Progress In Electromagnetics Research Letters, Vol. 89, 113–119, 2020

Design of a Reflectarray Antenna Using Graphene and Epsilon-Near-Zero Metamaterials in Terahertz Band

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Abstract—In this paper, a graphene-based reflectarray antenna using ENZ (Epsilon-Near-Zero) metamaterial at terahertz (THz) band is proposed, and the performance of its unitcell is investigated. Then, the phase distribution and radiation pattern of the antenna are examined. Benefiting from exceptional complex surface conductivity of graphene which is a novel 2-d material, the size reduction of reflectarray has been facilitated as a result of plasmonic mode propagation within the structure which in turn leads to an increase in propagation constant. Moreover, tunneling phenomenon in ENZ material, a kind of metamaterial which has a relative permittivity under 1, helps reduce the loss. Taking advantage of these outstanding features of both materials, the proposed reflectarray is designed to function at 1 THz and is composed of 150×150 elements with square-shape configuration. We have achieved 40 dB of gain using the combination of graphene and ENZ material in reflectarrays, and also it is the first time that they are used together in the reflectarray. This work mainly focuses on the impact of using ENZ material and graphene simultaneously which is not done before, then the results demonstrate that it has a considerable effect on increasing the reflectarray gain.

1. INTRODUCTION

Planar reflectarray is a highly remarkable technology which can be utilized for high gain applications. Since it combines the primary advantages of both parabolic and phased-array reflectors, generally, they enjoy compact structure, low cross-polarization, high efficiency, simple manufacturing process, and low loss. These arrays have reflector cells which generate a phase shift in the reflected incident wave hitting them which is feasible through the presence of passive elements which form an array [1]. The phase shift has been achieved by changing the dimension, rotation angles, or other features of the elements. The maximum range of the phase shift which can be acquired by altering some characteristics of single elements is considered one of the main indications of an appropriate reflectarray [1]. In terms of feeding, as the wave is radiated upon elements by a feed source at a distance, there is no need for lossy and bulky beamforming networks present in traditional arrays.

Phase distribution design on array surface makes the reflected waves form a directive beam with low radiation in undesirable directions. Although reflectarray antennas are broadly studied and used in microwave and millimeter-wave frequency bands [2], it is just recent that a number of researches have been carried out in THz frequencies [3, 4].

Over the last few years, numerous studies have been conducted on ENZ metamaterials. Owing to their uncommon characteristics at microwave and THz frequencies, the ENZ metamaterials have become especially appealing for researchers. An intense increase in transmission might be seen in ultra-narrow waveguide channels and bends filled with ENZ materials with arbitrary length, form, and geometry. Alternatively, ENZ materials improve the transmission through a boundary condition which might

Received 6 December 2019, Accepted 11 January 2020, Scheduled 25 January 2020
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have no effect on scattering parameters [5]. ENZ metamaterial is widely used to improve the antenna structure's performance, namely gain enhancement. Implementation feasibility of ENZ metamaterials is inspected in [6, 7]. Some structures have been introduced to work as ENZ metamaterials in specific frequency bands. They have a cutoff frequency region from low frequencies to ω_p which is called effective plasma frequency, and above ω_p, an ENZ region exists until effective permittivity reaches one. This region's specification mostly depends on the geometrical properties. Mousavi Roknabadi et al. have presented a configuration for ENZ implementation at 12 GHz [8] which, although it is not manufactured, can be considered one of the methods for implementing ENZ materials in the future.

With growing progresses in communication technology along with using THz frequencies, the need for instruments and systems in the mentioned frequency band is inevitable. Moreover, the need for materials which naturally have distinctive assets is clear for every single researcher. One of the usable materials in manufacturing THz devices is graphene [9] which is a 2-D material consisting of carbon atoms in a hexagonal lattice.

It is an incomparable choice in fabricating these tools for its unique properties and notable controllability. Exploiting graphene in antennas and other electromagnetic devices can bring advantages like a great level of size reduction, integration with RF graphene nano-electronic, effective dynamic adjustment in addition to transparency, and mechanical flexibility [10–15].

As regular materials for antennas have become quite lossy, it is reasonably predictable that graphene will have been applied at THz frequency band for it supports low-loss plasmonic resonances. Therefore, some researchers have attempted to design THz graphene antennas. A reconfigurable graphene reflectarray is proposed by Chang et al. for the generation of vortex radio waves at THz which could be reconfigured by changing biasing conditions for the generation of vortex radio waves at 1.6 THz [15]. In this paper, a reflectarray is proposed with a graphene patch and ENZ substrate, and the characteristics of its unitcell are investigated. It is a high gain and compact size reflectarray antenna at 1 THz. The novelty aspects of this design can be identified as simultaneously benefiting from distinctive features of graphene and ENZ material that finally improve the reflectarray gain noticeably.

The organization of this paper is as follows: first, we will investigate the basics of reflectarray antennas and some former works; then we will present the proposed unitcell; and last of all, we will examine the radiation characteristics of the proposed antenna in terms of gain, radiation pattern, etc.

2. DESIGN OF REFLECTARRAY

At first, it should be noticed that each element should shift the phase in such a particular amount so a collimated beam can be generated in a desirable direction. Based on the configuration in Fig. 1(a), the phase distribution on the elements to create a beam in (θ_b, ϕ_b) direction can be expressed as follows

$$\varphi\left(x_i, y_i\right) = -k_0 \sin\theta_b \cos\varphi_b x_i - k_0 \sin\theta_b \sin\varphi_b y_i \tag{1}$$

where k_0 is the free space propagation constant, and (x_i, y_i) are the coordinates of the ith element. The phase of the reflected field at each element equals

$$\varphi\left(x_i, y_i\right) = -k_0 d_i + \varphi_R(x_i y_i) \tag{2}$$

where $\varphi_R(x_i, y_i)$ is the phase-shift for element i, and d_i is the distance from the phase centre of the feed to the ith cell. From expressions (1) and (2),

$$\varphi_R = k_0(d_i - (x_i \cos\varphi_b + y_i \sin\varphi_b)\sin\theta_b) \tag{3}$$

To design the reflectarray, the phase of the reflection coefficient should be tuned in each unitcell to be compatible with phase-shift in the element; subsequently beam can be shaped through an independent phase adjustment for each element. The phase-shift in Eq. (3) is realized by modifying any of geometrical attributes in each element. The most typical phase adjustment is variable-sized patch based on variable resonant length of the elements.

Since the patch has a high Q feature, a small change in size yields a significant phase-shift in the reflected wave. The amplitude of reflection coefficient must be nearly equal to one, provided that there is no grating lobe or surface wave generation caused by the ground plane. The dissipative losses in the dielectric and on the metal patches cause a small reduction in the amplitude of reflection coefficient [16, 17].

The software used to simulate the unitcell is CST Microwave Studio which provides the phase curves versus patch dimensions, considering the incidence of a plane wave on an infinite array of rectangular patches. It also calculates the mutual coupling between the reflectarray elements. The phase variation versus the length is strongly nonlinear because of the narrow band behavior of elements demonstrating rapid changes around the resonance frequency.

3. DESIGN OF UNITCELL ELEMENT

The presented reflectarray element is depicted in Fig. 1(b). It includes a square graphene patch that lies above an ENZ material and is embedded in SiO_2 as external substrate which is a material with dielectric constant of 3.75 and loss tangent of 0.0184. The ground plane is located beneath the structure. Owing to the mono-atomic thickness of graphene, it can be considered an extremely thin surface with complex conductivity. This conductivity is described by the Kubo formula [18] and depends on frequency, absolute temperature, relaxation time, and chemical potential. Graphene conductivity in the absence of an external magnetic field is given by

$$\sigma = \frac{-je^2}{2h} \ln\left[\frac{4\pi|\mu_c| - (\omega - j2\Gamma)h}{4\pi|\mu_c| + (\omega - j2\Gamma)h}\right] - \frac{je^2 k_B T}{2h(\omega - j2\Gamma)}\left[\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\mu_c/k_B T} + 1\right)\right] \tag{4}$$

where T is the absolute temperature, Γ the particle scattering rate, e the electron charge, ω the radian frequency, h the Plank's constant, k_B the Boltzmann's constant, and μ_c the chemical potential. The values for temperature (T) and relaxation time (τ) are considered 300 K and 1 ps, respectively. Chemical potential (μ_c) is selected to be 0.6 eV which is feasible through chemical doping or electric bias. The complex conductivity of graphene with aforementioned characteristics for the 1–3 THz frequency band is presented in Fig. 1(c).

Since there is no reliable configuration for ENZ material yet, its dielectric constant is assumed to be 0.1 for conducting the simulations. The aforementioned allocating of permittivity vs frequency for ENZ material can be written as a Drude model [19]:

$$\varepsilon_{eff} = 1 - \omega_p^2/(\omega(\omega + j\zeta)) \tag{5}$$

where ζ is the damping constant demonstrating the dissipation. ω_p can be distinctively found for each configuration of ENZ metamaterial even though the implementation of ENZ material in THz band is a challenge yet [19].

The suggested graphene-based reflectarray using ENZ material is designed for 1 THz center frequency and is made of small unitcells. The size of the patch is nearly half wavelength in conventional patches, but in graphene patch it is different due to plasmonic mode propagation in graphene which makes its size below $\lambda/10$, allowing a notable size reduction [20]. The size of patch is 14 µm, and it has been changed through the simulation in order to acquire the phase shift for each cell size.

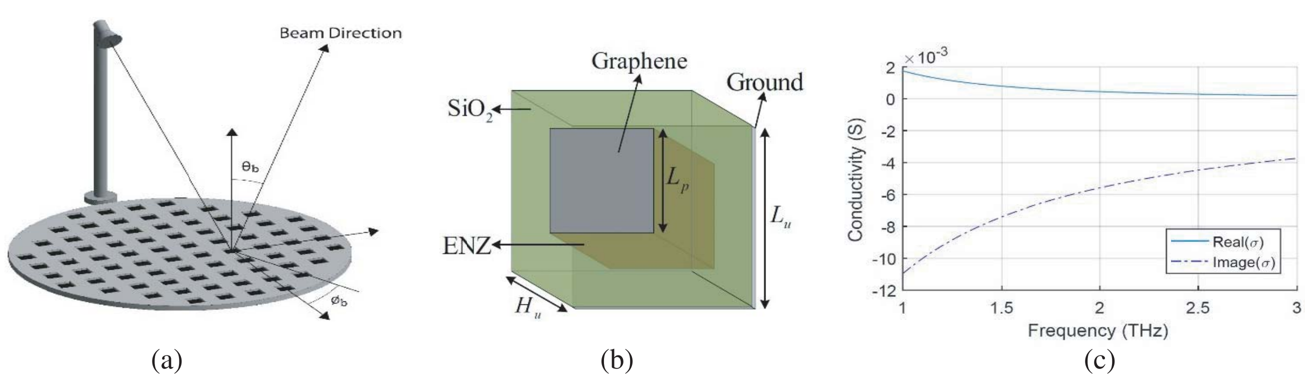


Figure 1. (a) Typical geometry of a printed reflectarray antenna [1]. (b) Proposed structure of graphene-based reflectarray unitcell using ENZ material. $L_u = 25$ µm and $H_u = 25$ µm. (c) Graphene complex conductivity which is calculated using Kubo formula.

The reflection coefficient off the proposed cell's surface is computed using CST full-wave simulation software, taking into account the coupling between the elements. The thickness of graphene in the simulations is considered to be 1 nm. The amplitude and phase of the reflection coefficient under normal incidence as a function of patch size is shown in Figs. 2(a) and 2(b). The normal incidence is the simple communication link between feed and receiving antenna [21].

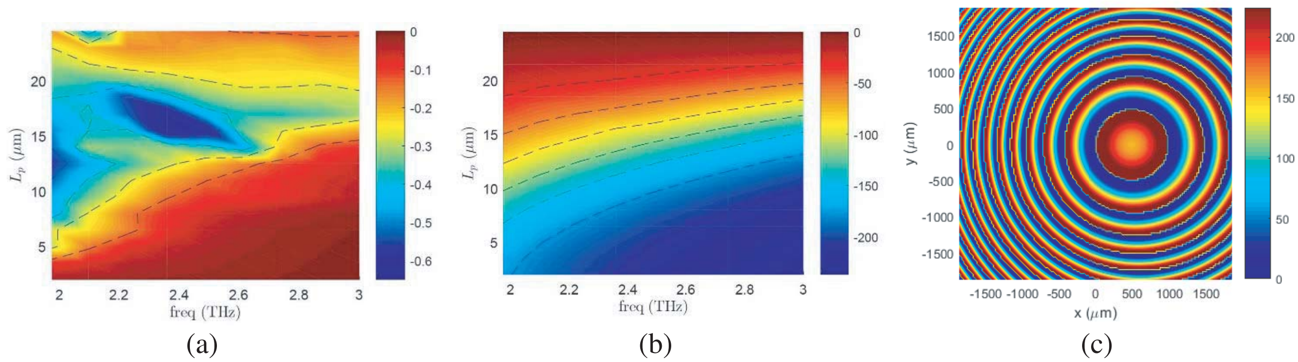


Figure 2. Reflection coefficient of the proposed element as a function of the patch size and frequency. (a) Magnitude (dB) and (b) phase (degree). (c) Phase distribution (in degrees) on the reflectarray designed by specifications given in Table 1.

This figure shows a wideband resonance in the patch when the length of the side of unitcell at center frequency is about $0.208\lambda_0$ while λ_0 is wavelength in free space. This phenomenon occurs because of plasmonic mode propagation in graphene. When the size of the patch is nearly half of the guided wavelength within the graphene, the patch resonates similarly to the way metal patches do. However, thanks to graphene's conductivity, which means that the impedance is inherently inductive, the guided plasmonic wavelength in it is really small. It should be noted that employing subwavelength elements to increase bandwidth in medium-sized reflectarrays is recommended.

4. DESIGN AND RESULTS

Eventually, an entire reflectarray grounded on graphene-based cells is proposed, designed, and analyzed. The main characteristics of the proposed square reflectarray are summarized in Table 1. Center of the reflecting surface is located at the origin of the coordinate system. It is to note that the size of the proposed reflectarray is far smaller than that of similar instances as a result of using graphene. The reason behind this is the plasmonic mode resonance in graphene. Since the complex conductivity of graphene can be controlled by electric field bias, the reflectarrays utilizing this material have dynamic readjustment capability.

The structure has superior bandwidth and less loss than non-ENZ structures. The reason is that if we have a low-loss ENZ material, it is possible to squeeze increasing energy through the narrow channel by decreasing its transverse cross-section which is called super-coupling effect [22]. This is the reason for the low-loss application of ENZ material. The low loss in turn leads to having smaller size.

Table 1. Reflectarray design table.

Frequency	1 THz
No. of Elements	150×150
Reflectarray Geometry	Square
Length of Sides	3750 µm
Position of feed	$x = 0,\ y = 0,\ z = 2500\,\mu\text{m}$
Radiation direction	$\theta = \pi/16,\ \phi = 0$

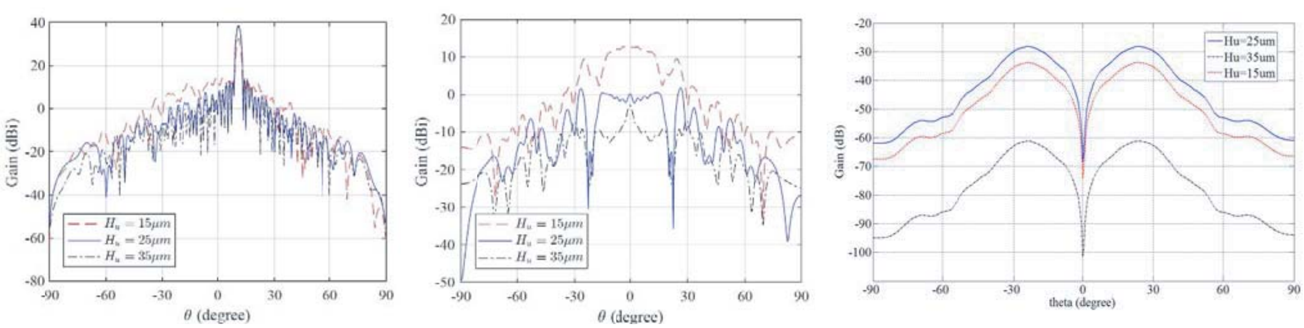
Through the entire band, 2 to 3 THz (40%), the minimum attained phase-shift range is 200 degrees, sufficient for beamforming. The achieved phase-shift range demonstrates an increase in bandwidth compared to [11] due to the presence of ENZ material. Furthermore, improvement of reflection coefficient amplitude is evident compared to the above-mentioned reference.

The incident field on each reflectarray cell depends on cell's location and radiation pattern of the source. So, a $\cos^q(\theta)$ function is used to model the source. The phase distribution which is required in each reflectarray cell in order to guide a pencil beam to $\theta = \pi/16$, $\phi = 0$ is displayed in Fig. 2(c). It is basically the required phase-shift on a 150×150 circular reflectarray with a centered focal point. Since in the proposed cell, a 224-degree phase shift is acceptable, phase distribution has become discrete meaning that for some cells the phase error is considered up to 68 degrees. 224-degree phase shift is adequate because the patch antenna itself has a narrow bandwidth, and this phase shift can cover patch's whole bandwidth.

The radiation pattern is calculated by both considering and not considering the loss. The radiation patterns in $\phi = 0$ and $\phi = 90$ planes for the mentioned condition are shown in Figs. 3(a) and 3(b) for 1 THz. In this figure, radiation pattern is calculated with variation in the height of unitcell Hu. Maximum gain is in direction $\theta = \pi/16$ and $\phi = 0$ and is equal to 32.4, 38.16, and 38.69 dBi for unitcell heights of 15, 25, and 35 µm, respectively. As can be seen, there is significant improvement in radiation gain with increase in height of unitcell from 15 to 25 µm, but the improvement is minimal for the change from 25 to 35 µm. The loss of graphene patches causes about 1 dB reduction in gain which is negligible. Cross-polar pattern achieved by this phase distribution is shown in Fig. 3(c), for H_u = 15, 25, and 35 µm. Table 2 compares the main features of the proposed reflectarray to two other works, and it shows that we achieve a higher gain.

Table 2. Comparison to similar works.

Frequency	Number of Elements	Elements in the main axes	Diameter /Length of side	Reflectarray geometry	Period	Period/λ	Gain	Reference
1.3 THz	25448	180	2520 µm	Circular	14 µm	0.06	30	[10]
1.6 THz	1700 × 8	8 (sectors)	1.875 mm	Circular	14 µm	0.08	17.85	[15]
1 THz	150 × 150	150	3750 µm	Rectangular	25 µm	0.08	40	This work



(a) (b) (c)

Figure 3. Radiation pattern of reflectarray in (a) $\phi = 0$ (E-plane) and (b) $\phi = 90$ (H-plane) planes. (c) Cross-polar pattern.

5. CONCLUSION

In this work, a reflectarray antenna is proposed based on ENZ metamaterial using graphene patches. The unitcell has been analyzed, and the related parameters have been extracted to be utilized in designing the reflectarray. It consists of a square graphene patch that overlies an ENZ material which is inserted in SiO_2 as external substrate. The size of graphene patch and the unitcell's period are initially set to 14 µm and 25 µm, respectively. The most critical characteristic of the unitcell is phase shift. Considering this feature, a high gain reflectarray consisting of 150×150 square graphene patches in a square array configuration is designed at 1 THz. The gain of the antenna is 40 dB which is comparatively higher than the previous works. Considering the antenna parameters, the cell size and loss have been decreased, and consequently the gain has been increased. The structure can be used for high frequency detectors, imaging devices, and THz sensors.

ACKNOWLEDGMENT

This work was supported by Irancapseal. Authors are thankful to Razi Institute of Telecommunication Research (RITR).

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