Materials exhibiting linear birefringence are of crucial importance in modern optics, providing necessary control of the polarization state of light. For example, uniaxial crystalline materials (e.g., quartz) are characterized with two different refractive indexes that result in a phase difference between orthogonally polarized waves traveling through the crystal, thereby permitting the construction of wave retarders, e.g., half- and quarter-wave plates. An alternative method for obtaining birefringence is to introduce a periodic anisotropy in the (nonbirefringent) material so that transverse electric and transverse magnetic waves experience different effective refractive indexes. Their difference, Δn, is known as form birefringence [1–3]. Generally, a high Δn is desired as it can lead to more compact optical components that can be used in on-chip photonics [4]. Although difficult to achieve at optical wavelengths (typically, Δn ≈ 0.1–0.2 [5]), it has recently been shown that the waveguide dispersion of surface plasmon polaritons (SPPs) in gold nanoslits can be used to create giant form birefringence Δn ≈ 2.7 at λ = 632.8 nm [6], facilitating sub-wavelength-thin wave plates. In a different approach [7], a subwavelength circular aperture in a gold film surrounded by an elliptical grating was used to introduce a phase shift between SPPs traveling along the ellipse axes, influencing the polarization of transmitted light.

We have recently shown that a plasmonic configuration of two dipolar scatterers resonating at different frequencies scatter light asymmetrically, which can be exploited for environmental sensing [8]. Based on a similar idea, we report in this Letter, both theoretically and experimentally, on a new method to construct a nanometer-thin quarter-wave plate that in contrast to previous studies [6, 7] works in reflection mode. Also, the quarter-wave plate relies on anisotropic detuned electric resonant scattering and not form birefringence as in grating-based circular polarizers (see, e.g., [2, 9]). Furthermore, the proposed nanostructures, constituting a unit cell in the metamaterial wave retarders, are not related to the optically active extrinsic chiral metamaterials [10] as they only display an electric response (no magnetic response), eliminating the possibility of extrinsic chirality.

Our approach can be illustrated by considering two perpendicular noninteracting electric dipolar scatterers centered at the origin of the coordinate system with electric dipole moments in the x- and y-direction, respectively, and the observation region being in the far field close to the z-axis (z ≫ x, y). Assuming that the resonances of the noninteracting dipole scatterers are equally detuned from the central frequency ω0, their dipole polarizabilities can be represented as follows:

\[ α_{1(2)}(ω) = \frac{Aω_0^2}{(ω_0 ± δ)^2 - ω^2 - iΓω}, \]

where δ is the detuning frequency, Γ is the damping factor, and A characterizes their strength. Detuned electrical dipoles (DED) can readily be implemented in plasmonics, e.g., with metal (gold or silver) nanoparticles whose resonances can be adjusted by tuning their aspect ratio [11]. For weak detuning (ω0 ≫ δ), the phase difference, ΔΦ, of the two polarizabilities is

\[ ΔΦ(ω_0) = (Φ_2 - Φ_1)_{ω=ω_0} = π - 2\arctan(Γ/(2δ)), \]

implying that for δ = Γ/2 the scattered light close to the z-axis will be circularly polarized. Consequently, a metamaterial consisting of subwavelength non-interacting DED unit cells will work as a circular polarizer as the polarizability of each cell, α1 + α2, adds coherently in this limit [12]. The above condition for circular polarized light is strictly valid only for noninteracting scatterers with the same strength and damping factor, but, as we will see below, the simplified description is still valid as a guideline for more realistic cases due to very weak dipole–dipole interaction for orthogonal
but of different length (i.e., orthogonal DEDs). Note that it is possible to excite individual plasmonic resonances by choosing the angle of polarization, $\beta$, of the incident linearly polarized wave to either $\beta = 0°$ or $\beta = 90°$ [Fig. 1(c)]. For intermediate angles, both resonances are excited, which allows us to construct a quarter-wave plate by properly choosing the length of the nanoantennas (detuning) and $\beta$ (influencing the relative strength of DEDs). The right choice of length is illustrated in Fig. 2(a) for $\beta = 45°$ when the short axis is fixed at $L_1 = 260$ nm and the long axis, $L_2$, is slightly varied. The figure depicts the phase difference between the $y$- and $x$-component of the scattered electric field ($E_{sc,y}$ and $E_{sc,x}$) along the $-z$-axis in the far field showing that for $L_2 = 338$ nm the phase difference is $\sim \pi/2$ at $\lambda \approx 1520$ nm. However, in order to get circular polarized light at $\lambda \approx 1520$ nm, we should require $|E_{sc,y}| = |E_{sc,x}|$ that can be satisfied at $\beta = 56°$ [Fig. 2(c)]. Note that in the simplified case of Eq. (1), we would expect circular polarization at $\beta = 45°$, but a lower dipole strength of the short nanoantenna requires $\beta > 45°$. Also importantly, the configuration has the wavelength range 1475–1560 nm where the phase difference variation is less than 2%, implying a relatively broadband operation of the proposed wave plate.

As an example of versatility of our approach, we construct a quarter-wave plate from a nanobrick of 50 nm thickness [Fig. 1(b)] exhibiting two orthogonal plasmonic resonances [see the scattering cross section in Fig. 1(d)]. This time, however, we choose the short axis to be $L_1 = 90$ nm satisfying the criteria for a quarter-wave plate at $\lambda \approx 770$ nm when $L_2 = 140$ nm [Fig. 2(b)] and $\beta = 52°$ [Fig. 2(d)]. The wavelength range in which the phase difference deviates with less than 2% is 748–796 nm.

Using electron-beam lithography and lift-off technique, a 400 nm-periodic (50 × 50 µm$^2$) array of the nanobrick configuration has been fabricated on a silica substrate [see inset in Fig. 3(a)] and subsequently covered with ~15 µm poly(methyl methacrylate) (PMMA) to create (almost) homogeneous surroundings. Reflection spectra are measured using a broadband halogen light source with a fiber output whose radiation is directed through a Glan–Thompson analyzer and sent through an achromatic quarter-wave plate (690–1200 nm) followed by a Glan–Thompson analyzer with varying analyzer angle with respect to (w.r.t.) the long axis of the brick [Fig. 3(b)]. If the reflected light from the fabricated array is circularly polarized it must be converted into linearly polarized light with an angle of...

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**Fig. 1.** (Color online) Schematic representation of (a) nanocross and (b) nanobrick configurations, showing also the polarization of incoming plane wave. Scattering cross sections $\sigma_{sc}$ of (c) nanocross ($L_2 = 338$ nm) and (d) nanobrick ($L_2 = 140$ nm) for different angles $\beta$.

**Fig. 2.** (Color online) The phase difference between the $y$-component $E_{sc,y}$ and $x$-component $E_{sc,x}$ of the scattered electric field along the $-z$-axis in the far field for (a) nanocross and (b) nanobrick structures at $\beta = 45°$. (c) The ratio of $|E_{sc,y}|$ and $|E_{sc,x}|$ along the $-z$-axis in the far field as a function of angle $\beta$ for the nanocross with $L_2 = 338$ nm at $\lambda = 1520$ nm. (d) The same as in (c) but for the nanobrick with $L_2 = 140$ nm at $\lambda = 770$ nm.
45° w.r.t. the fast axis (FA) of the quarter-wave plate. When fixing the FA w.r.t. the long axis of the brick at 0° and 90°, respectively, the output of the Glan–Thompson analyzer reveals linear polarization at angles −45° and 45°, respectively. Therefore, in this case, the criteria of equal strengths and a phase difference of ∼π/2 between the two resonances of the brick are approximately met, and the reflected light is circularly polarized. Note that the reflection as a function of the analyzer angle is not perfectly flat when β = 0° and β = 90° due to the commercial quarter-wave plate not providing a retardance of exactly one quarter at 780 nm.

In conclusion, it has been shown that a pair of perpendicular detuned electric dipoles can be used to construct reflecting wave plates of nanometer thickness. Qualitative considerations were exemplified with numerical simulations in which nanocross and nanobrick configurations were designed to show quarter-wave plate behavior at near-infrared wavelengths. It should be emphasized that both configurations are rather versatile so that quarter-wave plates can be designed for any desired wavelength from visible to infrared. A periodic array of nanobricks was lithographically fabricated and optically characterized, exhibiting the expected behavior of a reflective quarter-wave plate at λ = 780 nm. We envision that the control of the state of polarization presented in this Letter could have many applications in integrated photonics.

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References