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

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Keywords: graphene, Terahertz (THz), supercell, composite right/left-handed (CRLH), leaky-wave antennas (LWAs).

Abstract. A simple scheme for the realization of the terahertz (THz) fundamental-mode 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-scannable behaviors at THz with narrower bandwidth than that of the conventional graphene-based fundamental-mode CPW unit cell CRLH LWAs at THz without stopbands. Therefore, the proposed supercell CRLH LWAs could further improve the performance of the beam-steering antennas at THz.

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 [1]. 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 [2].

There is already a lot of literature on the realization of composite right/left-handed leaky-wave antennas (CRLH LWAs) 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 [3]. Besides, TM01 lateral mode has also been proposed to be employed in other structures for the achievement of CRLH LWAs at THz [4,5]. Some of these theories have been proved by experiments then [5,6]. Besides, graphene has also been supposed to have the potential for the development of the CRLH LWAs in the THz band.

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Derrick argues that CRLH LWAs can be realized through the first higher-order lateral mode propagated along the graphene ribbon with periodic gaps [7].

In addition, 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 [8].

In this paper, the graphene-based CPW supercells are reconstructed to achieve the narrow-band CRLH leaky-wave structures as Fig. 1(a) shows. Their equivalent circuit model is given in Fig. 1(b). 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. 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 (<10THz), the surface conductivity of graphene is mainly dominated by the intraband conductivity as [9]

$$\sigma = \frac{2e^2 k_B T}{\left(\tau^{-1} + j\omega\right)\pi\hbar^2} \ln\left[2\cosh\left(\frac{\mu_c}{2k_B T}\right)\right] \quad (1)$$

where ω is the radian frequency, μ_c is chemical potential, τ is the electron relaxation time, T is temperature, e is the charge of an electron, $\hbar$ is the reduced Plancks constant, and k_B is Boltzmann constant.

The surface impedance Z_S of the graphene sheet could be obtained from the surface conductivity σ of graphene as $Z_S = 1/\sigma = R_S + jX_S$. 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.

(a) (b)

Fig. 1. The proposed supercell CRLH leaky-wave structures. (a) Layout. (b) Equivalent circuit model.

CPW supercell technology achieves the narrow-band CRLH LWAs in the microwave range [8]. It could also provide a method for the perfect satisfaction of the closed-stopband condition at THz 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.

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.

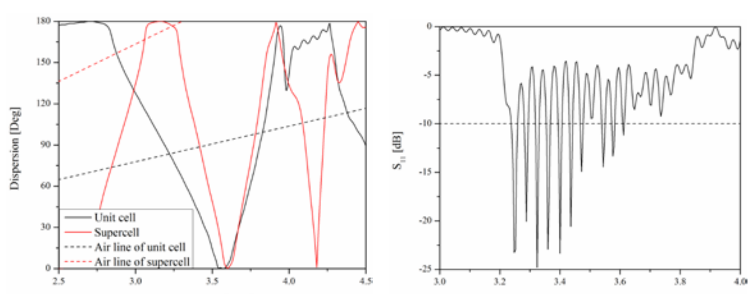
2.3 Dispersion analysis

The scan angle θ of the main radiation beam can be expressed by [10]

$$\theta(\omega) = \sin^{-1}\left[\frac{\beta(\omega)}{k_0}\right] \tag{2}$$

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 $2L$ can be obtained by the simulated *ABCD* matrix elements as [8]



(a) (b)

Fig. 2. (a) Dispersion diagram of the designed CRLH leaky-wave structure unit cell and supercell. The optimized parameters of the unit cell are: $g = 0.4\ \mu$m, $G = 3.24\ \mu$m, $W = 3.24\ \mu$m, $L = 19.9\ \mu$m, $s = 0.1\ \mu$m; the optimized parameters of the supercell are: $g = 0.4\ \mu$m, $G = 3.24\ \mu$m, $W = 3.24\ \mu$m, $2L = 36.6\ \mu$m, $s = 0.4\ \mu$m. (b) Optimized S11-parameters of the designed narrow-band CRLH LWA.

$$\beta \cdot 2L = \cos^{-1}\left(\frac{A+D}{2}\right) \tag{3}$$

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 μm. Their chemical potential μ_c and relaxation time τ of the graphene is 1 eV and 25 ps, respectively. CST simulates and exacts their *ABCD* matrix elements to obtain the dispersion diagram as is shown in Fig. 2(a).

As Fig. 2(a) 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 region of the graphene-based CRLH supercell structures is 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 dispersion curve. Thus, the predicted scanning range of the designed conventional graphene-based CPW unit cell CRLH LWA is over about -80° to 90°, 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.

3 Narrow Band CRLH LWA At THz

***S_{11}*-Parameters.** 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. 2(b).

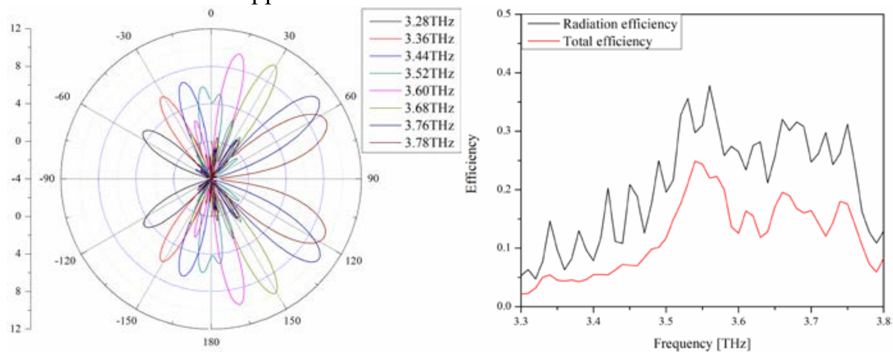
Fig. 2(b) shows the S_{11} is below -10 dB from about 3.3 to 3.8 THz. Thus the adopted impedance matching network works well enough and most of the energy fed into this structure is radiated to the free space or transformed into the ohmic loss between this band. Moreover, the leaky-mode region of the designed supercell LWA is also between this band. Besides, as Fig. 2(b) 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(a). 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.

3.1 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 are shown in Fig. 3(a).

Fig. 3(a) 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. 3(a) 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. 3(a) shows. It is worth mentioning that this is also reasonable in most applications.



(a) (b)

Fig. 3. (a) Radiation pattern of the designed narrow-band CRLH LWA. (b) Efficiency of the designed narrow-band CRLH LWA.

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.

3.2 Efficiency

After the farfield radiation performance is obtained, the efficiency of the designed supercell LWA is also given as displayed in Fig. 3(b). Because of the mismatch cause, its radiation efficiency is reasonable higher than the total efficiency.

Again, as Fig. 3(b) displays, it is obviously observed that the closed-stopband condition is perfectly satisfied without special weak efficiencies appearing.

Moreover, as is reported in Fig. 3(b), 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 [11]. 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 25ps.

4 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. Hence, the proposed supercell LWAs would further improve the performance of beam-steering antennas at THz.

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