Ultrahigh extinction-ratio circular polarization analyzer with chiral plasmonic lens

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ABSTRACT

A chiral plasmonic lens (CPL) suitable for circular polarization analyzer is designed and numerically investigated. It consists of two arrays of rectangular nanoslits milled into a gold film along Archimedes spirals. We demonstrate both theoretically and numerically that the designed structure can convert an incident circularly polarized light beam with prescribed chirality into a Bessel-like distributed focus, but the circularly polarized one with the opposite chirality cannot be transmitted and focused by the same CPL due to the alternative chirality. Further, three-dimensional finite-difference time-domain (FDTD) simulations show that an ultrahigh extinction ratio up to ten thousands of the CPL is numerically achieved with a device less than 10 λ_{spp}, which is two orders higher than that of a conventional plasmonic circularization analyzer with single Archimedes-spiral groove. The designed structure can be widely used in miniature polarimeter and detection of spin angular momentum.

Keywords: Surface plasmon polaritons; plasmonic lens; focusing; polarization

1. INTRODUCTION

Plasmonic lens structure with Archimedes-spiral distributed grooves, slits and holes have been proposed and investigated widely in recent years[1]. Due to the property that the focusing field distribution of this kind of plasmonic lens depends on the circular polarization state of the illumination light beam, studies aiming at the applications including circular polarizers and analyzers[2], vortex phase modulation[3], linearly polarized plasmonic lens[4], and others[1], have been conducted. In this paper, we design a novel chiral plasmonic lens (CPL) structure with metal film in which exist two arrays of rectangular nanoslits distributed along Archimedes spirals. Using the chiral property of the double arrays of nanoslits oriented by $\pi/2$ angle[4], the CPL can couple circularly polarized illumination into two SPPs waves, which can interfere constructively or destructively according to both the structure of the CPL and the handedness of circular polarization possessed by incident beam. Theoretical analysis and numerical simulations demonstrate the chirality of the CPL, and an ultrahigh extinction ratio up to ten thousands is numerically achieved with a device size less than 10λ_{spp}, which is two orders higher than that of a conventional plasmonic circularization analyzer with single Archimedes-spiral groove.

2. Schematic and Theory of the CPL

The schematic of the designed CPL is shown in Figure 1. Two arrays of rectangular nanoslits are penetrated through a thin gold film, and are arranged to be separated by an interval of D in the radial direction and to bend along the Archimedes spirals, which can be defined as follows

$$r = \begin{cases} r_0 + m\lambda_{\text{SPP}}\varphi / 2\pi, & \text{for inner curve} \\ r_0 + m\lambda_{\text{SPP}}\varphi / 2\pi + D, & \text{for outer curve} \end{cases} \tag{1}$$

where λ_{SPP} is the wavelength of the SPPs. The parameter m = 1 and = -1 represents the outward and inward spiraling of the curve, respectively, and Fig. 1 shows the outward spiraling arrangement with m = 1. The illumination beam with circular polarization incident from bottom side can be written as

$$\vec{E}(r,\varphi) = (\hat{x} + js\hat{y}) / \sqrt{2} = e^{js\varphi}(\hat{r} + js\hat{\varphi}) / \sqrt{2} \tag{2}$$

where $s = \pm 1$ refers to left- or right-handed circular polarization (LHCP or RHCP), respectively. After a simple derivation, the electric field intensity distribution on the exit surface of CPL is proportional to the Bessel function squared as following

$$I(R,\theta) \propto (s+d)^2 \left| J_{(s+m)}(k_{\text{SPP}}R) \right|^2 \tag{3}$$

where J denotes the Bessel function of the first kind, d = 1 and = -1 corresponds to the case of D = $3\lambda_{\text{SPP}}/4$ and = $\lambda_{\text{SPP}}/4$, respectively. For different circular polarization parameters s and CPL structure parameters m and d, the intensity is either a Bessel function distribution or zero, assuming that the CPL is large enough with respect to λ_{SPP}. Thus, the extinction ratio (ER) of the intensity distribution under RHCP (or LHCP) incident light to that of LHCP (or RHCP) can be defined as

$$R_{m,d} = \left(\frac{\int_0^{R_0} I(R,\theta)_{m,d,l} 2\pi R dR}{\int_0^{R_0} I(R,\theta)_{m,d,-l} 2\pi R dR} \right)^{1-|d-l|} = \left(\frac{\int_0^{R_0} (d+l)^2 \left| J_{(m+l)}(k_{\text{SPP}}R) \right|^2 2\pi R dR}{\int_0^{R_0} (d-l)^2 \left| J_{(m-l)}(k_{\text{SPP}}R) \right|^2 2\pi R dR} \right)^{1-|d-l|} \tag{4}$$

where R_0 is the radius of the detector's window placed in the center of the CPL, and parameters $d=\pm 1$, m = ±1 and l = -m. This ER describes the chirality of the designed CPL well. It is noted that the theoretical value of ER in Eq. (4) is a ratio of squared Bessel function to zero, thus giving an infinitely large value.

3. Simulations and discussion

The designed structure in Fig. 1 is numerically investigated by three-dimensional finite-difference time-domain (FDTD) simulations. The wavelength of the incident light is set to be 670 nm, the dielectric constants of gold and air are ε_m = -12.13+1.13j[5], and ε_d = 1 respectively, and the wavelength λ_{SPP} is 642nm. All other parameters are given in Fig. 1.

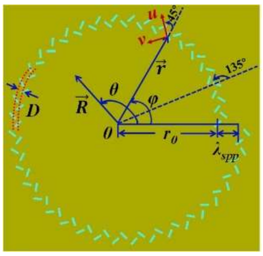

Figure 1 Shematic of the designed CPL. The thickness of the gold film is 200 nm. The length and width of a single rectangular nanoslit is 240 nm and 60 nm respectively. The interval parameter D is either $3\lambda_{\text{SPP}}/4$ or $\lambda_{\text{SPP}}/4$. *r0* is set to be $4\lambda_{\text{SPP}}$, corresponding to the distance between the starting point on the curve and the origin *O*. Other parameters are given in the text.

Figure 2 shows the electric field intensity distributions on the X-Y plane (the top surface of the CPL), corresponding to RHCP and LHCP illumination on different structure parameters described in Eq. (3). It is clear that for a specified structure of the CPL, the RHCP and LHCP incident lights exhibit different chirality. For example, for the case of d = 1 and m = -1 in Fig. 2(c-d), the electrical field intensity distribution for a LHCP incident light is proportional to the square of zero-order Bessel function, with a bright spot in the center of the top surface of the CPL. By contrast, the distribution resulted from RHCP, is far smaller and almost zero compared with the LHCP one.

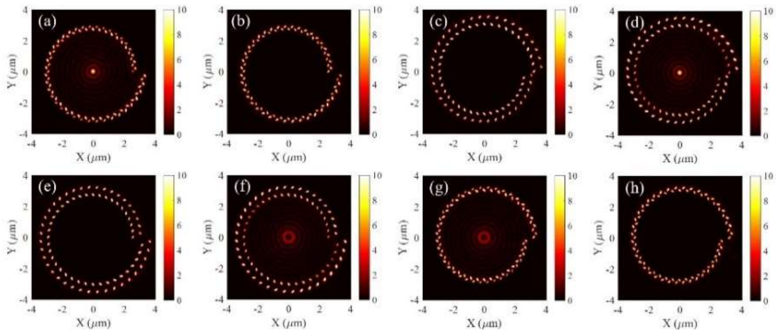

Figure 2 Electric field intensity distributions on the top surface of the CPL with parameters of (a) s = -1, d = -1 and m = 1, (b) s = 1, d = -1 and m = 1, (c) s = -1, d = 1 and m = -1, (d) s = 1, d = 1 and m = -1, (e) s = -1, d = 1 and m = 1, (f) s = 1, d = 1 and m = 1, (g) s = -1, d = -1 and m = -1, and (h) s = 1, d = -1 and m = -1.

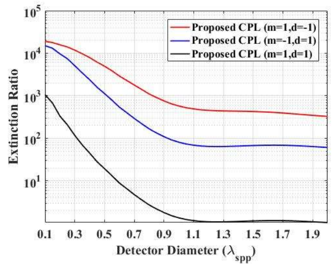

Figure 3 Circular polarization extinction ratio of different CPL structures versus the detector size. The red and blue curve correspond to the designed CPL with parameters m=1, d=-1 and m=-1, d-1 respectively. As contrast, the black curve corresponds to conventional[2] CPL structure.

Figure 3 plots the ER of different CPL structures versus the detector size. It is obvious that our designed CPL can get higher ER than that of a conventional one. Taking the case of m = 1 and d = -1 (the red curve in Fig. 3) for example, its ER can be and at least two-orders higher than that of the conventional one, when the detector diameter is larger than $0.3\lambda_{SPP}$. This ultrahigh ER property agrees with the theoretical analysis in Eq. (4), and demonstrates the strong chiral sensitivity of the designed CPL.

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References

[1] Z. Guo, Z. Li, J. Zhang, K. Guo, F. Shen, Q. Zhou and H. Zhou, "Review of the Functions of Archimedes' Spiral Metallic Nanostructures", Nanomaterials 7, 405 (2017).

[2] S. Yang, W. Chen, R. L. Nelson, Q. Zhan, "Miniature circular polarization analyzer with spiral plasmonic lens", Opt. Lett. 34, 3047-3049 (2009).

[3] Y. Wang, P. Zhao, X. Feng, Y. Xu, F. Liu, K. Cui, W. Zhang and Y. Huang, "Dynamically sculpturing plasmonic vortices: from integer to fractional orbital angular momentum", Scientific Reports 6, 36269 (2016).

[4] J. Liu, Yang Gao, L. Ran, K. Guo, Z. Lu, and S. Liu, "Focusing surface plasmon and constructing central symmetry of focal field with linearly polarized light", Appl. Phys. Lett. 106, 013116 (2015).

[5] E. D. Palik, [Handbook of optical constants of solids], Academic Press, New York, 723−729 (1985).