Numerical study on rotational force in a bi-layered gammadion chiral metamaterial

Yohan Lee, Eui-Young Song, Seung-Yeol Lee, Joonsoo Kim, Jaebum Cho, and Byoungho Lee*

National Creative Research Center for Active Plasmonics Application Systems, Inter-University Semiconductor Research Center and School of Electrical Engineering, Seoul National University, Seoul 151-744, Korea

E-mail: byoungho@snu.ac.kr

Abstract. Recently it has been demonstrated that chiral metamaterials show giant optical activity and circular dichroism. However, it has been rarely known about rotational force generated by incident wave in chiral metamaterials. We calculate the rotational force in the bi-layered gammadion chiral metamaterial. In addition, we show that a bi-layered structure, which has greater optical activity than a single-layered structure, changes the rotational force tendency greatly. This result can be used as a possible optical manipulation in biological sciences.

1. Introduction

Chiral metamaterials have attracted much attention due to their interesting properties, such as negative refraction, giant optical activity, and circular dichroism. These properties have been used in many applications such as optical particle manipulation [1, 2], optical modulation [3, 4], display devices [5, 6], etc. Especially, the rotational force generated by incident light on the chiral metamaterials may have potential applications of optical micromanipulation which has a major impact on the biological and colloidal sciences [7-9]. A gammadion structure, one of the representative structures in chiral metamaterial, has been studied numerously due to its high potential for applications such as optically-driven motor and biological sensors [9, 10]. Moreover, it has been shown that a bi-layered metamaterial can be used for observing another kind of resonance which is different from the resonance observed in single-layered structure. Therefore, in this paper, we apply a bi-layered structure into gammadion-shaped chiral metamaterial and calculate absorption spectrum and rotational force. By observing the electric field and surface charge distribution near the gammadion structure, we classify the characteristics of resonance into electric and magnetic dipole types, and compare the aspect of rotational force on those resonance conditions.

2. Simulation conditions

Schematic diagram of proposed bi-layered chiral metamaterial is shown in figure 1(a). Planar metal structures of two identical gammadion-shaped gold resonators are separated by a SiO_2 spacer of which thickness is 10 μm. The thickness, width, and diameter of gold resonators are 200 nm, 8 μm, and 60 μm respectively. For reference structure, single-layered chiral metamaterial is also designed with the

same dimension as proposed bi-layered chiral metamaterial as shown in figure 1(b). Finite difference time domain (FDTD) method is used to calculate the electromagnetic properties of these structures. We calculate the torque generated by electromagnetic (EM) wave on single- and bi-layered structure by using Lorentz equation in harmonic incident wave. The time-averaged force per unit volume is

$$<\mathbf{f}(\mathbf{r},t)>_{avg}=\frac{1}{2}\text{Re}[\rho^{*}(\mathbf{r})\mathbf{E}(\mathbf{r})+\rho(\mathbf{r})\mathbf{E}^{*}(\mathbf{r})]+\frac{1}{2}\text{Re}[\mathbf{J}^{*}(\mathbf{r})\times\mathbf{B}(\mathbf{r})+\mathbf{J}(\mathbf{r})\times\mathbf{B}^{*}(\mathbf{r})] \; . \qquad (1)$$

We substitute electric and magnetic field distributions obtained by FDTD method into equation (1). Then, we also calculate surface charge density (ρ) and current density ($\vec{J}$) from the Maxwell equation reversely,

$$\rho(\mathbf{r})=\nabla\bullet\mathbf{D} \; , \qquad (2)$$

$$\mathbf{J}(\mathbf{r})=\nabla\times\mathbf{H}-j\omega\mathbf{D} \; . \qquad (3)$$

Finally, the torque per unit volume is calculated by cross product force with directional unit vector

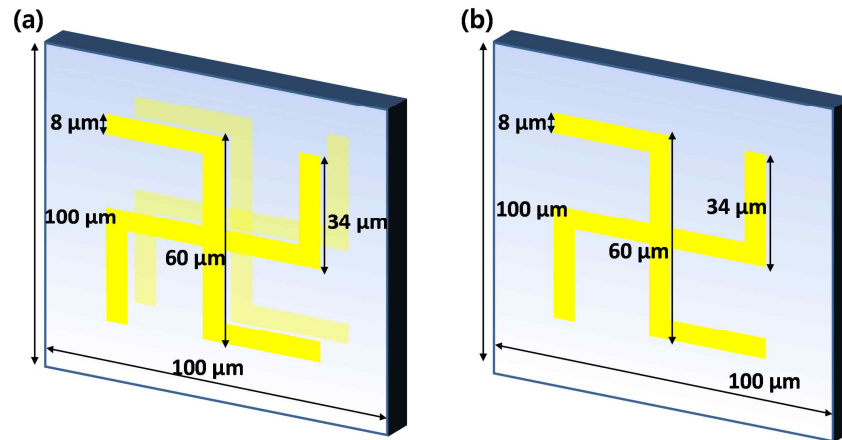$$\mathbf{N}=\iiint_{V}\boldsymbol{\tau}dv=\iiint_{V}(\mathbf{r}\times\mathbf{f})dv \; . \qquad (4)$$

Figure 1. Schematic diagram of the unit cell of the chiral metamaterials: (a) Bi-layered gammadion-shaped gold resonators (yellow) separated by SiO$_2$ spacer (white blue) and (b) single-layered gammadion gold resonator laid on SiO$_2$ spacer.

3. Results and Discussions

We investigate absorption spectrum along frequency range from 0.4 THz to 1.3 THz. In the case of single-layered structure, the spectral response of resonance is almost independent of incident polarization. It is also shown that only a broad resonance exists on 1.05 THz for single-layered structure while there are two resonance peaks on 0.75 THz and 1.2 THz for bi-layered structure as shown in figure 2(b). The resonance peak on 0.75 THz in bi-layered structure is remarkably high and sharp compared with other resonances.
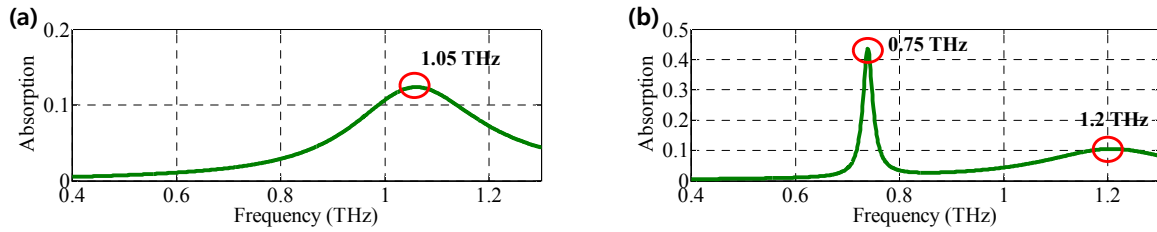
Figure 2. Absorption spectrum in (a) single-layered and (b) bi-layered gammadion chiral metamaterial.

In order to explain this tendency, distribution of E_x field, simplified surface charge, and surface current near the metal planes of bi-layered structure at two resonance conditions are shown in figure 3. As shown in figure 3(a), charge distribution of each resonator has opposite pattern at sharp resonance frequency (0.75 THz). In this condition, the electric field of the incident wave induces opposite direction of currents within each resonator and results in current loop in the central region between top and bottom resonators. Hence, a magnetic moments **m** is induced by this current loop. On the other hand, in figure 3(b), the directions of current on the two resonators are same at broad resonance condition (1.2 THz). In this case, charges oscillate and generate an electric moment **p**. Since the charge distribution on the resonance condition of single layered structure cannot be separated into opposite directions like figure 3(a), only the broad resonance modelled by electric dipole moment can appear for single-layered structure, whereas sharp resonance caused by magnetic dipole resonance cannot be shown.
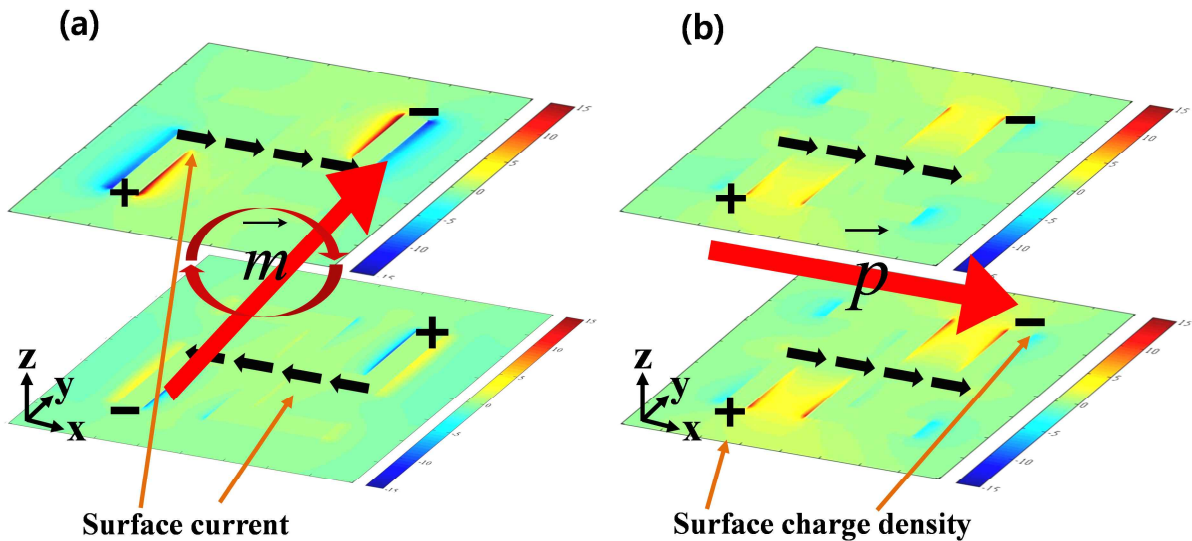

Figure 3. E_x field, surface charge and surface current at the resonance frequency of (a) 0.75 THz and (b) 1.2 THz in a unit-cell of bi-layered structure. The distance from each resonator to field plane is 500 nm. The phase is fixed at 0 degree.

According to this analysis, strong absorption peak shown in figure 2(b) comes from magnetic dipole moment and other peaks are based on electric dipole moment. Magnetic moment is formed by opposing electric dipoles. It is known that magnetic moment resonance generally has higher Q-factor as shown in figure 2(b) [11, 12].

Figure 4 shows the torque generated on the single- and bi-layered structure. Since intensity enhancement is the strongest at the resonance frequency, torque spectrum from numerical calculation shows similar tendency with absorption spectrum. Each peak value of torque by LCP or RCP in

single- layered structure is almost same. On the other hand, the torque responses between LCP and RCP incidence are quite different. The black dotted line shown in figure 4(b) is the difference of torque between LCP and RCP incidences. It is shown that torque difference is remarkably increased for both resonances. Moreover, the sharpness of torque difference is also well-matched to that of resonance spectrum shown in figure 2. Since this kind of sharp torque differences are only achievable in bi-layered structure, we expect our structure can be applied to chiral metamaterial which has both highly frequency-selective and polarization sensitive characteristics.
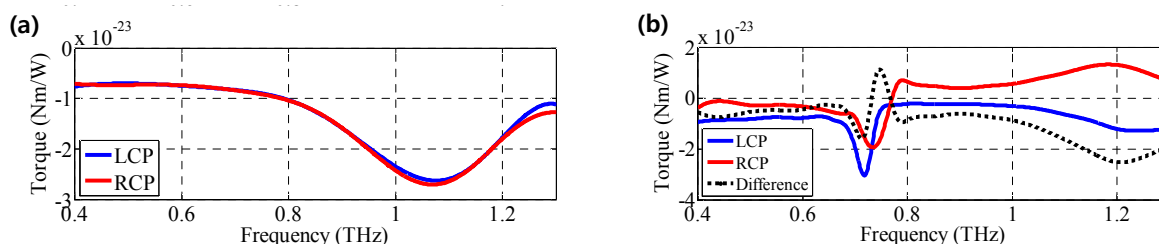

Figure 4. Torque plots along frequencies in (a) single-layered and (b) bi-layered structure.

4. Conclusion

We proposed a bi-layered gammadion chiral metamaterial which has sharp torque difference characteristics at around 0.7 THz. Our chiral metamaterial has strong rotational force on circular polarized EM wave incidence which is based on the magnetic moment resonance between bi-layered gammadion structures. In perspective of sharp peak, we can design microrotator which has the wavelength-sensitive property. Furthermore, this study on optical force can offer help in the field of optical micromanipulation , colloidal and biological sciences.

References
[1]   Baumgart K, Mazilu M and Dholakia K 2010 *Nat. Photonics* **2** 675-678
[2]   Dholakia K, Reece P and Gu M 2008 *Chem. Soc. Rev.* **37** 42–55
[3]   Yu N, Genevet P, Kats M A, Aieta F, Tetiennem J –P, Capasso F and Gaburro Z 2011 *Science* **334**, 333
[4]   Luo J, Yu H, Song M and Zhang Z 2014 *Opt. Lett.* **39** 2229-2231
[5]   Ni X, Kildishev A V and Shalaev V M 2013 *Nature commun.* **4** 2807
[6]   Huang L, Chen X, Muhlenbernd H, Zhang H, Chen S, Bai B, Tan Q, Jin G, Cheah K -W, Qiu C -W, Li J, zentgraf T and Zhang S 2013 *Nature commun.* **4** 2808
[7]   Fasman G D 1996 *Circular Dichroism and Conformational Analysis of Bio molecules* (New York: Plenum)
[8]   Barron L D 2004 *Molecular Light Scattering and Optical Activity* (London: Cambridge Univ. Press)
[9]   Hendry E, Carpy T, Johnston J, Popland M, Mikhaylovskiy R V, Lapthorn A J, Kelly S M, Barron L D, Gadegaard N and Kadodwala M 2010 *Nat. Nanotechnol.* **5** 783-787
[10] Liu M, Zentgraf T, Liu Y, Bartal G and Zhang X 2010 *Nat. Nanotechnol.* **5** 570-573
[11] Sersic I, Frimmer M, Verhagen E and Koenderink A F 2009 *Phys. Rev. Lett.* **103** 213902
[12] Evlyukhin A B, Novikov S M, Zywietz U, Eriksen R L, Reinhardt C, Bozhevolnyi S I and Chichkov B N 2012 *Nano Lett.* **12** 3749-3755