard M, Vafapour Z, Nine M J, Dinovitser A et al 2020 Tunable localized surface plasmon graphene metasurface for multiband superabsorption and terahertz sensing Carbon 158 559–67

Guan S, Cheng J, Chen T and Chang S 2020 Widely tunable polarization conversion in low-doped graphene-dielectric metasurfaces based on phase compensation Opt. Lett. 45 1742–5

Vakil A and Engheta N 2011 Transformation optics using graphene Science 332 1291–4

Miao Z, Wu Q, Li X, He Q, Ding K, An Z et al 2013 Widely tunable terahertz phase modulation with gate-controlled graphene metasurfaces Phys. Rev. X 5 041027

Yatooshi T, Ishikawa A and Tsuruta K 2015 Terahertz wavefront control by tunable metasurface made of graphene ribbons Appl. Phys. Lett. 107 053105

Shang X J, Zhai X, Li X F, Wang L L, Wang B X and Liu G D 2016 Realization of graphene-based tunable plasmon-induced transparency by the dipole–dipole coupling Plasmonics 11 419–23

Jung M, Dutta-Gupta S, Dabidian N, Brener I, Shcherbakov M and Shvets G 2018 Polarimetry using graphene-integrated anisotropic metasurfaces ACS Photonics 5 4283–8

Kim T T, Kim H, Kenney M, Park H S, Kim H D, Min B et al 2018 Amplitude modulation of anomalously refracted terahertz waves with gated-graphene metasurfaces Adv. Opt. Mater. 6 1700507

Liu W, Hu B, Huang Z, Guan H, Li H, Wang X et al 2018 Graphene-enabled electrically controlled terahertz meta-lens Photonics Res. 6 703–8

Ding P, Li Y, Shao L, Tian X, Wang J and Fan C 2018 Graphene aperture-based metalens for dynamic focusing of terahertz waves Opt. Express 26 28038–30

Li Z, Yao K, Xia F, Shen S, Tian J and Liu Y 2015 Graphene plasmonic metasurfaces to steer infrared light Sci. Rep. 5 12423

Jin B, Guo T and Argyropoulos C 2017 Enhanced third harmonic generation with graphene metasurfaces J. Opt. 19 94005

Long J, Geng B, Horng I, Girri C, Martin M, Hao Z et al 2011 Graphene plasmonics for tunable terahertz metamaterials Nat. Nanotechnol. 6 630–4

Kostyuk S N, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V et al 2004 Electric field effect in atomically thin carbon films Science 306 666–9

He Y, Liu Z, Liu Y, Zhou J, Ke Y, Luo H et al 2015 Higher-order laser mode converters with dielectric metasurfaces Opt. Lett. 40 5506–9

Yang H, Li G, Cao G, Zhao Z, Yu F, Chen X et al 2017 Polarization-independent metalens constructed of antennas without rotational invariance Opt. Lett. 42 3996–9

Gao H, Gu Z M, Liang B, Zou X Y, Yang J, Yang J et al 2016 Acoustic focusing by symmetrical self-bending beams with phase modulations Appl. Phys. Lett. 108 073501

Minovich A, Angela E K, Norik J, Thomas P, Dragomir N N and Yuri S K 2011 Generation and near-field imaging of Airy surface plasmons Phys. Rev. Lett. 107 116802 116802