How to improve the signal-to-noise ratio for circular polarizers consisting of helical metamaterials?

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Abstract: In this paper, we proposed new structured metamaterials with multi-helical nanowires to construct circular polarizers with higher S/N ratios. Compared with the single-helical ones reported by J. K. Gansel *et al.* [Science **325**, 1513 (2009), Opt. Express **18**, 1059 (2010)], which has a lower S/N ratio (~10 dB) due to the high intensity conversion, the circular polarizers with the multi-helical structures have average two orders higher S/N ratios (~35 dB). Simultaneously, other optical performances, such as operation bands, average extinction ratios, are also improved.

OCIS codes: (260.5430) Polarization; (160.3918) Metamaterials; (160.1585) Chiral media.

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1. Introduction

In the last few years, there has been growing interest in the study of the metamaterial both theoretically and experimentally due to the exciting potential applications ranging from perfect lenses [1], cloaking devices [2–4] to sub-wavelength optical waveguides [5] and the enhancement of magnetic resonance imaging [6]. Recently, Gansel [7,8] succeeded in developing a broadband circular polarizer using gold single-helical metamaterials. The devices offer giant circular dichroism in a wavelength band of 3-6 μm. Compared with other familiar methods, circular polarizers with the helical metamaterial have advantages of broad wavelength ranges and compact structures which are convenient to be integrated with other optical devices.

#140219 - $15.00 USD Received 4 Jan 2011; revised 16 Feb 2011; accepted 16 Feb 2011; published 17 Feb 2011

However, the single-helixes, mentioned in the Gansel's reports, have about 10 percent intensity conversions between right-circular polarization (RCP) and left-circular polarization (LCP) lights. Such high conversions will result in lower signal-to-noise (S/N) ratios (~10 dB), which will restrict the potential applications of the devices. In this work, we proposed a new type of circular polarizers with multi-helical nanowire metamaterials, for the purpose to improve the S/N ratio. Using the finite difference time domain (FDTD) method, the optical properties of the single-, double-, three-, and four-helixes were studied, respectively. The simulation results demonstrated that the S/N ratios of the polarizers with the multi-helical nanowire metamaterials reach two orders higher value (~35 dB) than that of the single-helical one. Simultaneously, broader operation bands, higher extinction ratios are also achieved in the multi-helical polarizers. There are some performance parameters used in this paper. To make them clear, Table 1 summarizes the definitions for each of them.

Table 1. Definitions of the Circular Polarizer's Performance Parameters

		Definitions (take right-circular helix as example)
Transmittance	*T(LCP)*	$I_{tr(LCP)}^{LCP} / I_{in}^{LCP}$
	T(RCP)	$I_{tr(RCP)}^{RCP} / I_{in}^{RCP}$
S/N ratio (dB)		$10 \cdot \log(I_{tr(LCP)}^{LCP} / I_{tr(LCP)}^{RCP})$
Conversion		$I_{tr(LCP)}^{RCP} / I_{in}^{LCP}$ or $I_{tr(RCP)}^{LCP} / I_{in}^{RCP}$
Extinction ratio		*T(LCP)/ T(RCP)*
Operation region		The wavelength range on which the extinction ratio is above 10:1
T(LCP): transmittance of LCP light; *T(RCP)*: transmittance of RCP light; I_{in}^{LCP} : intensity of incident LCP light; $I_{tr(LCP)}^{LCP}$: intensity of transmitted LCP light when the incident beam is LCP light; $I_{tr(LCP)}^{RCP}$: intensity of transmitted RCP light when the incident beam is LCP light; I_{in}^{RCP} : intensity of incident RCP light; $I_{tr(RCP)}^{RCP}$: intensity of transmitted RCP light when the incident beam is RCP light; $I_{tr(RCP)}^{LCP}$: intensity of transmitted LCP light when the incident beam is RCP light;		

2. Simulation models

Circular polarizers consisting of metamaterials with right-circular single-, double-, three-, and four-helical aluminum (Al) nanowires were simulated using the FDTD method. Figures 1(a), 1(b), 1(c), and 1(d) show the schematic diagrams of them, in which DW, NH, SG, LH, and DH stand for the diameter of the wire, the number of the helix-periods, the spacing of the grid, the length of the helix-period, and the diameter of the helix, respectively. The parameters of the metamaterial structure are: DW = 30 nm, NH = 3, SG = 190 nm, LH = 200 nm, and DH = 100 nm, respectively. The LCP light was used as the excitation source to irradiate the polarizers along the positive Z direction. To simplify the simulation, a broadband Gaussian-modulated pulsed light source is used as the excitation source. The perfectly matched layers (PML) [9] were along the Z direction. The boundaries along X and Y directions were confined with the periodic boundary conditions [10] due to the periodicity of the nanowire metamaterials.

During the calculation, the dielectric function of the Al materials was described by the Lorentz-Drude model, which can be expressed as Eq. (1) [11]:

$$\varepsilon_r(\omega) = \left[1 - \frac{\Omega^2}{\omega(\omega - i\Gamma_0)}\right] + \left[\sum_{j-1}^{k} \frac{f_j \omega_p^2}{(\omega_j^2 - \omega^2) + i\omega\Gamma_j}\right] \tag{1}$$

where ω_p is the plasma frequency; k is the number of oscillators with frequency ω_j, strength f_j, and lifetime $1/\Gamma_j$; while $\Omega = \sqrt{f_0} \cdot \omega_p$ is the plasma frequency associated with intraband transitions with oscillator strength f_0 and damping constant Γ_0.

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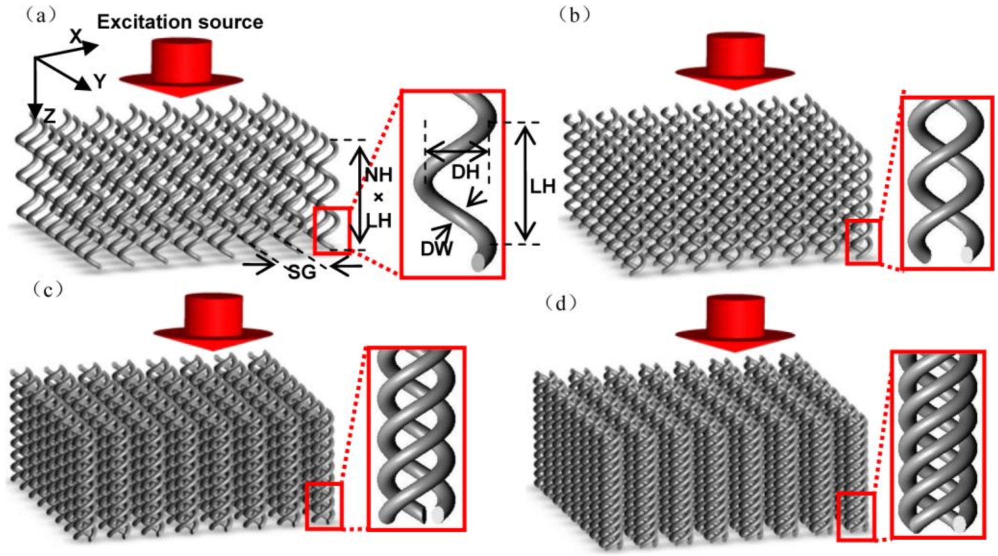

Fig. 1. Schematic diagrams of the optical circular polarizers using helical metamaterials.

3. Simulation results and analyses

The optical performances of the incident and transmitted lightwaves are shown in Fig. 2. Figure 2(a) shows schematic diagram of the amplitude (Amp.) and the phase angle (θ) of the electric vector; Fig. 2(b) shows the amplitude and the phase angle for the LCP incident light; Figs. 2(c), 2(e), 2(g), and 2(i) are the results for the transmitted lights through the single-, double-, three-, and four-helical structures, respectively; Figs. 2(d), 2(f), 2(h), and 2(j) are the S/N ratios for them, respectively. From the simulation results, it is very clear that the S/N ratios of the three- and four-helixes are two orders higher than those of single- and double-helical ones.

These phenomena can be explained in the language of the antenna theory. Our simulation model is based on the helical antennas with the so-called end-fire geometry. Such helical antennas are widely used in microwave wireless local-area network (WLAN) applications [12]. In the antenna theory, when the circular polarized wave propagates through the helical metamaterials, electrical currents will occur in the surfaces of the helical wires. We think that there is a certain relationship between the existence of the current and the S/N ratio of the transmitted light. In our cases, if the horizontal projection of the current's path is a perfect

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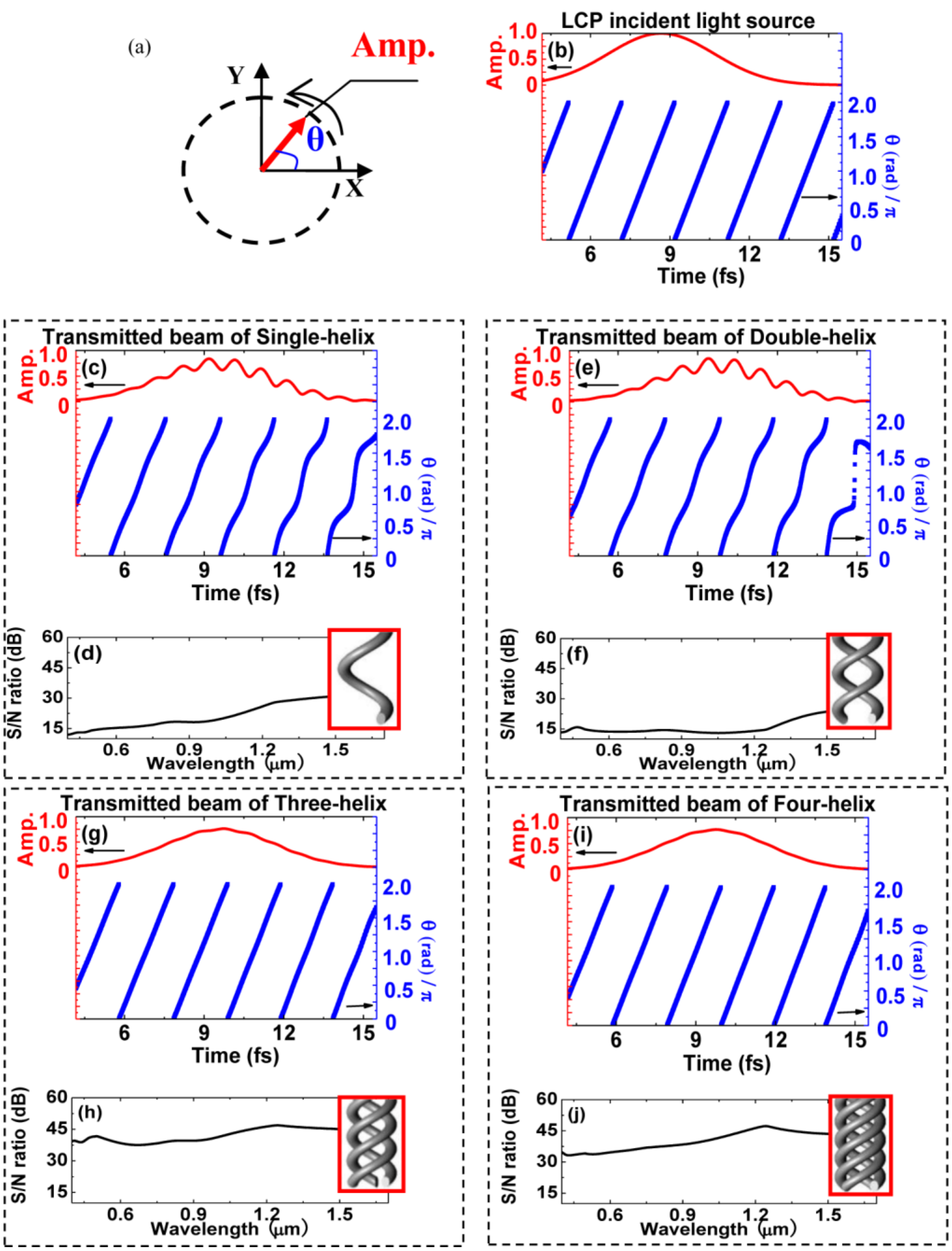

Fig. 2. Optical performances of LCP incident light, and transmitted lights through single-, double-, three-, and four-helix.

round, the transmitted light will be the perfect LCP light, which leads to a higher S/N ratio (shown in Fig. 3(a)); if the horizontal projection is not perfectly circular, the RCP light, noise to the incident light, will appear, which results in a lower S/N ratio (shown in Fig. 3(b)). Generally, the path of the current depends on two factors: one is the interaction between the neighbouring helical structures, which we call outer interactions; the other is that among the different helical wires within one multi-helix, which we call inner interactions. With the increase of the number of wires in one helix, the current path will be more and more

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dominated by the inner interaction, which leads to the trend of the current flowing in the inner radius of the helix. Therefore, the S/N ratios of the multi-helical metamaterials are great enhanced. For single-helix, in our opinion, the inner interaction is relatively weak, and then the current path is mostly determined by the outer interaction. However, since the outer interactions have not rotational symmetry, the horizontal projection of the path is not a perfect round. Therefore, single-helical metamaterials has a much lower S/N ratio.

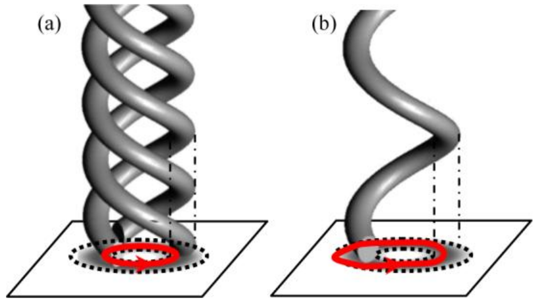

Fig. 3. Schematic diagrams of the different paths of electric currents.

To verify our expectation, the transmittance spectrums of both LCP and RCP incident lights through single-, double-, three-, and four-helical structures were simulated, with results shown in Fig. 4. In these results, it is obviously found that with the increase of helical numbers, a blue shift of the short-wavelength resonance occurs. According to the Ref. 8, this phenomenon just indicates that the electrical currents have a trend of moving along the inner radius of the helix. Furthermore, the comparison of the optical performances between single-, double-, three-, and four-helical metamaterials is shown in Table 2. In the results, the circular polarizers with multi-helical structures not only have higher S/N ratios, but also have broader operation regions and larger extinction ratios. In one word, the whole performances of the multi-helical circular polarizers are improved.

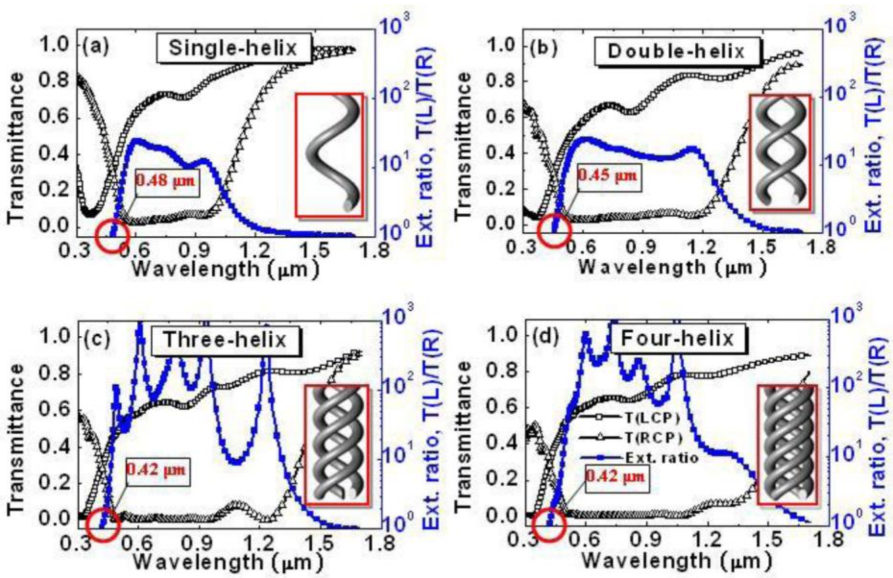

Fig. 4. LCP, RCP transmittance spectrums, and extinction ratio spectrums of single-, double-, three-, and four-helix.

#140219 - $15.00 USD Received 4 Jan 2011; revised 16 Feb 2011; accepted 16 Feb 2011; published 17 Feb 2011

4. Conclusions

In summary, optical circular polarizers with single-, double-, three-, and four-helixes nanowire metamaterials were studied. The simulation results demonstrated that the polarizers with the multi-helical nanowire metamaterials have two orders higher S/N ratios (~35 dB) than that of single-helix. The antenna theories were successfully used to explain the reasons of realizing the higher S/N ratio. Although in this paper we just studied the single-, double-, three-, and four-helixes, for more helical wire metamaterials our conclusion ought to be still valid: The circular polarizer with multi-helical metamaterials has a high S/N ratio.

It is certain that there are still some challenges on the fabrication of the polarizer. In our opinions, however, it can be expected that with the development of nanofabrication techniques, the kind of circular polarizers could be realized in the near future.

Table 2. Comparison of the Optical Performances Between Single-, Double-, Three-, and Four-Helical Metamaterials

	Operation regions	Average S/N ratios	Average transmittances of LCP light	Average extinction ratios
Single-helix	0.55-0.97 μm	16.8 dB	70%	16:1
Double-helix	0.52-1.22 μm	13.9 dB	67%	17:1
Three-helix	0.47-1.05 μm 1.11-1.31 μm	41.0 dB	64%	186:1
Four-helix	0.49-1.34 μm	37.7 dB	67%	270:1

Acknowledgments

This work was supported by the Natural Science Foundation of China (NSFC) (Nos. 10874024, 61007019 and 50735007), Doctoral Fund of Ministry of Education of China (No. 200804871147), the Natural Science Foundation of Hubei Province of China (No. 2008CDB004), the Special Funds of Central Colleges Basic Scientific Research Operating Expenses (No. 2010MS063), and also partly supported by China National Funds for Distinguished Young Scientists (No. 66945021).

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