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Planar electromagnetic band-gap structure based on graphene

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HIGHLIGHTS

- Analysing GEBG characteristic with equivalent circuit.
- Dynamically adjusting the electromagnetic wave propagation in ribbon arrays GEBG.
- Resonance characteristic can be dynamic adjustment in concentric rings GEBG.
- Spurious passband can be efficient suppression in spiral-GEBG.

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ABSTRACT

Electromagnetic band-gap structure with slow-wave effect is instrumental in effectively controlling electromagnetic wave propagation. In this paper, we theoretically analyze equivalent circuit model of electromagnetic band-gap structure based on graphene and evaluate its potential applications. Graphene electromagnetic band-gap based on parallel planar waveguide is investigated, which display good characteristics in dynamically adjusting the electromagnetic wave propagation in terahertz range. The same characteristics are retrieved in a spiral shape electromagnetic band-gap based on coplanar waveguide due to tunable conductivity of graphene. Various potential terahertz planar devices are expected to derive from the prototype structures.

1. Introduction

It is well known that periodic structures have gradually became popular in microwave and millimeter wave applications. Because of the similarity of their frequency selective behavior to carrier transport in semiconductors, these structures have been usually referred to as electromagnetic band-gap (EBG), which could suppress intrinsic spurious in band pass filters [1], optimize radiation patterns in microstrip antennas [2], improve input impedance bandwidth of low noise amplifier [3]. Evolved through a series of investigations, defected ground structure was realized, which is regarded as a simplified structure of a printed EBG on a ground plane [4]. This periodic structure such as EBG and DGS can suppress the propagation of electromagnetic waves in particular frequency bands. They have different shapes and sizes with different frequency responses, such as rectangular dumbbell [4], circular dumbbell [5], "U" shape [6], etc. It is probably to obtain more flexible frequency responses and slow-wave effects by adjusting the dimensions and distances of the structure. However, in practice, it is very difficult to change frequency responses by modifying the parameter of shapes which have fabricated on planar circuit or integrated in the circuit, even though it can be finite adjustment by loading lump component [7].

Graphene is the two-dimensional crystalline form of carbon atoms, it has remarkable electronic properties that surface conductivity can be large dynamically tuned [8,9,10]. This can be achieved by adjusting its Fermi energy, via varying chemical doping or electrostatic gating. Owing to its exciting electronic transport properties, graphene has important and wide applications to ultra-compact devices in infrared (IR) [11,12] and terahertz (THz) regimes [13,14]. Although more and more electromagnetic band-gap structures have been reported using composite structures [15,16], plasma [17] and carbon nanotubes [18], graphene may lead to the development of novel electromagnetic band-gap structure with enhanced performance in terms of reconfiguration capabilities, insertion losses, miniaturization, and integration. However, the use of graphene for the design of such structure has not been investigated yet. Consequently, graphene could provide a suitable alternative to realize electromagnetic band-gap, we propose the concept of graphene electromagnetic band-gap (GEBG).

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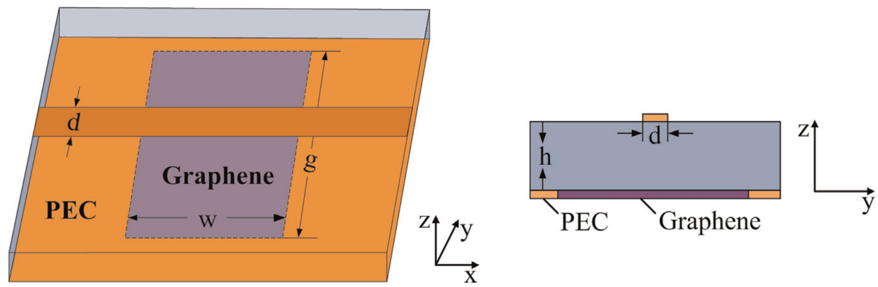

Fig. 1. (a) 3D view of GEBG structure model and (b) cross section. Ground plane is made of PEC and graphene, and graphene patch is etched into PEC.

In this work, the GEBG structures fabricate in parallel planar waveguide and coplanar waveguide (CPW), respectively. It should be mentioned that both the GEBG structures are based on graphene, which indicates that the transmission property of GEBG structure can be tuned by transforming graphene electrical properties. We study the propagation properties of electromagnetic wave along a parallel planar waveguide or coplanar waveguide with various GEBG structures in terahertz range, particularly focusing on the tunable resonance frequency and suppression spurious passband.

2. Theoretical analysis

The graphene is modeled as an infinitesimally thin conductive sheet, the surface conductivity value can be calculated using Kubo's formalism [14,19,20,21]:

$$\sigma(\omega, \mu_c, \Gamma, T) = \frac{je^2(\omega - j2\Gamma)}{\pi\hbar^2}\left[\frac{1}{(\omega - j2\Gamma)^2}\int_0^\infty \varepsilon\left(\frac{\partial f_d(\varepsilon)}{\partial\varepsilon} - \frac{\partial f_d(-\varepsilon)}{\partial\varepsilon}\right)d\varepsilon - \int_0^\infty \frac{f_d(-\varepsilon) - f_d(\varepsilon)}{(\omega - j2\Gamma)^2 - 4(\varepsilon/\hbar)^2}d\varepsilon\right] \tag{1}$$

where $-e$ is the charge of an electron, $\hbar$ is the reduced Planck's constant, f_d is the Fermi–Dirac distribution, and $f_d = 1/e^{(\varepsilon-\mu_c)/k_BT} + 1$, k_B is Boltzmann's constant, μ_c is chemical potential, T is the temperature. The first term of Eq. (1) is due to the intraband contribution, and the second term is due to the interband contribution. It is assumed that the local conductivity is isotropic without external magnetic field. For an isolate graphene sheet, the chemical potential μ_c is determined by the carrier density.

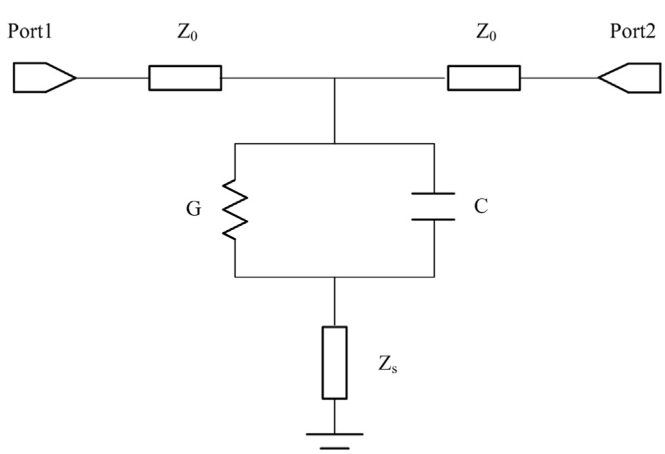

Fig. 2. Equivalent circuit model of GEBG structure.

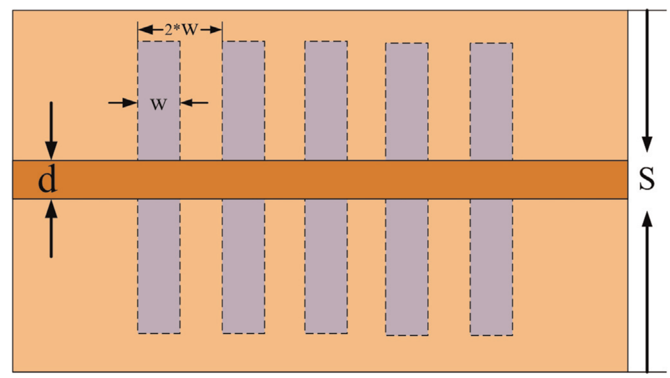

Fig. 3. Layout of graphene ribbon arrays (grape color) EBG structure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

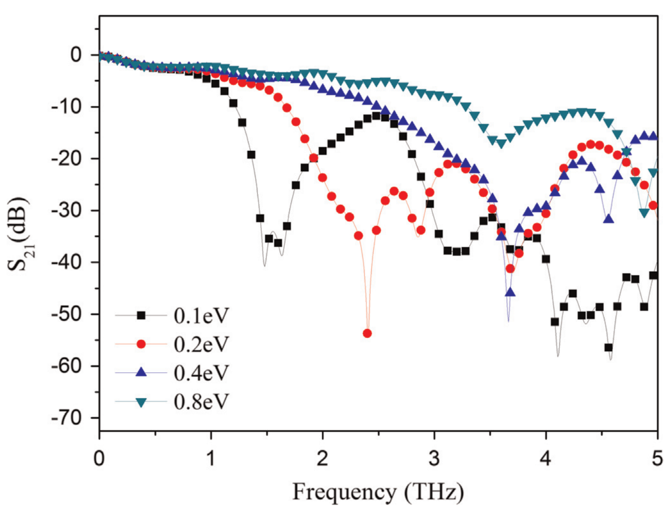

Fig. 4. The transmission spectrums of the GEBG structure: resonance property by chemical potential (square line for 0.1 eV, circle line for 0.2 eV, up-triangle line for 0.4 eV, down-triangle line for 0.8 eV).

$$n_s = \frac{2}{\pi\hbar^2 v_F^2}\int_0^\infty \varepsilon\left[f_d(\varepsilon) - f_d\left(\varepsilon + 2\mu_c\right)\right]d\varepsilon \tag{2}$$

Where v_F is the Fermi velocity. The carrier density can be controlled by application of a gate voltage or chemical doping. According to the relationship of gate voltage and chemical potential, the conductivity can be tuned via changing chemical potential which is controlled by gate voltage. Due to the surface conductivity is complex, it is written as $\sigma_G = \sigma_r + j\sigma_i$.

To analyze the characteristic of GEBG structure with finite unit number, the method of suspended microstrip [22] is utilized. Simple geometry of the GEBG is shown in Fig. 1, In this structure, the microstrip, which is placed at $z=h$, is assumed to be PEC ($\sigma\rightarrow\infty$) and the