Optical planar chiral metamaterial designs for strong circular dichroism and polarization rotation

Do-Hoon Kwon, Pingjuan L. Werner, and Douglas H. Werner

Department of Electrical Engineering, Pennsylvania State University
University Park, Pennsylvania 16802, USA

dhw@psu.edu

Abstract: Planar chiral metamaterials comprising double-layer dielectric-metal-dielectric resonant structures in the shape of a gammadion are presented in the near-infrared regime. The unit cell of the doubly-periodic metamaterial design is optimized using the genetic algorithm for maximum circular dichroism and for maximum optical activity. A circular dichroism value in excess of 50% is predicted for the optimized design. Maximum polarization rotatory powers in terms of the minimum allowed transmittances are also obtained and presented.

OCIS codes: (050.1930) Dichroism; (160.4760) Optical properties; (260.5430) Polarization.

References and links

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1. Introduction

Chirality refers to the geometrical property that the original microscopic or macroscopic structure cannot be brought to congruence with its mirror image. Circular dichroism (CD) and polarization rotation are the most distinguished properties of natural or artificial chiral materials compared to non-chiral materials. Recently, planar chiral structures have been reported. Polarization rotations in excess of 30° were experimentally observed from light diffracted by chiral metallic gratings at a visible wavelength [1], but not for the zeroth order reflected and the transmitted light. For an array of sub-wavelength chiral metal nanostructures that produces no diffraction, polarization rotations on the order of 1° were observed in [2, 3].

It was shown in [4] that loss is an essential component in planar chiral structures, allowing them to produce different transmission intensities for incident light waves of different handedness. When a mutually twisted pair of planar chiral strips were formed on the two sides of a dielectric substrate (a resonant structure), giant polarization rotation power was observed together with a high loss [5] in the microwave spectrum. A similar bilayered chiral structure was also investigated in the optical regime [6]. Polarization conversion properties in dielectric and metallic planar chiral metamaterials were numerically investigated in [7]. Strong polarization rotations on the order of tens of degrees were obtained from both types of planar chiral metamaterials. However, in comparison, the rotatory power was weaker for the metallic structure. The transmission properties from arrays of gammadion-shaped metal-dielectric-metal magnetic resonators were experimentally and numerically examined in [8]. Stronger CDs were observed for the double-layer metamaterial structures when compared to those of the single-layer metamaterials. This phenomenon has been attributed to the polarization-sensitive resonance of the former.

Only the CD aspect of the planar chiral structure was considered in [8], where a maximum CD of roughly 6% was observed in the near-infrared (near-IR) region. This paper presents a double-layer planar chiral metamaterial design optimized for the strongest CD and for the largest polarization rotations in the near-IR spectrum. The unit cell of the doubly-periodic planar chiral metamaterial comprises a silver-alumina-silver sandwich structure in the form of a gammadion shape. The geometrical features of the unit cell are optimized using the genetic algorithm (GA) [9].

2. Metamaterial design, analysis, and optimization methodologies

The unit cell of a doubly-periodic planar chiral metamaterial design is shown in Fig. 1. A planar resonator is arranged in the shape of a gammadion with the period equal to p in both the $\hat{x}$ and $\hat{y}$ directions. The resonator structure comprises two silver (Ag) layers of thickness t separated by an alumina (Al_2O_3) layer of thickness d. This is an example of the metal-dielectric-metal sandwich structures typically employed as planar magnetic resonators in optical negative-index metamaterials [10, 11, 12]. Each arm of the Γ-shaped resonator is composed of two rectangular blocks of dimensions $l/2 \times w$ and $s \times r$ connected at a right angle. A left-facing gammadion shown in Fig. 1(a) is employed in this study. The metamaterial is finally placed on an electrically thick glass substrate, which is treated as a half space in this study.

The metamaterial is subject to illumination by a normally incident right-hand circular polarized (RCP,$+$) and left-hand circular polarized (LCP,$-$) plane wave propagating in the $+\hat{z}$ direction. For each circularly polarized incident wave, the four-fold rotational symmetry of the metamaterial structure with respect to the $\hat{z}$ axis guarantees that the reflected and transmitted fields have purely circular polarization states of the opposite and the same handednesses as the incident wave, respectively. A periodic version of the finite element-boundary integral full-wave technique [13] is applied to analyze the scattering problem. The complex reflection and transmission coefficients, $r_\pm$ and $t_\pm$, corresponding to the RCP/LCP incident light waves are

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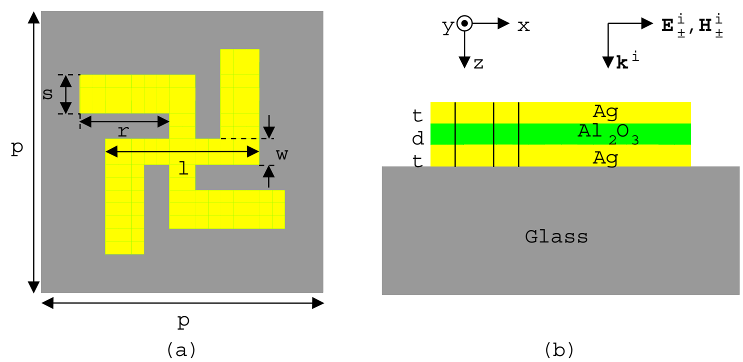

Fig. 1. The unit cell of the planar chiral metamaterial: (a) A top view, (b) A side view.

evaluated at the top surface and the metamaterial-glass interface, respectively. Furthermore, the reflectance ($R_\pm$) and transmittance ($T_\pm$) are obtained from the associated values of $r_\pm$ and $t_\pm$. Due to the four-fold structural symmetry, the four quantities $r_\pm$ and $t_\pm$ can be obtained from a single scattering analysis with an incident field linearly polarized either in the $\hat{x}$ or $\hat{y}$ direction. In the numerical analysis, alumina and glass are treated as lossless non-dispersive dielectric materials with relative permittivity values of 2.6244 and 2.25, respectively. Measured permittivity values reported in [14] are used to represent silver at near-IR wavelengths.

In Sections 3 and 4, the geometrical features of the unit cell shown in Fig. 1 are optimized for specific optical functions. This is performed using the genetic algorithm (GA) [9], which is a powerful optimization methodology based on the principles of survival-of-the-fittest and natural selection. For a given optimization goal, the performance of a particular realization of the design is quantified by a fitness function f. The value of f is maximized through an evolutionary process within the solution space of the parameters to be determined. The GA has been previously employed to optimize the unit-cell geometry of optical metamaterials in the visible range to achieve a desired set of equivalent material parameter values [15]. For the near-IR metamaterial design considered here, seven geometrical parameters – p, l, w, r, s, t, and d – are optimized. The allowable ranges of these parameters are set to $0.3\ \mu\text{m} \leq p \leq 0.55\ \mu\text{m}$, $0 \leq l \leq p$, $0 \leq w \leq 1$, $0 \leq r \leq (p-w)/2$, $0 \leq s \leq (l-w)/2$, $20\text{ nm} \leq t \leq 50$ nm, and $20\text{ nm} \leq d \leq 50$ nm. The ranges of l, w, r, and s permit a wide scope of sizes and shapes of the silver-alumina-silver resonator to be explored within the unit cell. At one extreme, no existence of any resonator structure is included (although this particular design realization is not interesting). At the other extreme, the entire unit cell volume may be filled with the resonator structure. It is noted that continuity of the gammadion structure across the unit cell boundaries is possible if $l = p$ is satisfied. The target wavelength λ for the optimal performance search is limited to $0.9\ \mu\text{m} \leq \lambda \leq 1.1\ \mu\text{m}$ in the near-IR range.

3. Strong circular dichroism

For maximum CD, the fitness to be maximized is defined as

$$f = |A_+ - A_-| = |T_+ - T_-|, \tag{1}$$

where $A_\pm$ are the absorbances for the RCP and LCP incident waves, which are given by $A_\pm = 1 - R_\pm - T_\pm$. The second equality in (1) follows from $R_+ = R_-$, which can be obtained from the reciprocity theorem for structures having four-fold rotational symmetry and a normally incident plane wave [7].

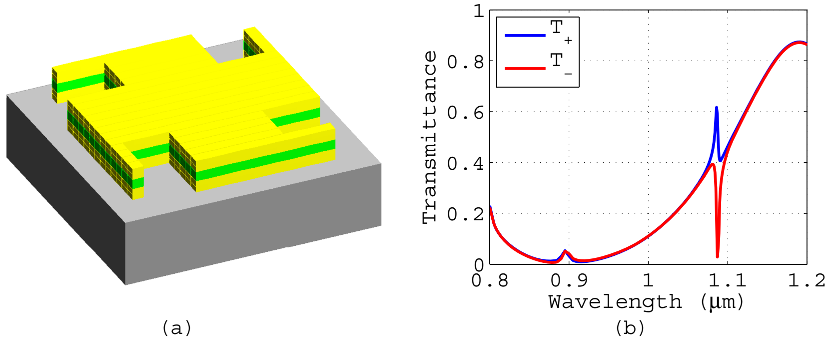

Fig. 2. An optimized metamaterial for strong CD in the near IR: (a) The optimized metamaterial geometry, (b) The transmittance responses.

The GA optimization converged to the maximum fitness of $f = 0.563$ with $T_+ = 0.591$ and $T_- = 0.028$ at $\lambda = 1.087$ μm. The optimized geometrical parameter values were found to be $p = 534$ nm, $l = 437$ nm, $w = 194$ nm, $r = 97.1$ nm, $s = 24.3$ nm, $t = 24.0$ nm, and $d = 20.0$ nm. The optimized metamaterial geometry and the transmittance spectra for the two circular polarizations are shown in Fig. 2. The transmittance curves for $T_\pm$ lie on top of each other away from the optimal wavelength 1.087 μm, around which T_+ and T_- change sharply in opposite directions. At the optimal wavelength, the absorbance values were found to be $A_+ = 0.090$ and $A_- = 0.653$. Since, based on reciprocity, the values $R_\pm = 0.318$ are both the same, then it follows that the difference in the transmittances relies completely on loss, which is in accordance with the observation made in [4]. The difference in the absorbances is attributed to the polarization-sensitive resonances and the associated losses from the chiral magnetic resonator [8]. It is noted that the CD of the optimized design is more than 5 times as strong as the theoretical and experimental results reported in [8] for the near-IR regime.

To investigate the significance of a resonance in producing CD, the metamaterial was optimized using the same fitness as used in (1) with the value of d forced to zero. Without the alumina spacer layer, there is no magnetic resonance to cause strong absorption. Even the design optimized for strong CD produced (results not shown) a meager fitness value of $f = 0.0026$, which practically amounts to a non-existent CD.

4. Large polarization rotation

Let the transmission coefficients $t_\pm$ be written as $t_\pm = |t_\pm| \exp(i\phi_\pm)$, where an $\exp(-i\omega t)$ time convention is assumed. For a linearly polarized illumination at normal incidence, the polarization rotation angle θ and the ellipticity τ of the transmitted wave are given by [7]

$$\theta = \frac{1}{2}(\phi_+ - \phi_-), \tag{2}$$

$$\tau = \frac{|t_+| - |t_-|}{|t_+| + |t_-|}. \tag{3}$$

The angle θ is measured from the polarization direction of the incident electric field. The maximum norm of practical importance for θ is equal to 90°.

To quantify a planar chiral metamaterial's capability to rotate the polarization vector of the wave close to 90°, a proper fitness for strong polarization rotation is defined as

$$f = \frac{1}{(\pi/2 - |\theta|)^2}. \tag{4}$$

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Table 1. Designs and the associated parameters for different values of $T_{\min}$ optimized for strong polarization rotation

$T_{\min}$	0	0.1	0.2	0.3	0.4	0.5
f	$4.6 \cdot 10^6$	$1.8 \cdot 10^4$	192	1416	0.86	0.69
θ (°)	90.0	90.0	-85.9	-91.5	28.4	21.0
λ (μm)	0.967	1.074	1.082	1.074	1.084	1.093
p (nm)	479	475	479	494	368	506
l (nm)	335	285	479	494	276	322
w (nm)	144	94.9	191	198	138	92.1
r (nm)	47.9	71.2	71.8	74.2	68.9	92.1
s (nm)	23.9	23.7	95.7	98.9	23.0	23.0
t (nm)	46.0	36.0	46.0	20.0	48.0	48.0
d (nm)	28.0	20.0	28.0	50.0	20.0	24.0
T_+	0.133	0.210	0.204	0.352	0.409	0.561
T_-	0.110	0.139	0.350	0.532	0.443	0.511
τ	0.049	0.118	-0.135	-0.102	-0.02	0.023

To date, for metallic planar chiral metamaterials in the optical regime, less than 1° of polarization rotation has been observed [6]. A rotation as large as 28° was verified for the same metamaterial design in the RF range, but it was accompanied by small values of $T_\pm$ as low as -30 dB [5]. If arbitrarily small values for $T_\pm$ are permitted, a polarization rotation by 90° may be easily obtained because only a small amount of polarization-sensitive response will be necessary to make θ large. This condition is satisfied if the two curves for $t_\pm$ in the complex plane traverse the origin in opposite directions as a function of wavelength or frequency. Therefore, it is expected that the maximum achievable polarization rotation will be a decreasing function of the minimum transmittance required during the optimization.

Several GA optimizations using the fitness defined in (4) were performed using different values for the minimum transmittance $T_{\min}$ by requiring $T_\pm \geq T_{\min}$ during the optimization. Six different values were used for $T_{\min}$ from 0 to 0.5 at an interval of 0.1. The converged fitnesses, optimized parameter values, and polarization rotation performances are summarized in Table 1 together with the associated values for $T_\pm$ and τ for each choice of $T_{\min}$. First, it can be observed that polarization rotations close to 90° can be obtained with values of $T_{\min}$ ranging from zero up to 30%. Beyond 30%, the maximum value of θ decreases and the polarization rotation power is limited. Secondly, the optimized planar chiral structure is connected across the unit cell boundary for $T_{\min} = 0.2$ and 0.3 because $l = p$. This shows that isolated planar chiral structures are not a requirement for strong polarization rotations. For all other designs, the gammadion resonators are physically separated from one another.

As an example, the optimized design and the associated performance parameters for the case $T_{\min} = 0.5$ are shown in Fig. 3. The total thickness of the metamaterial is found to be 120 nm. The maximum polarization rotation of 21.0° is realized at $\lambda = 1.093$ μm (Fig. 3(c)) with the values of transmittance $T_+ = 0.561$ and $T_- = 0.511$ (Fig. 3(b)). In terms of the specific rotation, this amounts to a giant rotatory power of $1.75 \times 10^{5\circ}$/mm. Around $\lambda = 1.093$ μm, $T_\pm$ are steeply decreasing functions of λ and they fall below the minimum requirement of 50% transmittance at longer wavelengths. The value of the ellipticity is equal to 0.023 at the optimal wavelength (Fig. 3(d)), indicating that the polarization of the transmitted light, resulting from linearly polarized incident light, will be close to linear.

As in the previous section, the metamaterial design was optimized using the same objective

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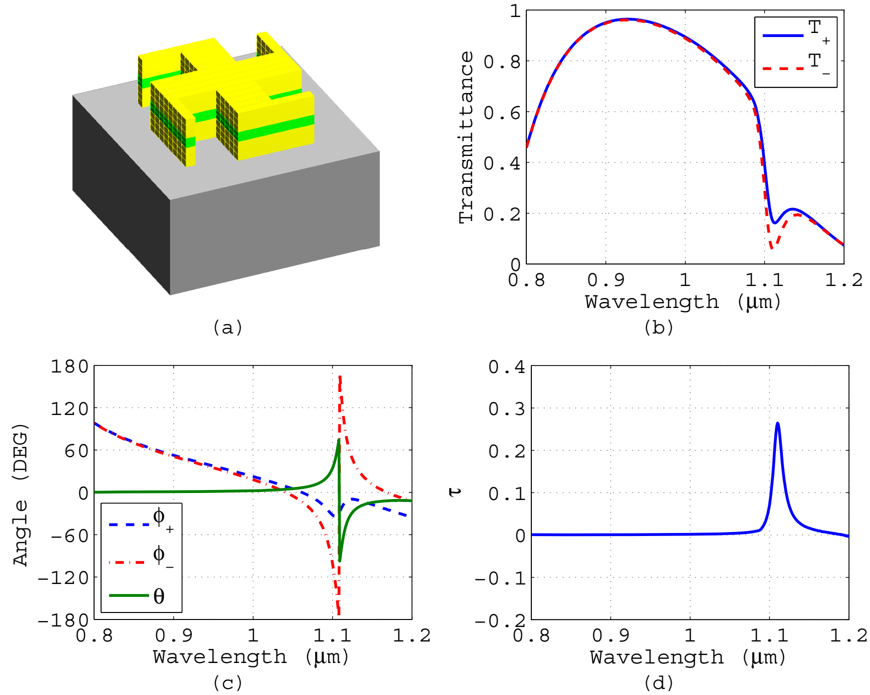

Fig. 3. An optimized metamaterial for strong polarization rotation under the condition $T_{\min} = 0.5$: (a) The optimized unit cell geometry, (b) the transmittances $T_{\pm}$, (c) $\phi_{\pm}$ and θ, and (d) the ellipticity τ. The maximum rotation of $\theta = 21^{\circ}$ is achieved at $\lambda = 1.093$ μm. The dimensions of the optimized design are listed in Table 1.

in (4) with the value of d forced to zero to eliminate the possibility of resonance. The optimization for $T_{\min} = 0.1$ resulted in $f = 0.414$ with $\theta = -0.96^{\circ}$, verifying that a resonance and the associated loss are essential in producing strong polarization rotations.

5. Conclusion

Numerical optimizations of planar chiral metamaterial designs were presented using the GA to achieve strong CD and for maximum polarization rotatory power in the mid-IR spectrum. A large CD value of 56% was predicted at $\lambda = 1.087$ μm for the optimized design, which is larger by an order of magnitude than those in previously reported designs. Maximum polarization rotatory powers were studied for the first time in relation to the minimum allowed transmittances. Strong polarization rotations close to 90° were obtained subject to the restriction that minimum transmittance values be less than 30%. Higher required transmittances were seen to result in weaker polarization rotation powers. However, a strong polarization rotation in excess of 20° was predicted for a 120 nm-thick metamaterial even when a 50% minimum transmittance restriction was enforced.

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