Graphene-based Microwave Metasurfaces and RF Devices: A Review

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Graphene, as a two-dimensional material, has attracted significant attentions owing to its particular electronic band structure and unique physical properties. Metasurfaces integrated with graphene hold great promise for dynamic manipulation of the electromagnetic waves, where metasurfaces with strong resonances enhance the interaction with incident waves and in turn facilitate a deep modulation through electrical doping of graphene. However, the tunable surface conductivity of graphene is very frequency dependent that makes graphene behave significantly different in THz and microwave band. Owing to the novel tuning method of graphene-electrolyte based sandwich structure, experimental studies of tunable microwave meta-devices have aroused wide interests in the past few years. In this paper, we briefly review the recent progress of graphene-based microwave metasurfaces and related devices, involved but are not limited to tunable absorbers, dynamic beam steering, reconfigurable antennas, and attenuators, enriching the experimental developments of graphene in microwave region.

1 Introduction

Metamaterials [1, 2] are artificially periodic electromagnetic (EM) structures with subwavelength thicknesses, exhibiting exotic properties that not naturally available. They were initially designed for breaking the fundamental physics laws such as the negative refraction [3] and subsequently proven to be a versatile platform to manipulate the electromagnetic waves throughout the whole spectrum [4, 5]. However, devising metamaterials for practical applications in real time still remain challenges due to their large volume and complex fabrication. The introduction of two-dimensional equivalence of metamaterials with planar profile, collectively labelled as metasurfaces, realize the abrupt changes of EM responses in an ultra-thin thickness, endowing the superior advantages of miniaturization and shifting the research interest from the exploration of novel physical phenomena towards practical applications [6-12]. Indeed, the unique EM responses of metasurfaces (such as abnormal refraction and negative phase velocity) depending on the ordered collection of subwavelength meta-atoms and their interactions, enabling plenty of innovative EM devices, including perfect absorbers[13], holographic imaging [14-18], high-gain antennas [19, 20], flat lens [21-24], and compact polarizers [25]. Within such a framework, the increasing technical demand for multifunctional and reconfigurable EM devices whose features can be engineered according to the adaptive requirements have boosted the interest toward the new insight of active metasurfaces with tunable and switchable functionalities. Active
metasurfaces capable of dynamic manipulations of electromagnetic waves in real time can give an extremely wide number of degrees of freedom for designing innovative adaptive systems and mitigate some significant drawbacks of passive metasurfaces such as narrow bandwidth and tolerance sensitivity [26-29]. Compared to mechanically-deformed tuning strategies based on dependence of electromagnetic response on structural variations, such as changing the lattice constants, resonator shapes or spatial arrangements under various external stimuli, the tuning strategies employing active components or materials including varactor diodes, semiconductors, liquid crystal and graphene can operate at a significantly faster speed and reduce the fabrication complexity [30-32]. As a straightforward way to achieve EM reconfigurability, the incorporation with active lumped elements (PIN or varactor diodes) at the subwavelength scale has been initially validated in metamaterials at radio-frequencies and then extended to other applicative scenarios [33-40]. However, the development of reconfigurable metamaterials within active lumped elements still face severe challenges in terms of flexibility, bandwidth, efficiency and costs due to the mandatory need of bias networks and control logics that are crucial for practical applications of tunable metasurfaces.

Graphene, a planar monolayer of carbon atoms that arranged in honeycombed structures, has recently triggered very intense and multidisciplinary research efforts since the advent of free-standing graphene sheets in 2004 [41-43]. Due to the linear dispersion relation of Dirac electronic states, graphene exhibits a large wide of interesting properties such as high carrier mobility, broadband operation, and a tunable band gap. The EM properties of graphene can be described by the surface conductivity which is originated from the contributions of electron transition related to the Fermi level. Importantly, the Fermi level and the corresponding charge carrier density of graphene can be drastically modified by either electrostatic or magnetostatic gating or via chemical doping, which leads to the dynamically tunable material properties [44-46]. Therefore, graphene has positioned itself as a very promising platform for active metasurface systems where graphene and resonators promote each other enabling strengthen the interaction of EM waves, and the tunable property of graphene in turn modulates the EM response of metasurfaces [47-50]. However, the outstanding tunable properties of graphene are expected to uncover best in higher THz region [51, 52] while do not provide the results expected in microwave band (considered as very lossy material), which causes some doubts regarding the possibilities to use graphene for microwave devices. Owing to the progresses in manufacturing high-quality and large-scale graphene [53-58], microwave active metasurfaces based on graphene have been studied widely and constantly with a plenty of theoretical designs and several experimental breakthroughs.

The aim of this paper is to survey the latest progress in the field of graphene-based microwave metasurfaces and RF devices and provide a comprehensive and balanced discussion on current trends and envisaged future research developments. Toward this end, the outline of the paper is as follows: The property and tuning method of graphene in microwave frequencies will be firstly introduced (Section 2) and their applicability in absorbers (Section 3), beam steering (Section 4), multifunctional metasurfaces (Section 5), reconfigurable antennas (Section 6.1), and attenuators (Section 6.2) will be reviewed and discussed. At the end, some conclusions are eventually drawn (Section 7).

2 Tunable EM Propriety of Graphene

The EM response of graphene is determined fundamentally by its dynamic surface...
conductivity closely related to chemical potential or Fermi level. In the absence of magnetic bias, the surface conductivity of graphene originated from the contribution of intra-band and inter-band transitions can be modelled by the well-known Kubo formula derived with the random phase approximation (RPA) theory [59, 60]:

\[
\sigma(\omega, \mu_c, \Gamma, T) = \sigma_{\text{inter}}(\omega) + \sigma_{\text{intra}}(\omega) = -\frac{e^2}{4\pi\hbar} \ln \left[ \frac{2|\mu_c|}{2|\mu_c| + (\omega - j2\Gamma)\hbar} \right] + \frac{e^2 k_B T}{4\pi\hbar(\omega - j2\Gamma)k_B T} \left[ \frac{\mu_c}{k_B T} + 2 \ln \left( 1 + e^{\frac{\mu_c}{k_B T}} \right) \right], \tag{1}
\]

where \( e \) is the charge of an electron, \( \hbar \) is the reduced Planck’s constant, \( k_B \) is the Boltzmann’s constant, \( T \) is temperature, \( \omega \) is the angular frequency, and \( \mu_c \) is graphene’s chemical potential. On the condition of \( \hbar\omega < 2|\mu_c| \), which holds at THz and lower frequencies for moderate \( \mu_c \), the energy of EM waves is insufficient to excite the inter-band transition of electrons bound by covalent bonds in graphene. Thus, the inter-band part in Equation (1) can be neglected and graphene’s surface conductivity depends only on intraband contributions which can be expressed as:

\[
\sigma(\omega, \mu_c, \Gamma, T) = -\frac{e^2 k_B T}{\pi\hbar(\omega - j2\Gamma)} \left[ \frac{\mu_c}{k_B T} + 2 \ln \left( 1 + e^{\frac{\mu_c}{k_B T}} \right) \right]. \tag{2}
\]
Figure 1: (a) Real and (b) imaginary parts of surface conductivities of graphene under different chemical potentials. (c) Schematic view of (c) direct gating the graphene sheet and (d) a graphene-based sandwich structure. The working principle of graphene-based sandwich structure at (e) diffusion and (f) accumulation states [61]. (g) Variation of the chemical potential of graphene as the bias voltage increases from 0 to 5 V.

Figures 1(a) and 1(b) show the calculated surface conductivity of graphene based on Equation (2). It is seen in microwave band that the real part of graphene’s surface conductivity can be dynamically modulated by the chemical potential while the imaginary part of graphene is almost zero. Therefore, graphene could be considered as a frequency-independent material at microwave frequencies with nearly resistive conductivity controlled by chemical potential. As one of traditional methods to shift the chemical potential of graphene, the configuration of direct gating the graphene sheet is shown in Fig. 1(c), where the graphene sheet is transferred onto a SiO₂/Si wafer and the bias voltage is applied to graphene and Si substrate. The difference of electrostatic
potentials between graphene and Si substrate causes the injection of more carriers into the graphene and finally shifts the chemical potential of graphene. An approximate closed-form formula to determine the chemical potential $\mu_c$ by bias voltage $U$ is given by:

$$\mu_c \approx \hbar v_F \sqrt{\pi \varepsilon_r \varepsilon_0 U / \epsilon_t},$$

where $\varepsilon_r = 3.9$ is the relative permittivity of silicon dioxide, $\varepsilon_0$ is the permittivity of vacuum and $v_F \approx 10^6$ m/s is the Fermi velocity in graphene. The relation of chemical potential to bias voltage in the direct gating structure (blue dashed line) is shown in Fig. 1(g) showing that the chemical potential slowly increases to 0.15 eV when the bias voltage is set to 5 V. In order to improve the doping efficiency, the graphene-based sandwich structure (GSS) is proposed as shown in Fig. 1(d). The GSS consists of two large-sized graphene sheets on flexible polymer support and electrolyte medium between them. The tuning mechanism of the GSS is illustrated in Figs. 1(e) and 1(f) [61]. Without bias voltage, positive and negative ions float freely in the electrolyte layer and is referred as the “diffusion” state. When a voltage bias applies homogeneous electric field between the top and the bottom graphene sheets, this field polarizes the electrolyte and forms ionic layers on the graphene–electrolyte interface with opposite polarizations, which is referred to the “accumulation” state. Due to the ions of the electrolyte have very low mobility, they cannot respond to the electric field of microwaves. Unlike directly applying voltages between the graphene and Si substrate with linear drops, the GSS method enables the voltage drops sharply at the electrolyte layer (in a few nanometers), which generates very large electric fields under a safety bias voltage. Figure 1(g) demonstrates that the chemical potential rises sharply as the increase of the bias voltage in the configuration of GSS. Compared to direct bias method, the significant advantage of GSS method is the higher chemical potential of graphene under the same bias voltage level. Owing to the unique EM properties and the efficient tuning method, graphene endows various applications with diverse tunabilities, such as shifting the operation frequency, modulating the efficiency of wavefront shaping, and switching among multiple functionalities, as will be detailed in Sections 3-6.

3 Graphene-based Tunable Absorbers
Since graphene is nearly resistive at microwaves, a straightforward application is to design high efficiency metasurface absorbers. Over the past decades, absorbers are widely used in both civil and military fields for reducing the interference of EM waves and radar cross section of object \cite{65, 66}. Facing the increasing complexity of EM environment, traditional microwave absorbers such as Salisbury or Jaumann screen have the drawback of relatively fixed bandwidth or bulky dimensions. Introduction of graphene into the design of absorbers opens an exciting route to dynamically and actively taming the absorptive performance in a desired manner. The review of this session is classified by the EM functionalities as amplitude-modulated absorbers and frequency-shifted absorbers.
3.1 Amplitude-Modulated Absorbers

According to the naturally thin, frequency-independent, and tunable resistive properties of graphene, it is regarded as a promising absorbing material in amplitude-modulated microwave absorbers. In 2015, Balci et al. [45] presented an electrically switchable radar-absorbing surface based on GSS. By applying bias voltages to graphene layers, the carrier density of graphene and their Fermi levels could be dynamically tuned, which in turn change the microwave absorptivity of graphene from 21% and 45%. They also fabricated Salisbury screen absorber by replacing the traditional resistive film with the GSS and demonstrated its electrically tunable absorptivity with highest reflectivity of $-68$ dB can be achieved at an operational voltage of 1.5 V. Later on, using a similar graphene-based active Salisbury screen structure, voltage-controlled resonant absorption and step-like phase shifting were realized simultaneously by the same group [67]. These works all focus on the graphene-based Salisbury screens whose thicknesses are fixed to nearly a quarter of the operating wavelength. On the other hand, metasurfaces perfect absorbers have been extensively studied for achieving extremely absorption within deeply subwavelength profiles [68, 69]. In order to reduce the thickness and expand the working bandwidth, a large amount of investigations on graphene-based metasurfaces have been presented in the past few years. The basic idea is a subwavelength pattern made of graphene or hybrid graphene/metal that enhances the EM resonance, and therefore several outstanding features can be realized. Recently, a low profile dynamically tunable microwave absorber was experimentally demonstrated [62]. By combining GSS with metallic high impedance surface, tunable reflection can be achieved from $-30$ dB to $-3$ dB at the operating center frequency of 11.2 GHz. Compared to previous works, the entire thickness of this absorber is only 2.8 mm, nearly one tenth of the operating wavelength, which promotes the practical applications of graphene-based metasurfaces at microwave frequencies. Similar configurations have been implemented to improve the working bandwidths. Song et al. [70] proposed a broadband and active radar absorber by integrating GSS with resistive frequency-selective surfaces, showing a tunable reflectivity ranges from $-4.6$ dB to $-13.5$ dB controlled by bias voltages. Moreover, the proposed absorber can achieve a wideband absorption from 3.3 to 16 GHz with the fractional bandwidth of about 132% at the bias voltage of $-1.5$ V. The tunable graphene-based absorbers reported in previous literature obtain the desired absorption under a pre-set normal incidence of EM waves, the angular characteristic is also an significant factor in some applications. Actually, the absorption performance will deteriorates as the incident angle deviates from the vertical angle due to the mismatch of the wave impedance between free space and the metasurface under oblique incidence. In 2019, Zhang et al. [63] experimentally demonstrated electrically tunable broadband coherent perfect absorption using GSS in a waveguide system. Notably, the frequency-independent coherent perfect absorption could be realized for either TE or TM polarization at incident angles up to $80^\circ$ by electrically gating the Fermi level of graphene in a relatively low range from 0 to 0.22 eV. Later on, an angle tunable absorber working at TM polarization is realized in the graphene-based metausurface, achieving perfect absorption covering a wide range of incident angles [64].

3.2 Frequency-Shifted Absorbers

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Figure 3: (a) Multilayer square-patterned graphene absorber and (b) its absorption spectrum at various patterned graphene layers [71]. (c) Schematic of the absorber consisting of patterned multilayered graphene and (d) its tunable absorption for different sheet resistances [72]. (e) Three-dimensional views of the proposed graphene-based tunable metasurface. (f) Photograph of the fabricated samples of GSS and active high impedance surface. (g-h) Experimentally measured reflection spectra for different bias voltages $U_2$ and $U_1$ applied to varactor diodes and GSS [61]. (i) Schematic model of the polarization-insensitive absorber based on GSS and varactor-loaded metausurface. (j) Photograph of the fabricated samples of varactor-loaded metausurface; (k) its reflection coefficients with different values of the sheet resistance of graphene and the varactor capacitance. (l) Measured reflection characteristics of the fabricated sample under normal incidence at the bias voltage applied to graphene [73]. (m) Schematics and (n) photograph of the
frequency-shifted absorber. (o) Absorption coefficients of the frequency-shifted absorber as a function of the frequency and the resistivity of graphene. (p) The measured absorption coefficients under different sheet resistances of the graphene [74]. (q) Schematic diagram and (r-s) photograph of the transparent and flexible metasurface. (t) Dynamically tunable absorptivity of the transparent and flexible metasurface with different sheet resistances of graphene [75].

Due to the nearly pure resistive conductivity of monolayer graphene at microwave frequencies, the amplitude modulation is a fundamental function in graphene based metasurface while it is still difficult to alter the phase response of EM waves that hampers the realization of frequency-shifted microwave devices. Therefore, it is still elusive to achieve the advanced and simultaneous control of the frequency and amplitude responses although it is highly demanded in microwave absorbers. In 2017, Yi et al. [71] experimentally presented a mechanically reconfigurable absorber with square-patterned graphene on a PET substrate. Although lacking of dynamically tuning, this absorber exhibit different resonant frequencies from 12.5 GHz to 13.3 GHz and 12.3 GHz to 13.5 GHz by utilizing graphene with different sheet resistances or stacking the graphene/PET layers. Chen et al. [72] proposed a microwave metasurface absorber with reconfigurable bandwidth using multilayer graphene based frequency selective surface. Different working bandwidths can be obtained by using multi-layered graphene with different sheet resistances, which could be realized by simply changing its growth temperature. More recently, Zhang et al. [61] reported a tunable metasurface based on the combination of a GSS with a varactor-loaded active high-impedance surface, as shown in Figs. 3(a-b). Such an electrically dual-tunable scheme has been validated in a single polarization that the continuous frequency tuning from 3.4 to 4.55 GHz and resonant reflection from $-3$ to $-35$ dB can be controlled by two independent bias voltages, as shown in Figs. 3(c-d). Later on, Huang et al. [73] have improved the polarization response of the combination of a GSS with an active surface which enabling the independent control of frequency and amplitude for both $x-$ and $y-$polarized incidence [see Figs. 3(e-h)]. In addition to integration of graphene with active resonators to achieve dual functions of frequency-shift and amplitude-modulation, the structured graphene with sub-wavelength patterns is another effective solution to solely realize the dynamic modulation of absorption frequency. In 2020, Geng et al. [74] proposed a dynamic gigahertz-band frequency tunable absorber based on a patterned graphene metasurface. By applying external bias voltage, the proposed absorber achieves the continuously shift of the central frequency from 13.9 to 16.4 GHz while maintaining high absorption over 92%. The whole thickness is only one sixteenth of wavelength, which opens a novel way of tunable and ultra-thin microwave absorber. Furthermore, owing to the nearly perfect transmittance (97.7%) of visible light with the thickness of 0.34 nm, graphene shows natural compatibility with transparent and flexible microwave absorbers applied in some special scenarios, such as camouflage of cockpit’s windows and sophisticated optical machines. In 2021, Zhang et al. [75] experimentally proposed an optically transparent and flexible microwave metasurface absorber with tunable absorption for the first time. As shown in Fig. 3(m-p), such a metasurface absorber is made of patterned GSS backed by an ITO film with the thickness only about 1/13 wavelength. Controlling by the bias voltage applied to the patterned GSS, the absorbing band of the proposed metasurface absorber can be continuously shifted among single band (13 GHz), dual band (7 and 17.6 GHz), and wide band (7–18 GHz).

4 Graphene-based Beam Steering

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Arbitrary manipulation of EM wave is of great importance in both physics and engineering fields. Especially, dynamic wavefront shaping is a highly-desirable feature towards practical applications including, but not limited to radar detection and wireless communication [79-84]. Metasurfaces have been applied with great success for efficient wavefront shaping due to their compactness and flexibility compared to conventional lens. Actually, the phase shift should cover the range of $2\pi$ with a uniform amplitude response to realize full wavefront control. The concept of digital metasurfaces described through $n$-bit coding elements with gradient phases further simplifies the design and optimization procedure of controlling wavefront. [31, 85-89] In reality, although it is difficult to achieve full control of wavefront at microwave frequencies due to the inability of graphene to changing the phase covering by a complete $2\pi$ with uniform amplitudes, the need of only binary phase distribution with phase difference of $\pi$ in 1-bit coding metasurface greatly increases the possibility of graphene-based wavefront control. Inspired by the concept of a coding metasurface, Chen et al. [76] investigated the microwave beam reconfiguration based on graphene ribbons, where excellent agreements have been achieved between measurement and simulation results. However, these designs are not really dynamically reconfigurable. Later on, they further experimentally presented programmable graphene metasurfaces achieving dynamic wavefront shaping for the first time in 2020 [77]. A graphene-based unit cell with different bias voltages was designed to act as “0” and “1” elements in the digital metasurface, providing an opposite phase and nearly equal amplitudes. After arranging the “0” and “1” elements to form arrays in accordance with their phase distributions, the dynamic control of reflected wavefronts have been realized by applying bias voltages to graphene. As shown in Fig. 4(d), the main beam of the measured scattering wavefront undergoes a shift from...
around 23° to 53° with the change of voltage sequences. However, the main shortcoming in this work is that the binary phase response lies on the resonance of patterned graphene and metal structures, leading to the reasonably weak reflection (about 0.3) due to the high loss of graphene in microwave. In the same year, Zhang et al. [78] proposed another feasible scheme that directly introduce independent amplitude modulation into phase coding metasurface to dynamically manipulate the wavefront at microwave frequencies. In view of this thought, a novel graphene-based digital coding metasurface was designed and fabricated by the combination of GSS and metallic array of binary coding elements. Different from Chen’s work, the binary phase distribution is mainly determined by two kinds of metallic resonators to avoid the resonant loss in graphene. When applying bias voltages on the graphene layer, continuous amplitude modulation can be achieved for the specific elements while the others are not affected. In this way, two degrees of freedom, pre-set phase coding and dynamical amplitude modulation are realized in single metasurface that can perform continuously tunable scattering patterns from directive reflection to diffusion.

5 Multi-functional Metasurfaces

Figure 5: (a) Schematics of the graphene-driven multi-functional metadevice and its meta-atom. (b) Measured reflection and (c) transmission curves of the graphene-driven multi-functional metadevice under the different bias voltages [90]. (d) Schematic model and photograph of the graphene-based active frequency selective surface and measured S-parameters under normal illumination with different bias voltage applied to the graphene in (e) absorption and (f) transmission modes [91]. (g) Schematic model of the multi-functional reconﬁgurable metasurface based on patterned graphene and PIN-loaded structure. (h) Measured absorbing performance of the fabricated sample with the different voltages [92]. (i) Graphical representation,
Apart from the applications of absorber and beam steering, graphene can also be used in multifunctional metasurfaces to realize dynamic manipulation of EM waves in different modes, frequencies, or polarizations. For example, a multifunctional electrically tunable metasurface was proposed for dynamical manipulation of the reflectivity and simultaneous high-efficiency transmission at two different frequency bands [90]. Such a metasurface is fabricated by integrating GSS with a multi-layered passive metasurface. By applying bias voltages on graphene layer, experimental results verified that this metasurface achieved dynamical control of the reflection amplitude from $-5$ dB to $-20$ dB over a wide band of 5-15 GHz, while kept nearly transparent from 23-25 GHz with high transmittance of nearly $-3$ dB. Furthermore, Huang et al. [91] presented a multi-functional active metasurface for both transmission and absorption modes based on the combination of the PIN diode switching and graphene tuning techniques. Specifically, the PIN-loaded metallic structure enables the dynamical EM switching between transmission and reflection by regulating the bias states of PIN diodes, while the graphene capacitor layer was employed to achieve the amplitude modulation by varying the graphene’s resistance. The experimental results show the absorption works at 5-8.4 GHz with the tunable absorptivity from 0.65 to 0.95 and the switchable transmission mode operates at 6-7 GHz with the tunable insertion loss tuned between 1.1 and 4.8 dB. Apart from achieving multi-functionalities in aspect of working mode including transmission and reflection, the concept of combination of GSS and PIN-loaded active metasurfaces can also be exploited to achieve other functionalities. For instance, a multi-functional active metasurface based on the similar combination of the GSS and the PIN-loaded metallic structure layer is reported in 2020 [92]. Via the external control of bias voltage, the GSS can dynamically modulate the reflection amplitude of the active metasurface, while the binary phases are distributed by switching the PIN diodes. In the merit of these two tunable EM features, the directions of the scattering wave can be dynamically manipulated through the phase coding metasurface while the intensity of each beams can also be further modulated by changing the resistance of graphene. Another multi-functional metasurface based on GSS and active structure is proposed to dynamical control the multiple responses of EM waves including working frequency, bandwidth, and amplitude[93]. By controlling the characteristics of graphene and PINs through the external bias voltages, the metasurface can not only achieve the switchable absorptive bandwidth from ultra-wide band to narrow band, but also modulate the amplitude at all of the working frequencies. These works provide much more degrees of freedom and open an avenue of flexibly controlling full responses of EM waves for multi-functional manipulation, which could be developed for potential applications in smart and reconfigurable EM devices and systems.

6 Graphene-based Antennas and RF Devices

6.1 Pattern Reconfigurable Antennas
Figure 6: (a) Optical image of the fabricated graphene based antennas. (b) Photograph of the fabricated sample and the measurement setup. (c) $S_{11}$ in X band for three different bias voltages: 0 V (solid black trace), 50 V (dashed trace), and -200 V (solid grey trace) [94]. Graphical representation of the frequency reconfigurable antennas for (d) WiFi and (e) LTE applications. Reflection coefficients for (f) the WiFi design and (g) LTE design with intermediate sheet resistance of graphene [95]. (h) Configuration of the pattern reconfigurable Vivaldi antenna. (i) Radiation patterns in the $H$ and $E$ planes of different states of graphene [96]. (j) Schematic and (k) photographs of the pattern-reconfigurable antenna and its Tunable far-field pattern of the array antenna at 4.5 GHz [97].

Reconfigurable antennas have received significant attention for their potential to enhance the radiation beam performance. Alternating the antenna patterns can enable steering the radiation beam toward target direction and avoiding multi-path fading and interference in noisy environments [98-102]. The perspectives of graphene-based antennas in microwave frequencies are very limited due to the input power dissipation originated from the losses of graphene. Therefore, pattern reconfigurable antennas based on graphene for microwave applications have been rarely reported. A microwave slot antenna in a coplanar configuration based on graphene was presented in 2015 [94]. As shown in Fig. 6(a), the rectangular patch is made of graphene and separated by a slot from the rest of the gold circuit. The outer gold electrodes are grounded while the central electrode is excited by the microwave signal. The measured overall reflection losses of...
the graphene-based antenna under different bias voltage are plotted in Fig. 6(c). It is seen that two resonances located at 8.8 GHz and 11.4 GHz corresponding to the minimum $|S_{11}|$ values of $-12.2$ dB and $-13.4$ dB, respectively, when there is no applied DC bias. When the bias voltage changes to 50 V and 200 V, the resonances are shifted left or right about 24 MHz. Later on, Alvarez et al. [95] presented two reconfigurable antennas based on hybrid metal-graphene structures in microwave range for WiFi and LTE applications. Although the antenna’s efficiencies and gain with graphene is still lower compared to other technologies, the proposed structure indeed allowed large frequency tunability of 1.2 GHz and improved bandwidth of 225 MHz. In 2020, Chi et al. [96] proposed a real pattern reconfigurable graphene-based antenna consisting of a pair of back-to-back modified Vivaldi antennas with two graphene nanoplate pads symmetrically loaded on the feed line. The graphene nanoplate with controllable resistance under bias voltage was applied to the design of a pattern reconfigurable antenna for the first time. By applying different bias voltages, the radiation pattern of Vivaldi antenna can be shifted from two opposite beams to one single beam. The experimental results also show that the proposed antenna is capable of switching its radiation beams at 90° and/or 270°, which can be further extended to various pattern reconfigurable antennas. Almost at the same time, Wang et al. [97] presented a graphene-based reconfigurable antenna with voltage-controlled radiation patterns in the microwave frequency band. As shown in Fig. 6(j), the proposed antenna consists of two metal patches with the planar feed network mainly composed of a graphene-based attenuator and a power divider with a hybrid graphene–metal phase shifter. In this way, the output phase of the phase shifter can be dynamically changed by a bias voltage on the graphene. The measured results in Fig. 6(l) show the two operating states with different beam directions when the bias voltage is between 0.7 and 5 V. Although the graphene-based antennas reported before enable the reconfigurable features such as operating frequency, reflection loss, and radiation pattern, it is still confronted with challenges in practical applications which mainly due to the lower radiation efficiency compared with metallic antennas.

6.2 Tunable Attenuators
Figure 7: Graphene-based attenuators on (a) half-mode SIW [103] and (b) SIW [104]. (c) Exploded views of the attenuator on SIW. The inset below exhibits the cross section of substrate. The inset above presents the structure of an L-shaped GSS. Black, green, and brown represent the graphene monolayer, diaphragm paper soaked with ion liquid, and cellulosic paper with carbon paste brushed on it. (d) Insertion loss versus surface impedance of graphene at 9 GHz. Comparison between the simulated and measured (e) $|S_{21}|$ and (f) $|S_{11}|$ of the attenuator. (g) Graphene-based attenuator on microstrip line [105]. (h) Tunable grounded coplanar waveguide attenuator based on graphene nanoplates [106]. (i) Graphene-based attenuator on slot line [107]. (j) Spoo surface plasmon polaritons attenuator based on graphene [108]. (k) Flexible attenuator based on spoof surface plasmon polaritons waveguide loaded with graphene [109]. (l) Multi-functional attenuator based on spoof surface plasmon polaritons waveguide loaded with graphene [110].

An attenuator is a significant device in microwave systems or RF circuits to weaken the signal down to the desired level for the improvement of the contiguous circuit stability. Attenuators have more potential advantages in various communication systems if their...
performance can be dynamically controlled. For this reason, the PIN diodes, varactor diodes, and FETs have been utilized to build tunable microwave attenuators in previous works. However, the bias circuit to controlled these active components is relatively complex that hinder the practical performance of applications. As an ultra-thin two-dimensional and tunable resistive material at microwave frequencies, graphene is an excellent candidate in developing the flexible and tunable attenuators\[106-109\]. The graphene-based attenuators on substrate integrated waveguide (SIW) and half-mode SIW achieving dynamically tunable attenuation are proposed in 2018 \[103, 104\]. Figure 7(a-c) show that the graphene-based attenuators was produced by depositing the GSS on the substrate of SIW (or half-mode SIW) as a conductivity-tunable E-plane septa to dissipate the EM field inside the SIW. By applying a bias voltage on the GSS, the surface impedance of graphene and the attenuation of the attenuators can be dynamically tuned. The measured results in Fig. 7(d-f) show that the attenuation operating from 7 to 14.5 GHz ranges from 2 to 15 dB as the bias voltage changing from 0 to 4 V. Furthermore, the return loss of the graphene-based attenuators keeps below −15 dB over the operating band. Due to multi-mode EM fields in the SIW, it is difficult to avoid the bad flatness of attenuation in high frequency band. To overcome this limitation, the designs of attenuators based on micro-strip line, coplanar waveguide and slot line are put forward gradually as shown in Fig. 7(g-i) \[105-107\]. These attenuators show the same tunable attenuation performances controlled by bias voltages while maintain the return loss to a relatively low level in the working band. Recently, the dynamically control of tunable attenuation is extended to flexible spoof surface plasmon polariton (SSPP) transmission line \[108-111\]. Combining GSS and SSPP, the transmission lines can realize attenuation, amplification, and transmission at the microwave frequencies simultaneously, which paves the way to engineer compact, flexible and highly integrated adjustable microwave devices or RF circuits.

7 Conclusions and Outlook

In summary, the recent progresses of graphene-based microwave metasurfaces and RF devices have been reviewed with emphasis on the dynamical control of EM waves. Due to the high surface resistance in microwave frequencies, the electrical properties of graphene controlled by applying bias voltage shows insufficient results for achieving large tunability in microwave metasurface or devices. This leads to wider explorations of new tuning methods, such as graphene-based sandwich structure and the combination with active components, and thus the microwave tunable metasurfaces and devices based on graphene have been experimentally investigated constantly in the past three years. This paper has presented a brief overview of the graphene-based tunable microwave metasurfaces and RF devices applied to tunable absorbers, beam steering, reconfigurable antennas, tunable annuators and so on.

The behavior of graphene-based devices is tightly associated with the graphene material itself. Although large-scale and high-quality graphene is desirable has been realized by chemical vapor deposition. However, the following transfer process and doping method need be optimized to minimize the damage to graphene sheet. Plenty of novel mechanisms including surface plasmon resonance, quantum dot doping, and resonant cavity structures can be introduced to substantially improve the control of graphene’s properties. On the other hand, investigations of materials for metamaterials with felexible, tunability, optical transparent, and CMOS compatibility have been very active in recent years. It can be predicted that grahene offers great advantages in flexible metamaterials that promise the potential of integration with other components and non-planar structures. The advancement of graphene with high-resolution micro-scale patterns holds the key
to the future of flexible meta-device. We believe that future progresses on graphene-based functional metasurfaces and devices will receive increasing attentions and development, enriching the novel microwave devices and addressing challenges for the next generation microwave technologies.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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Owing to its particular structure and unique features of graphene, metasurfaces integrated with graphene enable dynamic manipulation of the electromagnetic waves in multiple dimensions such as amplitude, frequency and radiation patterns. The recent progresses of graphene-based microwave metasurfaces and related devices, involved but are not limited to tunable absorbers, beam steering, reconfigurable antennas, and attenuators are reviewed in this paper which enriching the experimental developments of graphene in microwave region.
