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DOI:

[10.1021/acsphotonics.7b01363](https://doi.org/10.1021/acsphotonics.7b01363)

Document Version

Peer reviewed version

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Citation for published version (APA):

Minovich, A. E., & Zayats, A. V. (2018). Geometric-Phase Metasurfaces Based on Anisotropic Reflection: Generalized Design Rules. *ACS Photonics*, 5(5), 1755-1761. <https://doi.org/10.1021/acsphotonics.7b01363>

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Geometric-phase metasurfaces based on anisotropic reflection: generalized design rules

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Abstract

Metasurfaces based on the control of a geometric phase have been proven as one of the most efficient designs for both transmission and reflection operation. However, the constituent nanostructures are often studied only numerically in order to find best geometric parameters while lacking the analysis of physical principles of their operation and, therefore, predictability. Here we formulate a general concept for the design of reflection-type geometric-phase metasurfaces based on anisotropic reflective nanostructures. We demonstrate that the simplest anisotropic element such as a wire-grid polarizer can be used as a building block of a geometric-phase metasurface with operation bandwidth over the entire visible spectrum. We show that a similar anisotropy-based principle is the basis of a widely-used plasmonic resonator design for reflective metasurfaces, and derive and analyze the conditions for achieving high efficiency and broadband performance for the plasmonic nanoantenna metasurfaces. We demonstrate that the concept of the reflection anisotropy can also be applied to devise reflective metasurfaces built from high-contrast dielectric materials (such as titanium dioxide nanopillars) with the structure height almost 3 times lower compared to the waveguide-mode-based designs. We also show how a broadband metasurface performance in the visible range

can be achieved utilizing multiple resonances. The general rules for the reflective metasurface design which we formulate here can provide useful guidelines and hints for the engineering of metasurfaces for practical purposes and applications.

Keywords

Metasurfaces, geometric phase, wire-grid polarizer, polarization conversion, half-wave plate, dielectric metasurfaces.

Introduction. Metasurface represents a thin nanostructured layer, which nevertheless exhibits strong interaction with light while having only small optical losses. It has been demonstrated that metasurfaces can very efficiently manipulate light propagation and beaming properties, such as steering and focusing, as well as perform spectral filtering, enhancement of nonlinearities, and holographic-type information encoding among others.¹⁻⁴

Spatial phase modulation is one of the most useful metasurface applications promising miniature flat lenses, beam splitters, deflectors, and highly efficient reflection and transmission holograms. Metasurface-based phase control methods are closely related to optical zero-order diffraction gratings and phased array antennae used in radar technology. Metasurfaces are designed from an array of nanoelements that apply locally the required phase shift for transmitted or reflected light. Such nanostructures achieve high efficiency due to the sub-wavelength size of array's pitch, which eliminates unwanted diffraction orders. Two main approaches have been reported to achieve the phase tailoring: via the implementation of resonant nanoantennas or through a propagation phase delay. The structures that are based on the resonant behavior include gap-plasmon reflection patterns,⁵ nanoantenna-based metasurfaces,⁶ transmission Huygens surfaces⁷⁻⁹ etc. Huygens metasurfaces are realized via the combination of electric and magnetic resonances in dielectric structures, such as Si nanorods.⁷⁻⁹ The proper combination of the electric and magnetic responses allows for

a highly efficient transformation of the incident wave at the metasurface interface following the Huygens principle of secondary wave sources.

Another suggested method for the metasurface design utilizes a propagation phase delay and, in contrast to the above mentioned technique, is non-resonant. In visible spectral range, high-contrast dielectric elements made from TiO_2 are utilized as building blocks. Controllable fill-factor (of the high contrast dielectric) for the metasurface array elements provides the method for the engineering of the effective refractive index and, therefore, the propagation phase delay. The examples of such structures are transmission blazed binary structures,^{10–12} transmission¹³ and reflection achromatic metalenses,¹⁴ as well as silicone nitride based phase masks and metalenses.¹⁵ However, only a limited number of nanostructures can provide a full range ($0 - 2\pi$) phase modulation utilizing the methods mentioned above. Introducing Pancharatnam-Berry (PB) geometric phase technique greatly expands the range of elements which can be combined together either with a resonant or a propagation phase technique for the metasurface design.^{16,17}

The essential point in the PB phase implementation is a set of birefringent elements exhibiting different optical properties for two perpendicular polarizations of light, such as metal nanorods or high aspect ratio TiO_2 nanofins. The PB effect is related to the phase acquired during the parallel transport along a closed path on the Poincaré sphere of polarization states (see^{16,18} for more details). The PB phase is equal to the solid angle of the closed path. To detect the PB effect, the observation has to be done in the opposite polarization: the output polarization state has to be different from the input one. That is why, as a rule, two different circular polarizations are used and the output is usually cross-polarized relative to the input. The geometric phase is relative, which means that the shift is counted between the waves scattered from two elements, not between the scattered and incident light. For two nanorods with different axis orientation illuminated by a circularly polarized light, the phase difference between the two scattered waves (due to the PB phase) is equal to the double value of the angle between nanorods' axes. There is an additional advantage: the

PB phase does not depend on the wavelength of incident light. However, the efficiency of polarization conversion on nanostructures usually greatly varies across the spectrum, for the reasons presented below. We will show how to overcome this limitation and propose a design for broadband PB metasurface elements for the entire visible spectral range.

Plasmonic resonance in a nanorod antenna cannot provide a full 2π phase span based only on the resonant phase delay.¹ However, an array of the nanoantennae can cover the full phase range through the PB effect by rotating the orientation of the nanorods' axes.¹⁹ Different types of structures have been shown to perform the phase modulation based on the PB phase, such as blazed gratings,²⁰ V-shaped plasmonic antennae,⁶ high-contrast dielectric (TiO₂) nanofins,²¹ and others. While the dielectric structures can provide high efficiency for transmission metasurfaces, the performance of plasmonic resonators in this configuration is limited. Placing the metal nanoantennae above a ground plate, and thus working in reflection mode, can raise the metasurface efficiency above 80%.¹⁸ The detailed analysis of the structure provided in¹⁸ predicts high efficiency of the metasurface near the nanorod resonant frequency. In this work, we analyse the factors that determine the operational bandwidth for the structures. Moreover, we show that this type of behavior is not specific only to the plasmonic resonators, but there is a broad class of anisotropic nanostructures that can serve as building blocks for metasurfaces. Thus, we derive a general concept of the PB reflective structures and discuss a number of conditions which constituents of metasurfaces have to satisfy.

One of the crucial requirements in achieving the high performance of a PB-phase metasurface (in addition to low losses) is to provide an efficient polarization conversion from one circular polarization state to another. This is similar to a half-wave plate effect but must be applicable at the nanoscale. In this paper, we systematically analyze the data on reflective birefringent nanostructures, generalize the concept of a PB-phase metasurfaces based on reflective anisotropy, and determine the conditions for their efficient and broadband performance.

General theory. In the most general case a reflective geometric (PB) phase metasurface represents a 3-layer system (Figure 1(a)) consisting of a nanostructure characterized by forward (backward) reflection r (r') and transmission t (t') coefficients, which can be different for incident light polarized along Y and X directions. The nanostructure sits on a dielectric spacer with refractive index n_s above a highly reflective ground plate (usually a metal film) with reflection coefficient r_m . The phase delay due to the optical path through the nanostructure is included in its complex-valued transmission coefficients and, therefore, the system can be described similar to a Fabry-Perot resonator with reflection ($\tilde{r}$) defined by the expression¹⁸

$$\tilde{r} = r + \frac{tt'r_me^{i\varphi}}{1 - r_mr'e^{i\varphi}}, \quad (1)$$

where $\varphi = 2k_0dn_s$ is the phase delay due to the round-trip of light through the spacer, k_0 is the free-space wavenumber, d is the spacer thickness, and n_s is the spacer refractive index. In the case when the nanostructure exhibits birefringence, its reflection and transmission coefficients will be different for two principal directions X and Y , and the resulting reflection should be determined by the projection of the reflection components ($\tilde{r}_x$ and $\tilde{r}_y$) onto a chosen polarization basis. In the Hecht's notation²² ($e^{i(kz-\omega t)}$), $r_r = \frac{1}{\sqrt{2}}(r_x - ir_y)$ for right-circular polarized light and $r_l = \frac{1}{\sqrt{2}}(r_x + ir_y)$ for left-circular polarized light.

For an illustrative purpose, let us consider a simplified Fabry-Perot resonator with a ground plate being a nearly perfect reflector $r_m = -0.99$ (for a perfect reflector with $r_m = -1$, the reflection from the system is always 1, since there is no energy distribution between reflection and transmission). The reflection coefficients at another interface r, r' are considered to be real-valued and no losses are assumed. Two options for the signs of backward and forward reflection coefficients are possible for such a system, depending on the relative refractive indices of materials involved. If the cavity is formed only by a dielectric slab, $r' = -r$ and, taking into account $tt' = T = 1 - R = 1 - r^2$, we obtain²³

$$\tilde{r} = \frac{r + r_me^{i\varphi}}{1 + r_mr'e^{i\varphi}}, \quad (2)$$

Figure 1: (a) Schematic illustration of a cross-section of a metasurface element consisting of a birefringent nanostructure (yellow) separated from a ground plate by a spacer. (b–c) Calculated Fabry-Perot reflection phase for different values of the nanostructure’s reflection coefficient (r) and phase delay (φ) in the dielectric spacer for a nearly perfect ground plate reflection $r_m = -0.99$ in the case of (b) $r' = -r$ and (c) $r' = r$. (d) Fabry-Perot reflection phase cross-sections plotted from (c) at fixed r values of -0.9 , 0 , and 0.9 marked by dashed-lines in (c)).

where T and R are the intensity transmission and reflection, respectively. The Fabry-Perot reflection phase $\Phi = \arg(\tilde{r})$ in this case is presented in Figure 1(b). Alternatively, it is possible that the first reflecting surface represents some (potentially metal) thin-layer structure for which reflection is symmetric²⁴): $r' = r$. However, since the reflecting film represents another three-medium system, this imposes the relation between the reflection and transmission phases. When $r' = r$ and is real-valued, the transmission becomes complex-valued $t = it_r$ and $t' = it'_r$, where t_r and t'_r are real. This is because the film thickness is finite and the wave acquires a phase shift while propagating through it. Noting that $tt' = -t_r t'_r = -(1 - r^2)$, we obtain²⁴

$$\tilde{r} = \frac{r - r_m e^{i\varphi}}{1 - r_m r e^{i\varphi}}. \quad (3)$$

This case is presented in Figure 1(c) (cf. Figure 1(b)). From the maps of Fabry-Perot reflection phase plotted for different values of the reflection coefficient r and phase delay φ (Figures 1(b-c)), one can see that when the magnitude of reflection is small, Φ depends linearly on the phase delay φ from the round-trip inside the cavity (cross section for $r = 0$ is plotted in Figure 1(d)(green curve)). In contrast, when $|r|$ becomes higher than 0.5, the Fabry-Perot reflection phase Φ tends to a constant value (Figure 1(b-c) and Figure 1(d)(blue and red curves)).

For a birefringent nanostructure with low reflection for light linearly polarized in X direction and high reflection for Y -polarized light ($|r_y| > 0.5$), there is a certain value of the phase delay φ when the phase difference between the Fabry-Perot reflection components $\Phi_x = \arg(\tilde{r}_x)$ and $\Phi_y = \arg(\tilde{r}_y)$ will be equal to π , being the difference between a constant and a linear function. For non-resonant metallic nanostructures (such as films or wires) with reflection phase usually being close to $-\pi$ and, therefore, $r < 0$, this condition will be located near $\varphi = 0$ (Figure 1(d)), that is in the Fabry-Perot reflection maximum. It means that such a structure with the anisotropic reflection can perform the conversion of circular polarization similar to a half-wave plate. If an element with these properties can be fabricated at the nanoscale dimensions then, by controlling the orientation of the nanostructure's principal

axis, the PB phase variation is possible to achieve.

Wire-grid structure. One of the simplest example of such an anisotropic reflection system is a wire-grid polarizer combined with a dielectric spacer and a silver mirror (Figure 2(a)). It exhibits high reflection for the light polarized along metal stripes (high reflection channel) and a high transmission for the polarization that is perpendicular to the wires (low reflection channel). As we showed above, the condition for the highest efficiency of polarization conversion, when the phase difference between perpendicular components of reflection $\tilde{r}_x$ and $\tilde{r}_y$ equals π , is mainly determined by the Fabry-Perot delay phase (φ) which depends on the spacer thickness d as

$$\varphi = 2k_0 n_s d + \varphi_m, \quad (4)$$

where φ_m is the phase shift acquired upon reflection from the metallic ground plate. Calculated cross-polarized (for circular polarization) reflectance spectrum for different spacer thickness d is shown in Figure 2(b). As one can see, in the plane of (λ, d) , the maxima of cross-polarized reflectance represent lines, as expected from Eq. 4. They lay close to the Fabry-Perot resonances $\varphi = 2\pi m$ (black lines in Figure 2(b)), where m is an integer number, confirming our earlier observation that for negative r the highest polarization conversion is achieved near $\varphi = 0$. The line with zero phase delay $\varphi = 0$ is above thickness $d = 0$ because the reflection from the silver film causes a phase shift close to $-\pi$. The small deviation of reflectance (R_{lr}) maxima from the Fabry-Perot resonances (marked with black lines in Figure 2(b)) is due to the additional phase shift inside the wire-grid structure, which results in the complex-valued reflection and transmission coefficients. The angle formed by each line representing the Fabry-Perot resonances with the axis λ is directly proportional to the spacer refractive index n_s . This is why the spacer material with low refractive index is advantageous for a broadband operation, such as MgF_2 with $n_s = 1.38$. In this case, as seen in Figure 2(b), the line corresponding to a first maximum has an inclination angle that is small enough to achieve a broadband performance across the whole visible spectrum

for a fixed d . For example, the cross-polarization conversion for $d = 60$ nm is between 0.7 and 0.9 across the visible range (Figure 2(c))(blue curve R_{lr}). Numerically simulated (CST Microwave Studio, FDTD solver) reflection coefficients for the aluminum wire-grid structure on a semi-infinite MgF_2 substrate along ($|r_y|^2$) and perpendicular ($|r_x|^2$) to wires clearly reveal a high reflection anisotropy (Figure 2(c)). The numerically evaluated transmission and reflection coefficients for linear polarization basis were used in Eq. 1 to calculate the Fabry-Perot reflection for different d . They were then used in the circular polarization basis to plot the reflectance R_{lr} and R_{rr} . This semi-analytical method allows a quick search for the optimal spacer thickness d . Finally, we point out that a reflective PB-phase metasurface design is possible using the patches of the demonstrated wire-grid structure with different orientation of the pattern to provide a spatial phase variation analogous to blazed diffraction grating structures demonstrated in Ref. 16.

Figure 2: (a) Schematic illustration of an aluminum wire-grid structure. (b) Calculated cross-polarized reflection spectrum (circular polarization) of the aluminum wire-grid for different spacer thickness d . Structure parameters are $W = 40$ nm, $H = 50$ nm, and $P_x = 150$ nm. Solid lines indicate Fabry-Perot delay phase φ . (c) Cross-polarized reflectance (R_{lr}) and co-polarized reflectance (R_{rr}) at $d = 60$ nm (marked by dashed-line in (b)); numerically simulated linearly-polarized reflectance along the wires ($|r_y|^2$), and perpendicular to the wires ($|r_x|^2$) of the Al wire-grid on a semi-infinite MgF_2 substrate are shown with red and cyan lines.

Polarization conversion is an important practical task by itself, and a number of studies have reported subwavelength structures suitable for this process. The examples include a set of two perpendicular nanoslits in a metal film²⁵ or two perpendicular nanorods²⁶ for waveplate design, elliptic nanoantennas for visible spectrum,²⁷ various types of grating

patterns for visible,^{28–31} and gratings and bigratings above a ground plate for microwaves.³² The presented results can be helpful for development of new polarization devices.

Plasmonic resonator. Plasmonic resonators are widely used in PB phase metasurface structures. The simplest version of the design represents a nanorod antenna (see Figure 3(a)). It has been shown that a reflective metasurface pattern based on gold nanoantennas exhibits high efficiency ($> 80\%$) and broadband performance above 650 nm.¹⁸ The theoretical description of such structures is presented in detail in Ref.^{18,33} Localized surface plasmon resonance excited in the nanorod by the incident light can be presented by an induced electric polarization with a Lorentzian shape of the spectrum¹⁸

$$P = -\frac{g}{\omega - \omega_0 + i\gamma}, \quad (5)$$

where g is the resonance strength, ω_0 is the resonance frequency (related to a wavelength as $\lambda_0 = 2\pi c/\omega_0$), and γ is the damping coefficient. Main resonant features (amplitude and phase for the associated reflection) are depicted in Figure 3(b) as an illustrative example. For the nanorod, the resonance strength is strongest when the light is polarized along the antenna axis and is smallest for a perpendicular direction. It is possible to derive nanostructure's transmission and reflection coefficients (r, r', t, t') from the electric polarization P using the Fresnel equations for a 3-layer medium (see, e.g., Ref. 18). As it was shown in Ref. 18, near the resonance frequency and under condition that the Fabry-Perot delay phase $\varphi = 0$, the reflected radiation acquires a steady phase shift of π relative to the perpendicular non-resonant (low reflection) channel. These are exactly the terms required for polarization conversion. In Figure 3(c), we show an example of the cross-polarized reflectance R_{lr} spectrum for different spacer thickness d . The values for λ_0 , g , and γ for the resonance are taken from Ref. 18 where they were obtained as fitting parameters for the numerically simulated reflection and transmission coefficients of the gold nanorod on a semi-infinite MgF_2 substrate. The center of high (cross-polarized) reflectance area (Figure 3(c)) matches the Fabry-Perot phase delay

$\varphi = 0$, corresponding to maximum reflection. This condition was derived analytically in Ref. 18 from the laborious model treating a nanorod and a resonator; our approach leads to the same conclusions from the consideration of a simplified Fabry-Perot cavity. We note that in comparison to the wire-grid structure (Figure 2(b)), the area of high efficiency is rotated to better match the horizontal λ -axis, which provides a broadband performance for a fixed spacer thickness d . This occurs because of the phase delay associated with the resonance (Figure 3(b)). From the cross sections of R_{lr} , R_{rr} , and the nanorod's linear reflection coefficient $|r_y|^2$ at $d = 130$ nm displayed in Figure 3(d), one can see that our previous estimates for the high efficiency threshold as $|r_y| > 0.5$ or $|r_y|^2 > 0.25$ are valid, and the cross-polarized reflection quickly drops as soon as the nanorod's linear reflection goes below this value.

Figure 3: (a) Schematic illustration of a gold nanoantenna metasurface. (b) An example of reflection amplitude and phase of a plasmonic resonator described by the Lorentzian model. (c) Calculated cross-polarized reflection spectrum (circular polarization) of the nanostructure for different spacer thickness d . Parameters of the resonance along the antenna axis (Y -direction) are $\lambda_0^y = 720$ nm, $g_y = 0.2$, and $\gamma_y = 2\pi \cdot 6.35 \cdot 10^{12}$ rad/s, and no resonance is considered in X -direction. Resonant parameters are retrieved from the numerical simulation of a gold nanorod on a MgF_2 substrate with $W = 80$ nm, $L = 200$ nm, $H = 30$ nm, $P_x = P_y = 300$ nm. Solid lines indicate the Fabry-Perot phase delay φ . (d) Cross-polarized reflectance (R_{lr}), co-polarized reflectance (R_{rr}), linearly-polarized reflectance $|r_y|^2$, and $|r_x|^2$ for $d = 130$ nm (marked by dashed-line in (c)).

Dielectric resonator. The concept of metasurface elements based on reflection anisotropy is not limited to only plasmonic resonators. In a similar manner, dielectric building blocks can be utilized. It was demonstrated that high refractive index (high-contrast) Si gratings can perform polarization conversion similar to a quarter-wave plate in transmission.³⁴ Dielectric reflection metasurfaces for linear polarization based on Si nanofins have also been demonstrated in the infra-red.³⁵ In the visible spectral range, such materials as TiO_2 are usually used as metasurface building blocks.²¹ In Huygens metasurface designs, magnetic and electric resonances have to occur at the same frequency to suppress backward scattering.⁷ However, in order to obtain the reflection anisotropy in our approach, we only need to excite either an electric or magnetic resonance to provide high reflection for one polarization and to be away from the resonances for the opposite polarization. This can be achieved with a structure stretched along one direction. An example of such metasurface based on TiO_2 nanofins is presented in Figure 4(a). From the cross-polarized reflectance displayed in Figure 4(b), we can see that the metasurface has a high efficiency in the short-wavelength spectral range. The reflection anisotropy due to the resonant mode excitation can be clearly seen in Figure 4(c). It should be pointed out that the height of the structure is almost 3 times less than the 600 nm tall nanofins used in the design of a transmission metasurface lens.²¹

Multiple resonances for broadband performance. When the spectral width provided by a single resonance is not enough to cover a required spectral range, the excitation of two resonances, under certain conditions, can broaden the range of the high efficiency. In wire-grid (or grating) structure, it is possible to achieve another resonance by creating slits along the second direction. Such a so-called bigrating structure has broadband performance as was demonstrated in the microwave regime.³² With plasmonic resonators, such as a nanorod antenna, the second resonance is naturally excited along a short axis. The calculated reflectance spectra for a model with 2 Lorentzian resonances³⁶ show that, with an appropriate

Figure 4: (a) Schematic illustration of a TiO₂ nanopillar structure. (b) Calculated cross-polarized reflection spectrum (circular polarization) of the TiO₂ metasurface for different spacer thickness d . Structure parameters are $W = 80$ nm, $L = 200$ nm, $H = 230$ nm, and $P_x = P_y = 300$ nm. (c) Cross-polarized reflectance (R_{lr}), co-polarized reflectance (R_{rr}), and linearly-polarized reflectance components $|r_y|^2$ and $|r_x|^2$ at $d = 100$ nm (marked by dashed-line in (b)).

choice of the resonant frequencies, the high cross-polarized reflectance is achievable over the whole visible spectral range (Figure 5(a–b)). However, if the two resonances are located too close to each other, their interaction is destructive (Figure 5(c–d)) and, if the two resonances for perpendicular polarizations coincide with each other, reflection anisotropy is absent. The reflection phase in this case changes from $-\pi$ to π across the resonance (Figure 3(b)). When the two resonances are close to each other, the phase difference between two polarization channels is still close to 2π . Only when they are considerably apart, the phase difference of π is achieved, which provides the required polarization conversion. When the optimal separation is exceeded, the region of high reflectance turns into a narrow band following a Fabry-Perot maximum (Figure 5(e–f)), and broadband performance for a fixed d is not achievable.

The discussion above provides only simple qualitative explanation, however in practice, the resonance strength at shorter wavelength is typically significantly smaller and, in order to determine the optimal separation of the resonances, full evaluation of Eq. 1 is required, which is too complex to extract intuitively understandable rules for resonance locations. When designing nanorod resonators, it is important to keep in mind that in such material as gold the resonant band is limited to the spectral region above 600 nm. It is also hard

Figure 5: (a, c, e) Calculated cross-polarized reflectance spectrum at different spacer thickness d for a 2-resonance model. (b, d, f) Reflectance simulated for various thicknesses d : (b) $d = 70$ nm, (d) $d = 90$ nm, and (f) $d = 90$ nm. Resonance wavelengths for x - and y -polarization are $\lambda_0^x = 390$ nm and $\lambda_0^y = 720$ nm for (a–b), $\lambda_0^x = 540$ nm and $\lambda_0^y = 720$ nm for (c–d), $\lambda_0^x = 310$ nm and $\lambda_0^y = 1000$ nm for (e–f). Resonance strength coefficients $g_x = g_y = 0.2$ and damping coefficients $\gamma_x = \gamma_y = 2\pi \cdot 6.35 \cdot 10^{12}$ rad/s are the same for all structures. Black lines indicate Fabry-Perot phase $\varphi = 2\pi m$, white lines $\varphi = \pi + 2\pi m$ (where m is integer), and white dashed-lines indicate cross-sections at fixed d which are displayed in the corresponding bottom plots.

to obtain resonances at the short wavelengths with silver, but aluminum seems to be an appropriate material to cover the whole visible spectrum.³⁷ The excitation of surface-plasmon polaritons (SPPs) at a metal/dielectric interface is also omitted in the simplified model described by Eq. 1. However, their spectral location is easy to determine using the standard SPPs dispersion law and the lattice vector of the nanostructure.⁷ It is advisable to verify the results of the semi-analytical analysis with full-wave numerical simulations for the chosen spacer thickness d to observe all spectral features in greater detail.

Conclusions. We have analyzed the concept of a birefringent reflective nanostructure combined with a Fabry-Perot resonator for the design of reflective PB-phase metasurfaces. We have shown that the condition to achieve an efficient performance of such a metasurface is the presence of two polarization channels in reflection from constituent nanostructures: one is with a high reflection $|r| > 0.5$ and another is with a low reflection (high transmission). We have demonstrated that this principle is applicable for the design of PB metasurfaces based on wire-grid structures as well as dielectric nanofins. We have shown that, in addition to the previously demonstrated PB-phase reflective metasurfaces based on plasmonic resonators, the reflection anisotropy design can be applied to dielectric, such TiO_2 or Si resonators, and the height of the structures can be almost 3 times lower in comparison to the waveguide-mode-based designs. Finally, we have shown how a spectral range of metasurface operation can be broaden through the use of multiple resonances. We believe that the concept of PB-phase metasurfaces based on anisotropic reflection will be useful for the design of novel ultra-thin geometric and diffractive optical elements for the entire visible spectrum.

Acknowledgement

A.M. acknowledges support from the Royal Society (Newton International Fellowship). A.Z. acknowledges support from the ERC, the Royal Society and the Wolfson Foundation.

References

- (1) Genevet, P.; Capasso, F.; Aieta, F.; Khorasaninejad, M.; Devlin, R. Recent advances in planar optics: from plasmonic to dielectric metasurfaces. *Optica* **2017**, *4*, 139–152.
- (2) Kildishev, A. V.; Boltasseva, A.; Shalaev, V. M. Planar Photonics with Metasurfaces. *Science* **2013**, *339*, 1232009.
- (3) Yu, N.; Capasso, F. Flat optics with designer metasurfaces. *Nature Mat.* **2014**, *13*, 139–150.
- (4) Minovich, A. E.; Miroshnichenko, A. E.; Bykov, A. Y.; Murzina, T. V.; Neshev, D. N.; Kivshar, Y. S. Functional and nonlinear optical metasurfaces. *Laser & Photonics Reviews* **2015**, *9*, 195–213.
- (5) Pors, A.; Albrechtsen, O.; Radko, I.; Bozhevolnyi, S. Gap plasmon-based metasurfaces for total control of reflected light. *Scientific Reports* **2013**, *3*, 2155.
- (6) Yu, N.; Genevet, P.; Kats, M. A.; Aieta, F.; Tetienne, J.-P.; Capasso, F.; Gaburro, Z. Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction. *Science* **2011**, *334*, 333–337.
- (7) Decker, M.; Staude, I.; Falkner, M.; Dominguez, J.; Neshev, D. N.; Brener, I.; Pertsch, T.; Kivshar, Y. S. High-Efficiency Dielectric Huygens Surfaces. *Advanced Optical Materials* **2015**, *3*, 813–820.
- (8) Arbabi, A.; Horie, Y.; Ball, A. J.; Bagheri, M.; Faraon, A. Subwavelength-thick lenses with high numerical apertures and large efficiency based on high-contrast transmitarrays. *Nature communications* **2015**, *6*, 7069.
- (9) Yu, Y. F.; Zhu, A. Y.; Paniagua-Domínguez, R.; Fu, Y. H.; Luk'yanchuk, B.; Kuznetsov, A. I. High-transmission dielectric metasurface with 2π phase control at visible wavelengths. *Laser & Photonics Reviews* **2015**, *9*, 412–418.

- (10) Lalanne, P.; Astilean, S.; Chavel, P.; Cambril, E.; Launois, H. Blazed binary subwavelength gratings with efficiencies larger than those of conventional échelette gratings. *Optics letters* **1998**, *23*, 1081–1083.
- (11) Lalanne, P. Waveguiding in blazed-binary diffractive elements. *JOSA A* **1999**, *16*, 2517–2520.
- (12) Lalanne, P.; Astilean, S.; Chavel, P.; Cambril, E.; Launois, H. Design and fabrication of blazed binary diffractive elements with sampling periods smaller than the structural cutoff. *JOSA A* **1999**, *16*, 1143–1156.
- (13) Khorasaninejad, M.; Zhu, A.; Roques-Carmes, C.; Chen, W.; Oh, J.; Mishra, I.; Devlin, R.; Capasso, F. Polarization-insensitive metalenses at visible wavelengths. *Nano letters* **2016**, *16*, 7229–7234.
- (14) Khorasaninejad, M.; Shi, Z.; Zhu, A. Y.; Chen, W. T.; Sanjeev, V.; Zaidi, A.; Capasso, F. Achromatic Metalens over 60 nm Bandwidth in the Visible and Metalens with Reverse Chromatic Dispersion. *Nano Letters* **2017**, *17*, 1819–1824.
- (15) Zhan, A.; Colburn, S.; Trivedi, R.; Fryett, T. K.; Dodson, C. M.; Majumdar, A. Low-Contrast Dielectric Metasurface Optics. *ACS Photonics* **2016**, *3*, 209–214.
- (16) Hasman, E.; Kleiner, V.; Biener, G.; Niv, A. Polarization dependent focusing lens by use of quantized Pancharatnam-Berry phase diffractive optics. *Applied Physics Letters* **2003**, *82*, 328–330.
- (17) Bliokh, K. Y.; Rodríguez-Fortuño, F.; Nori, F.; Zayats, A. V. Spin-orbit interactions of light. *Nature Photonics* **2015**, *9*, 796.
- (18) Zheng, G.; Mühlenbernd, H.; Kenney, M.; Li, G.; Zentgraf, T.; Zhang, S. Metasurface holograms reaching 80% efficiency. *Nature Nanotechnology* **2015**, *10*, 308–312.

- (19) Huang, L.; Chen, X.; M?hlenbernd, H.; Li, G.; Bai, B.; Tan, Q.; Jin, G.; Zentgraf, T.; Zhang, S. Dispersionless Phase Discontinuities for Controlling Light Propagation. *Nano Letters* **2012**, *12*, 5750–5755.
- (20) Bomzon, Z.; Kleiner, V.; Hasman, E. Pancharatnam–Berry phase in space-variant polarization-state manipulations with subwavelength gratings. *Opt. Lett.* **2001**, *26*, 1424–1426.
- (21) Khorasaninejad, M.; Chen, W. T.; Devlin, R. C.; Oh, J.; Zhu, A. Y.; Capasso, F. Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging. *Science* **2016**, *352*, 1190–1194.
- (22) Hecht, E. *Optics*; Addison-Wesley, 2002.
- (23) Born, M.; Wolf, E. *Principles of optics*; Cambridge University Press, Cambridge, 2005; p 572.
- (24) Ismail, N.; Kores, C. C.; Geskus, D.; Pollnau, M. Fabry-Pérot resonator: spectral line shapes, generic and related Airy distributions, linewidths, finesses, and performance at low or frequency-dependent reflectivity. *Opt. Express* **2016**, *24*, 16366–16389.
- (25) Khoo, E. H.; Li, E. P.; Crozier, K. B. Plasmonic wave plate based on subwavelength nanoslits. *Optics letters* **2011**, *36*, 2498–2500.
- (26) Zhao, Y.; Alu, A. Tailoring the Dispersion of Plasmonic Nanorods To Realize Broadband Optical Meta-Waveplates. *Nano Letters* **2013**, *13*, 1086–1091.
- (27) Wang, F.; Chakrabarty, A.; Minkowski, F.; Sun, K.; Wei, Q.-H. Polarization conversion with elliptical patch nanoantennas. *Applied Physics Letters* **2012**, *101*, 023101.
- (28) Hooper, I.; Sambles, J. Broadband polarization-converting mirror for the visible region of the spectrum. *Optics letters* **2002**, *27*, 2152–2154.

- (29) Watts, R. A.; Sambles, J. R. Polarization conversion from blazed diffraction gratings. *Journal of Modern Optics* **1997**, *44*, 1231–1241.
- (30) Seshadri, S. Polarization conversion by reflection in a thin-film grating. *JOSA A* **2001**, *18*, 1765–1776.
- (31) Passilly, N.; Ventola, K.; Karvinen, P.; Laakkonen, P.; Turunen, J.; Tervo, J. Polarization conversion in conical diffraction by metallic and dielectric subwavelength gratings. *Applied optics* **2007**, *46*, 4258–4265.
- (32) Tremain, B.; Rance, H.; Hibbins, A.; Sambles, J. Polarization conversion from a thin cavity array in the microwave regime. *Scientific Reports* **2015**, *5*, 9366.
- (33) Ye, W.; Guo, Q.; Xiang, Y.; Fan, D.; Zhang, S. Phenomenological modeling of geometric metasurfaces. *Opt. Express* **2016**, *24*, 7120–7132.
- (34) Mutlu, M.; Akosman, A. E.; Kurt, G.; Gokkavas, M.; Ozbay, E. Experimental realization of a high-contrast grating based broadband quarter-wave plate. *Opt. Express* **2012**, *20*, 27966–27973.
- (35) Yang, Y.; Wang, W.; Moitra, P.; Kravchenko, I. I.; Briggs, D. P.; Valentine, J. Dielectric meta-reflectarray for broadband linear polarization conversion and optical vortex generation. *Nano letters* **2014**, *14*, 1394–1399.
- (36) Matlab script for study a Lorentzian resonance metasurface model can be found here https://alexminovich.wordpress.com/anisotropicr_ms_matlab/.
- (37) Huang, Y.-W.; Chen, W. T.; Tsai, W.-Y.; Wu, P. C.; Wang, C.-M.; Sun, G.; Tsai, D. P. Aluminum Plasmonic Multicolor Meta-Hologram. *Nano Letters* **2015**, *15*, 3122–3127.

Graphical TOC Entry