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Non-Reciprocity with Graphene Magnetoplasmons and Application to Plasmonic Isolators

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***Abstract*—Plasmons and magnetoplasmons along a graphene strip immersed in a uniform tangential electric field are investigated. The uniform electric field creates a p-n junction in the middle of the strip. In the case of a magnetic bias, the magnetoplasmon mode localized at the p-n junction propagates only in one direction, thus realizing a plasmonic isolator. Other plasmonic p-n junction configurations are proposed to realize low-loss plasmonic isolators.**

I. INTRODUCTION

Graphene, a one atom layer thick carbon material, has spurred huge research interest since it was first produced in 2004 [1]–[3]. Due to its linear band-structure, graphene exhibits unique properties, such as ballistic transport, ambipolarity and half integer quantum Hall effect [2], [3]. Moreover when it is biased by a perpendicular magnetic field, it exhibits gyrotropic and non-reciprocal properties, which have been recently investigated at microwave, terahertz and optical frequencies [4]–[8].

Like 2D electron gases (2DEG's), graphene supports plasmons [9], [10] and, in the presence of a magnetic static field, magnetoplasmons [8], [11] at terahertz and higher frequencies, where the imaginary part of its conductivity becomes significant. A graphene strip supports an infinite number of bulk (2D) modes and two almost degenerate symmetrical and anti-symmetrical edge modes [8]. Under a magnetic field bias, the degeneracy of the two edge modes is lifted, leading to non-reciprocity [8]. For a chemically doped graphene strip, these magnetoplasmon modes are shown in Fig. 1 [8]. In such a strip, the carrier density is uniform, as a result of the zero net charge. In contrast, in an electrically doped graphene, the net charge is non-zero and the resulting Coulomb forces between the charge carriers (electrons and/or holes) lead to a non-uniform carrier density across the strip, which results in a non-uniform conductivity [9]. For a graphene strip in a constant electric field, shown in Fig. 2, the carrier density is different at the opposite sides of the strip. This specific configuration supports magnetolasmon waves localized at the center of the strip with interesting properties that will be discussed in Sec. II.

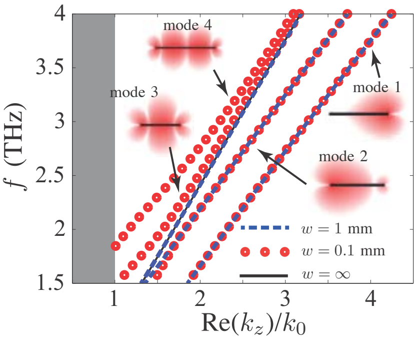

Fig. 1. Dispersion curves and electric field magnitudes for the bulk and edge modes of a graphene strip with parameters $\tau = 0.1$ ps, $n_s = 10^{13}$ cm^{-2} and $B_0 = 1$ T.

In this paper, the non-reciprocity of the magnetoplasmon waves along a magnetically biased graphene strip in a constant electric field is investigated. The non-reciprocity of the resulting modes is used to design a plasmonic isolator. Based on this configuration, other electrically or chemically doped structures are explored as plasmonic isolators. The electromagnetic modeling is performed using the finite difference frequency domain (FDFD) method [12] with the graphene strip being modeled as a zero thickness conductive sheet characterized by a nonuniform Drude conductivity tensor [4], with the diagonal and off-diagonal components reading

$$\sigma_d = \sigma_0 \frac{1 + j\omega\tau}{(1 + j\omega\tau)^2 + (\omega_c\tau)^2}, \tag{1a}$$

$$\sigma_o = \sigma_0 \frac{\omega_c\tau}{(1 + j\omega\tau)^2 + (\omega_c\tau)^2}, \tag{1b}$$

where ω_c is the cyclotron frequency, τ is the relaxation time, and σ_0 is the static conductivity in the absence of a static magnetic field [8]. The Drude model gives accurate results under the conditions $\mu_c \gg k_B T$, $\mu_c \gg \hbar\omega_c$, $\hbar\omega \ll 2\mu_c$, i.e. when the chemical potential is sufficiently far from the Dirac point, the Landau levels are smoothed out and there are no interband transitions, respectively.

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II. MAGNETOPLASMONS IN A GRAPHENE P-N JUNCTION

Electrical doping of graphene creates a non-uniform carrier density across the graphene strip [9]. For a graphene strip inside a constant electric field across the strip, the carrier density is found by solving the integral equation

$$\int_{-w/2}^{w/2} \rho(x', y') G(x, y; x', y') dx' - E_0 x = 0, \tag{2a}$$

$$-w/2 \le x \le w/2, \quad y = 0, \quad y' = 0, \tag{2b}$$

for the charge density $\rho(x', y')$, where $G(x, y; x', y') = \frac{-1}{2\pi\epsilon_0} \ln \sqrt{(x' - x)^2 + (y' - y)^2}$ is the 2D free-space Green function for the Poisson equation. The resulting carrier density is shown in Fig. 2 for a graphene strip with width $w = 50$ μm. This type of gating results in the presence of different carrier types at the opposite sides of the strip and the subsequent formation of a p-n junction at the center of the strip.

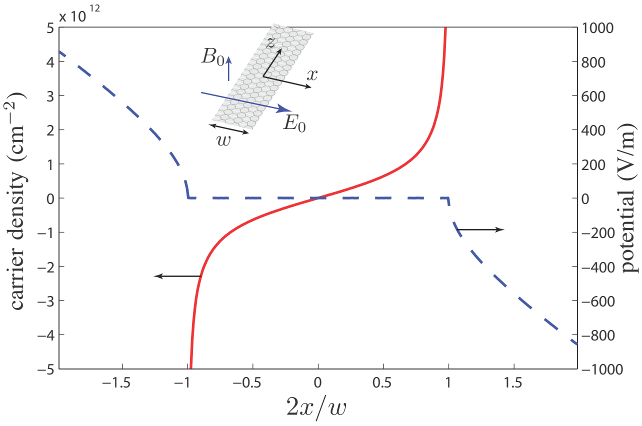


Fig. 2. Carrier density and electric potential for a graphene strip doped with an electric field; $w = 10$ μm and $E_0 = 10^8$ V/m.

The slow-wave factor and loss of the plasmon modes ($B_0 = 0$ T) of a graphene strip under a static electric field is shown in Fig. 3. Since the carrier density is low around the center of the graphene strip, the p-n junction mode has a higher loss compared to the other modes. The loss is decreased for the modes farther from the center of the strip and closer to the edges.

For a magneticaly biased graphene strip the resulting magnetoplasmon modes show interesting properties. Since the carrier density is low around the center of the strip, even a very small magnetic field can create a strong gyrotropic effect [4]. The p-n junction mode propagates only in one direction, as shown in the dispersion diagram of Fig. 4 for $B_0 = 0.1$ T. This interesting feature can be used to design non-reciprocal devices like isolators, as discussed in the next section.

III. APPLICATION TO PLASMONIC ISOLATOR

The magnetically biased electrically doped graphene strip shown in Fig. 5(a) supports a p-n junction magnetoplasmon mode that propagates only in one direction, realizing a plasmonic isolator. However, since the carrier density is low around the p-n junction the resulting device will be very lossy. In order to overcome this difficulty, the plasmonic isolator of Fig. 5(b) is proposed. This isolator consists of two parallel

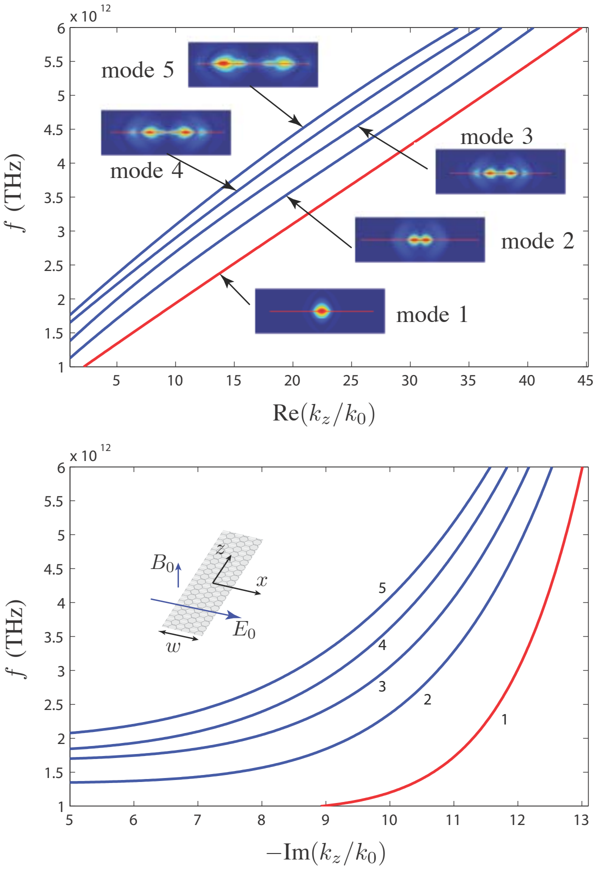


Fig. 3. Slow-wave factor and loss for a graphene strip biased by an electric field. $w = 50$ μm, $E_0 = 10^8$ V/m, $B_0 = 0$ T, $\tau = 0.1$ ps, $T = 300$ K. The p-n junction mode is represented in red.

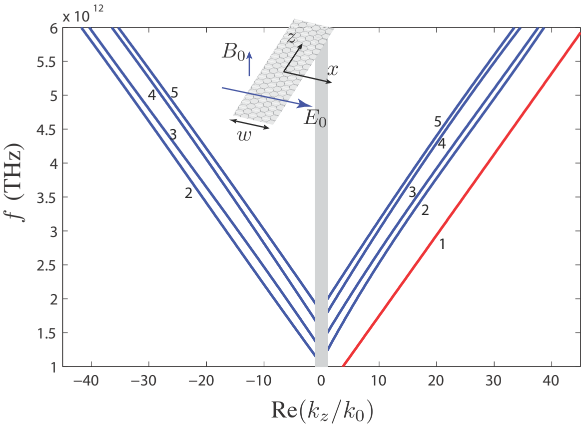
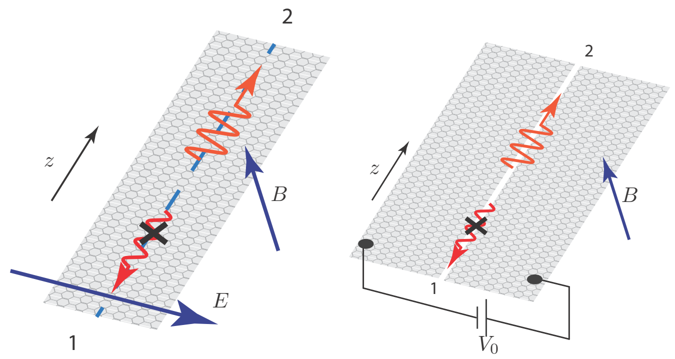


Fig. 4. Dispersion curves for a magnetically biased graphene strip biased by an electric field. $w = 50$ μm, $E_0 = 10^8$ V/m, $B_0 = 0.1$ T, $\tau = 0.1$ ps, $T = 300$ K. The p-n junction mode is represented in red.

graphene strips very close to each other, both magnetically biased, and with a potential difference applied between them, as shown in Fig. 5(b). Such a structure supports a localized plasmonic mode close to the inner edges of the strips. Since the carrier density close to the inner edges of the strips is high, a higher magnetic field is required to create a significant amount of gyrotropy. However, the resulting isolator device will be less lossy than the single strip configuration.



(a) (b)

Fig. 5. Electrically doped graphene plasmonic isolators.

An alternative plasmonic isolator consisting of two chemically doped graphene strips with opposite polarity is shown in Fig. 6. As the structure of Fig. 5(b), this structure supports a plasmonic mode localized around the inner edges of the strips. For magnetically biased strips, this mode exhibits nonreciprocal properties and propagates only in one direction. In this case the loss can be controlled by the amount of doping.

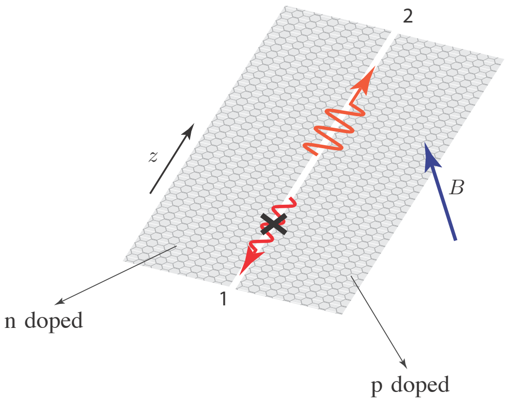


Fig. 6. Chemically doped graphene plasmonic isolator.

IV. CONCLUSION

The non-reciprocity of the magnetoplasmon modes of magnetically biased graphene strips can be used to design nonreciprocal plasmonic graphene-based devices. For a graphene strip inside a uniform tangential electric field, the nonreciprocity of the magnetoplasmon mode localized at the p-n junction is ideal for the realization of plasmonic isolator devices. Based on this structure, other conceptually similar plasmonic isolator devices are proposed.

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