BANDWIDTH AND GAIN ENHANCEMENT OF A GRAPHENE-BASED METAMATERIAL ANTENNA FOR THE THz BAND

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ABSTRACT

In this paper, a reconfigurable THz patch antenna based on graphene is presented, whose resonance frequency can be changed depending on the applied voltage. The antenna is located over an array of split ring resonators (SRR) also made of graphene; this array actually behaves like a metamaterial. By exploiting the possibility of changing the chemical potential of graphene, independently for the patch and for the array, both bandwidth and radiation properties are optimized. The radiation properties of the proposed layout are then enhanced by introducing an extended hemispherical lens.

Keywords: grapheme, THz, reconfigurability, lens antenna.

INTRODUCTION

Up to the recent past, the terahertz (THz) region (with the wavelength typically ranging from 30 um to 3 mm) has been regarded as a 'gap' in the electromagnetic spectrum, enclosed between the infrared and microwave regions. The reason for that was the lack of efficient sources and devices to manipulate THz waves. This has recently changed: the researchers' interest in the THz region has raised in the last decade and recent innovations in THz technologies are bringing a wide variety of applications including time-domain spectroscopy, biological imaging, high-speed communication, THz imaging, THz radars, etc [1]. Thanks to the recent progresses in nano-structuring, planar antennas have advantages that make them very suitable for THz applications, like robustness and low cost fabrication (using photolithography); on the other hand the extremely thin substrate is considered the main hazard in the construction of THz patch antenna [2]. Photonic crystals have also been used in this context to enhance radiation from the substrate to free space [3]. The availability of suitable materials for THz science and technology is a key issue to bridge the 'gap'; among new materials, graphene has found its way for THz applications and in particular in the field of THz antennas. Graphene is a novel two-dimensional material in which carbon atoms are arranged into honeycomb lattices, and it possesses some extraordinary electrical, thermal and mechanical properties in a wideband frequency range; because of these properties, such as high carrier mobility (around 200,000 $cm2$ $V-1$ $s-1$), flexibility, high mechanical strength and good stability. Graphene has received extensive attention in recent years [4-6]; Graphene strips and patches support a plasmonic wave at THz frequencies and its wavelength is of the order of micrometers. These plasmon waves can be manipulated by varying the bias voltage applied to the layers of graphene. Therefore we can control the resonance frequency of the graphene antenna by changing the bias voltage of the layers, since this changes its conductivity. Unfortunately, there still are some problems in the design of effective devices, like narrow bandwidth, low gain and mismatch losses; on this respect, several

strategies have been proposed to overcome the problem of low gain and narrow bandwidth and in this paper we have applied some of them. Firstly, to improve the characteristics of the patch antenna we used a hybrid realization, using both graphene and metal; in this way the gain increases, but still we have a narrow bandwidth, as shown in [7]. Metamaterials give us the possibility to increase the bandwidth with an acceptable gain which is still larger than the normal case of patch antenna. Recently, metamaterials with sub-wavelength scale unit cell have attracted intense attention due to their potentially exotic properties that are unavailable in nature, such as invisibility cloaking, perfect lensing and negative index of refraction. Recently graphene has emerged as a novel plasmonic material with advantageous properties even for metamaterial design. In order to further enhance the optical response of graphene and to extend the photonic applications of graphene, the coupling of graphene and metamaterials has been investigated [8-10]. Split-rings are central elements of many metamaterial structures because they are capable of supporting strong induced currents, leading to a resonant magnetic response down to the near infrared [11]. Split-ring resonators (SRR) can be driven by the excitation of plasmons that propagate along the ring circumference, particularly when its length is of the order of half the plasmon wavelength. In this work, we exploit the effect of an SRR metamaterial array made with graphene (designed to operate in the terahertz electromagnetic region) and its interaction with a hybrid patch antenna. We first present a tunable patch graphene antenna and we then modify its characteristics by introducing an SRR array; we discuss the antenna properties for different values of the voltage applied to the grapheme sheets. Finally, we describe how to further enhance the antenna gain by using a dielectric lens.

ANTENNA STRUCTURE AND DESIGN

In general, the conductivity of graphene is highly frequency-dependent, and can have completed different behavior e.g. at microwave and THz frequencies [12]. In our desired frequency range the Kubo formula for graphene conductivity can be written as [13]:

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$$\sigma^{-1} = (2\Gamma + j\omega)g(\mu_c, T) \qquad (1)$$

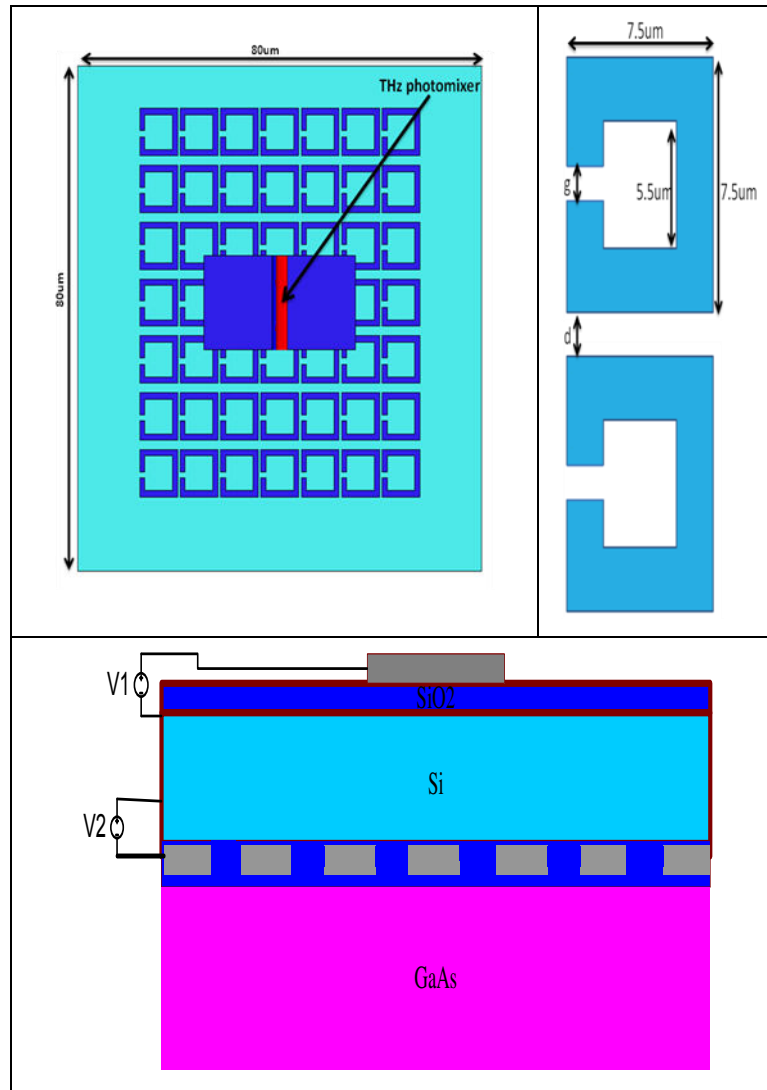Where $g(\mu c, T)$ is a real function independent of frequency given by:

Figure-1. Geometry of the antenna layout.

$$g(\mu_c, T) = \frac{\pi\hbar^2}{q_e^2\, k_B\, T}\left[\frac{\mu_c}{k_B\, T} + 2\ln\left(1 + e^{-\frac{\mu_c}{k_B\, T}}\right)\right]^{-1} \qquad (2)$$

Where ω is the radian frequency, μ_c the chemical potential, Γ a phenomenological scattering rate assumed to be independent of energy, T the temperature, q_e the electron charge, and $\hbar$ the reduced Planck's constant. The relation between the bias voltage and chemical potential can be calculated by:

$$E = \frac{e}{\pi\hbar^2\varepsilon_0 v_f}\int_0^\infty \varepsilon(f_d(\varepsilon)f_d(\varepsilon + 2\mu_c))d\varepsilon \qquad (3)$$

Where

$$f_d(\varepsilon) = (e^{\frac{(\varepsilon-\mu)_c}{k_B\, T}} + 1)^{-1}$$

is the Fermi-Dirac distribution, ε is energy, and k_B is Boltzmann's constant. In this work, CVD grown monolayer graphene on SiO2 deposited silicon substrate is used. The SiO$_2$ layer plays an important role to provide a convenient way to dynamically control graphene complex conductivity by varying the applied voltage as schematically shown in Figure-1. The proposed design is composed of a rectangular graphene patch antenna, its length equal to 28μm and width is 15μm, based on Silicon dioxide (SiO$_2$, ε_r = 3.8) with a thickness of 100nm deposited on 1000 nm highly doped silicon layer and 1800 nm layer of GaAs (ε_r = 12.9, tan δ = 0.001), feeding a THz photo mixer which has an internal high impedance of about 10 kΩ as shown in Figure-2. When the applied DC voltage V$_1$ is changed, the graphene conductivity changes and the plasmon wavelength with it; the resonant frequency of the patch antenna can be therefore dynamically tuned. Graphene SRR array is added on the lower layer of the substrate (SiO$_2$ with 150 nm thickness). The dimensions of the SRR are shown in Figure-1, where the gap g equals 0.8 um and the distance between each two

array elements equals 1 um. A DC voltage V_2 will be applied between the Graphene SRRs and the silicon layer to obtain a tunable conductivity of graphene SRRs elements; as a result the substrate behaves as a reconfigurable metamaterial.

SIMULATION RESULTS AND DISCUSSIONS

Initially, we started with designing the conventional patch antenna without the SRR metamaterial array and we verified that the resonance frequency can be changed due to the change of the DC bias voltage V_1 at the graphene layers and thus the chemical potential μ_c as indicated by equation (2). This leads to a change in the conductivity of the layer and consequently of the antenna parameters. Figure-2 shows the real and imaginary parts of the antenna's impedance. As an example, in the case of μ_c equal to 0.2eV, the resonance frequency is 2.2 THz. We then introduced the 7×7 SRR graphene array at the bottom level of substrate and connected it to the same bias voltage as the patch layers, so that its graphene chemical potential has the same value. We now discuss the effect of the metamaterial array on the antenna behavior.

Figure-3 shows the reflection coefficient in both cases with/ without SRR at different chemical potential values (related to the applied voltage); we can see an degradation in the reflection coefficient when we add the SRR array to the patch antenna. As shown in Figure-3, the central resonance frequency is the same as before, but the bandwidth of the antenna (at -10dB) is increased, with an increase depending on the applied voltage. This improvement in the bandwidth is more than twice the reference bandwidth for the conventional case.

Infact it is 102 GHz at μ_c = 0.1 eV for the graphene with SRR, and by increasing μ_c to 0.5 eV, it is about 260 GHz as indicated in Figure-3. When we change just the bias voltage for the graphene SRR (V2) with a fixed bias voltage for the patch graphene (V1) (for example at a fixed chemical potential for the graphene patch equal to 0.2 eV), the combined layout increases the bandwidth. In fact it is 0.08THz at μ_c = 0 eV for the graphene SRR, and by increasing μ_c to 0.5 eV, it is about 0.5THz which means an improvement in the bandwidth from 25% to 44% with respect to the conventional layout case. It is also noticed however that the central operating frequency is not fixed like in the previous case in Figure-3, but it is changing. This implies that the biasing voltage for the rings plays an important role in determining both the resonance peak and the band of operation. If we analyze the results in Figure-4, we can notice that the central resonance frequency has a little shift towards lower frequencies with respect to the conventional one. So, the main effect in this combined layout is that we have the possibility to control both the operating frequency and the bandwidth. By adding the SRR array

the gain also increases as shown in Figure-5, having now a maximum value equal to 1.2 dB. This should be compared to the simple case without the SRR array which is about - 8dB with u_c = 0.1eV for the same patch. This improvement comes from the improved efficiency and from the lens effect of the SRR surface. So we can say that the tunable mechanisms of using the graphene SRR metamaterial structure are mainly dependent on the applied voltage and thus Fermi level. As the Fermi level of the graphene layer increases, the resonant responses of the graphene SRR metamaterial structure become stronger, and the resonant band is shifted to higher frequency. By varying the applying bias voltage, significant enhancement of the frequency and amplitude is achieved. The results are very helpful in the design of novel plasmonic devices. Another modification on the layout considers the use of lens to improve the radiation properties.

Using of the lens with the antenna layout has the role of increasing directivity. It is known that THz antennas on a flat substrate generally suffer from a large decrease in directivity and radiation efficiency because the internal reflection effects produce a substrate mode loss, so lens are used to collimate incident divergent energy to prevent it from spreading in undesired directions. By properly shaping the geometrical configuration and choosing the appropriate material of the lenses, they can transform various forms of divergent energy into plane waves and also lens substrate can reduce the internal reflection and increase the directivity of the radiation pattern by beam focusing [14]. As shown in Figure-6, we use a hemispherical lens with the proposed antenna with hemisphere radii R equal to 15um as the size of the thickness H at u_c is equal to 0.2eV ($V_1=V_2$). The gain was increased to about 3.56dB when using SRR, which is a clear improvement from 0.85dB (Gain without SRR). But in the case of enhancing the structure with a hemispherical lens, the antenna becomes even more directive and the gain increases to about 10dB. This represents a significant improvement on the antenna gain, comparable to THz resonant metal implementations which achieve slightly better total efficiencies, but on a narrower band, with larger sizes and without the frequency reconfigurability offered by graphene. For the rings, voltage plays an important role in determining both the resonance and the bandwidth. In Figure-4, we can notice also that the central resonance frequency has a little shift towards lower frequencies with respect to the conventional no-SRR case. When the electrochemical potential of graphene changes in the range 0–0.5 eV, the resonant band of the reflection coefficient curves can be tuned in the range of (1.1-1.18) THz, and (1.8–2.4)THz respectively. In summary, the main effect in this combined layout is that we have the possibility to control both the operating frequency and the bandwidth.
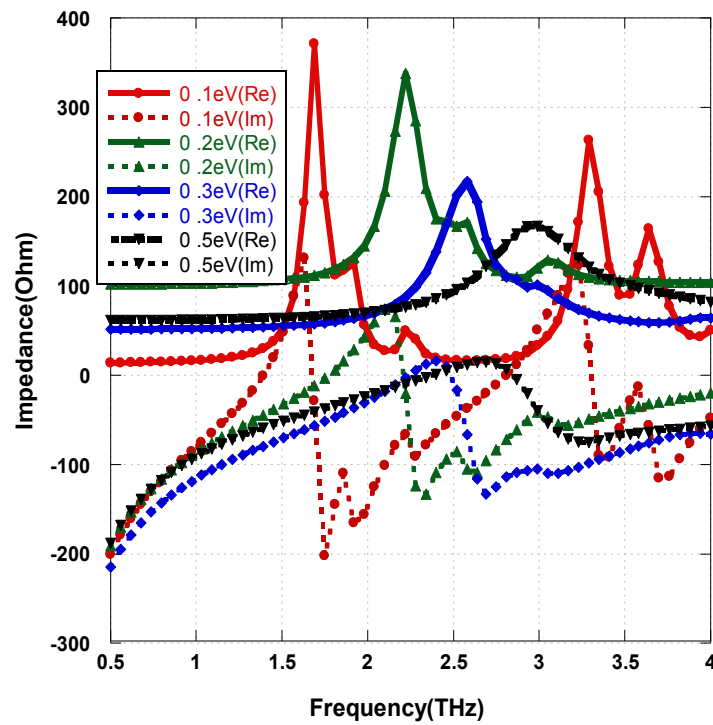
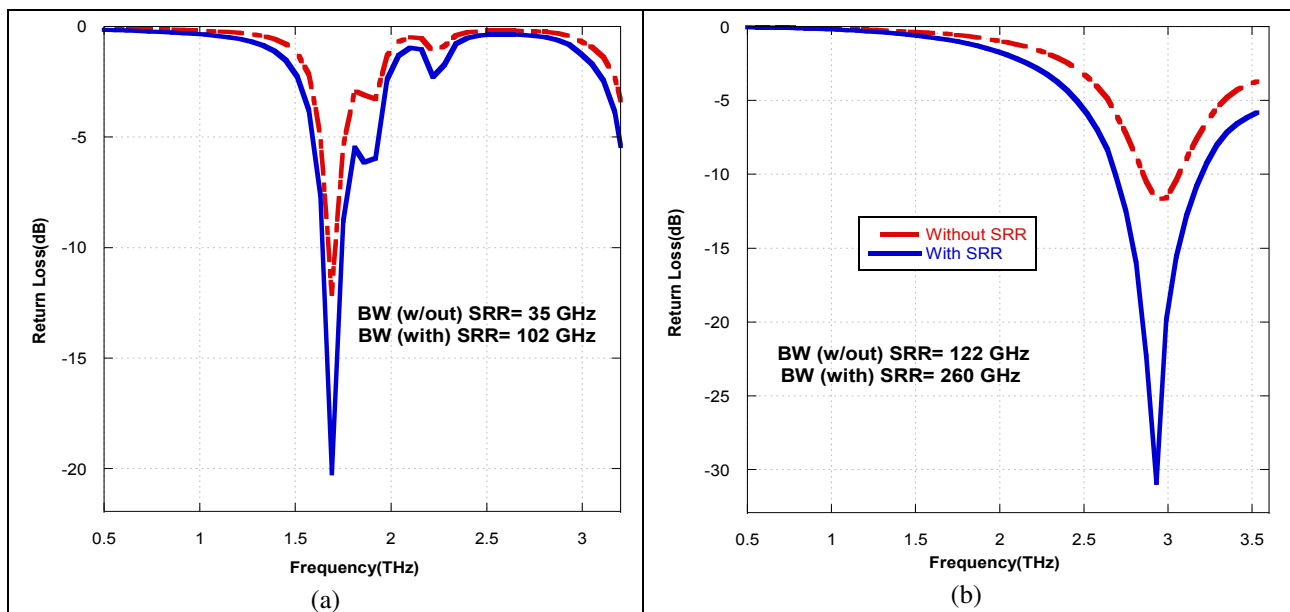**Figure-2.** Input impedance at different bias voltage V1.

Figure-3. The reflection coefficient (S11) for the combined layout in case of V1 equal to V2 at different chemical potential (a)μ_c = 0.1 eV, (b) μ_c= 0.5 eV.
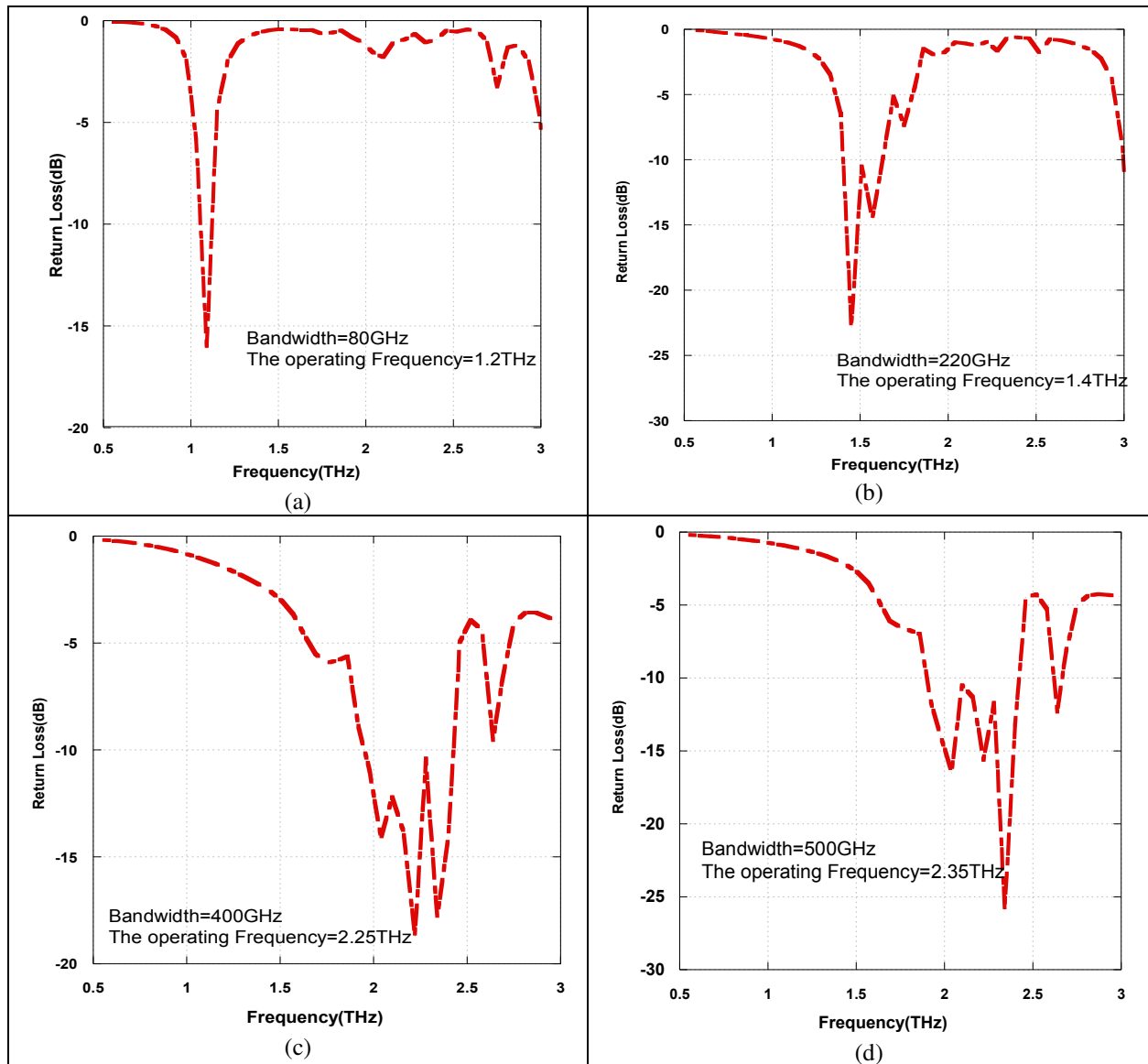
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Figure-4. The reflection coefficient (S11) for the combined layout at different chemical potential (a)μ_c = 0 eV, (b) μ_c = 0.1 eV, (c) μ_c= 0.3 eV, (d) μ_c= 0.5 eV.
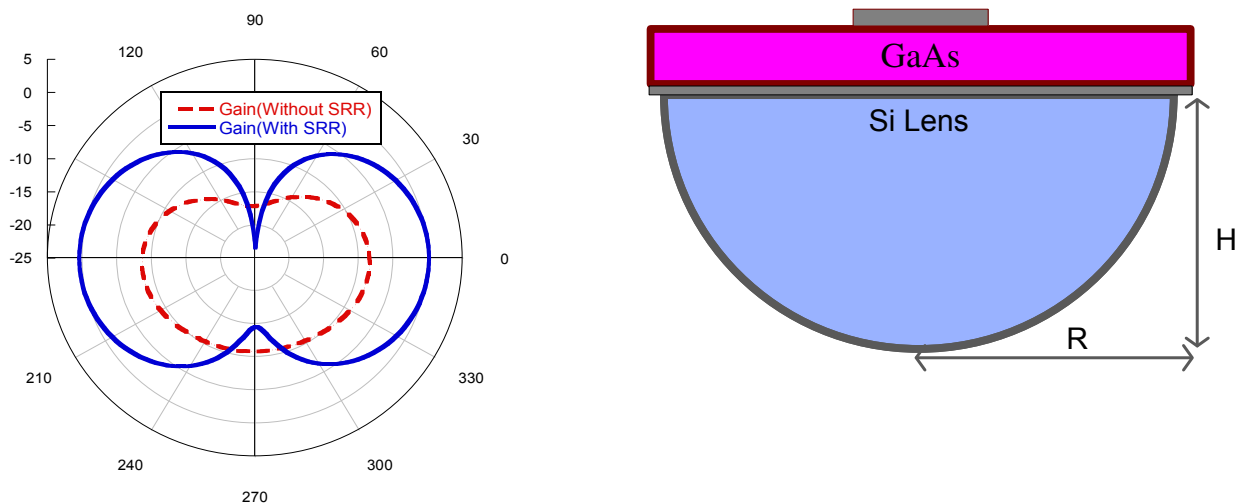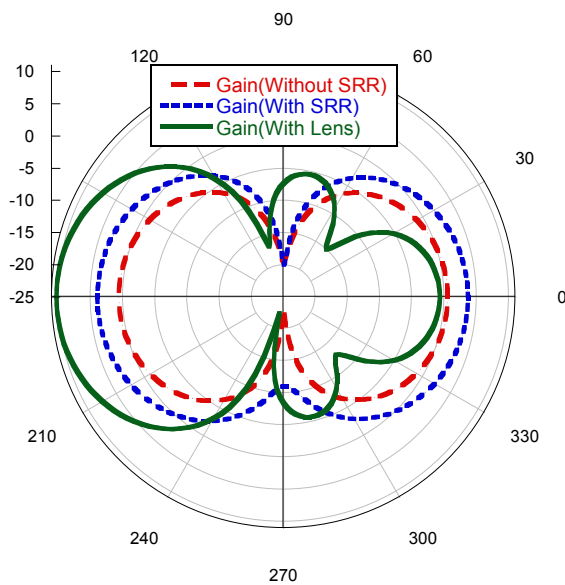

Figure-5. Gain at μ_c=0.1eV.

Figure-6. Extended hemispherical lens substrate structure and the gain.

CONCLUSIONS

We have described a tunable THz radiation band antenna whose radiation properties have been improved by adding a graphene SRR array. In particular, by using a graphene-based metamaterial structure, the tunable resonant properties of graphene antenna deposited SiO2/Si have been investigated in the THz regime and compared to a conventional structure. The proposed structure offers a larger bandwidth and a better match between the photomixer and the antenna. An extended hemispherical lens is added to the layout and a remarkable improvement of the gain can be observed, with value larger than 10 dB.

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