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Planar chiral metamaterial design utilizing metal-silicides for giant circular dichroism and polarization rotation in the infrared region

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ABSTRACT

A planar chiral metamaterial (PCMM) comprizing double-layer sandwich structure utilizing metal-silicides in the shape of windmill is proposed in the infrared region (IR). Giant circular dichroism (CD) and polarization rotation are observed simultaneously. Furthermore, the effect of Drude model parameters (ω_p, ω_τ) of metal-silicides on CD and optical activity are also investigated. The results show that CD and optical activity reach maximum if ω_p and ω_τ are in the distribution of narrow trumpet shape.

1. Introduction

Chiral metamaterials (CMMs) are artificially structured media that show peculiar properties, such as giant circular dichroism (CD) and polarization rotation that are very weak in natural materials. Chirality is a geometric property of a structure, which is non-superposable on its mirror image. Compared with 3D CMMs (e.g. helix [1]), PCMMs are easier to be fabricated. However, PCMMs exhibit a weak optical activity. Later, Rogacheva et al. [2] demonstrated that giant optical activity can be achieved in an electromagnetic coupled bilayered chiral structure, with two layers of planar metal rosette patterns separated by a dielectric slab and twisting with respect to each other. Inspired by this pioneering work, various bilayered planar chiral structures functioning in the region from microwave to infrared have been proposed [3–7]. Besides, planar structures consisting of more than two layers were also investigated [8–10]. Simultaneously, effective material parameter retrieval procedure was developed and optimized constantly [11,12]. Recently, a silver-alumina-silver sandwich structure in the form of gammadion shape was numerically geometrical optimized to obtain the maximum CD and polarization rotation [13]. A large CD value of 0.75 and a strong polarization rotation close to 90° were obtained. The origin of the optical activity and CD lies in the fact that incident waves of different handedness have different optical responses to polarization-sensitive magnetic resonance [14]. Absorption loss is a crucial factor in planar chiral structures, which plays a significant role in producing different transmission intensities for incident right-hand circular polarized (RCP, +) and left-hand circular polarized (LCP, -) waves.

However, applications of these structures are limited due to the fact that noble metals, such as gold and silver that are used during their fabrications, are incompatible with semiconductor processing (e.g. CMOS). In addition, giant polarization rotation angle and strong CD are seldom realized simultaneously on these geometrically optimized structures. This is mainly because polarization rotation was a decreasing function of corresponding transmittance during the optimization [13]. In contrast to noble metals, metal-silicides (NiSi, $NiSi_2$, Pb_2Si and TiSi, *etc.*) not only exhibit good optical properties in the infrared region (IR) [15], but also are compatible with CMOS processing. Furthermore, the permittivity values of metal-silicides are in a wide range, which varied with the composition and concentration of metal-silicides. Therefore, the Drude model parameters of metal-silicides are also in a wide range. [15–18]. Since permittivity is a function of frequency, it is more convenient to characterize metal-silicides by Drude model parameters, which are obtained by fitting measured permittivity data with Drude dispersive model.

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Thus, it may inspire an optimizing way to engineer optical properties of PCMMs by finding a kind of metal-silicide with an appropriate pair of Drude model parameters.

In this paper, a PCMM comprizing of double-layer sandwich structure utilizing NiSi in the shape of windmill is proposed. Its CD, polarization rotation angle and ellipticity are investigated. Similar phenomena are also found in the PCMMs utilizing other metal-silicides. Moreover, the effect of Drude model parameters of metal-silicides on CD and optical activity are numerically investigated using a commercial software (COMSOL Multiphysics).

2. Designed metal-silicides PCMM and simulated results

Fig. 1 depicts the unit cell of proposed PCMM design. Resonating structure consisting of two metal-silicide layers with thickness of t is separated by an alumina layer with thickness of d, which is placed on a silica glass substrate. Since the image part of the permittivity of metal-silicides is relatively small, the employed resonator as a planar magnetic resonator is thicker than the ones in metal-dielectric-metal sandwich structures in other PCMMs. Each arm of the structure is composed of a 90° ring and a rectangle. The periodic constant is p in the x and y directions. The optimized geometrical parameters are t=100 nm, d=60 nm, r=100 nm, R=200 nm, L=300 nm, m=100 nm, p=770 nm.

The illumination on the designed metamaterial is a normally incident plane wave of circular polarization propagating in the $-z$ direction. Four transmission coefficients, T_{++}, T_{-+}, T_{+-}, and T_{--}, corresponding to the complex transmission coefficients of the RCP/LCP incident light wave, are calculated at the top surface and the interface of metamaterial and glass, respectively. The absence of circular polarization conversion (T_{-+}, T_{+-}), due to the four-fold rotationally(C4) symmetry of the PCMM with respect to the z axis, guarantees that the reflected and transmitted fields have purely circular polarization states of the opposite and the same handedness for each circular polarized incident wave, respectively. Thus, transmission coefficients for incident LCP and RCP light are equivalent to T_{--} and T_{++}, respectively. As for the numerical method, alumina and glass are treated as lossless non-dispersive dielectric materials with relative permittivity values of 2.62 and 2.25 respectively. Glass substrate is treated as infinite in $-z$ direction. Resonating structures with four kinds of metal-silicides are simulated respectively. As show in Table 1, the PCMM with NiSi exhibits larger CD and polarization rotation. The effect of Drude model parameters on circular dichroism and polarization rotation will be discussed in next section. In this section, resonating structure is selected as NiSi which is characterized by Drude model with plasma frequency ω_p=3.8 eV, collizion frequency ω_τ=0.035 eV [17]. The real and imaginary parts of the complex permittivity are given by

Table 1
The Drude model parameters, the corresponding CD, polarization rotation angle and extinction ratio performances of NiSi, Pb_2Si, TiSi and $NiSi_2$.

Silicide	Drude model parameter		Simulation results		
	plasma frequency (eV)	collizion frequency (eV)	Circular dichroism	Polarization rotation angle (°)	Extinction ratio
NiSi	3.8 [13,15]	0.035 [13,15]	0.43	74.7	190
$NiSi_2$	6 [13,15]	0.2 [13,15]	0.44	43.4	26
Pb_2Si	3.1 [13,16]	0.03 [13,16]	0.45	43.9	33
TiSi	4.2 [13,14]	0.015 [13,14]	0.19	38.7	3

$$\begin{cases} \varepsilon' = \varepsilon_\infty\left[1 - \dfrac{\omega_p^2}{\omega_\tau^2(1+\omega^2/\omega_\tau^2)}\right] \\ \varepsilon'' = \dfrac{\varepsilon_\infty\omega_p^2}{\omega_\tau\omega(1+\omega^2/\omega_\tau^2)} \end{cases} \tag{1}$$

For silicides, ε_∞ is taken as unity (ε_∞=1), since it is assumed that the carrier concentration is sufficiently high to screen the polarization of the lattice, as in metals [15].

Fig. 2 shows the simulation results. CD is given by $|\Delta T|=|T_{++}|-|T_{--}|$. Polarization rotation angle and the ellipticity are defined as [19]:

$$\begin{cases} \theta = \left[arg(T_{++}) - arg(T_{--})\right]/2 \\ \eta = atan\left[\left(abs(T_{++}) - abs(T_{--})\right)\right. \\ \qquad \left./\left(abs(T_{++}) + abs(T_{--})\right)\right] \end{cases} \tag{2}$$

It can be observed that the transmission curves (see Fig. 2b) for LCP and RCP light separate at λ_1=2.05 μm and λ_2=2.58 μm, which correspond to the magnetic and electrical resonating mode respectively. At λ_1=2.05 μm, CD reaches a maximum of 0.44 and the polarization rotation angle reaches the largest value of 74.7° with an ellipticity of 0.71. While they are very low at λ_2=2.58 μm. These optical properties contribute to different absorption losses for incident light waves of different handedness. This phenomenon has

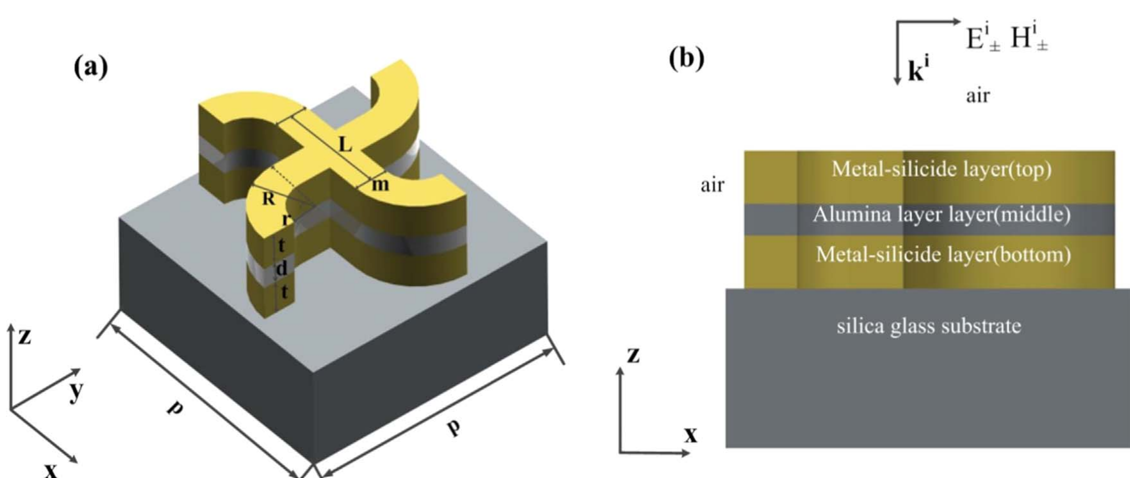

Fig. 1. The unit cell of the planar chiral metamaterial. (a) 3D model of the unit cell, (b) a side view. The geometrical parameters are indicated and given by r=100 nm, R=200 nm, L=300 nm, m=100 nm, p=770 nm, t=100 nm, and d=60 nm.