Beam Steering Using Grpahene-based Magnetic Resonator

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***Abstract* – We propose an active metasurface based on graphene magnetic resonator in reflection mode. The reflection angle is controlled by the phase gradient, which can be tuned by engineering the Fermi level distribution in the super-cell along the metasurface. By changing the period of the super-cell from n = 4 to n = 8 (thus the phase gradient of the metasurface), the beam direction is steered approximately from $\theta = 51°$ to $\theta = 23°$. The simulation results agree well with the calculated results given by the generalized Snell's law, demonstrating the possibility of dynamic beam steering base on the proposed metasurface.**

***Index Terms* — Beam steering, graphene, metasurface, magnetic resonator.**

1. Introduction

Metasurfaces, composed of subwavelength building blocks arranged on a surface, are capable of manipulating wave propagation in a prescribed manner [1, 2]. For example, via engineering a phase gradient on an interface, one can accomplish unparalleled control of anomalous reflection and refraction described by the generalized Snell's law [3, 4]. Graphene, a monolayer of carbon atoms arranged in a honeycomb structure, have attracted tremendous interest due to its unique electrical and mechanical properties [5, 6]. The tunability of graphene's electron density can be achieved via electrostatic voltage, making graphene a promising candidate for building active devices.

Different researchers have proposed a variety of graphene metasurfaces, and different strategies, such as Fabry-Perot resonator [7], are adopted to expand the phase coverage of the metasurfaces. Recently, a new graphene resonator, which can cover nearly 360° phase shift range, has been proposed in [8]. In this scheme, graphene behaving as a gate-tunable loss is used to modify the resonance characteristics of the proposed resonator, and in this way a large phase modulation range is obtained. In this paper, we propose an electrically dynamical metasurface based on gate-controlled graphene magnetic resonators. By engineering the phase gradient (associated with the distribution of Fermi levels controlled by gate voltages) along the metasurface, the capability of dynamic beam steering is demonstrated.

2. Results and Discussions

Figure 1 shows the schematic diagram of the graphene magnetic resonator. A metal film is first evaporated on a SiO_2/Si substrate to serve as a reflective surface for incident waves. Subsequently, there are dielectric and metal mesa. Finally, a graphene layer is placed on the structure. When a normally incident wave impinges on the structure, a circulating ac current is induced in the metal plane and mesa that form a magnetic resonator. The metal plane and mesa are spaced by a dielectric layer; the coupling between them is determined by the thickness of the dielectric layer. A bias voltage applied between graphene and a top gate can control the resistance of graphene and thus modulate the resonance characteristics of the resonator. Varying the gate-controlled graphene resistance drastically changes the resonance behavior of the proposed metasurface, resulting in a wide phase modulation range.

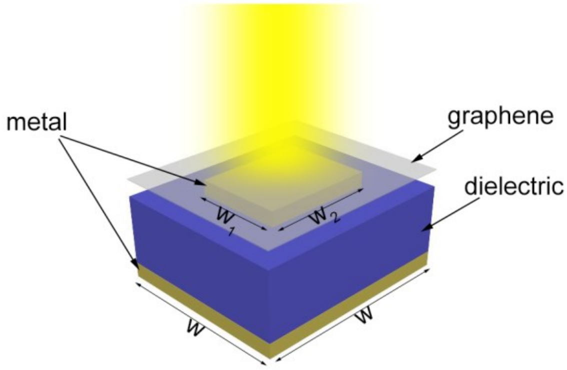

Fig. 1. Schematic diagram of the graphene magnetic resonator.

We first study the phase response and reflectivity of the proposed resonator, the unit cell for constructing metasurfaces. In our simulations, the graphene is modeled as an impedance surface due to its one-atom thickness. The resistance of graphene is calculated from the widely adopted conductivity formula $R_s = \pi\hbar^2 v_F^2 / e\mu_C E_F^2 + \rho_s$, with $v_F = 10^6$ m s^{-1} being Fermi velocity, $\mu_C = 390{,}000$ cm^2 V^{-1} s^{-1} representing the E_F -independent mobility and $\rho_s = 80\,\Omega$ representing short-range scattering [9, 10]. The results given by the above equation are consistent with experiment results [10].

Figure 2 gives the reflection phase curve as a function of frequency and Fermi level. The simulation is performed using a full-wave electromagnetic solver (CST Microwave Studio). For each Fermi level (0 eV to 1 eV) of gate-controlled graphene, the frequency of the incident plane wave, impinging normally into the unit cell, scans from 0.2 THz to 0.6 THz. Each unit cell manipulates both the amplitude and phase of the reflected wave near the resonance. At 0.4 THz (immediately below the resonance frequency, 0.42 THz, in device A), varying Fermi level allows a phase modulation range approximately from –180°to 0, as shown in Fig. 2. To cover wider phase modulation range at 0.4 THz, we introduce another independently controlled unit cell (device B) with geometrically different structure. The resonance frequency in device B is slightly below 0.4 THz. In contrast to device A, changing the Fermi level from 0 eV to 1 eV allows a phase modulation range from 0 to 140° in device B. As a result, a large phase modulation is available within the frequency interval between the two resonances, with a maximum modulation range of 320° at 0.4 THz.

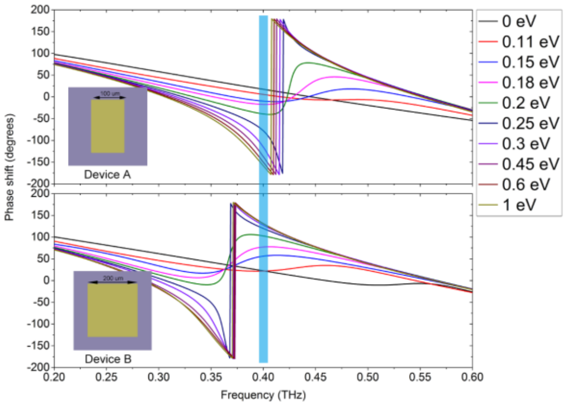

Fig. 2. The phase-frequency curves of the magnetic resonator with the Fermi level of graphene changing from 0 eV to 1 eV.

Tunable metasurfaces, with nearly arbitrary phase distribution (thus shape the wavefront), can be formed by engineering the Fermi levels distribution in the super-cell along the metasurface. According to the general Snell's law, an incident wave is anomalously reflected depending on the phase gradient along the metasurface. When a linear 2π variation of the phase shifts is formed in a super-cell L, the phase gradient approaches $d\varphi/dx = 2\pi/L$. For the case of normal incidence, the reflection angle is given by

$$\theta_r = \sin^{-1}\left(\frac{\lambda_0}{2\pi}\frac{d\varphi}{dx}\right) \quad (1)$$

where θ_r is reflection angle, λ_0 is the wavelength in air and $d\varphi/dx$ is the phase gradient along the metasurface, respectively. In order to form a clear wavefront, a constant phase gradient along the metasurface is needed. The metasurface is composed of the unit cells having the same sizes and the phase gradient of it can be achieved by engineering the local distribution of Fermi levels via electrostatic gating. For example, the combination of four Fermi levels, with an equal phase shifts interval of $\pi/2$, is designed to cover the nearly 2π phase shifts in the super-cell L. The phase gradient of the proposed metasurface equals approximately to $d\varphi/dx = 2\pi/L$. In addition, because L is determined by the total number of unit cells in the super-cell, the reflection angle can be discretely steered by patterning a periodic local phase distribution of the unit cells.

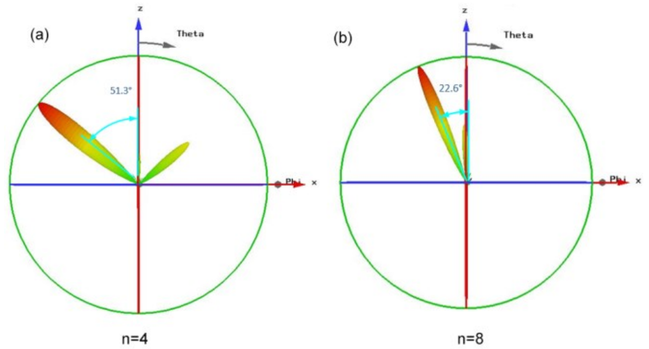

Fig. 3. The far field radiation patterns of the metasurface, for the cases of n = 4 and n = 8, respectively.

The far field radiation patterns of the metasurface, at the operation frequency of 0.4 THz, is studied using CST Microwave Studio by a normal plane wave excitation. Figure 3 shows the radiation patterns corresponding to the cases of n =4 and n =8 in a super-cell. The main beams center at 51.3° (n =4), 22.6° (n = 8), which agree well with the calculated results given by Eq. (1). By tuning the Fermi level distribution via electrostatic gating, the switching between the two states of the metasurface can be achieved, thus steer the beam direction from 23° to 51° actively. However, the steering angle can only change discretely due to definite sizes of the unit cell.

3. Conclusions

In conclusion, we design a tunable metasurface based on gate-controlled graphene magnetic resonators. By engineering the Fermi level distribution (associated with the gating configuration), the metasurface can be switched between two states, demonstrating the capability of beam steering dynamically.

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