Terahertz Reflectarray Antenna with a Square Patch Surrounded by Two Concentric Square Rings as a Unit Cell

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***Abstract*—Graphene is being used as a patch as it possesses a number of desirable electromagnetic and mechanical properties that assist in providing flexible and reconfigurable antenna structure. A graphene reflective unit cell is examined to demonstrate that the reflection coefficient can be controlled by changing the chemical potential and size of the graphene patch. The phase compensation of the reflected waves is achieved by patches with different sizes. Reflection coefficient phase variations for 0°–525° with a variable slope are obtained for different graphene conductivities. A graphene-based reflectarray antenna is proposed. A reflect array with dimensions of $20\,\lambda \times 20\,\lambda$ that operates at 1.6 THz is analyzed. The reflectarray is composed of 40x40 unit cells with $\lambda/2\,x\,\lambda/2$ for each unit cell size. They are placed upon silicon dioxide substrate. A horn antenna is used as a feed. The focal-length-to-diameter (F/D) ratio is equal to one. A maximum gain of 20.7, 13.6, and 21.4 dBi are obtained at 1.4, 1.8, and 1.6 THz respectively.**

***Keywords*— Graphene, Reflect array, Unit cell, Reflection phase**

I. INTRODUCTION

Terahertz (0.1–10 THz) band communication has a great attention in modern technology to satisfy the increasing demand for ultra-high-speed wireless links. Over the last three decades, the data rates are increasing rapidly, it is doubled every 18 months [1]. The wireless data rates of 100 Gb/s and even 1 Tb/s will become reality within the next decade [1]. The THz spectrum region has applications in spectroscopy, defense applications, medical imaging, high-speed communications and chemical characterization [2-6]. The antenna is an essential element in THz region. Researchers try many types of antennas. They use different categories of antennas, varying the shape and dimensions of the antennas' elements, or using different types of substrate material which support THz spectrum radiation. The wavelengths at THz are very small which reduces the size of antenna, hence antennas at THz frequencies encounter a lot of design difficulties. In the last few years, many antenna researches were conducted to improve and enhance antennas' characteristics. The Planar reflect array is one of the most important antenna categories utilized for high gain applications, which has the main advantages of parabolic reflectors and phased arrays [8, 9, 14]. The planar reflect array antenna system consists of a dielectric substrate sandwiched between reflect array patches and ground plan with center feeding horn antenna. Generally, reflect arrays possess compact structure, low cross-polarization, high efficiency, simple manufacturing process, and low loss. The main problem in reflect arrays is the path lengths are not equal. Compensation for the path differences is carried out by the elements themselves. This compensation process can be performed using variable patch sizes. The reflect array antenna system with center feeding horn antenna is illustrated in Fig. 1. It is composed of an array of patches illuminated with a feed horn located at (Xf, Yf, Zf). The required phase delay from the feeding point to a fixed aperture in front of the reflect array must be constant for all reflect array antenna elements [9]. To collimate a beam in a certain direction in space considering that the reflection phase from each reflect array element is dependent on its position, a compensation phase γ_i is required to satisfy the following equations (1, 2) [9, 15].

$$K_o(R_i - \vec{r}_i \,.\, \hat{r}_b) - \gamma_i = 2N\pi \quad (1)$$

$$R = \sqrt{(x_i - x_f)^2 + (y_i - y_f)^2 + z^2} \quad (2)$$

where $K_o = \frac{2\pi}{\lambda}$ is the free-space wave number.

Conventional materials cannot be utilized at THz because they have weak electric and magnetic responses [3]. Graphene possesses abnormal characteristics in THz region, therefore it is widely used in antenna design. Graphene supports a plasmonic propagation at THz spectrum that leads to extremely interesting properties for practical antennas applications [7-8]. Graphene has good properties in terms of mechanical strength, mobility, optical transparency, electrical and thermal conductivity [10,11].

Different reflect array antennas based on graphene [3,8,14,16] has been studied. In [3] a graphene-based metamaterial reflectarray antenna with frequency tunable radiation characteristics has been investigated. The unit-cell element consists of graphene split-ring resonator with two gaps printed on a grounded SiO_2 substrate. Reference [8] contains a design of a reflectarray at 1.3 THz which comprises more than 25000 elements of size about $\lambda_o/16$. In [14] a graphene-based reflectarray antenna using Epsilon-Near-Zero metamaterial at 1 THz is proposed. The reflectarray is composed of 150x150 elements with square-shaped configuration. Four different reflectarrays, [16], namely, metal-only-block reflectarray, waveguide reflectarray, dielectric reflectarray, and traditional microstrip patch reflectarray are designed to give high gain at 1 THz.

An exciting application of reflectarrays is the generation of vortex beams, [17-19]. Vortex beams are characterized by their orbital angular momentum (OAM) and they allow to increase the spectral efficiency. OAM provide enhanced transmission capacity than any other known communication system.

In this paper, a graphene based reflect array antenna at 1.6 THz is constructed based on two concentric square rings with a solid square patch to achieve a high gain and reliable antenna. The dynamic variation of graphene surface conductivity, combined with reflect array elements provides a promising approach to design dynamically tunable planar devices. Finite integration technique is used in this work. The overall dimensions of the designed reflectarray is the same as that of other published works in [8, 14, 17]. But the number of elements in our design is less than 10% of the number of elements of other works. This makes the fabrication process much easier. The gain is about the same as that of reference [8] but higher than that of reference [17].

II. GRAPHENE-BASED REFLECT ARRAY ELEMENT

Graphene is considered a Drude like material [17]. It can be modeled as an extra thin surface with conductivity σ (ω, Γ, μc, T) where ω is radian frequency, μc is chemical potential, Γ is a phenomenological scattering rate that is assumed to be independent of energy, and T is temperature [12]. This conductivity can be modeled with the help of Kubo formula [14]. This conductivity is complex and frequency-dependent and is given by equations (3, 4, and 5) [3,7, 12,13]. The silicon dioxide is a more suitable substrate applied for enhancing the graphene layers in THz antennas [3].

$$\sigma(\omega) = \sigma_{intra}(\omega) + \sigma_{inter}(\omega) \qquad (3)$$

where $\sigma_{intra}(\omega, \mu_c, \Gamma, T)$is the intra-band term given by [3,9]

$$\sigma_{intra}(\omega, \mu_c, \Gamma, T) \simeq -j\frac{q_e^2 K_B T}{\pi\hbar(\omega - j2\Gamma)} x(\frac{\mu_c}{K_B T} + 2\ln(e^{-\mu_c \tau K_B T} + 1)) \qquad (4)$$

And $\sigma_{inter}(\omega, \mu_c, \Gamma, T)$ is the inter-band term eigen by

$$\sigma_{inter}(\omega, \mu_c, \Gamma, T) \simeq -j\frac{q_e^2}{4\pi\hbar} \ln\left(\frac{2|\mu_c| - (\omega - j\tau^{-1})\hbar}{2|\mu_c| + (\omega - j\tau^{-1})\hbar}\right) \qquad (5)$$

where j is the imaginary unit, μc is the chemical potential, τ is the relaxation time, K_B is Boltzmann's constant, T is the temperature, ω is radian frequency. Γ = 1/2τ is scattering rate it represents loss mechanism, q_e is the electron charge, and $\hbar$ = h/2π is the reduced Planck's constant [3].

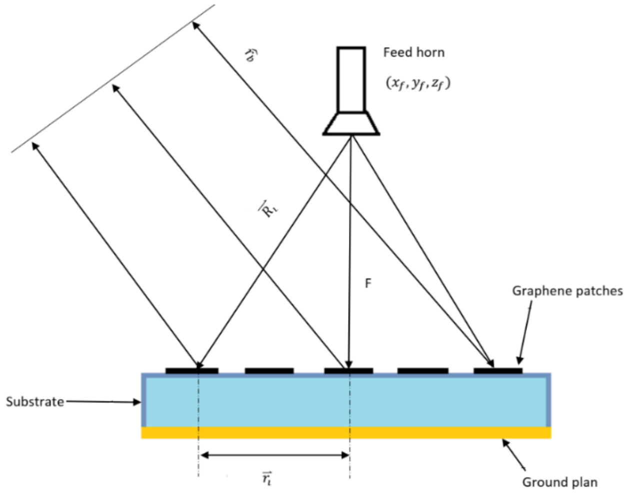


Figure (1) Reflect array antenna

Fig.2 illustrates the unit cell of the proposed reflect array and its parameters. It consists of two concentric square rings with solid square patch of graphene over a grounded silicon dioxide substrate with thickness h = 24 μm. The unit cell parameters are shown in table 1.

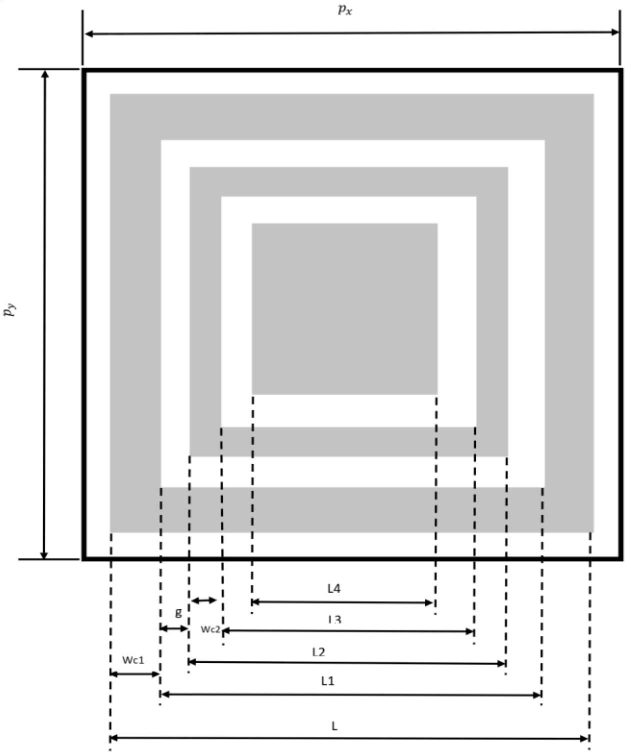


Figure (2) Unit cell

Table 1: Reflect array unit cell parameters

Parameter	Value
Substrate length and width (px x py)	$(\frac{\lambda}{2} \text{x} \lambda/2)$=(93.75 µm x 93.75 µm)
Substrate dielectric constant, silicon dioxide, SiO2, ε_r)	3.9
Substrate height (h)	24 µm
l	outer ring side
l_1	$l - wc$
l_2	$l_1 - g$
l_3	$l_2 - wc$
l_4	$l_3 - g$
wc_1	12 µm
g	7.8 µm

Fig. 3. illustrates the reflection coefficient phase against patch size at different graphene chemical potentials. Patch size varies from 40 to 95 µm. As the patch size increases, the reflection phase increases with negative value. The rate of variation is slow for chemical potential 0.2 and 0.4 eV. The variation rate is large for chemical potential of 0.8 and 1 eV. The range of values of reflection coefficient phase at graphene chemical potential 0.8 eV is 0 to 550^o so it is chosen to construct the reflectarray. The curve for 0.8eV is piece-wise linear which is an added advantage. Reflection phase Vs. frequency for L = 46.875 µm is shown in Fig. (4). Reflection coefficient magnitude against patch size for different values of chemical potential is shown in Fig. (5).

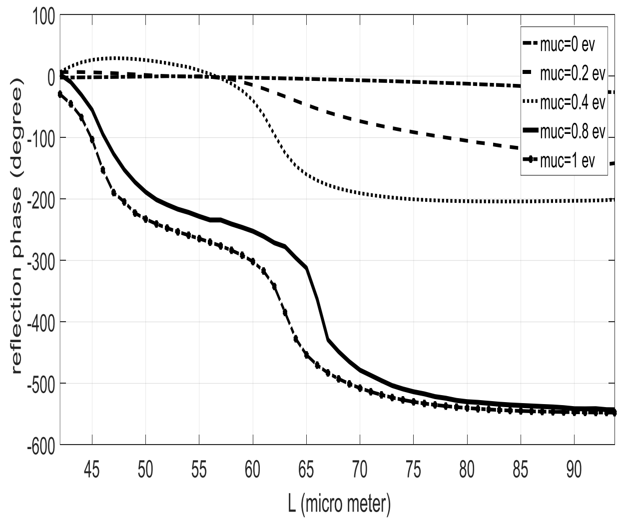


Figure (3) Reflection phase with different graphene chemical potential values

III. REFLECTARRAY ANTENNA DESIGN AND RESULTS

In this section, a complete reflect array antenna based on the proposed graphene unit cell element is designed and analyzed. The reflect array has dimensions of $20\,\lambda \times 20\,\lambda$.The reflect array is composed of 40 x 40 unit cells with $\lambda/2 \times \lambda/2$ size placed upon silicon-dioxide substrate with thickness h = 24 µm. The feeder is a circular horn used to illuminate patches. The horn is placed at a distance of 20λ from the center of the reflect array such that the F/D ratio is equal to one, as shown in Fig. 6. Figure 7 shows the phase distribution required on the reflect array aperture to produce a broadside single beam with center feeding. Fig.8 shows the 3D radiation patterns of the reflect array. Figure 9 shows the radiation pattern at frequencies 1.6 THz ,1.4 THz and 1.8 THz. A good result is obtained compared with [3,5,13] referring to number of array elements, patch shape of elements and patch size, where the main advantages of our design is using a mixture of different elements in the unit cell to enhance gain [6]. A comparison between our work and work in references [8,14,17], is shown in table (2).

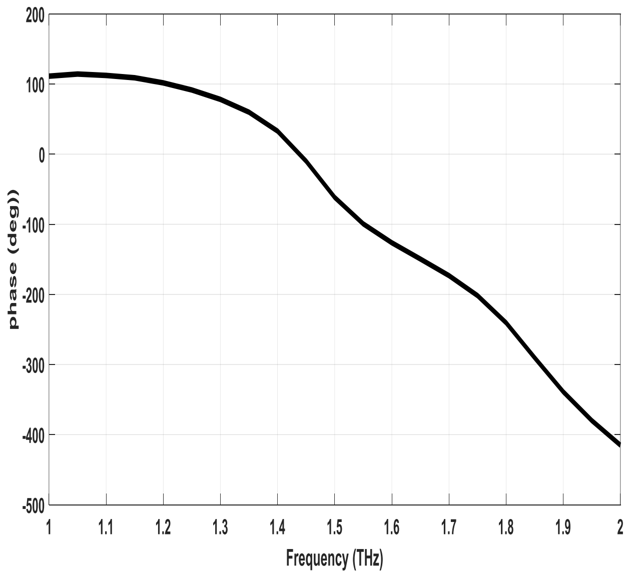


Figure (4) Reflection phase Vs. frequency for L= 46.875 µm.

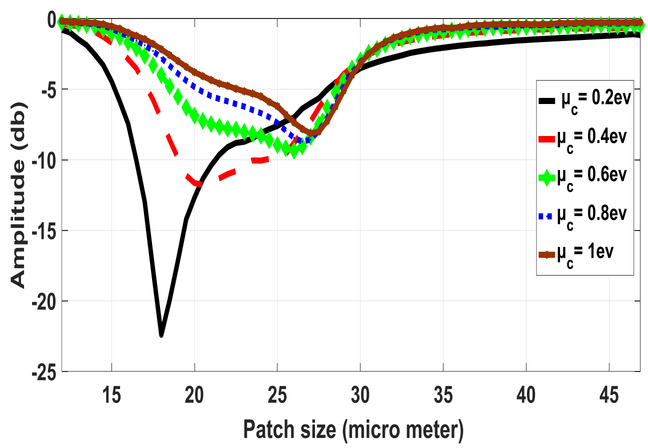


Figure (5) Reflection coefficient magnitude with different graphene chemical potential values

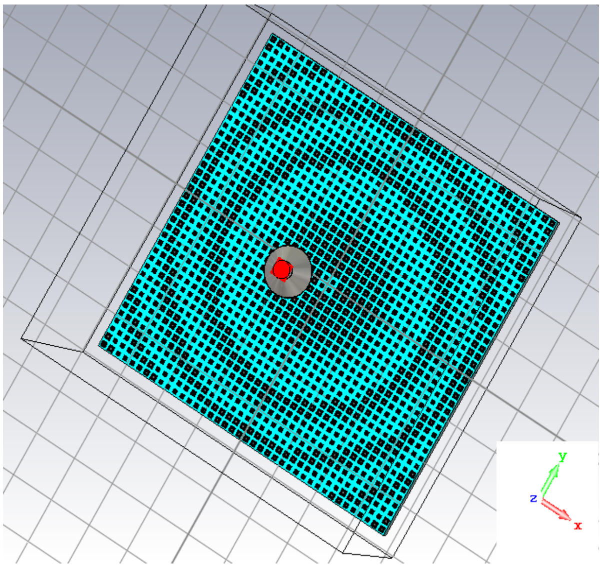


Figure (6) Reflect array with central feed circular horn

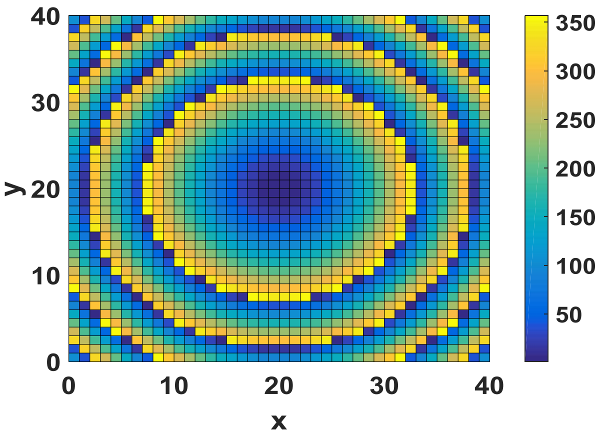
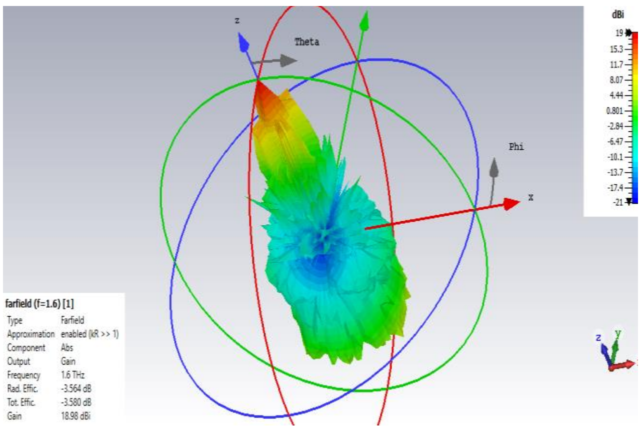
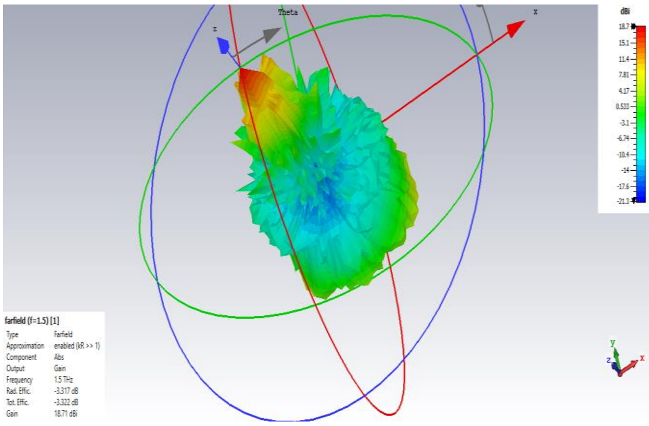


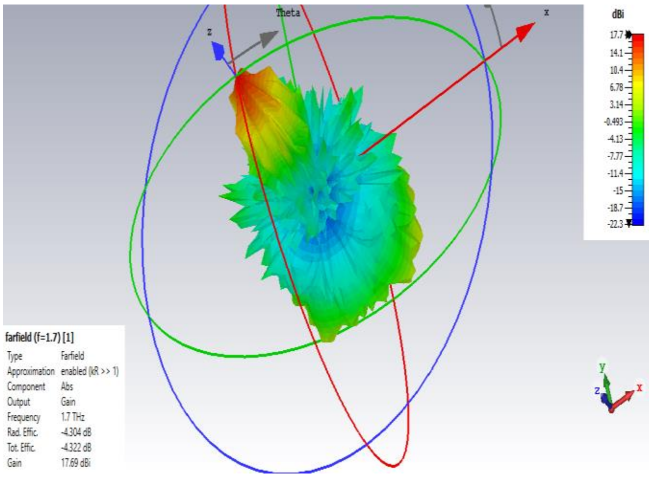
Figure (7) The required phase distribution on reflect array surface for broad side radiation



(a)

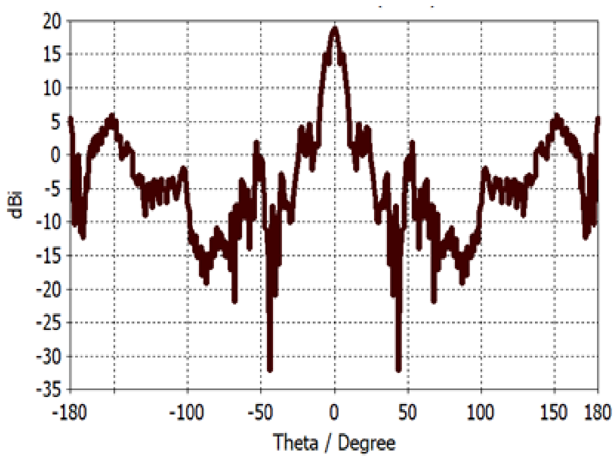


(b)

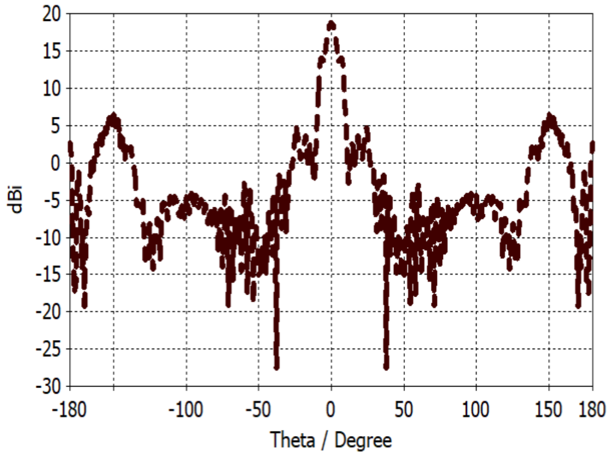


(c)

Figure (8) 3-D radiation patterns for the reflect array (a) 1.6 THz , (b) 1.4 THz and (c) 1.8 THz



(a)



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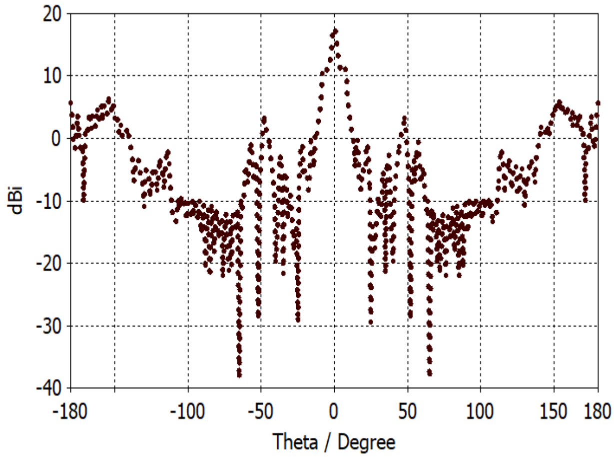

(c)

Figure (9) The overall gain of the reflect array (a) 1.6 THz , (b) 1.4 THz and (c) 1.8 THz

From table 2, our design has larger patch size so it is easier to manufacture. Our work gain is very good referring to number of unit cells required. In [17] patches require different chemical potentials which complicates the design and implementation.

IV. Conclusion

A reflect array antenna is designed at 1.6 THz. The size of the array is 3.75x3.75 mm which corresponds to 20x20λ. The array consists of 40x40 unit cells. Each unit cell is half wavelength. Unit cells are based on graphene . A parametric study to illustrate the effect of graphene chemical potential on the reflection phase is conducted. Chemical potential of 0.8 eV gives reflection phase of 550^{o} . The unit cell is composed of two concentric square rings and square solid patch. The reflect array is illuminated by circular horn. The horn is placed at a distance of 20λ from the center of the reflect array such that the F/D ratio is equal to one. The gain of the reflect array is 21.4 dBi which is good referring to the number of unit cells used. The number of unit cells is less than 10% compared with other works. The size of the unit cell is large compared to other works which makes fabrication easier.

Table (2) Comparison with other works

	Proposed work	[14]	[8]	[17]
Unit cell	Two concentric square rings with solid patch inside	square solid patch	square solid patch	square solid patch
Operating frequency	1.6 THz	1 THz	1.3 THZ	1.6 THz
Size	3.75mm×3.75mm sio2 substrate thickness 24µm	3.75mm×3.75mm substrate.	grounded quartz substrate 2.24 mm x 2.24mm.	grounded substrate 2.32mm x 2.32 mm.
Number of Elements	40×40 unit cells	150 × 150 units cells	160 x 160 unit cells graphene patches	116 × 116 unit cells
application	Single beam communications	Single beam communications	Single beam communications	Reconfigurable reflect array for vortex beam
gain	21.4dBi	40 dB	22.7dB	17.8, 12.9, 13.8, 13.1, and 13.1 dBi

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