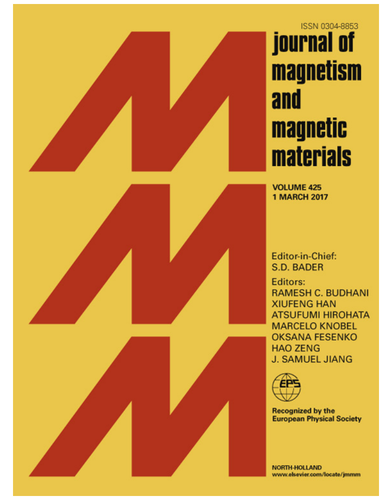

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Manipulation of the Faraday Rotation by Graphene Metasurfaces

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Abstract: We demonstrate a simple structure including circular shape patterned graphene surface for manipulation of Faraday rotation phenomenon. The patterned structure can be utilized in the building blocks of vast tunable non-reciprocal components. The behavior of the structure is discussed analytically by circuit model approach and verified by numerical simulation. Obviously, manipulation of polarization rotation is attained from the circular shape pattern. Also, we show that Faraday rotation effect takes place at higher frequencies compared to the similar effect in uniform and un-patterned graphene.

Keywords: *Equivalent circuit model, Faraday rotation, Graphene based structures, Non-reciprocal components, Patterned graphene.*

1. INTRODUCTION

Terahertz technology, the science of utilization of unoccupied frequency spectra region called *terahertz gap*, between microwave and farinfrared, can be considered as a candidate to be exploited extensively in various applications of communication [1], processing [2], and sensing [3]. In addition, terahertz radiation possessing the feature of line of sight propagation, with safe, non-ionizing, and non-destructive penetration into a wide category of materials, can be regarded to be utilized in various imaging systems capable in spectroscopy [4], defect detection of industrial products [5], material recognition [6], security systems [7], and surgery devices [8]. Therefore, to implement efficient terahertz modules, various tunable components utilizing the magneto-optical effects of Kerr [9] and Faraday rotation [10] can be required.

Faraday rotation is one of the magneto-optical effects extensively employed realizing non-reciprocal features [10]. As a lightwave transmits along a transparent material with a normal magneto-static bias, its polarization rotates encountering non-reciprocal feature applicable in various devices of isolators [11], circulators [12], phase shifters [13], and switches [14]. Formerly, ferrites were often used to generate the Faraday rotation effect [15]. However, due to the mandatory requirement for creation of devices at scales down to the sub-wavelength to confine and guide lightwaves, the ferrite components are large to be implemented in photonics integrated circuits [16]. So far, myriad of non-reciprocal components based on subwavelength magneto-plasmonic effects by noble metals have been proposed and investigated [17, 18]. On the other hand, relatively high amount of loss and lack of enough tunability in metal based structures have caused some restrictions in their applications [19]. An arrangement of carbon atoms in a two dimensional honeycomb lattice possessing the properties of one-atom thickness material, graphene, has been found to be a good replacing material due to its intriguing features such as exceptional high mobility characteristic [20], extreme electromagnetic confinement [21], high nonlinear Kerr Effect [22], and dynamically tuning with electro-static and magneto-static bias fields [23]. So far, many graphene based structures have been investigated [20-26].

Among the fantastic features, magneto-optical properties of graphene, exhibiting exceptional and extremely large values of Faraday rotations in spite of its single atom thickness, can be considered as a promising candidate to implement non-reciprocal components [27, 28]. Under a perpendicular bias magnetic field, a remarkable amount of Faraday rotation is created owing to incorporation of two individually effects of the resonances originated from cyclotron effect and transitions in inter-Landau-levels in classical and quantum mechanical points of view, respectively [29]. The most interesting feature of Faraday rotation effect by graphene is the possibility of dynamic tunability via applying an external electric field [30]. However, despite the invaluable and remarkable magneto-optical effect of graphene, there are still some challenges. A uniform layer of graphene does not create enough Faraday rotation for realizing practical non-reciprocal devices. In addition, the effect is observed at lower terahertz frequencies and in expense of large amount of magnetic bias fields [31]. In [32], the fundamental constraints in realization of non-reciprocal graphene components in specific configurations have been established. So far, many attempts have been carried out to achieve higher amount of Faraday rotation in lower magnetic bias fields and in higher frequency spectra regions based on employing some patterns of a graphene layer such as arrangements of ribbon arrays [33, 34], cross shape configuration of ribbons [35], circular patterns [36, 37] and also, exploiting Fabry-Perot like structures amplifying the effect [38]. Patterning the graphene layer makes it as a metasurface exhibiting some interesting features. According to this concept, different patterns for providing various properties such as negative refraction and tunable photonic band gap have been investigated for implementation of some modified graphene based structures of absorbers [39] and cloaks [40]. In experimental point of view, electron beam lithography and oxygen plasma etching can be employed to realize patterned graphene structures [35].

Recently, an enhanced Faraday rotation due to excitation of magneto-plasmons in microribbon patterns has been proposed [31]. Based on some artificially created capacitive properties in patterned graphene, the Faraday rotation by graphene has been manipulated [35]. Periodic antidote pattern has been proposed to manipulate the magneto-optic feature by graphene [36]. The antidotes operate as two-dimensional resonators which the magneto-plasmonic resonances are gate-tunable. It is stated that in patterned graphene, magneto-resonances are observed at higher frequencies compared to the uniform ones. However, still realization of relatively considerable Faraday rotation, requires high values of magnetic fields. It has been demonstrated that by making circular pattern on pristine graphene, Faraday rotation up to