Research article

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Subwavelength sorting of full-color based on anti-Hermitian metasurfaces

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Abstract: Splitting the spectrum of incident light at nanoscale has been of great scientific and practical interest due to its potential application in various optical sensors. For many years, researchers have been striving to realize the full-color sorting of light at subwavelength scale, while keeping the loss of incident photons to a minimum. In this article, we present semiconductor-based metasurfaces that facilitate the efficient sorting of full-color by inducing anti-Hermitian coupling between multiple nanoantenna arrays. To achieve this, we first explore how the coherent interactions between maximally crafted nanoantennas in the metasurfaces can be effectively controlled by judiciously positioning them in both lateral and vertical directions, which leads to the switched coupling of light at each target position. Based on the analysis, we demonstrate a metasurface-based absorber that features efficient, spectropolarimetric detections over the entire visible spectrum, ranging from 470 to 630 nm. In addition, the metasurface detects relatively narrow spectral linewidth of 60 nm and shows the sensitivity up to 70%, which surpasses the previous works on subwavelength photon sorting or color filter-based detection system. We envision that our approach provides guidelines for realizing the metasurfaces with enhanced functionalities, that is the increase of spectral channels for detection in a given subwavelength-scaled unit cell.

1 Introduction

The ability of metasurfaces composed of nanostructured metals or dielectric materials to control the wavefronts of light has attracted considerable attention due to its potential applications to optical devices including spatial light modulators [1–5], biosensors [6–7], and photodetectors [8–14], to name a few. In particular, significant efforts have been devoted to developing metasurface-based photodetectors, which feature more elaborated fashion of light detection than conventional devices by judiciously controlling the phase of scattered light in absorbing nanostructures [15, 16]. Examples of these include the sensing of specific spectra [17–24], polarizations [25, 26], and incident angles [27, 28], as the light passes through ultrathin, nanostructured films.

More recently, the novel concept of an ultrathin photodetector that optically mimics the phenomena of anti-Hermitian system in quantum mechanics has emerged [29–31]. Anti-Hermitian in optics facilitates the effective narrowing down of absorption spectrums in resonant nanostructures that reduces the spectral overlaps and optical crosstalk between nanoresonators. The anti-Hermitian analogy of optical metasurface has been intensively exploited to spectrally split and detect over a relatively narrow spectral range of light at subwavelength-scale, thereby enabling efficient and filterless nanophotonic sensing. However, the number of splitting channels for subwavelength photon sorting has been quite small, typically only two, or three with significantly sacrificed efficiency. This is because the size of a unit cell comprising metasurfaces are generally very small at the deep subwavelength scale to support only the zeroth-order diffraction while suppressing all other higher order diffraction. As a result, the unit cell cannot contain multiple metaatoms. Because the number of splitting channels is determined by the number of meta-atoms integrated in a unit cell,

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the realization of the metasurface with multiple functionalities has eluded scientists and engineers for a long time. Thus, there is a great need to build a new design strategy to facilitate and increase the detection functionalities, targeting the realization of practically applicable photodetection schemes using metasurfaces.

In this article, we demonstrate the efficient photon sorting across the entire visible wavelength regime with three discrete absorption channels by using the anti-Hermitian principle in the semiconductor-based metasurface composed of multiple nanoantenna arrays. The proposed configuration circumvents the aforementioned challenges by invoking coherent interactions [15, 16] of multiple nanoelements that are both laterally and vertically integrated in metasurfaces [32–34]. We achieve this by judiciously aligning the interspacing of composed nanostructures at deep subwavelength scale, which ultimately leads to effective control over the coupling strength by inducing super- or sub-radiant conditions [35–39] between vertically aligned nanoelements. In particular, we use the strategy of vertically aligned configurations, which has been applied to various optical appliances including thin film solar cells and other nanophotonic devices [40–42]. It turns out that invoking both the vertical and lateral integration of nanoantennas can efficiently realize the anti-Hermitian coupled metasurface with substantially enhanced detection functionalities on a given constraint of subwavelength structural design on a unit cell.

This article is organized as follows: First, we analyze how the coupling strength of light between two, vertically

aligned nanobeam arrays is effectively switched by the subtle shift of vertical positions. Then, we demonstrate the vertically integrated metasurfaces, which present polarimetric, spectrally sorted light absorption that surpasses the previous works in its efficiency, number of channels, and full color extractions useful for practical applications.

2 Results and discussion

Figure 1a illustrates two representative models of integrated metasurfaces that feature effective switching in the coupling of light between the two nanostructured layers. We analyze the model using the refractive index of poly-Si obtained from the experimentally measured values that are fitted to the finite-difference time-domain (FDTD) simulation presented in the supporting information. The potential steps for the experimental fabrication of the sample with backside illumination are illustrated in the Figure S4 of the Supplementary Material.

Figure 1b shows the cross-sectional shape of the metasurfaces. The bottom metasurface is composed of the array of nanobeams of 100-nm-width and 140-nm-height, which excites resonance near the 500 nm wavelength of light with the polarization parallel to the nanobeam's axis. It is noteworthy that the nanobeams are entrenched into metals, combined with which the bottom layer serves as an effective reflector and induces standing wave pattern above the surface [40].

The top layer is positioned above the surface of the bottom metasurface and carved as fin-type beams that

Figure 1: Vertically aligned metasurfaces that feature switched coupling of incident light for y -directed polarization.

(a) Schematic of integrated metasurfaces composed by the arrays of two different types of nanobeams. Nanobeams at the bottom are entrenched into metal reflector and nanobeams at the top are percolated into silica superstrate for experimentally realizable scheme with backside illumination. (b) Cross-sectional image of nanobeam array with 100-nm-width (w_L), 140-nm-height (d_L) for bottom nanobeams and 10-nm-width (w_S) and 80-nm-height (d_S) for top nanobeams. The nanobeams are laterally separated by the period of 320 nm that is less than the wavelength of incident light. Top nanobeams are aligned at the height of h_1 or h_2 associated with the different positions of standing wave that are generated by bottom metasurface. (c, d) Image of total electric field intensity with power flow lines with the top nanobeams positioned at the height of h_1 (c) or h_2 (d). The incident power effectively avoids the top nanobeams (c) or shadows the bottom nanobeams (d).

percolate into the silica (SiO_2) superstrate. It excites fundamental, dipolar-like, resonance at the 500 nm wavelength that spectrally overlaps with the resonance of the bottom layer. Scattered light from each layer coherently interacts and invokes super- or sub-radiant conditions to selectively excite the resonance among the layers that spectrally features the phenomena of anti-Hermitian coupling.

Depending on the vertical position where the top metasurface is placed, the strength of resonance is exclusively enhanced or suppressed between the two separated layers. First, when it is placed at the point where scattered light is destructively interfered with, the resonators are under sub-radiant conditions, owing to the weak coupling of light associated with the suppressed absorption. Such an effect is visually illustrated in Figure 1c, which depicts the image of electric field with power flow lines by connecting the Poynting vectors of incident light. The image clearly shows that the flow of incident power avoids the position of the top nanobeams and is effectively absorbed in the array of beams at the bottom layer. Alternatively, when the top layer is placed on the constructively interfered, bright position in the standing wave, the top nanobeams are under super-radiant condition with enhanced absorption, keeping the strength of coupling minimum at the bottom layers. The electric field in Figure 1d shows the effective capture of incident power at the top nanobeams that virtually block the power flow at the bottom layer at steady state.

To examine the switched coupling of light quantitatively, we investigate the associated absorptivity of light in each layer for the two representative cases as depicted in Figure 2. Figure 2a shows that when the top metasurfaces are placed at the height of 145 nm, the composed nanobeams at the top do not afford any resonance, and feature virtually optical transparency, which results in the absorption spectrum (blue line) being broadly suppressed. The absorption in the bottom metasurface (red line) is significantly high compared with the top metasurface, which approximately functions as if there were no top metasurface integrated (black line). On the other hand, when the top layer is displaced by the quarter wavelength by being positioned at the height of 225 nm (Figure 2b), the top nanobeams support resonance near the wavelength of 500 nm and suppress the absorption at the bottom. The trend of periodically modulated absorption is visually illustrated in Figure S2 of the Supplementary Material, where the enhancement and suppression of absorptions exclusively emerge between the two metasurfaces with respect to the vertical position of the top metasurface. The period of such pattern is approximately half wavelength of

Figure 2: Simulated absorption spectra illustrating switched coupling of light with the top metasurface positioned at the height of h_1 (145 nm) and h_2 (225 nm) respectively.

(a) Absorptions with the top metasurface at the height of h_1 . The bottom metasurface (red line) excites resonances at both wavelengths of 500 and 645 nm, which leads to the absorption of top metasurface (blue line) being broadly suppressed. Black dashed line indicates the absorption of bottom metasurface without the vertical integration which closely resembles the spectrum of bottom metasurface with vertical integration. (b) Absorptions with the top metasurface at the height of h_2 . The absorption of bottom metasurface (red line) is effectively suppressed at the wavelength of 500 nm at which the top metasurface (blue line) excites the resonance. Black dashed line indicates the absorption of top metasurface with bare silver reflector, which closely resembles the absorption of integrated metasurface.

a standing wave from the metal reflector and is expressed as $P_H = (\lambda/n_{\text{SiO}_2})/2$, where n_{SiO_2} is the refractive index of the superstrate.

As a next stage, we aim to integrate additional nanoelements in the proposed metasurfaces for the increase of the spectral channels of detection. We start by investigating the representative metasurfaces composed of two differently sized nanobeams as illustrated in the schematics in Figure 3a and b. Figure 3a shows that, akin to the previous example in Figure 2, the top layer is optimally positioned to have maximum light absorption at the wavelength of 480 nm that suppresses the absorption in the bottom layer. On the other hand, at the longer wavelength of 620 nm, the bottom beams excite the fundamental mode of resonance with the enhanced peak of absorption, whereas the fin-type beams at the top do not excite any resonance in this spectral region. In this way, targeted spectra of red and blue are effectively split and extracted vertically in each nanobeam array. Next, to create another detection channel, we intentionally add additional nanobeams at the bottom layer. The size of the added nanobeam is initially equal to the neighboring nanobeams, as schematically illustrated in Figure 3b. It is noteworthy from the spectra that the absorption at the red

Figure 3: The evolved abilities of three-color sorting in integrated metasurfaces with varying width of added nanobeams.

(a) Metasurfaces composed by two different types of nanobeam arrays ($w_L = 100$ nm, $d_L = 130$ nm, $w_S = 10$ nm, $d_S = 80$ nm, $P = 300$ nm) to have coherent interactions in vertical directions. (b) The absorptions with the increased density of bottom nanobeams. The magnitude of absorption decreases and the spectrum is significantly broadened due to the overcoupling of incident light. (c, d) The creation of additional, detecting channels by the reduced width of added nanobeams as 90 nm (c) and 75 nm (d). The absorption spectra are split and blue-shifted from panel (b) as the width of the nanobeams decreases, and the magnitude of absorption is enhanced by the destructive interference of scattered light from the array of two different-sized nanobeams at the bottom layer. The circle marks indicate the wavelength of the maximum light absorption in added nanobeams. Black dotted line is the total absorption in metasurfaces. (e) Magnitude of maximum absorption (blue line) and the corresponding wavelength (orange line) of the added nanobeam array as the width varies from 45 to 100 nm. The optimal condition for the sorting of full-color is indicated as green circular mark.

spectral region is significantly lowered, compared with the one without added beams in Figure 3a. This is because the denser nanobeams typically couple and scatter an increased amount of light, and thereby the designed system is on overcoupled state, resulting in the broadening of spectrum, and reducing the magnitude of absorption peaks. With this, we gradually decrease the size of the added nanobeams to explore the evolved feature of absorption spectra, as exhibited in Figure 3b–d. It is clearly evident in the figures that an additional, efficient channel for spectral detection is created. Specifically, as the width of the nanobeams is reduced from 100 to 75 nm, the spectral peak of absorption is shifted to the shorter wavelength. This also causes the shift of phase in the scattered light, rendering it out of phase with the scattered light from the original nanobeams. In the end, the absorption increases in both nanobeams owing to the destructively interfered, scattered light that suppresses reflection.

Figure 3e illustrates the overall trend of spectral shift and enhanced absorption. As the size of beam decreases from 100 to 60 nm, the resonant peak shifts from the red (620 nm in the wavelength) to green (545 nm in the wavelength) spectral region with the increase of the magnitude of absorption. By contrast, when the size of the beams becomes less than 60 nm, the resonant peak approaches the blue spectral regions, being disturbed by the top metasurface and resulting in the decrease of absorption.

Finally, we design an integrated metasurface absorber that efficiently splits full color spectra and is operated potentially as a filterless photodetector by extracting current separately in each nanobeam array, as illustrated in Figure 4a. The design is based on the further optimizations from the analysis of Figure 3 by slight variations of the periods and sizes. Regarding the feasibility of experimental realization, the evaluation of the design reveals that the performance is not seriously distorted by the lateral displacement of the top nanobeams that could occur during fabrication error, as exhibited in Figure S4 of the Supplementary Material.

To evaluate the ability to sort and absorb the target wavelength of light, we analyze the absorption spectra as depicted in Figure 4b. The absorptivity in each nanobeam exceeds 60% at the resonant wavelengths with the total absorption maximally being 85% near the blue spectral region, and the system shows efficient performance on sorting color by suppressing the absorption by less than 10% at the nonresonant nanobeam arrays due to the coherent interactions between the three different types of nanobeam arrays. It is noteworthy that the absorptivity of large nanobeams (red line) is doubly suppressed at the wavelengths of 480 and 556 nm by inducing sub-radiant coupling at both spectra, otherwise being enhanced due to the arising of higher-order resonant mode [43]. In addition, the parasitic absorption in silver reflector is calculated in Figure S5 of Supplementary Material. The spectrum of anti-Hermitian coupled metasurfaces can be formalized

Figure 4: Integrated metasurface for the subwavelength, full-color sorting with the potential extraction of photocurrents. (a) Schematic of different-sized nanobeam arrays vertically integrated as layered metasurfaces for the effective sorting of full-visible color. (b) Absorption spectra in each nanobeam arrays illustrating enhanced absorption and exclusive suppression of the spectra by anti-Hermitian coupling. Solid line: finite-difference time-domain (FDTD) simulation, dashed line: theoretical line based on coupled mode theory (CMT). (c, d, e) Electric field profiles and the associated power flow lines at the wavelength of 480 nm (c), 556 nm (d), and 626 nm (e). Each nanobeam array excites Mie resonance at the target wavelength of incident light.

by temporal coupled mode theory (CMT) [44, 45] with the optical excitations of three coupled resonators, as follows:

$$\frac{\partial}{\partial t} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} = i \begin{bmatrix} \omega_1 + i(\gamma_{a1} + \gamma_{r1}) & \omega_{12} + i\gamma_{12} & \omega_{13} + i\gamma_{13} \\ \omega_{12} + i\gamma_{12} & \omega_2 + i(\gamma_{a2} + \gamma_{r2}) & \omega_{23} + i\gamma_{23} \\ \omega_{13} + i\gamma_{13} & \omega_{23} + i\gamma_{23} & \omega_3 + i(\gamma_{a3} + \gamma_{r3}) \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} + \begin{bmatrix} \kappa_1 \\ \kappa_2 \\ \kappa_3 \end{bmatrix} S_+ \quad (1)$$

where, c_i is the amplitudes of resonant mode, κ_i indicates the coupling strength of incident plane wave, S_+ is the amplitude of the incident light, and ω_i , γ_{ai} , and γ_{ri} represent the resonance frequency, absorption, and radiation losses of each system, respectively. Off-diagonal terms ω_{ij} and γ_{ij} denote direct near-field and indirect far-field interactions among the coupled resonant systems. CMT provides the insight of operating principle in the designed metasurface. The subwavelength period of the array in Figure 4a supports only the 0th diffraction order, and thus, the designed metasurface modeled using CMT interacts through a single radiation channel, where the relative phase of the scattered light from each nanobeam arrays suppresses each other's radiation. Specifically, by judiciously placing the top nanobeams at destructively interfered position vertically above the metasurface at the bottom, it realizes three anti-Hermitian coupled resonant systems as modeled in Equation (1) with the off-diagonal terms being purely

imaginary [30, 31]. Such model is indicated as dashed line in Figure 4b and closely follows the full-field simulations.

More intriguing than the strong light absorption is the enhancement of the absorption cross-section of nanobeams [46]. For example, the narrow beams at top occupy only 3.3% of the total geometric cross-sectional area. Such narrow beams effectively capture most of the incident light, and virtually significantly shadow the bottom metasurfaces, as illustrated in the optical field with power flow lines (Figure 4c). Similarly, incident light with green and red spectra avoids the top nanobeams, and is effectively absorbed in the target nanobeam arrays, as illustrated in Figure 4d and e.

The metasurfaces consisting of the one-dimensional geometry of nanobeam arrays offer an additional degree of freedom of its functionalities over spectral sensing as a trade-off for the reduced geometric axis for structural design. Owing to the rotational asymmetry, the configuration of nanobeams naturally interacts differently to the two orthogonally polarized light. Figure 5a–c shows the absorption spectra for the incident light with the polarization parallel to the nanobeam's axis (solid line, transverse magnetic [TM]), and with the polarization perpendicular to the axis (dashed line, transverse electric [TE]). The evaluations clearly indicate that there are negligible levels of absorption in all three arrays of less than 20% under the TE polarization. This is ascribed to the polarization dependency of Mie resonance, in which the resonance is weakly supported for the TE polarization

Figure 5: Simulated nanobeam absorption under the incident light with two orthogonal polarizations.

(a) The absorption spectrum of top nanobeam array (nanobeam 1) for transverse magnetic (TM) polarization (solid line, electric field parallel to the axis) and transverse electric (TE) polarization (dashed line, electric field orthogonal to the axis). Inset shows the cross-sectional image of integrated metasurfaces and the polarization of incident light. (b, c) The absorption spectrum of the small (nanobeam 2) and large (nanobeam 3) nanobeam array at the bottom under TM and TE polarizations. The absorption spectra of three nanobeam arrays show more than 60% at TM polarization via Mie resonance excited by the nanobeams. (d, e, f) Map of the spectral absorption in the nanobeam array 1 (d), the nanobeam array 2 (e), and the nanobeam array 3 (f) as the function of the angle of polarizations (ψ) with respect to the nanobeam's axis. The composed nanobeam arrays support fundamental mode of Mie resonance under TM polarization and shows high absorption near $\psi = 0^\circ$.

at the nanobeams with size of less than 100 nm [47]. In addition, the plasmonic resonance is weakly launched at the deep subwavelength periods of the array. In regard to the application of photodetector, one-dimensional geometry facilitates potentially easier fabrication of electrical contacts by laterally extracting the photocurrents. It

is also possible to realize a metasurface with efficient color sorting for both TE and TM polarizations by designing symmetric nanostructures using nanocylinder and nanomesh (see Supplementary Note 6).

Most notably, the designed metasurface effectively splits and detects three spectral ranges of full color and

Figure 6: (a) Absorbance of this work and previous works on subwavelength photon sorting using metasurfaces based on plasmonic resonance (blue symbol) [9], multi-junction absorber (yellow) [13], sub-wavelength grating (purple) [14], anti-Hermitian coupling (green) [30], and holographic diffraction (magenta) [48]. (b) Sorting efficiency and full width at half maximum (FWHM) of this work and previous works. The sorting efficiency is defined as the ratio of the absorbed power in the target nanostructure to the total absorbed power, i.e., $\eta_s = P_{\text{target}}/P_{\text{total}}$.

polarizations, which surpasses the previous designs of subwavelength-scaled nanophotonic metasurfaces in their efficiency, number of functionalities and spectral range of interests, as indicated in Figure 6.

3 Conclusions

To summarize, we presented integrated metasurfaces that feature three-color sensing, including the efficient detection of blue spectral regions. Strong light absorption near 70% was shown in the overall visible spectrum with exclusive suppression of light less than 10% at each target spectra. We achieved this by evaluating how the optical coupling is effectively controlled between two vertically aligned nanobeam arrays by inducing coherent interactions based on anti-Hermitian coupling. In addition, the one-dimensional nature of the nanobeam geometry provides efficient polarimetric sensing and offers potential design of electrical contact for photocurrent extractions. We believe our design paves practical pathways toward realizing nanophotonic optical sensors for the subwavelength-scaled detection of target spectra of light.

4 Methods

The numerical simulation of subwavelength sorting of full-color based on anti-Hermitian metasurfaces is performed using commercial FDTD software from Lumerical Solutions. The simulation of the metasurface is taken with the background refractive index 1.46, representing the status of SiO_2 . In the unit cell, the periodic boundary condition is used in the x -direction, and the perfectly matched layer absorbing boundary conditions is applied along the z -direction. The height of the polysilicon nanobeam located at the bottom and the top metasurfaces is fixed to 130 and 80 nm, respectively. The width of the nanobeam is optimized depending on the target wavelength. The absorptions of each nanobeams are calculated by the Ohmic loss, i.e., $0.5 \cdot \omega \epsilon'' |E|^2$, where ϵ'' is imaginary part of the dielectric constant obtained experimentally from ellipsometry. Power flow lines are plotted by calculating the Poynting vector which is defined as the cross product of the E & H fields.

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