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Letter

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Wave retarders, including quarter- and half-wave plates, are used in many optical systems for polarization conversion. They are usually realized with anisotropic crystalline materials. However, much thinner and possibly also less expensive wave plates can be made of micro- and nanostructures. We present a new way to create thin-film optical retarders based on a highly birefringent metamaterial. The wave plate is capable of low-loss, broadband operation, which we verify both numerically and experimentally. Owing to the remarkable simplicity of our design, the wave plates operating on the proposed principle can meet the requirements of largescale production and find widespread application in optics and photonics. © 2019 Optical Society of America

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In the quest for more compact optical devices, modern nanooptics is turning to planar nanopatterned surfaces, such as metasurfaces, for the manipulation of light. A metasurface typically consists of a single layer of subwavelength structural units that each interact with an incoming optical field and change, e.g., its polarization or phase. Often, metasurfaces are designed to have spatially varying transmission and reflection characteristics for various beam-shaping applications such as ultrathin high-numerical-aperture lenses [1-4].

One basic optical component, the wave retarder, is particularly intriguing to implement using the metasurface concept. Conventional wave retarders, such as quarter- and half-wave plates, are made of anisotropic crystalline materials and are fairly thick and expensive. This is also true of, e.g., total-internal-reflection-based systems, where exceptional stability and spectral uniformity are achieved at the cost of using multiple components [5–8]. Nanostructured materials, on the other hand, can be designed to have a very large degree of anisotropy, opening up the possibility to make optical wave plates very thin. Furthermore, such thin-film devices can be designed to act as polarization-sensitive spatial light modulators, in which the local optical properties depend on the transverse coordinate. For example, there is a substantial body of work utilizing dielectric gratings (sometimes called form-birefringent structures in this context) to provide wave plate functionality [9-13]. These structures, if based on relatively low-refractive-index

photoresists and glasses, often require high-aspect-ratio structures surrounded by air, which makes fabrication challenging. While the usage of silicon with its high refractive index reduces this problem, it prevents efficient operation at wavelengths below 800 nm or so due to absorption loss. Hence, alternative principles of optical wave retardation by nanostructures are of great interest. Previously, also nanopatterned metal surfaces have been demonstrated to provide wave retardation for reflected light [14-17]. However, they cannot be used in the usually more convenient transmission mode. Finally, various plasmonic metasurface designs provide wave plates that are very thin but typically operate in a narrow bandwidth and with fairly high losses [18-21].

In this work, we present a transmissive wave plate that acts as a highly birefringent metamaterial thin film, or a metasurface. It is composed of periodic infinitely long, parallel metal nanostripes embedded in a dielectric material. The nanostripes do not essentially affect light polarized perpendicular to the stripes, while for orthogonal polarization, they make the metasurface exhibit a low refractive index. This provides the required high optical anisotropy for the wave plate. We present a simple analytical model of the proposed metamaterial film and verify our theoretical predictions by fabricating and experimentally demonstrating a quarter-wave plate based on this principle. We use a nanofabrication method based on oblique-angle metal deposition on the sidewalls of a dielectric grating [22] to fabricate the nanostructures required in our wave plate design. In general, the wave-retardation principle that we propose allows the wave plates to be thin and have low-loss broadband operation. Owing to the design simplicity, the structures can be fabricated on largearea substrates using fast and cost-effective methods of, e.g., optical-interference [23] and nanoimprint lithography [24].

The structure of the wave retarder is an array of infinitely long metal nanostripes inside a transparent dielectric medium (see Fig. 1). It is, essentially, a metamaterial layer of height h. The thickness of the metal stripes, d_m , is fairly small compared to their separation distance $d_{\rm d}$. The dielectric material, therefore, takes up most of the unit cell. This also makes the wave plate different from wire-grid polarizers where the metal wires take up a significant part of the unit cell. For an intuitive understanding, let us consider a single unit cell, comprising a central dielectric part surrounded by metal walls. From the elementary theory of metal waveguides, we know that for TE polarization



Fig. 1. Structure of a metal-dielectric wave plate consisting of vertical metal stripes embedded in a dielectric medium. The plates are effectively infinite in the y direction.

(parallel to the *y* axis), this structure has a cutoff frequency below which the electromagnetic modes are evanescent, while above the cutoff frequency, the effective refractive index of the mode is small, being given by $n_{\rm TE} = \sqrt{n_{\rm d}^2 - [\lambda_0/(2d_{\rm d})]^2}$, if the metal is a perfect conductor [25]. On the other hand, for TM polarization (along the *x* axis), the boundary conditions are different and the field is approximately transversely uniform in the dielectric region, giving an effective refractive index $n_{\rm TM} \approx n_{\rm d}$. With realistic metal that does not conduct perfectly, both modes slightly penetrate into the metal, and the TM mode is slightly concentrated on the metal surfaces due to coupling to surface plasmon polaritons [14].

The birefringence of the structure is large if $n_{\rm TE}$ is tuned to be low. However, when approaching the cutoff condition, the structure becomes highly reflective for TE-polarized light, which is unacceptable (this is the regime where the structure acts like a wire-grid polarizer). This conundrum can be solved by slightly increasing the distance between the plates and setting the height of the structure to satisfy the Fabry–Perot resonance condition for TE-polarized light, i.e., $h = \lambda_0/(2n_{\rm TE})$. If we then design the structure such that $n_{\rm TM} = 2n_{\rm TE}$, we obtain a phase shift of π for TE polarization and 2π for TM polarization, thus imparting a half-wave retardance. For a quarter-wave plate, the required retardance is smaller, and the height h can be reduced.

To calculate the effective refractive indices of TE and TM waves, n_{TE} and n_{TM} , more accurately, we use the corresponding characteristic equations

$$\frac{\tan\left(\sqrt{\epsilon_{\rm d}} - n_{\rm TE}^2 k_0 d_{\rm d}/2\right)}{\tan\left(\sqrt{\epsilon_{\rm m}} - n_{\rm TE}^2 k_0 d_{\rm m}/2\right)} = -\frac{\sqrt{\epsilon_{\rm m}} - n_{\rm TE}^2}{\sqrt{\epsilon_{\rm d}} - n_{\rm TE}^2},$$
(1)

$$\frac{\tan\left(\sqrt{\epsilon_{\rm d}} - n_{\rm TM}^2 k_0 d_{\rm d}/2\right)}{\tan\left(\sqrt{\epsilon_{\rm m}} - n_{\rm TM}^2 k_0 d_{\rm m}/2\right)} = -\frac{\sqrt{\epsilon_{\rm m}} - n_{\rm TM}^2}{\sqrt{\epsilon_{\rm d}} - n_{\rm TM}^2} \frac{\epsilon_{\rm d}}{\epsilon_{\rm m}}, \qquad (2)$$

where k_0 is the wavenumber in vacuum [14]. These are valid for the fundamental, symmetric TE and TM modes that do not have electric-field nodes at the centers of the dielectric and metal parts. In addition, we use them with complex-valued refractive indices and permittivities, thereby accounting for plasmonic absorption losses. The effective impedance of the mode, defined as the ratio of the spatially averaged electric and magnetic fields, is for both polarizations determined from

$$\eta_{\rm eff} = \frac{\eta_0}{n_{\rm eff}},\tag{3}$$

where η_0 is the impedance of vacuum, and n_{eff} is either n_{TE} or n_{TM} . With both *n* and η known, the transmission and reflection coefficients of the structure can be calculated in terms of the Fresnel-type transmission and reflection coefficients [26]. In general, while Eqs. (1) and (2) can be applied to multimode structures, the definition of impedance in Eq. (3) is valid only for one mode at a time. Even if the higher-order modes are evanescent, they can still modify the coupling in and out of the wave plate. Hence, for rigorous calculations, one must consider the mode matching in the multiple mode regime, or perform a full-wave numerical calculation to obtain the optical properties of the structure. However, the simple single-mode calculation presented above can still be used as a quick approximation.

To demonstrate the concept, we design a quarter-wave plate made of glass (n = 1.5) and silver for the operation wavelength $\lambda_0 = 790$ nm. Figure 2(a) shows the birefringence $n_{\rm TM} - n_{\rm TE}$ for a range of values of d_d and d_m . The largest values of c.a. 1.7 are obtained at small d_d and large d_m . It is interesting that while $n_{\rm TE} \approx 0$, we have $n_{\rm TM} > 1.5$. For the wave plate, we choose $n_{\rm TM}$ – $n_{\rm TE} \approx 0.5$ to increase the transmission of the TE wave. Figure 2(b) shows the average transmittance $(T_{\text{TE}} + T_{\text{TM}})/2$ of the wave plate with $h = (\pi/2)/[k_0(n_{\rm TM} - n_{\rm TE})]$, which gives the quarter-wave retardation. The transmittance is high (over 95%) everywhere except close to the cutoff region. This high-transmission region results from the modes existing mostly in the glass parts and interacting only weakly with metal. These plots imply that it is possible to make a quarterwave plate with either both d_d and d_m being small, or both of them being large. To make fabrication easier, we choose to make d_d and d_m large. Furthermore, we would like to pick a point where $k_0 n_{\text{TE}} h = \pi$ to achieve a Fabry–Perot transmission resonance for the TE polarization, thus minimizing reflection losses. This condition is satisfied in the points on the dashed line in both parts of Fig. 2.

After further optimization by full numerical calculations (using Comsol Multiphysics software), we selected $d_d = 335$ nm, $d_m = 65$ nm, and h = 330 nm. The spectrum of the electric permittivity of silver was taken from Ref. [27]. Figure 3(a) shows the spectra of the absolute values of the transmission coefficients for TE and TM polarizations. Results from direct numerical calculations are shown by the solid line, while the dashed line shows the results of the analytical single-mode approximation. At the design wavelength $\lambda_0 = 790$ nm, the transmission coefficients are high for both polarizations, as desired. Past $\lambda_0 = 900$ nm, the transmission decreases because of the onset of the TE mode cutoff. Figure 3(b) shows the spectra of



Fig. 2. Optical properties of the silver–glass quarter-wave plate at $\lambda_0 = 790$ nm for a range of values of d_d and d_m . The birefringence $n_{\text{TM}} - n_{\text{TE}}$ is shown in (a), while (b) shows the average transmittance, $T_{\text{avg}} = (T_{\text{TM}} + T_{\text{TE}})/2$, of the device. In both plots, the dashed line denotes the points at which the TE mode is at the Fabry–Perot resonance.

the phase shift between the TM and TE modes. This shows not only that the phase shift is $\pi/2$ as required, but also that the wave plate works well in a broad band from about 650 nm to 850 nm (shown by the shaded region). This is comparable to birefringent-crystal-based zero-order wave plates. Figure 3(c) shows the polarization states at four different wavelengths, indicating that within this wavelength band, they are all close to circular. The Poincaré vectors [25] for the states, containing the normalized Stokes parameters $\mathbf{S} = (S_1, S_2, S_3)$, are $\mathbf{S}(\lambda_0 = 650 \text{ nm}) = (0.00, 0.15, 0.99), \quad \mathbf{S}(\lambda_0 = 733 \text{ nm}) =$ $(-0.01, 0.10, 1.00), \ \mathbf{S}(\lambda_0 = 816 \text{ nm}) = (0.01, -0.03, 1.00),$ $\mathbf{S}(\lambda_0 = 900 \text{ nm}) = (-0.02, -0.32, 0.95).$ and Finally, Figs. 3(d) and 3(e) show the intensity distributions of a plane wave passing through the wave plate, verifying that the zerothorder TE and TM modes are indeed the ones excited. In this case, at the design wavelength, the refractive indices of the modes are $n_{\text{TE}} = 1.09$ and $n_{\text{TM}} = 1.61$. All of these calculations were performed at normal incidence. However, we have determined that the phase shift stays within the $\pi/2 \pm 0.2$ rad region for angles up to 10° (for light incident from air). Regarding other possible deviations from the considered operation conditions, we expect the wave plate to be stable against modest changes in temperature and stress because the structure is very thin.

As an experimental demonstration, we fabricated the designed quarter-wave plate. In addition to using silver as the metal, we chose to use PMMA as the dielectric medium in which the stripes are embedded. The choice of PMMA is due to the fact that it provides better adhesion for silver films compared to glass, and the dielectric constant of PMMA is very close to that of glass. The fabrication process is outlined in



Fig. 3. (a) Spectrum of the magnitude of the transmission coefficient of the designed quarter-wave plate. The blue and red lines correspond to TE and TM polarizations, respectively. The dashed line denotes analytical results, and the solid lines are obtained from numerical calculations. (b) Spectrum of the phase retardation between TM and TE polarizations $\Delta \varphi = \arg(t_{\rm TM}) - \arg(t_{\rm TE})$. The shaded region contains values limited by $\pi/2 \pm 0.2$ rad. (c) Ellipses of the polarization states that appear after 45° linearly polarized light passes through the wave plate at four different wavelengths. (d) Intensity distribution of a TE-polarized plane wave transmitted through the wave plate at $\lambda_0 = 790$ nm. The silver stripes are outlined with gray contours. (e) Intensity distribution of a TM-polarized wave.

Fig. 4. A glass microscope slide is cleaned in soap solution, followed by acetone and isopropyl alcohol (IPA) cleaning in a sonicator. Then, the slide is spin-coated with a 330 nm thick layer of a PMMA e-beam resist (molecular weight 950k, 4% solution by volume in anisole) [Fig. 4(a)]. The resist is patterned with the e-beam at 100 keV (Vistec EPBG5000pES, dose 700 µC/cm², current 1 nA) and developed in 1:3 methyl isobutyl ketone-IPA solution to produce PMMA gratings with a period of 800 nm and stripe width of 335 nm [Fig. 4(c)]. Further, a 10 nm sacrificial layer of aluminium (Al) is deposited at normal incidence, and then silver (Ag) is deposited (using an e-beam evaporator) on both sidewalls by tilting the sample [Fig. 4(d)]. This gives a 65 nm thick silver film on the side walls of the PMMA grating. Since Ag is deposited also on top of the PMMA grating as well, we remove it by subjecting the sample to argon (Ar) plasma (Oxford PlasmaLab 80Plus, RF power 50 W, pressure 20 mtorr, etch rate 4 nm/min) at normal incidence [Fig. 4(e)]. To remove any re-deposited silver from the horizontal surfaces of the sample, the underlying aluminium film is etched with a type D Al etchant solution (Transene Company Inc.). The sample is then covered with PMMA by spin coating, which makes the period of the grating equal to 400 nm [Fig. 4(f)]. The total size of the structure is 200 μ m × 200 μ m. Figure 4(g) shows the surface of a representative sample after metal deposition [step (d)]. The sample is tilted by 20°. We observe that the surface of silver is smooth, showing good adhesion to PMMA. To verify that the sidewalls are vertical, we cover the polymer grating after step (d) with 20 nm of Ag (to avoid charging in scanning electron microscopy). We then mill the sample using focused ion beam milling at a tilt angle of 52° (in the plane parallel to the stripes) to obtain a cross-sectional view, shown in Fig. 4(h). The sidewalls are indeed seen to be vertical. We also note that in some samples, the Al



Fig. 4. Schematic and analysis of the fabrication process. Fabrication steps: (a) spin coating of PMMA resist, (b) e-beam patterning, (c) development of the exposed resist to obtain a PMMA grating and deposition of aluminium, (d) deposition of silver on the sidewalls of PMMA, (e) plasma etch using Ar ions followed by chemical etching of Al, and (f) covering the structure by spin coating a 630 nm layer of PMMA on top of the grating. (g) Scanning electron microscope (SEM) image of sample surface after step (d). (h) SEM image of the sample after step (d) milled with a focused ion beam. Inset: schematic of the imaging.

etching damaged the silver stripes. We believe that this problem can be alleviated by enhancing the adhesion between silver and PMMA.

Figure 5(a) shows the magnitudes of the transmission coefficients of TE- and TM-polarized light (blue and red curves, respectively) that were measured using a xenon lamp as a white -ight source, a broadband polarizer, and a fiber-coupled spectrometer (Ocean Optics USB2000+). The measured values of |t| are slightly lower than the theoretically predicted ones, presumably due to fabrication errors. In particular, the metal surface after step (e) is not perfectly flat at the metal-air interface. Therefore, after covering the sample with PMMA, a double periodicity of 800 nm appears, resulting in a small diffractive loss. We indeed observed some weak diffraction orders in the experiments predominantly for TE polarization. Also, the optical properties of Ag can be different from the ones used in the simulations, due to, e.g., grain-size and surface inhomogeneityrelated scattering losses. Figure 5(b) shows the measured phase retardation between TM and TE polarizations. It reaches the design value of $\pi/2$ at the wavelength of 840 nm, which is shifted from the design wavelength of 790 nm. Besides the shift, the phase retardation follows the theoretical prediction well [Fig. 3(b)], including the large wavelength range of the approximate quarter-wave retardation. This is also illustrated by the polarization ellipses plotted in Fig. 5(c). These represent the polarization states resulting from transmitting linearly polarized light through the wave plate, and even at wavelengths far from 840 nm, a nearly circular polarization state is achieved. The corresponding Poincaré vectors are $S(\lambda_0 = 650 \text{ nm}) =$ $\mathbf{S}(\lambda_0 = 733 \text{ nm}) = (-0.05, 0.24, 0.97),$ (0.00, 0.30, 0.95), $\mathbf{S}(\lambda_0 = 816 \,\mathrm{nm}) = (-0.12, 0.06, 0.99), \text{ and } \mathbf{S}(\lambda_0 = 900 \,\mathrm{nm}) =$ (-0.18, -0.12, 0.98). In the transmission measurements we used linearly polarized incident light with the polarization at an angle of 45° with respect to the grating lines. The transmitted light was analyzed with another polarizer at the angles of 0°, 30°, and 90°. We used the spectra measured at these angles to deduce the phase difference spectrum in a way described in Ref. [11] [see Eq. (4) therein].

In conclusion, we presented a design of a transmissive wave retarder based on a metamaterial structure with low-refractiveindex operation for TE polarization. As an experimental demonstration, we fabricated and characterized a quarter-wave plate



Fig. 5. Measured spectra of (a) |t| and (b) $\Delta \varphi = \arg(t_{\rm TM}) - \arg(t_{\rm TE})$ of the fabricated quarter-wave plate. The shaded region in (b) contains the phase retardations limited by $\pi/2 \pm 0.2$ rad. The four polarization ellipses in (c) show the polarization states that result from passing 45° linearly polarized light (denoted by the dashed lines) through the wave plate at different wavelengths.

based on the proposed principle. Our design operates in a broad spectral range between 650 nm and 900 nm, which can be shifted also to other wavelengths. The possibility of incorporating the presented wave plate in a tunable achromatic wave retarder system such as the one from Ref. [8] to miniaturize the system is another interesting avenue for future research. Furthermore, wave plates of this type can be fabricated on large-area substrates using standard optical interference lithography or nanoimprinting, which is important from the point of view of possible mass production of the proposed wave retarders.

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