Graphene-based terahertz closed-stopband tunable composite right/left-handed leaky-wave antennas

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Abstract
A simple scheme for the realization of the terahertz (THz) fundamental-mode tunable closed-stopband composite right/left-handed leaky-wave antennas (CRLH LWAs) is presented. The proposed CRLH LWAs are reconstructed by graphene-based coplanar waveguide (CPW) transmission line supercells. Their shunt inductances achieved by narrow graphene strips of two unit cell structures are halved. The CRLH LWAs are designed and confirmed by numerical simulations. They also exhibit frequency-scanning behaviors at THz with narrower bandwidth than that of the conventional graphene-based fundamental-mode CPW unit cell CRLH LWAs at THz. Besides, the LWAs also exhibit strong tunable characteristics and achieve the closed-stopband condition more effectively. Therefore, the proposed supercell CRLH LWAs could further improve the performance of the beam-steering antennas at THz.

Keywords Graphene · Tunable · Terahertz (THz) · Supercell · Narrow-band · Composite right · Left-handed (CRLH) · Leaky-wave antennas (LWAs)

1 Introduction

With the rapid development of the transmission rates of wireless communication, radar, and satellite systems, terahertz (THz) antenna technology is a hot research area (Yang et al. 2016; Kemp 2003). Graphene metamaterial attracts lots of attention for its potential on the development of antennas at THz, especially in the mid-infrared region due to its unique electronic properties, strong tunable characteristics, and high electron mobility (Correas-Serrano et al. 2015; Novoselov et al. 2012).
In recent years, thanks to the strong tunable characteristics of graphene, many special graphene-based leaky-wave antenna (LWA) designs in which main radiation beams scan with the variation of graphene’s chemical potential have been proposed (Cheng et al. 2017; Liang et al. 2018). Comparing to these LWAs, the CRLH LWAs have more advantages, such as ease to integrate and excite, frequency variable, and so on. However, due to the complex structure of CRLH LWAs, they have great difficulty adapting to the fabrication requirements of THz.

There are already lots of literature on the realization of composite right/left-handed (CRLH) LWAs at THz with configurations that are simple enough to be fabricated at THz. Philip has proposed the cavity antenna model for the CRLH LWAs in the THz band by the TM01 lateral mode of the reconstructed metal–metal waveguide (Hon et al. 2012). Besides, TM01 lateral mode has also been proposed to be employed in other structures for the achievement of CRLH LWAs at THz (Hon et al. 2013; Liu et al. 2012). Some of these theories have been proved by experiments then (Liu et al. 2012; Tavallaee et al. 2013). Besides, graphene has also been supposed to have the potential for the development of the CRLH LWAs in the THz band. Derrick argues that CRLH LWAs can be realized through the first higher-order lateral mode propagated along the graphene ribbon with periodic gaps (Chu et al. 2016).

Graphene-based coplanar waveguide (CPW) technology could also be applied for the development of the conventional CRLH LWAs at THz for their simple structure. In many application cases, the CRLH LWAs should satisfy a closed-stopband demand. However, the conventional graphene-based CPW unit cell CRLH LWAs cannot completely close the stopband. Therefore, the implementation of the graphene-based CPW supercell technology is supposed to realize the CRLH LWAs at THz with closed-stopbands (Mehdipour and Eleftheriades 2014).

The graphene surface impedance in a pure graphene-based CPW unit cell could be equivalent to the series resistance and inductance components, while the gap between the ground and the signal line is equivalent to the shunt capacitance components as shown in Fig. 1a. In addition, the periodically grounded narrow straight/meander graphene strips in the graphene-based CPW unit cell CRLH LWAs could be equivalent to the shunt inductance components, and the parallel-plates periodically added along the signal line could be equivalent to the series capacitance components.

In this paper, the graphene-based CPW supercells are reconstructed to achieve the narrow-band CRLH leaky-wave structures as Fig. 1b shows. Their equivalent circuit model is given in Fig. 1c and d. Their narrow graphene strips for realizing the shunt inductance components $L_L$ are halved of each two conventional graphene-based CRLH unit cells. CST verified the proposed leaky-wave structures. Their dispersion relation is extracted from the designed leaky-wave supercell structures and its leaky-mode regions are acquired. The simulation results indicate that the scanning angle of their main radiation beams also steers obviously with the frequencies scanning from the backward-to-forward quadrant at THz. Besides, the proposed supercell CRLH LWAs achieve the closed-stopband condition more effectively than the conventional graphene-based unit cell CRLH LWAs. Furthermore, the strong tunable characteristics of the proposed supercell LWAs are discovered at THz as well. Comparing to the LWAs proposed in Cheng et al. (2017), Liang et al. (2018), the graphene-based CPW supercell LWAs could operate in the fundamental-mode instead of higher-order mode, which is a great breakthrough. This enables the LWAs to have integrable characteristics and easy to be excited. Hence, the proposed supercell LWAs would further improve the performance of beam-steering antennas at THz.
2 Model analysis

2.1 Surface impedance of graphene

The proposed supercell CRLH LWAs are developed by graphene metamaterial. In the low THz band (< 10 THz), the surface conductivity of graphene is mainly dominated by the intraband conductivity as (Fuscaldo et al. 2017)

\[
\sigma = \frac{2e^2 k_B T}{(\tau^{-1} + j\omega) \pi \hbar^2} \ln \left[ 2 \cosh \left( \frac{\mu_e}{2k_B T} \right) \right]
\] (1)
where \( \omega \) is the radian frequency, \( \mu_c \) is chemical potential, \( \tau \) is the electron relaxation time, \( T \) is temperature, \( e \) is the charge of an electron, \( h \) is the reduced Planck's constant, and \( k_B \) is Boltzmann constant.

The surface impedance \( Z_s \) of the graphene sheet could be obtained from the surface conductivity \( \sigma \) of graphene as:

\[
Z_s = \frac{1}{\sigma} = R_s + jX_s
\]

By using the equivalent circuit model directly obtained from the analysis of the surface impedance \( Z_s \), the explanation for the periodic equivalent circuit model of the graphene-based CRLH LWAs is easier.

2.2 CRLH leaky-wave supercell structures

Graphene-based CPW technology could be used for achieving the fundamental-mode CRLH LWAs at THz. The parallel-plates are periodically added along their signal line to achieve the series capacitance components \( C_L \). Their signal line and ground planes are periodically shorted by narrow straight/meander graphene strips to realize the shunt inductance components \( L_L \).

CPW supercell technology achieves the narrow-band CRLH LWAs in the microwave range (Mehdipour and Eleftheriades 2014). It could also provide a method for the perfect satisfaction of the closed-stopband condition with some proper optimizations. To achieve the narrow-band closed-stopband CRLH LWAs at THz, graphene-based CPW supercell structures are proposed. By removing the narrow graphene strips from each second section of the conventional CRLH leaky-wave unit cell structures, their scanning range is reduced. Moreover, compared with metal material, graphene is more suitable for THz antenna applications. Besides, it will provide a strong tunable characteristic to the development of the fundamental-mode CRLH LWAs at THz.

Silica with the dielectric constant \( \varepsilon_r = 3.9 \) is chosen as the substrate of these THz LWAs so that the fundamental-mode will be well excited in the CRLH leaky-wave structures rather than surface plasmons.

In our work, the thickness of the graphene sheet is set as 1 nm. In addition, to reduce the computation amount of the proposed graphene-based antenna during the simulation process, FDTD mode in CST is chosen.

It is worth mentioning that the fabrication technology of the regular shaped graphene-based nano-devices like the proposed LWA in this paper could reach micron or even nanometer level. Hence, with the current technological conditions, it is quite possible to make such an antenna.

3 Dispersion analysis

The scan angle \( \theta \) of the main radiation beam can be expressed by Caloz and Itoh (2005)

\[
\theta(\omega) = \sin^{-1} \left[ \frac{\beta(\omega)}{k_0} \right]
\]

where \( \beta(\omega) \) is the phase constant of this leaky-wave structure, \( k_0 \) is the wavenumber of the free space.

The dispersion diagram for the CRLH leaky-wave structure supercells with a period length of \( 2L \) can be obtained by the simulated \( ABCD \) matrix elements as (Mehdipour and Eleftheriades 2014).
\[ \beta \cdot 2L = \cos^{-1} \left( \frac{A + D}{2} \right) \] (3)

Under the detailed illustration above, two graphene-based closed-stopband CRLH unit cells and supercell leaky-wave structures with narrow graphene straight strips loaded are designed and printed on the silica with a thickness of 1 \( \mu \text{m} \). Their chemical potential \( \mu_c \) and relaxation time \( \tau \) of the graphene is 1 eV and 25 ps, respectively. CST simulates and extracts their \( ABCD \) matrix elements to obtain the dispersion diagram as is shown in Fig. 2.

As Fig. 2 shows, the two designed leaky-wave structures both present a CRLH behavior. Besides, it also proves that the proposed graphene-based CPW supercell structures have a narrower leaky-mode region compared with the conventional unit cell structures.

The LH and RH regions of the graphene-based CRLH supercell structures are an almost seamless transition at around 3.6 THz. It is known that the leaky-mode region is between the intersection of the air line and the dispersion curve. Thus, the predicted scanning range of the designed conventional graphene-based CPW unit cell CRLH LWA is over about \(-80^\circ\) to \(90^\circ\), and its frequency scanning bandwidth is approximately 0.55 THz from about 3.25 to 3.8 THz. But for the designed CPW supercell LWA, its scanning range and frequency bandwidth are narrower. Even more, its actual scanning band is difficult to be predicted because its air line is easy to beyond the range of its dispersion curve.

4 Narrow-band CRLH LWA at THz

4.1 \( S_{11}\)-Parameters

A graphene-based taper line is implemented as the impedance matching technology for this designed narrow-band CRLH LWA with 9 supercells. The final optimized \( S_{11}\)-parameters of this supercell LWA are shown in Fig. 3.

\[ \frac{\mu}{u_1} \cdot 2L = \cos^{-1} \left( \frac{A + D}{2} \right) \]
Figure 3 shows the $S_{11}$ is below −10 dB from about 3.3 to 3.8 THz. Thus the adopted impedance matching network works well enough and most of the energy fed into this structure is radiated to the free space or transformed into the ohmic loss between this band. Moreover, the leaky-mode region of the designed supercell LWA is also between this band. Besides, as Fig. 3 indicates, its $S_{11}$ has a seamless transition at around 3.5 THz due to the complete satisfaction of the closed-stopband condition which is provided by the employment of the graphene-based CPW supercell technology. Note that, the transition frequency of the designed supercell LWA is at around 3.5 THz as the simulated $S_{11}$-parameters show.

It is also observed that the leaky-mode region and transition frequency obtained from the $S_{11}$-parameters is quite close to the result predicted by the dispersion diagram in Fig. 2. Although there is a slight difference between the predicted results of the designed supercell and its LWA structure, the errors are all in an allowable range.

4.2 Radiation pattern

To demonstrate the frequency scanning behavior of the proposed graphene-based CPW supercell CRLH LWAs, CST simulates the farfield radiation performance of the designed CRLH LWA with 9 supercells, and the simulation results of the radiation patterns at the E-plane are shown in Fig. 4.

Figure 4 shows the radiation patterns of the designed LWA from 3.28 to 3.78 THz. The angle of its main radiation beam steers as the frequency scanning from about −58° to 63°, which is also close to the predicted results from the dispersion diagram. Their radiation beams show that the supercell LWA presents a radiation performance higher than 5 dB between this band. As Fig. 4 indicates, its transition frequency is at about 3.52 THz, which is also close to the prediction from the dispersion diagram. Besides, the magnitude of the radiation beams in the LH region is lower than 8 dB. However, their magnitude in the RH region is higher than that in the LH region as Fig. 4 shows. It is worth mentioning that this is also reasonable in most applications.
A seamless transition of the radiation beams is observed at around 3.52 THz because of the more effective satisfaction of the closed-stopband condition compared with the conventional unit cell LWAs.

Figure 5 show the 3D pattern of the designed narrow-band CRLH LWA at different frequencies. It is observed that its main radiation beams are omnidirectional and steer obvious from the backfire to the endfire as its operation frequencies varied from 3.44 to 3.52 THz and 3.68 THz. Hence, the frequency scanning behavior of the proposed CRLH LWAs is further demonstrated.

4.3 Efficiency

After the farfield radiation performance is obtained, the efficiency of the designed supercell LWA is also given as displayed in Fig. 5. Because of the mismatch cause, its radiation efficiency is reasonable higher than the total efficiency.

Again, as Fig. 5 displays, it is observed that the closed-stopband condition is perfectly satisfied without special weak efficiencies appearing.

Moreover, as is reported in Fig. 5, the efficiency is at a lower magnitude than the metal-based LWA in the microwave range because a dispersive model (Drude model) is used to characterize the graphene metamaterial at THz frequencies. At a low THz band, it is generally adequate to model the material losses with the skin effect (Memarian and Eleftheriades 2015). Thus, the efficiencies of the graphene-based LWAs in the THz band will be a reasonable case as the maximum efficiency reaching 40% at τ equals 25 ps.

Again, as is mentioned in Memarian and Eleftheriades (2015), since a dispersive model introduces more errors to the calculation of THz antenna’s losses, some mismatches of the simulated results between the S11 parameters and the radiation performance would appear.
Fig. 5 3D pattern of the designed narrow-band CRLH LWA at 
a 3.44 THz, b 3.52 THz, c 3.68 THz
However, the variation trend of our simulation results is still worth referring to. In the practical application, the FDTD algorithm used in the simulation needs to be optimized to obtain more accurate results.

5 Tunable characteristics of graphene

5.1 Dispersion tuning

It is well known that the transition frequency of a graphene-based CRLH LWA could be obtained from its series and shunt frequencies as (Caloz and Itoh 2005)

$$\omega_0 = \sqrt{\omega_{se} \cdot \omega_{sh}}$$ (4)

Again, the series and shunt frequency of a graphene-based CRLH LWA could be obtained by its equivalent circuit elements which are related to the surface conductivity or impedance of graphene (Mehdipour and Eleftheriades 2014; Caloz and Itoh 2005). Also, the surface conductivity could be tuned by the chemical potential of graphene as Eq. (1) shows. Hence, the transition frequency of the graphene-based CRLH LWAs is supposed to be tuned by the chemical potential $\mu_c$ of graphene.

As the illustration for the graphene-based LWAs shows, the transition frequencies of the graphene-based CPW supercell CRLH LWAs are also supposed to be tuned by the chemical potential $\mu_c$. To understand how a change in the $\mu_c$ can affect the dispersion characteristics of a graphene-based CPW supercell CRLH LWA, CST extracts the dispersion relation versus $\mu_c$ of the designed CRLH supercell structure and its results are displayed in Fig. 6.

As Fig. 6 shows, with the linear increase of $\mu_c$ from 0.8 to 1.2 eV, the transition frequency also increases from about 3.25 to 3.6 and 3.9THz. Therefore, the transition frequency of the designed narrow-band CRLH LWA could be obtained from its series and shunt frequencies as (Caloz and Itoh 2005)
frequency of the proposed supercell CRLH LWAs could also be changed very flexibly according to actual design demand, which is a capability that metal-based CRLH LWAs is absent as well. This characteristic is also expected to provide the proposed CPW supercell CRLH LWAs with more application fields than the conventional metal-based CRLH LWAs.

5.2 Radiation patterns tuning

Figure 7 confirms that the radiation patterns of the proposed supercell LWAs could be tuned by different chemical potentials $\mu_c$ as 1.5 and 2 eV, respectively. Consider Figs. 4 and 7, it could be observed that the transition frequency of the designed supercell CRLH LWA is shifted from about 3.52 to 4.28 and 4.84 THz by tuning $\mu_c$.

Note that, due to the employment of graphene, the main radiation beams of the proposed supercell LWAs are supposed to be changed through $\mu_c$ varying as the LWAs in Esquius-Morote et al. (2014); (Wang et al. 2015). To describe how this change occurs, the operating frequency of the designed graphene-based CPW supercell LWA is fixed at 3.52 THz which can be extended to the cases of other operating frequencies. The simulated radiation patterns give the scanning angle of its main radiation beams versus $\mu_c$ as shown in Fig. 8.

As Fig. 8 shows, the main radiation beam of the designed supercell CRLH LWA steers obviously as $\mu_c$ varying from 0.9 to 1.1 eV. As is observed from the simulated results, the proposed scheme provides the graphene-based CPW supercell CRLH LWAs with the scanning capability as chemical potential $\mu_c$ varying at THz by employing graphene as well.

![Fig. 7 Dispersion diagram versus chemical potential $\mu_c$](image-url)
5.3 Efficiency tuning

Again, as well as the illustration for the graphene-based LWAs shows, the efficiency of the proposed CPW supercell LWA is also supposed to be tuned by $\tau$.
To understand the change of the efficiency versus $\tau$ of the proposed supercell CRLH LWAs, we also fix the operating frequency of the designed graphene-based CPW supercell CRLH LWA at 3.52 THz. Its simulated results of the radiation and total efficiency are displayed in Fig. 9.

As is shown in Fig. 9, the efficiency increases obviously as the relaxation time $\tau$ increasing. However, the efficiency will reach a limitation above 50%. Note that, we could choose a suitable $\tau$ to obtain the efficiency that satisfies the actual design demand. Again, the maximum radiation efficiency is higher than the presented efficiency of 46% in Memarian and Eleftheriades (2015) with a high relaxation time Fig. 10.

6 Conclusion

A simple scheme for realizing the THz graphene-based closed-stopband CRLH LWAs is proposed in this paper. The narrow-band CRLH leaky-wave structures are achieved by removing the narrow graphene strips from each second section of the graphene-based CRLH leaky-wave unit cell structures. To demonstrate the proposed structures, a CRLH leaky-wave supercell structure is designed and its dispersion relation to leaky-mode regions is extracted. The simulation results indicate that the scanning angles of its main radiation beams also steers obviously with the frequencies varying and a backfire-to-endfire radiation capability is achieved at THz. Besides, the proposed supercell CRLH LWAs could achieve the closed-stopband condition more effectively at the broadside angle. Furthermore, the strong tunable characteristics of the proposed supercell LWAs are discovered at THz as well. Hence, the proposed supercell LWAs would further improve the performance of beam-steering antennas at THz.

Fig. 9 Radiation patterns at E-plane versus chemical potential $\mu_c$ at 3.52 THz
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Data availability  The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interests  The authors declare that they have no conflict of interest.

Consent to participate  The author gives his consent to participate.

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