Full-Stokes polarimetry for visible light enabled by all-dielectric metasurface

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Decoding arbitrary polarization information from an optical field has triggered unprecedented endeavors in polarization imaging, remote sensing and information processing. Therefore, developing a polarization detection device with full on-chip integration and miniaturization holds tremendous potential for many areas of optical sciences. Here, we propose a full-Stokes polarimetry device for visible light based on an all-dielectric metasurface. By combining both geometric phase and propagation phase modulation, we design the metasurface to provide two uncorrelated phase profiles for the two orthogonal states of input polarization, which we then use to spatially separate the various polarization states of incident light. Through the use of a millimeter-scale multiplexed metasurface array, we further achieve successful characterization of the full polarization distribution of space-variant polarization fields. This proof-of concept ultracompact and ultrathin metasurface is expected to open new pathways in full-Stokes polarization detection, machine vision and navigation.

KEYWORDS: Metasurface, polarization, polarimetry, full-Stokes parameters

Polarization is an intrinsic attribute of light that describes the oscillatory orientation of electric field along the optical path. However, it is often not captured in a photograph because most image sensors are only sensitive to the intensity and color of the incident field. Separate from spectrally decoding the information about material constituents in an imaging field such as done using hyperspectral imaging techniques [1], polarization metrology can reveal minuscule, and often invisible, characteristics of emitting light sources or scattering objects such as surface stress and roughness. Therefore, polarimetry has found use in a wide range of applications such as remote sensing [2], machine vision [3], biomedical imaging [4] and surface analysis [5]. Traditionally, polarimetry has been realized using either the division-of-time (DoT) [2-4] or division-of-aperture (DoA) [5] technique. In DoT, the intensity of light with different polarization states is recorded by a detector after passing through a rotating wheel equipped with polarizers mounted at different orientation angles. The DoT technique sacrifices temporal resolution, and also requires mechanically moving parts which is not desirable in an optical setup. On the other hand, in DoA the light is split by a series of polarization optics and recorded by several separate detectors. This approach has the disadvantage of requiring a fairly long propagation space between the various optical components as well as strict alignment between them. In recent years, much of the polarization metrology interest has focused on the development of division-of-focal plane (DoFP) technique, where a photodetector array is placed at the focal plane covered with different polarization filters [6-8]. Despite their successful commercialization, DoFP devices are unable to provide measurement of the full-Stokes parameters, or detection of polarization structured beams with high spatial resolution. Other novel polarimetry approaches, such as using black phosphorus [9] or graphene [10], are still premature and need further development to be integrated into functional devices.

Metasurfaces, consisting of a single layer of subwavelength optical nanoantennas, have provided the ability to arbitrary control multi-dimensional properties of light, including phase [11-15], polarization [16-18], frequency [19,20], and amplitude [21, 22]. As a result, metasurfaces have been widely explored to tailor the wavefront of incident light for applications in holography [23-25], high-resolution imaging [26-28], structural colors [29-31] or orbital angular momentum (OAM) generation [32-35]. Recently, using diffractive and matrix Fourier optics, a DoA full-Stokes polarization camera has been demonstrated [36]. Furthermore, using Si metasurfaces, DoFP fullStokes polarimetry has been demonstrated in the near-infrared spectral range [37-40]. Besides dielectric metasurfaces, plasmonic metasurfaces have also been utilized for polarization detection [41-45]. However, metallic nanostructures suffer from large intrinsic absorption losses which significantly limit their efficiencies, especially while operating in the transmission mode.

In this work, we propose and experimentally demonstrate DoFP full-Stokes polarimetry for visible light using all-dielectric metasurface. The metasurface is composed of an array of subwavelength-spaced elliptical shaped titanium-dioxide (TiO₂) nanopillars acting as nanoscale birefringent waveplates. By combining both geometric phase and propagation phase modulation, we designed the metasurface to provide two uncorrelated phase profiles for the two orthogonal polarization states of incident light, which is then used to spatially separate the various polarization states of spatially uniform beams, we demonstrate fabrication of a millimeter-scale metasurface array to successfully map the complete spatially varying polarization distribution of cylindrical vortex beams (CVBs). Offering the advantages of integration in a compact and ultrathin architecture, we envision this metasurface platform to offer new capabilities for polarization analysis, Stokes holography and multidimensional imaging.

Fundamentally, any arbitrary polarization state of a monochromatic plane wave can be represented using the Stokes vector formalism as, $\mathbf{S} = [S_0, S_1, S_2, S_3]^T$, where T indicates the transpose of the matrix. The various matrix components are defined as: $S_0 = I = I_0 + I_{90} = I_{45} + I_{135} = I_R + I_L$, $S_1 = (I_0 - I_{90})$, $S_2 = (I_{45} - I_{135})$, $S_3 = (I_R - I_L)$ where, *I* is the total incident intensity, I_0 , I_{90} , I_{45} , I_{135} are the intensities of light with polarization oriented at 0°, 90°, 45°, 135° with respect to the *x*-axis, respectively and I_R (I_L) denote the intensity of right (left) circularly polarized light (RCP/LCP). Due to the direct quantitative relationship between the polarization states of incident light and intensity of certain polarization basis, the Stokes vector offers enormous simplicity and is therefore widely used in polarization metrology [36-46]. Here, instead of using a traditional set of optic elements, a single layer metasurface composed of birefringent TiO₂ nanopillars is designed to split three pairs of orthogonal states of input polarization (0°/90°, 45°/135° and RCP/LCP) with high efficiency, and simultaneously focus them to different positions on the sensor plane (Fig. 1a). The full-Stokes parameters can be obtained by measuring the intensities of the six different polarization bases at the focal plane, and thus the polarization state of incident light can be determined. Figure 1b shows the schematic diagram of the proposed planar metasurface element consisting of three polarization beam splitters spatially arranged in a hexagonal pattern. Each beam splitter occupies a rhomb region, and has the ability to separate and focus a pair of orthogonal polarization states along the diagonal direction. The phase profile of each metasurface beam splitter can be calculated as: $\varphi_n = -\frac{2\pi}{\lambda} [\sqrt{(x-x_n)^2 + (y-y_n)^2 + f^2} - f]$, where x_n and y_n denote the deflecting coordinates of the two polarization states, subscript n = 1, 2 represents two orthogonal polarization states, and f is the focal distance of the designed metasurface. Therefore, six different polarization bases (0°/90°, 45°/135° and RCP/LCP) are equidistantly distributed at the focal plane to form a regular hexagon shape.

For the metasurface to achieve spatial separation of arbitrary orthogonal polarization states $(|k^+\rangle, |k^-\rangle)$ of incident light, two independent phase profiles $\varphi_1(x, y)$ and $\varphi_2(x, y)$ should be endowed to the orthogonal input polarization states. In other words, the Jones matrix *T* of the designed metasurface should simultaneously satisfy the following transformations: $T(x, y)|k^+\rangle = e^{i\varphi_1(x,y)}|(k^+)^*\rangle$ and $T(x,y)|k^-\rangle = e^{i\varphi_2(x,y)}|(k^-)^*\rangle$, where * represents complex conjugate. For two orthogonal linear polarization (for example, *x*- and *y*- polarization, *i.e.*, 0°/90°), the Jones matrix *T* can be derived as,

$$T(x,y) = \begin{bmatrix} e^{i\varphi_1} & 0\\ 0 & e^{i\varphi_2} \end{bmatrix}$$
(1)

According to the diagonal character of matrix *T*, one can directly obtain the phase shifts $\delta_x = \varphi_1(x, y)$ and $\delta_y = \varphi_2(x, y)$ along the symmetry axes of linearly birefringent nanopillars, which also indicates that for this polarization pair (0°/90°) the metasurface can impart polarizationindependent phases by only leveraging the propagation phase offered by the nanostructures with no requirement for nanopillar rotation or geometric phase modulation (Fig. 1c). The transmission coefficient and phase shifts along the *x*-axis are simulated as a function of the in-plane dimensions of TiO₂ nanopillars, and corresponding results are shown in Fig. 1d. By discretization of the phase profiles, a series of structural parameters (SI Table 1) are selected to provide eight discrete phase levels covering the full 0 to 2π phase range and offering high efficiencies at a visible wavelength of 530 nm. In addition, using simple coordinate transformation, the spatial decoupling of 45° and 135° linear polarization states can be realized by rotating every elliptical TiO_2 nanopillar in the previous configuration by 45° relative to the *x*-axis.

Finally, to spatially decouple the two orthogonal circular polarization states, RCP and LCP, the Jones matrix T can be calculated as [28],

$$T(x,y) = \frac{1}{2} \begin{bmatrix} e^{i\varphi_1} + e^{i\varphi_2} & -ie^{i\varphi_1} + ie^{i\varphi_2} \\ -ie^{i\varphi_1} + ie^{i\varphi_2} & -e^{i\varphi_1} - e^{-i\varphi_2} \end{bmatrix}$$
(2)

The unitary nature and symmetry of this matrix guarantees that it can be diagonalized by solving the characteristic equation. The eigenvalues and eigenvectors of this Jones matrix require that the constituent nanopillars have a birefringent response with phase shifts (φ_x, φ_y) along the two perpendicular symmetry axes, and an orientation angle θ of the fast-axis as a function of the reference coordinate. We can find analytical expressions for required phase shifts and orientation angles as $\varphi_x = (\varphi_1 + \varphi_2)/2$, $\varphi_y = (\varphi_1 + \varphi_2)/2 - \pi$, $\theta = (\varphi_1 - \varphi_2)/4$. In this case, the decoupling of two orthogonal circular polarization states is achieved through a combination of both the propagation phase and geometric phase (Fig. 1e). Therefore, it is imperative to find a set of nanostructures with varying in-plane dimensions and orientation angles, offering the full 0 to 2π phase coverage. Based on the above analysis, eight nanopillar structures with high transmission efficiencies are selected from the calculation results (marked by black circles with #1 to #8 in Fig. 1f). Figure 1g and 1h show an optical photograph and scanning electron microscope (SEM) images of the fabricated TiO₂ metasurface, respectively. The detailed fabrication process is described in the Methods section.

Figure 2a shows the custom-built experimental setup for full-Stokes polarization detection. A collimated, linearly polarized input illumination at a free-space wavelength of 530 nm is generated from a supercontinuum laser attached to an acousto-optic tunable filter (AOTF) and a linear polarizer (LP). Subsequently, a half- or a quarter- waveplate (HWP or QWP) is used to tailor the incident light with any discretionary polarization state before illuminating the metasurface. The transmitted light through the metasurface is then captured using a 50× objective lens and recorded on a charge coupled device (CCD) camera. To characterize the polarization response of the metasurface device, we first illuminate it with six basis polarization states (0°/90°, 45°/135°, and LCP/RCP) in successive order. The experimental results shown in the first row of Fig. 2b

demonstrate that the device can route different polarization components to different focal spots. For each incident polarization state, the full intensity distribution at the focal plane is unique, and an obvious extinction can be observed for the focal-spot position corresponding its orthogonal polarization state. By adding the recorded intensity information at the CCD pixels occupied by each focal spot, the power-distribution of the six polarization components can be quantified and the normalized Stokes parameters can be reconstructed (second row of Fig. 2b). Figure 2c shows the simulation results of the metasurface device with different input states, including polarizationresolved intensity distribution and the corresponding Stokes parameters. As plotted on the Poincaré sphere (Fig. 2d), both the experimentally reconstructed and numerically simulated Stokes parameters agree well with the theoretical values, and the result of the accuracy analysis using twonorm error are shown in Fig. S3a. The detailed Stokes parameters from experiment and simulation are shown in SI Table 2. Benefiting from reasonable nanostructure design and accurate nanofabrication process, the measured transmission efficiency of the metasurface is nominally 54 %. The efficiency can be further improved by leveraging inverse design or an expanded design library that offer higher transmission coefficients while being less susceptible to errors from nanofabrication process variation. The high-quality polarization control capability achieved here ensures that the designed metasurface can be utilized for optical polarimetry.

Next, to validate the detection capability of the device for full-Stokes polarization characterization, eight random polarization states are selected to illuminate the metasurface. These input polarization states are generated by rotating the HWP and QWP on the basis of linearly polarized light and can be represented by spherical coordinates (α , β), where $\alpha/2$ and $\beta/2$ denote the shape and orientation of polarization ellipse (SI Note 1 for details). As expected, the transmitted beam through the metasurface is separated into six polarization components and focused to different points at the focal plane. Figure 3a summarizes the polarization-resolved intensity distributions for each input state and the corresponding normalized Stokes parameters reconstructed from the experimental measurements, which agree well with the results of the numerical simulation plotted on the Poincaré sphere agree with the theoretical values, the accuracy analysis using two-norm error are shown in Fig. S3b. The detailed Stokes parameters of experimental/simulated reconstructed and

theoretical calculations are shown in SI Table 3.

In addition to identifying a spatially uniform polarized input state, the proposed metasurface device can also be used for detection of space-variant polarization fields with high spatial resolution. Towards this end, we fabricate a 1 mm diameter polarimetry metasurface array (PMA) composed of sub-metasurface pixels arranged in a hexagonal lattice with a lattice constant of 34 μ m (Fig. 4a). The optical micrograph of the fabricated PMA and an SEM image of one sub-metasurface pixel are shown in Fig. 4b and 4c, respectively. To demonstrate the versatility and verify the performance of this metasurface platform, we fabricate a liquid crystal (LC) *q*-plate (Fig. 4d) to generate a cylindrical vector beam (CVB) with space-variant polarization fields. The detailed fabrication process of LC *q*-plate is described in the Methods section. The CVB is generated by superimposing two orthogonal circularly polarized optical vortex beam carrying topological charges of $l = \pm 1$ (SI Note 2 for details).

The experimental setup used for the detection of space-variant polarization fields is shown in supplementary Fig. S4. A square-wave electric function of 5.8 V and 1 kHz is applied to satisfy the half-wave condition of 530 nm and maximize the convention efficiency. For x- and y- linearly polarized beams incident on such a LC q-plate, a radially and azimuthally polarized CVB is respectively generated and marked by M1 and M2 on the higher-order Poincaré sphere (HOPS). M3 and M₄ are the two poles of HOPS corresponding to the LCP and RCP incident waves, respectively (Fig. 4e). As shown in the left column of Fig. 4f, for the cross-section of each theoretically calculated CVB, the polarization state varies with the coordinate position and results in a donut-shape intensity distribution. Here, the theoretical polarization distributions are calculated and indicated by white arrows whose length and direction denotes the strength and polarization state of the incident beam. As a reference, the middle column of Fig. 4f show the experimentally measured intensity patterns of CVB and corresponding reconstructed polarization distributions based on the traditional DoT polarimetry method using bulk optical elements (HWP and QWP), which are used to verify the polarization distribution of the incident beam (SI Fig. S5). In order to demonstrate the polarization detection of space-variant polarization fields by the proposed DoFP metasurface device, each CVB is directly projected onto the PMA. An objective lens is used to collect polarization-resolved intensity distribution at the focal plane. Figure 4f (right column) illustrate the experimental results

for different CVB input states labeled by M₁ to M₄. The 13x13 metasurface pixel array can be clearly identified in each image. Here, the direction of each white arrow denotes the polarization information, which is derived from each metasurface pixel by calculating the normalized Stokes parameters. At the same time, the intensity information can be obtained by averaging the power of three rhombus areas within each of the metasurface pixels and are denoted by the length of each white arrow. Compared to traditional polarimetry methods, the proposed PMA does not need bulk optical elements and has the advantage of performing measurement in a single shot. The experimental results achieved here agree well with the theoretical predictions, and demonstrate that polarization manipulating metasurface optics can enable full-Stokes detection and be used as an integrated component in devices or systems requiring in-line polarization metrology.

In conclusion, we propose and demonstrate division-of-focal plane full-Stokes polarimetry for visible light based on an all-dielectric metasurface platform. By tailoring the propagation and geometrical phases offered by constituent TiO_2 birefringent nanopillars placed on a hexagonal lattice, we designed metasurfaces to split and focus three pairs of orthogonal polarization states of light to six spatially separated focal positions. To validate the metasurface performance, eight random states of input polarization are generated and measured using the metasurface polarimeter verifying good polarization measurement capabilities of the metasurface. Furthermore, a large-scale metasurface array is fabricated to successfully characterize the full polarization distribution of a cylindrical vortex beam generated by a liquid crystal *q*-plate. We envision the lightweight and ultracompact all-dielectric metasurface platform proposed here to provide promising capabilities for integrated polarization metrology and multidimensional imaging.

METHODS

Metasurface Fabrication. Double-side polished fused-silica substrates are first coated with a layer of hexamethyldisilazane (HMDS) and positive-tone electron beam resist with the thickness of 600 nm. Subsequently, samples are coated with 10 nm of aluminum via thermal evaporation to avoid charging effects during the electron-beam lithography (EBL) step. The EBL is used to expose the designed pattern at an accelerating voltage of 100 kV. Next, the patterned samples were coated with TiO₂ using atomic layer deposition (ALD) process at the temperature of 90 °C. Later, overcoated

 TiO_2 layer of ALD is etched by inductively coupled-plasma reactive ion etching (ICP-RIE) until the resist is exposed. Finally, the samples are exposed to UV irradiation and soaked by n-methyl-2-pyrrolidone to remove the resist.

Liquid Crystal q-plate Fabrication. Indium-tin-oxide glass substrates were cleaned and then spincoated with the UV-polarization-sensitive photoalignment agent dissolved in dimethylformamide at 0.3 %. After curing at 100 °C, two pieces of substrates were sealed with a 6 µm thick spacer to form a cell. Then, it was placed at the imaging plane of a digital-micro-mirror based dynamic photopatterning system [47, 48] to receive the space-variant UV polarization exposure. Afterwards, the optical axis distribution of the q-plate was imprinted into the orientations of photoalignment agent, which would further guide the orientations of LCs. Finally, nematic LCs were infiltrated into the photo-patterned cell at 80 °C and gradually cooled to room temperature, yielding an electrically tunable q-plate.

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NOTES

The authors declare no competing interest.

REFERENCES

- Filiz Yesilkoy, Eduardo R. Arvelo, Yasaman Jahani, Mingkai Liu, Andreas Tittl, Volkan Cevher, Yuri Kivshar, and Hatice Altug, *Ultrasensitive hyperspectral imaging and biodetection enabled by dielectric metasurfaces*. Nature Photonics, 13(6), 390-396, (2019).
- 2. J. Scott Tyo, Dennis L. Goldstein, David B. Chenault, and Joseph A. Shaw, Review of passive

imaging polarimetry for remote sensing applications. Applied Optics, 45(22), 5453-5469, (2006).

- Yuanhuan Zhu, Yang Dong, Yue Yao, Lu Si, Yudi Liu, Honghui He, and Hui Ma, *Probing layered structures by multi-color backscattering polarimetry and machine learning*. Biomedical Optics Express, 12(7), 4324-4339, (2021).
- 4. Valery V. Tuchin, Lihong V. Wang, and Dmitry A. Zimnyakov, *Optical polarization in biomedica applications*: Springer, (2006).
- 5. J. Larry Pezzaniti and B. Chenault David. *A division of aperture MWIR imaging polarimeter*. in *Proc.SPIE*. 2005.
- Gregory P. Nordin, Jeffrey T. Meier, Panfilo C. Deguzman, and Michael W. Jones, *Micropolarizer array for infrared imaging polarimetry*. Journal of the Optical Society of America A, 16(5), 1168-1174, (1999).
- 7. Junpeng Guo and David Brady, *Fabrication of thin-film micropolarizer arrays for visible imaging polarimetry*. Applied Optics, **39**(10), 1486-1492, (2000).
- 8. V. Gruev, J. Van der Spiegel, and N. Engheta. *Image sensor with focal plane extraction of polarimetric information. IEEE International Symposium on Circuits and Systems.* 2006.
- James Bullock, Matin Amani, Joy Cho, Yu-Ze Chen, Geun Ho Ahn, Valerio Adinolfi, Vivek Raj Shrestha, Yang Gao, Kenneth B. Crozier, Yu-Lun Chueh, and Ali Javey, *Polarization*resolved black phosphorus/molybdenum disulfide mid-wave infrared photodiodes with high detectivity at room temperature. Nature Photonics, **12**(10), 601-607, (2018).
- 10. Jingxuan Wei, Cheng Xu, Bowei Dong, Cheng-Wei Qiu, and Chengkuo Lee, *Mid-infrared semimetal polarization detectors with configurable polarity transition*. Nature Photonics, **15**, 614-621, (2021).
- Nanfang Yu, Patrice Genevet, Mikhail A. Kats, Francesco Aieta, Jean-Philippe Tetienne, Federico Capasso, and Zeno Gaburro, *Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction*. Science, **334**(6054), 333-337, (2011).
- 12. Dianmin Lin, Pengyu Fan, Erez Hasman, and Mark L. Brongersma, *Dielectric gradient metasurface optical elements*. Science, **345**(6194), 298, (2014).
- Fei Zhang, Mingbo Pu, Xiong Li, Ping Gao, Xiaoliang Ma, Jun Luo, Honglin Yu, and Xiangang Luo, All-Dielectric Metasurfaces for Simultaneous Giant Circular Asymmetric Transmission and Wavefront Shaping Based on Asymmetric Photonic Spin–Orbit Interactions. Advanced Functional Materials, 27(47), 1704295, (2017).
- 14. Shuming Wang, Pin Chieh Wu, Vin-Cent Su, Yi-Chieh Lai, Mu-Ku Chen, Hsin Yu Kuo, Bo Han Chen, Yu Han Chen, Tzu-Ting Huang, Jung-Hsi Wang, Ray-Ming Lin, Chieh-Hsiung Kuan, Tao Li, Zhenlin Wang, Shining Zhu, and Din Ping Tsai, *A broadband achromatic metalens in the visible*. Nature Nanotechnology, **13**(3), 227-232, (2018).
- 15. Yueqiang Hu, Ling Li, Yujie Wang, Min Meng, Lei Jin, Xuhao Luo, Yiqin Chen, Xin Li, Shumin Xiao, Hanbin Wang, Yi Luo, Cheng-Wei Qiu, and Huigao Duan, *Trichromatic and*

Tripolarization-Channel Holography with Noninterleaved Dielectric Metasurface. Nano Letters, **20**(2), 994-1002, (2020).

- Amir Arbabi, Yu Horie, Mahmood Bagheri, and Andrei Faraon, *Dielectric metasurfaces for* complete control of phase and polarization with subwavelength spatial resolution and high transmission. Nature Nanotechnology, **10**, 937, (2015).
- J. P Balthasar Mueller, Noah A. Rubin, Robert C. Devlin, Benedikt Groever, and Federico Capasso, *Metasurface Polarization Optics: Independent Phase Control of Arbitrary Orthogonal States of Polarization*. Physical Review Letters, **118**(11), 113901, (2017).
- Xiaoliang Ma, Mingbo Pu, Xiong Li, Yinghui Gao, and Xiangang Luo, *All-metallic wide-angle* metasurfaces for multifunctional polarization manipulation. Opto-Electronic Advances, 2, 180023, (2019).
- Bo Wang, Fengliang Dong, Qi-Tong Li, Dong Yang, Chengwei Sun, Jianjun Chen, Zhiwei Song, Lihua Xu, Weiguo Chu, Yun-Feng Xiao, Qihuang Gong, and Yan Li, *Visible-Frequency Dielectric Metasurfaces for Multiwavelength Achromatic and Highly Dispersive Holograms*. Nano Letters, 16(8), 5235-5240, (2016).
- Yanjun Bao, Ying Yu, Haofei Xu, Chao Guo, Juntao Li, Shang Sun, Zhang-Kai Zhou, Cheng-Wei Qiu, and Xue-Hua Wang, *Full-colour nanoprint-hologram synchronous metasurface with arbitrary hue-saturation-brightness control.* Light: Science & Applications, 8(1), 95, (2019).
- Adam C. Overvig, Sajan Shrestha, Stephanie C. Malek, Ming Lu, Aaron Stein, Changxi Zheng, and Nanfang Yu, *Dielectric metasurfaces for complete and independent control of the optical amplitude and phase*. Light: Science & Applications, 8(1), 92, (2019).
- 22. Mingze Liu, Wenqi Zhu, Pengcheng Huo, Lei Feng, Maowen Song, Cheng Zhang, Lu Chen, Henri J. Lezec, Yanqing Lu, Amit Agrawal, and Ting Xu, *Multifunctional metasurfaces* enabled by simultaneous and independent control of phase and amplitude for orthogonal polarization states. Light: Science & Applications, **10**(1), 107, (2021).
- Guoxing Zheng, Holger Mühlenbernd, Mitchell Kenney, Guixin Li, Thomas Zentgraf, and Shuang Zhang, *Metasurface holograms reaching 80% efficiency*. Nature Nanotechnology, 10(4), 308-312, (2015).
- 24. Xiong Li, Lianwei Chen, Yang Li, Xiaohu Zhang, Mingbo Pu, Zeyu Zhao, Xiaoliang Ma, Yanqin Wang, Minghui Hong, and Xiangang Luo, *Multicolor 3D meta-holography by broadband plasmonic modulation*. Science Advances, 2(11), e1601102, (2016).
- 25. Haoran Ren, Xinyuan Fang, Jaehyuck Jang, Johannes Bürger, Junsuk Rho, and Stefan A. Maier, *Complex-amplitude metasurface-based orbital angular momentum holography in momentum space*. Nature Nanotechnology, (2020).
- 26. Ren Jie Lin, Vin-Cent Su, Shuming Wang, Mu Ku Chen, Tsung Lin Chung, Yu Han Chen, Hsin Yu Kuo, Jia-Wern Chen, Ji Chen, Yi-Teng Huang, Jung-Hsi Wang, Cheng Hung Chu, Pin Chieh Wu, Tao Li, Zhenlin Wang, Shining Zhu, and Din Ping Tsai, *Achromatic metalens array for full-colour light-field imaging*. Nature Nanotechnology, 14(3), 227-231, (2019).

- Pengcheng Huo, Cheng Zhang, Wenqi Zhu, Mingze Liu, Song Zhang, Si Zhang, Lu Chen, Henri J. Lezec, Amit Agrawal, Yanqing Lu, and Ting Xu, *Photonic Spin-Multiplexing Metasurface for Switchable Spiral Phase Contrast Imaging*, Nano Letters, 20(4), 2791-2798, (2020).
- Alexander Minovich, Angela E. Klein, Norik Janunts, Thomas Pertsch, Dragomir N. Neshev, and Yuri S. Kivshar, *Generation and Near-Field Imaging of Airy Surface Plasmons*. Physical Review Letters, **107**(11), 116802, (2011).
- 29. Bo Yang, Wenwei Liu, Zhancheng Li, Hua Cheng, Duk-Yong Choi, Shuqi Chen, and Jianguo Tian, *Ultrahighly Saturated Structural Colors Enhanced by Multipolar-Modulated Metasurfaces*. Nano Letters, **19**, 4221-4228, (2019).
- Pengcheng Huo, Maowen Song, Wenqi Zhu, Cheng Zhang, Lu Chen, Henri J. Lezec, Yanqing Lu, Amit Agrawal, and Ting Xu, *Photorealistic full-color nanopainting enabled by a low-loss metasurface*. Optica, 7(9), 1171-1172, (2020).
- Wenhong Yang, Shumin Xiao, Qinghai Song, Yilin Liu, Yunkai Wu, Shuai Wang, Jie Yu, Jiecai Han, and Din-Ping Tsai, *All-dielectric metasurface for high-performance structural color*. Nature Communications, **11**(1), 1864, (2020).
- 32. Haoran Ren, Xiangping Li, Qiming Zhang, and Min Gu, *On-chip noninterference angular momentum multiplexing of broadband light*. Science, **352**(6287), 805, (2016).
- Elhanan Maguid, Igor Yulevich, Dekel Veksler, Vladimir Kleiner, Mark L. Brongersma, and Erez Hasman, *Photonic spin-controlled multifunctional shared-aperture antenna array*. Science, 352(6290), 1202, (2016).
- Yijie Shen, Xuejiao Wang, Zhenwei Xie, Changjun Min, Xing Fu, Qiang Liu, Mali Gong, and Xiaocong Yuan, Optical vortices 30 years on: OAM manipulation from topological charge to multiple singularities. Light: Science & Applications, 8, 90, (2019).
- 35. Yinghui Guo, Shicong Zhang, Mingbo Pu, Qiong He, Jinjin Jin, Mingfeng Xu, Yaxin Zhang, Ping Gao, and Xiangang Luo, *Spin-decoupled metasurface for simultaneous detection of spin* and orbital angular momenta via momentum transformation. Light: Science & Applications, 10(1), 63, (2021).
- Noah A. Rubin, Gabriele D'Aversa, Paul Chevalier, Zhujun Shi, Wei Ting Chen, and Federico Capasso, *Matrix Fourier optics enables a compact full-Stokes polarization camera*. Science, 365(6448), eaax1839, (2019).
- Zhenyu Yang, Zhaokun Wang, Yuxi Wang, Xing Feng, Ming Zhao, Zhujun Wan, Liangqiu Zhu, Jun Liu, Yi Huang, Jinsong Xia, and Martin Wegener, *Generalized Hartmann-Shack array of dielectric metalens sub-arrays for polarimetric beam profiling*. Nature Communications, 9(1), 4607, (2018).
- Ehsan Arbabi, Seyedeh Mahsa Kamali, Amir Arbabi, and Andrei Faraon, *Full-Stokes Imaging Polarimetry Using Dielectric Metasurfaces*. ACS Photonics, 5(8), 3132-3140, (2018).
- 39. Fei Ding, Bingdong Chang, Qunshuo Wei, Lingling Huang, Xiaowei Guan, and Sergey I.

Bozhevolnyi, Versatile Polarization Generation and Manipulation Using Dielectric Metasurfaces. Laser & Photonics Reviews, 14, 2000116, (2020).

- 40. Yuxi Wang, Zhaokun Wang, Xing Feng, Ming Zhao, Cheng Zeng, Guangqiang He, Zhenyu Yang, Yu Zheng, and Jinsong Xia, *Dielectric metalens-based Hartmann-Shack array for a high-efficiency optical multiparameter detection system*. Photonics Research, 8(4), 482-489, (2020).
- 41. Anders Pors, Michael G. Nielsen, and Sergey I. Bozhevolnyi, *Plasmonic metagratings for simultaneous determination of Stokes parameters*. Optica, **2**(8), 716-723, (2015).
- 42. Fei Ding, Anders Pors, Yiting Chen, Vladimir A. Zenin, and Sergey I. Bozhevolnyi, *Beam-Size-Invariant Spectropolarimeters Using Gap-Plasmon Metasurfaces*. ACS Photonics, 4(4), 943-949, (2017).
- Pin Chieh Wu, Jia-Wern Chen, Chih-Wei Yin, Yi-Chieh Lai, Tsung Lin Chung, Chun Yen Liao, Bo Han Chen, Kuan-Wei Lee, Chin-Jung Chuang, Chih-Ming Wang, and Din Ping Tsai, *Visible Metasurfaces for On-Chip Polarimetry*. ACS Photonics, 5(7), 2568-2573, (2018).
- Jing Bai, Chu Wang, Xiahui Chen, Ali Basiri, Chao Wang, and Yu Yao, *Chip-integrated plasmonic flat optics for mid-infrared full-Stokes polarization detection*. Photonics Research, 7(9), 1051-1060, (2019).
- 45. Lingfei Li, Junzhuan Wang, Lei Kang, Wei Liu, Li Yu, Binjie Zheng, Mark L. Brongersma, Douglas H. Werner, Shoufeng Lan, Yi Shi, Yang Xu, and Xiaomu Wang, *Monolithic Full-Stokes Near-Infrared Polarimetry with Chiral Plasmonic Metasurface Integrated Graphene–Silicon Photodetector*. ACS Nano, 14(12), 16634-16642, (2020).
- 46. Fei Ding, Yiting Chen, and Sergey I. Bozhevolnyi, *Metasurface-Based Polarimeters*. Applied Sciences, **8**(4), (2018).
- Peng Chen, Bing-Yan Wei, Wei Hu, and Yan-Qing Lu, Liquid-Crystal-Mediated Geometric Phase: From Transmissive to Broadband Reflective Planar Optics. Advanced Materials, 32(27), 1903665, (2020).
- Chun-Ting Xu, Peng Chen, Yi-Heng Zhang, Xing-Yu Fan, Yan-Qing Lu, and Wei Hu, *Tunable band-pass optical vortex processor enabled by wash-out-refill chiral superstructures*. Applied Physics Letters, 118(15), 151102, (2021).



Figure 1. **a**, Schematic of the designed metasurface consisting of TiO₂ nanopillars on a fused-silica substrate. **b**, Sketch of the proposed planar metasurface consisting of three polarization beam splitters spatially arranged on a hexagonal pattern. **c**, Schematic of the $|x\rangle$ and $|y\rangle$ polarization manipulation which employs only the propagation phase. **d**, The mapping of transmission coefficient and phase shift along the *x*-axis as a function of the parameters of slow (D_x) and fast (D_y) axis of the elliptical TiO₂ nanopillars. **e**, Schematic of the $|L\rangle$ and $|R\rangle$ polarization manipulation achieved by combining propagation and geometric phases together. **f**, The conversion efficiency and phase shift as a function of D_x and D_y . **g**, Optical photograph of the ortho-hexagonal metasurface. Scale bar: 20 µm. **h**, Scanning electron microscope (SEM) images of TiO₂ metasurface using only the propagation phase (left), or one that uses both the propagation and geometrical phases (right). Scale bar: 2 µm.



Figure 2. **a**, Experimental set-up for full-Stokes polarimetry. The experimental (**b**) and simulated (**c**) intensity distributions of the metasurface and corresponding reconstructed Stokes parameters for the selected six basis polarization states. The intensity is normalized to the maximum intensity for each polarimetry measurement. Error bars in the experimental results represent one standard deviation for repeated measurements. **d**, The reconstructed Stokes parameters for experimental (red stars), simulated (green triangles) and theoretical (black points) results, plotted on the surface of the Poincaré sphere.



Figure 3. The experimental (**a**) and simulated (**b**) power distributions of the metasurface and corresponding reconstructed Stokes parameters at the selected eight random input polarization states. Error bars in experimental results represent one standard deviation for repeated measurements. **c**, The polarization states of the selected eight input polarizations N₁ to N₈ (left), and the corresponding reconstructed Stokes parameters for experimental (red stars), simulated (green triangles), and theoretical (black points) results, plotted on the surface of the Poincaré sphere (right).



Figure 4. **a**, Conceptual schematic of the PMA with metasurface pixels arranged on a regular hexagonal pattern. The inset shows the sketch of LC *q*-plate which when activated with an applied voltage transforms an input plane wave to CVB. **b**, Optical photograph of the fabricated PMA, scale bar: 250 µm. Bottom inset depicts a magnified optical photograph, scale bar: 20 µm. **c**, SEM images of the PMA, scale bar: 20 µm. Bottom inset is the magnified SEM, scale bar: 2 µm. **d**, Optical micrograph of the LC *q*-plate with q = +1/2 measured using a transmittance polarizing microscope (TPM), scale bar: 200 µm. The arrows (bottom) present the orthometric polarizer of TPM. **e**, The schematic diagram of a HOPS, where the two points on equator represent the radially (M₁) and azimuthally (M₂) polarized CVB. The two poles (M₃, M₄) have the same ellipticity but opposite topological charges and represented by $e^{i\varphi}|R\rangle$ and $e^{-i\varphi}|L\rangle$, respectively. **f**, Various CVBs labeled by M₁ to M₄ are generated using the LC *q*-plate. Left column: Theoretical light field and polarization distribution. Middle column: Experimental light field distributions generated by LC *q*-plate and

polarization distribution detected by traditional DoT polarimetry methods. Scale bar: 50 μ m. Right column: Experimental light field distributions with PMA and single shot reconstructed spatial polarization. Scale bar: 50 μ m. The length and direction of the white arrows indicates the intensity and polarization of CVBs, respectively.

Supporting Information

Full-Stokes polarimetry for visible light enabled by an all-dielectric metasurface

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Supplementary Note 1: Theoretical Stokes parameters calculation.

As mentioned in the main text, an arbitrary polarized state of light can be obtained by rotating a half/quarter waveplate (HWP/QWP) pair, and can be represented by spherical coordinates (α , β), where $\alpha/2$ and $\beta/2$ denote the shape and orientation of polarization ellipse (Fig. S1). The state of polarization can be denoted by a point on the Poincaré sphere, and the relationship of the Stokes parameters to intensity and polarization ellipse parameters can be expressed as [1],

$$S_0 = I \tag{S1}$$

$$S_1 = S_0 cos \alpha cos \beta \tag{S2}$$

$$S_2 = S_0 cos \alpha sin\beta \tag{S3}$$

$$S_3 = S_0 sin\beta \tag{S4}$$

where *I* is the total intensity of the incident wave. Thus, the theoretical Stokes parameters can be calculated based on the coordinate (α , β) of any polarization state.

Supplementary Note 2: Liquid crystal q-plate for cylindrical vector beam generation.

The cylindrical vector beams (CVB) used in this work is generated by a q-plate. The q-plate [2, 3] is a kind of geometric phase optical element, which can be realized by nematic liquid crystals (LC). It is essentially a half-wave plate with inhomogeneous optical axes in the x-y plane:

$$\alpha_1 = q\Phi + \alpha_0 \tag{S5}$$

where α_1 is the orientation angle of the LC director, $\Phi = \arctan(y/x)$ is the azimuth angle, and α_0 is assumed to be zero here. Proper voltage should be applied to the LC *q*-plate to maintain the halfwave condition for the incident light. In this case, the Jones matrix of a LC *q*-plate is formulated as

$$\mathbf{J} = \begin{bmatrix} \cos(2q\Phi) & \sin(2q\Phi) \\ \sin(2q\Phi) & -\cos(2q\Phi) \end{bmatrix}$$
(S6)

Consider a horizontal linearly polarized light as the incident light, the output light after propagating through the LC q-plate can be deduced as,

$$|\psi_{out}\rangle = \mathbf{J} \cdot \boldsymbol{e}_x = |\mathbf{R}_{+2q}\rangle / \sqrt{2} + |\mathbf{L}_{-2q}\rangle / \sqrt{2}$$
(S7)

 $|\mathbf{R}_{+2q}\rangle$ and $|\mathbf{L}_{-2q}\rangle$ is the right/left circularly polarized (RCP/LCP) optical vortex, carrying topological charges of m = +2q and l = -2q, respectively. Thus, for horizontal polarization, a q-plate with q = +1/2 can generate a cylindrical vector beam with radial polarization.

Supplementary Reference

[1] B. E. A. Saleh, M. C. Teich, Fundamentals of photonics, Wiley, (2007).

[2] L. Marrucci, C. Manzo, D. Paparo, *Optical spin-to-orbital angular momentum conversion in inhomogeneous anisotropic media*, Physical Review Letters, **96**, 163905, (2006).

[3] Chunting Xu, Peng Chen, Yiheng Zhang, Xingyu Fan, Yanqing Lu, and Wei Hu, *Tunable band*pass optical vortex processor enabled by wash-out-refill chiral superstructures, Applied Physics Letters, **118**, 151102, (2021).



Figure S1. **a**, Schematic of a Poincaré sphere. Each point on the surface represents a specific state of polarization. **b**, Polarization ellipse.



Figure S2. Sketch of the experimental set-up for detection of CVB.



Figure S3. Experimental results of the CVBs generated by LC q-plate through different incident polarizations with output polarization at 0°, 45°, 90°, 135°, LCP and RCP, respectively. Scale bar: 50 μ m.

Table 1. The structural parameters of eight phase levels of the investigated metasurface, D_x and D_y represents the slow and fast axis of the elliptic unit cell, respectively.

y x		0	π/4	$\pi/2$	$3\pi/4$	π	$5\pi/4$	$3\pi/2$	$7\pi/4$
0	D _x (nm)	195	230	310	100	125	135	150	165
	D _y (nm)	195	180	165	295	220	225	205	195
π/4	D _x (nm)	185	210	295	350	115	130	140	155
	D _y (nm)	225	210	195	185	300	275	260	245
π/2	D _x (nm)	170	195	255	320	350	125	130	145
	D _y (nm)	280	285	265	235	225	350	350	320
3π/4	D _x (nm)	295	185	235	315	155	175	190	225
	D _y (nm)	100	350	320	315	125	120	115	110
π	D _x (nm)	220	300	225	125	345	160	175	200
	D _y (nm)	125	115	350	155	345	140	135	130
5π/4	D _x (nm)	225	275	350	120	140	155	170	190
	D _y (nm)	135	130	125	175	160	155	150	145
3π/2	D _x (nm)	205	260	350	115	135	150	165	185
	D _y (nm)	150	140	130	190	175	170	160	155
$7\pi/4$	D _x (nm)	195	245	320	110	130	145	155	175
	D _y (nm)	165	155	145	225	200	190	185	175

Table 2. The Stokes parameters of six basis polarization states of theoretical, simulated and experimental results. The errors in the experimental results represent one standard deviations for repeated measurements.

Polarization states	Theoretical results			Simulated results			Experimental results		
	S ₁	S ₂	S ₃	S ₁	S ₂	S ₃	S ₁	S ₂	S ₃
I	1.00	0	0	0.99	0.07	0.05	0.99±0.02	0.09±0.02	0.04±0.01
п	-1.00	0	0	-0.99	0.01	0.01	-0.98±0.02	0.12±0.09	-0.07±0.06
ш	0	1.00	0	0.02	0.98	0.15	0.03±0.02	0.98±0.02	-0.02±0.01
IV	0	-1.00	0	-0.06	-0.98	-0.08	-0.04±0.01	-0.98±0.01	-0.22±0.08
V	0	0	1.00	-0.02	0.06	0.99	0.09±0.01	-0.07±0.01	0.98±0.01
VI	0	0	-1.00	0	0.01	-0.99	-0.07±0.01	-0.09±0.01	-0.98±0.01

Polarization states	Theoretical results			Simulated results			Experimental results			
	S ₁	S ₂	S ₃	S ₁	S ₂	S ₃	S ₁	S ₂	S ₃	
N ₁	0.50	0.87	0	0.51	0.87	0.05	0.47±0.04	0.88±0.01	0.06±0.01	
N ₂	-0.50	0.87	0	-0.48	0.85	0.06	-0.58±0.05	0.80±0.01	0.08±0.03	
N ₃	-0.50	-0.87	0	-0.53	-0.84	-0.05	-0.45±0.08	-0.84±0.07	0.11±0.10	
N ₄	0.50	-0.87	0	0.49	-0.83	-0.05	0.53±0.08	-0.82±0.07	-0.23±0.09	
N ₅	0.75	0.43	-0.50	0.74	0.46	-0.46	0.83±0.09	0.49±0.10	-0.44±0.09	
N ₆	0.75	-0.43	0.50	0.80	-0.34	0.48	0.81±0.10	-0.35±0.10	0.46±0.06	
N ₇	0.25	0.43	-0.87	0.26	0.44	-0.86	0.23±0.08	0.51±0.06	-0.86±0.09	
N ₈	0.25	-0.43	0.87	0.22	-0.35	0.89	0.22±0.10	-0.34±0.07	0.89±0.08	

Table 3. The Stokes parameters of eight random polarization states of theoretical, simulated and experimental results. The errors in the experimental results represent one standard deviations for repeated measurements.