Peer Review File

On-chip multifunctional metasurfaces with full-parametric multiplexed Jones matrix

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

This paper proposes and demonstrates a new strategy of on-chip metasurface design on the LNOI platform to realize full-parametric modulation of the Jones matrix for guided wave radiation. Through four-element supercell arrangement and combined modulation via geometric phase and detour phase, the metasurface enables the multifunctional output. The results are solid and sound. This work is interesting and organized well, which may attract widespread interests in relevant communities. I suggest it can be accepted after solving the following concerns. Below are some comments:

1. This work has generated holographic images with a maximum of eight channels. However, the comparative work cited in the supplementary materials (Adv. Funct. Mater. 34, 2312705 (2023)) achieved up to 16 channels. The authors need to clarify the innovative contributions of this work in comparison to previous work and justify the necessity of employing a full-parametric Jones matrix. For example, at least the improvement in signal-to-noise ratio should be quantified and compared.
2. Besides the mentioned above literature, many similar works have been reported in free space. What are the concrete advantages of the on-chip strategy compared with those in the free space. Important issues such as energy efficiency, device sizes, channel numbers, channel crosstalk, and image quality (e.g., PSNR or SSIM) are suggested to be presented and compared.
3. The concept of full-parameter control of Jones Matrix is proposed in the free space by composite phase control in multi-atom structures (Nat. Commun. 13, 7550 (2022)). It is intentional to introduce some new mechanisms from free space into on-chip platforms. Whether it is possible to achieve generalized geometric phase on the on-chip platform? (Phys. Rev. Lett. 126, 183902 (2021)).
4. Considering the whole device is a static one and does not involve dynamic modulation, why the authors chose the LNOI platform rather than the SOI platform with lower loss and fabrication cost. In the manuscript, Eqs. (3) and (4) indicate the relationship between the Jones matrices of the subunits and supercells. To demonstrate the accuracy of these equations, the authors should present a comparison between the theoretical results and full-wave simulation results.
5. The study utilizes a grating coupler to excite the TE mode within the waveguide. The authors should state the coupling efficiency of the grating coupler and describe the calculation method in detail.
6. Figure 1 illustrates the nanoprinting is a “Yang” shape, i.e., the letter is bright and the background is dark. However, the nanoprinting in Fig. 3 is a “Yin” shape, i.e., i.e., the letter is dark and the background is bright. I suggest the authors to change the figure 1 or further added similar “Yang” shape results in Fig. 3. If both the nanoprinting and holographic images are “Yang” shape, how about the crosstalk between the channels. More results are suggested to be given.
7. I recommend that the authors include a schematic diagram of the experimental setup to enhance clarity.
8. Some references about composite phase control in freespace are provided for authors.

(1) Li X, Chen QM, Zhang X, Zhao RZ, Xiao SM et al. Time-sequential color code division multiplexing holographic display with metasurface. Opto-Electron Adv 6, 220060 (2023). doi: 10.29026/oea.2023.220060.
(2) Y. Guo, S. Zhang, M. Pu et al., Spin-Decoupled Metasurface for Simultaneous Detection of Spin and Orbital Angular Momenta Via Momentum Transformation, Light Sci. Appl. 10, 63 (2021).
(3) Nan T, Zhao H, Guo JY et al. Generation of structured light beams with polarization variation

along arbitrary spatial trajectories using tri-layer metasurfaces. Opto-Electron Sci 3, 230052 (2024). doi: 10.29026/oes.2024.230052.
(4) F. Zhang, Y. Guo, M. Pu et al., Meta-Optics Empowered Vector Visual Cryptography for High Security and Rapid Decryption, Nat. Commun. 14, 1946 (2023).
(5) Z. L. Deng, M. Jin, X. Ye et al., Full-Color Complex-Amplitude Vectorial Holograms Based on Multi-Freedom Metasurfaces, Adv. Funct. Mater. 30, 1910610 (2020).

Reviewer #2 (Remarks to the Author):

In the manuscript entitled "On-chip multifunctional metasurfaces with full-parametric multiplexed Jones matrix", the authors demonstrated an on-chip metasurface design on lithium niobate on an insulator platform to realize modulation of Jones matrix for guided wave radiation. Through four-element supercell arrangement and the joint modulation of geometric phase and detour phase, the amplitude and phase of extracted guided waves can be manipulated to achieve four nano-printing and four holographic images under the guided waves propagating along x- and y-directions. Furthermore, by joint modulation of the detour phase, geometric phase, and propagation phase, the on-chip metasurface can eliminate the conjugated effect under forward- and backward-propagating guided wave illuminations for direction-multiplexed modulation.

On-chip metasurfaces have garnered increasing attention, spanning both academia and industry, and they represent a pivotal solution for the construction of compact photonic devices. Given that the topic of this work is a recent emerging trend, it would be of interest and significance to a broad range of readers for Nature Communications. The manuscript is mostly clear to understand and presents notable progress in developing high-capacity multiplexing and multifunctional on-chip meta-optics. Overall, I would recommend it for consideration to be published in NC. However, there are some noted issues that need to be addressed.

1. In this work, the authors proposed the design strategy of a four-element supercell arrangement based on the detour phase and geometric phase and attempted to achieve full-parametric modulation of the Jones matrix. Similar Jones matrix modulation has been reported in the free-space scheme before [Science Advances, 2021, 7(25): eabh0365]. However, I kindly suggest the authors reconsider if it is appropriate to claim as a full-parametric modulation of the Jones matrix here.

For the guided wave propagating along the x-direction, the authors demonstrated the parameter modulation of Jyy and Jyx of the Jones matrix; For along the y-direction, the author demonstrated the corresponding parameter modulation of Jxx and Jxy, (Figure 3c). That means it changes the illumination condition (direction), which is not applicable to the full parameter modulation of the Jones matrix. In my humble opinion, full-parametric modulation of the Jones matrix should keep the illumination condition unchanged rather than changing any of the illumination conditions (such as incident angle/directions) except polarization.

For instance, to compare with the previous work [Science Advances, 2021, 7(25): eabh0365], they realize the parameter modulation of three components Jyy, Jyx/Jxy, and Jxx in free-space under the same illumination condition (oblique along one orthogonal direction), and it does not realize the decoupling of Jyx and Jxy, which is reasonably the upper-limit for a single-layer metasurface.

Therefore, it should be super careful to claim as the full parameter modulation of the Jones matrix by a single-layer metasurface. Overall, I would suggest the author make corresponding explanations or remove the statement of full parameter modulation.

2. As mentioned in Comment 1, in Figure 3, for the guided wave propagating along the x-direction, the demonstration of the parameter modulation of Jxx is lacking. This is because the input TE0 mode propagating along the x-direction is equivalent to y-linearly polarized light, so there is a lack of x-linearly polarized incident light along the x-direction. In [Optics Express, 2019, 27(24): 35631-35645], polarization-selective metamaterial waveguide holograms have been demonstrated by illuminating the grating coupler with two different polarization beams (TE and TM). By referring to this work, is it possible to generate TM mode guided waves by coupling x-polarized free-space incident light into a waveguide through a grating, thus achieving x-linearly polarized incident light along the x-direction? In this case, is it possible to achieve the parametric modulation of the Jones matrix component Jxx for the same illumination condition (along the x-direction)?

3. Following Comment 2, here, the input TE0 modes propagating along the x-direction are actually equivalent to y-polarized light. I am curious that if propagating as TM guided mode, it can be regarded as which polarization state. In addition, for grating coupling in Fig. 3a, what is the polarization state of the incident light to generate the TE0 guided mode?

4. In the Introduction section, the authors mention that the “harmonic strategy” was proposed and utilized to improve the multiplexing capability. I advise the authors to add the corresponding explanation regarding the concept of “harmonic strategy.”

5. Owing to the on-chip propagation scheme, on-chip metasurfaces enjoy the unique merits of no zero-order diffraction, which makes it promising for practical high-quality display applications such as augmented reality (AR). I recommend that the authors briefly mention this advantage and the AR applications in the introduction, possibly by referring to some latest peer works in the field.

6. The simulated extraction efficiency of Tx and Ty can reach up to ~ 0.25. How about the up-extraction efficiency of the on-chip metasurface in the experiment? In addition, there is a 100 nm spacing layer of SiO2 between the LNOI waveguide and Si nanopillars. What is its function? Utilized as a buffer layer? Would it reduce the efficiency of extracting light from the waveguide?

7. There might be some minor mistakes to correct.
(i) In the Numerical Simulation section of the Methods, we agree that a perfectly matched layer (PML) can be utilized as a boundary condition along the on-chip propagation direction (y- or x-direction). However, why do the authors apply periodic boundary conditions along the z-direction (page 13, line 250)? Is that a mistake or not? The authors should clarify this or correct it.
(ii) In addition, the mention of Figures 4a-4d in the main text (page 12, lines 219-220) does not match the figure sequence label. Please carefully check the format and language to further improve the manuscript.

Reviewer #3 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Manuscript ID: NCOMMS-24-36422

Title: On-chip multifunctional metasurfaces with full-parametric multiplexed Jones matrix

Corresponding Author: Tao Li, Nanjing University

Dear Reviewers,

We thank all the Reviewers for their comments and constructive revision advices. Now, we would like to reply to all the comments and revise the manuscript accordingly. Below are the detailed replies. The revisions are highlighted with red text in the manuscript. In the end, we list out the changes of this revised version.

Best regards

Tao Li

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Responses to Reviewer's Comments (reply in blue color)

Reviewer #1:

This paper proposes and demonstrates a new strategy of on-chip metasurface design on the LNOI platform to realize full-parametric modulation of the Jones matrix for guided wave radiation. Through four-element supercell arrangement and combined modulation via geometric phase and detour phase, the metasurface enables the multifunctional output. The results are solid and sound. This work is interesting and organized well, which may attract widespread interests in relevant communities. I suggest it can be accepted after solving the following concerns.

Authors reply:

We would thank the reviewer for the positive comments and supports on our work. The comments are replied one by one in the following and the manuscript has been improved according to the suggestions from the reviewer.

1. This work has generated holographic images with a maximum of eight channels. However, the comparative work cited in the supplementary materials (Adv. Funct. Mater. 34, 2312705 (2023)) achieved up to 16 channels. The authors need to clarify the innovative contributions of this work in comparison to previous work and justify the necessity of employing a full-parametric Jones matrix. For example, at least the improvement in signal-to-noise ratio should be quantified and compared.

Authors reply:

We appreciate the reviewer for raising this key point.

In the peer work (Adv. Funct. Mater. 34, 2312705 (2023)), they utilized detour phase with two design variables δ_x and δ_y to achieve 16 modulation channels through z-plane multiplexing and harmonic strategy. The equivalent Jones matrix of the corresponding on-chip metasurface could be described as

$$J_{\pm} = \begin{bmatrix} e^{i\varphi_{\pm xx}^{z_1,z_2,z_3,z_4}} & 0 \\ 0 & e^{i\varphi_{\pm yy}^{z_1,z_2,z_3,z_4}} \end{bmatrix}. \tag{R1}$$

In detail, the four multiplexed channels at four z-planes (z_1, z_2, z_3 and z_4) were generated through one optimized phase mask while the direction-multiplexed channels (± for forward- and backward propagating guided waves) derived from the harmonic strategy. The number of independent modulation channels in their design could be regarded as 2 in essence, since there are only two design variables δ_x and δ_y. Additionally, their work could only modulate the two diagonal terms of Jones matrix without polarization modulation capability.

In our work, although we also use detour phase with two design variables δ_x and δ_y (similar to the peer work), the differences and innovative contributions could be considered as two following points.

(1) **Full-parametric Jones matrix modulation capability.** Aside from detour phase, we also employ geometric phase in a **supercell design** with 12 design variables. In such design, the induced detour phase along x and y directions breaks the symmetry of Jones matrix while

the interference effect in supercell makes Jones matrix non-unitary, which unlocks all the four elements of Jones matrix and achieves eight independent modulation channels. Hence, our work possesses advantages both in the number of independent modulation channels and in polarization modulation capability (modulation of non-diagonal terms).

(2) **Breaking the conjugated relation between Jones matrices $J_{\pm}$ for direction-multiplexing**. Different from the harmonic strategy used in peer work where the conjugated relation between $J_{\pm}$ was not really broken, our work employ joint modulation mechanisms of geometric phase, detour phase and propagation phase to break the conjugated relation between $J_{\pm}$, which allows arbitrary direction-decoupled phase modulation channels for forward- and backward-propagating illuminations.

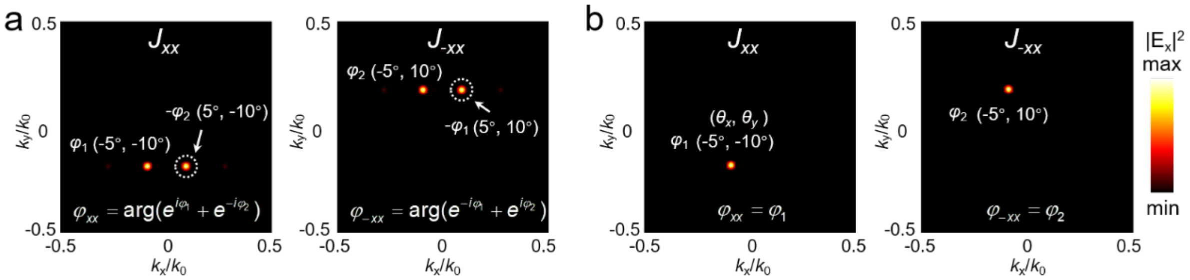


Fig. R1 Comparison of the peer work with our work in terms of direction-multiplexed modulation. Simulated far-field deflection beams based on (a) harmonic strategy and (b) our direction-multiplexed design. The dashed circles outline the undesired conjugated beams.

To distinguish our work from peer work more clearly, we performed further numerical simulations. Considering a case where two deflection beams with phase profile φ_1 and φ_2 are desired in the far-field with deflection angle (θ_x, θ_y) of (-5°, -10°) and (-5°, 10°) under +x and –x illuminations. Figure R1a shows the simulated far-field distributions using harmonic strategy. It would simultaneously cause two deflection beams, owing to the conjugated relation between φ_{xx} and φ_{-xx}. Figure R1b displays the simulated results based on our proposed direction-multiplexed design where two deflection beams are totally decoupled without undesired conjugated beams. Our work constructs two independent direction-multiplexed Jones matrices of on-chip metasurface, which has not been demonstrated by pervious works.

To evaluate the signal-to-noise ratio (SNR) of guided wave radiation, we performed full-wave simulations to generate eight focal points based on the direction-multiplexed design. Figure R2a lists the generated eight focal points distributed at different horizontal positions. Here, we utilize focusing efficiency $\gamma=P_{focus}/P_{total}$ to evaluate SNR, where P_{focus} and P_{total} denote the power of focal point and the monitor plane, respectively. The averaged SNR of eight channels is calculated to be 0.70. As comparison, we also established a referenced simulation based on harmonic strategy to generate four focal points, show in Fig. R2b. The averaged SNR of generated focal points is 0.62. Hence, our work demonstrates improvements not only in the number of modulation channels, but also in the SNR of guided wave radiation.

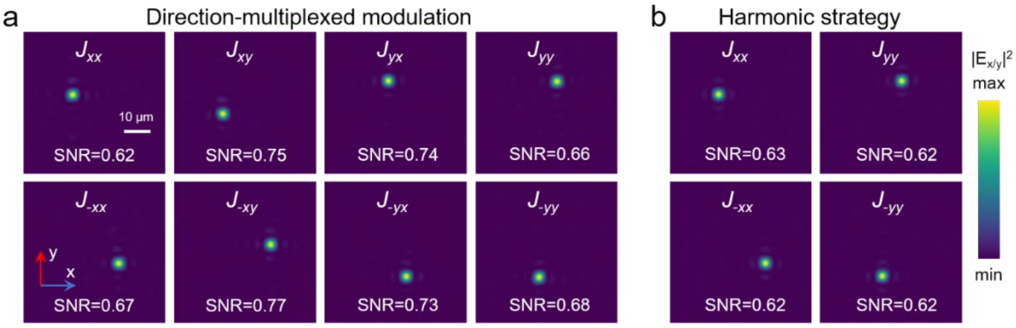


Fig. R2 Evaluation of SNR of guided wave radiations based on (a) direction-multiplexed design and (b) harmonic strategy.

In fact, our approach for Jones matrix modulation can be compatible with other multiplexing strategies to achieve more number of channels. As proof of concept, we combine our design with harmonic strategy and z-plane spatial multiplexing to demonstrate a 32-channel focal points through a single on-chip metasurface. As illustrated in Fig. R3, for +x, +y, -x and -y direction illuminations, 32 focal points are located at different spatial positions at four z-planes (z=50 μm, 75 μm, 100 μm and 125 μm), achieving up to 32 channels.

To illustrate the compatibility of the proposed design for parameter modulation of Jones matrix, we have provided additional content in Supplementary material as "***Supplementary Note 8. Combination of direction-multiplexed modulation with harmonic strategy and z-plane spatial multiplexing***".

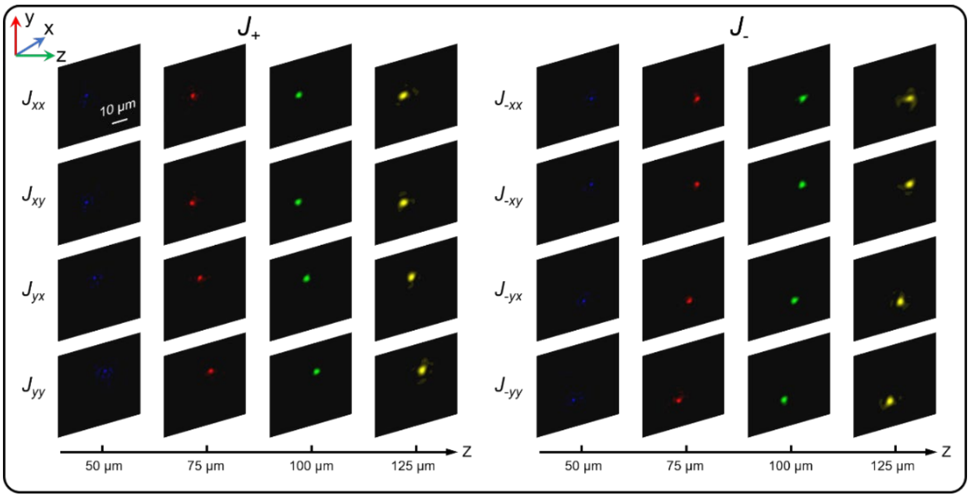


Fig. R3 Direction-multiplexed modulation combined with harmonic strategy and z-plane spatial multiplexing for generating 32-channel multiplexed focal points.

2. Besides the mentioned above literature, many similar works have been reported in free space. What are the concrete advantages of the on-chip strategy compared with those in the free space. Important issues such as energy efficiency, device sizes, channel numbers, channel crosstalk, and image quality (e.g., PSNR or SSIM) are suggested to be presented and compared.

Authors reply:

We thank the reviewer for the comment. Compared with metasurfaces in free space, we consider the proposed on-chip strategy for Jones matrix modulation has three major advantages.

First, increased number of modulation degree of freedom (DOF). For on-chip metasurface, the illumination source is in-plane guided wave and thus the modulation phase could experience phase accumulation from guided wave propagation (i.e., detour phase). Such detour phase provides additional DOF for phase modulation and number of multiplexed channels. To be specific, through incorporating detour phase with geometric phase in a supercell design in our work, full-parametric Jones matrix modulation could be accomplished in a single-layer on-chip metasurface, which was only realized in double-layer configuration for free-space metasurface (Nat. Commun. 13, 7550 (2022)).

Second, free of zero-order diffraction. Due to the on-chip propagation scheme, on-chip metasurface for guided wave radiation benefits from no zero-order diffraction. While free-space metasurfaces for holographic projection used to suffer from large zero-order diffraction and inevitable background noise. Thus, on-chip metasurfaces have shown great potentials for practical high-quality display in augment reality (AR) devices (Optica 9, 670-676 (2022), Laser Photonics Rev. 16, 2100638 (2022)).

Third, device miniaturization. On-chip metasurfaces are utilized to manipulate the optical field of guided waves and this dispenses with out-of-plane optical path required in free-space metasurfaces, contributing to the miniaturization of optical systems and integration with functional devices.

With regard to energy efficiency, the efficiency of the extracted guided waves through on-chip metasurface (estimated to be 3%~10%, the ratio of the power of the guided wave radiations to the power of input guided waves) is generally lower than the efficiency of free-space metasurface. This is because the interaction process in free space is quite different from that in on-chip scheme. In free-space metasurface, the incident light only interacts with meta-atoms once, while for on-chip metasurface, the guided wave will be scattered by multiple meta-atoms successively in weak interaction process. In fact, the efficiency of on-chip metasurface is can be adjusted by the geometric sizes of meta-atoms and further improved through introducing coupling structure (e.g., micro-ring) to increase the interaction length.

In addition, we compare the quality of images generated by on-chip metasurface and free-space metasurface through structural similarity (SSIM) with the targets, as illustrated in Fig. R4. The mean SSIM for on-chip full-parametric modulation design is 0.87, which is almost identical to that for free-space polarization-multiplexed deign (SSIM=0.90). The image quality of on-chip strategy is comparable to that of free-space design, owing to the accurate modulation capability of on-chip metasurface.

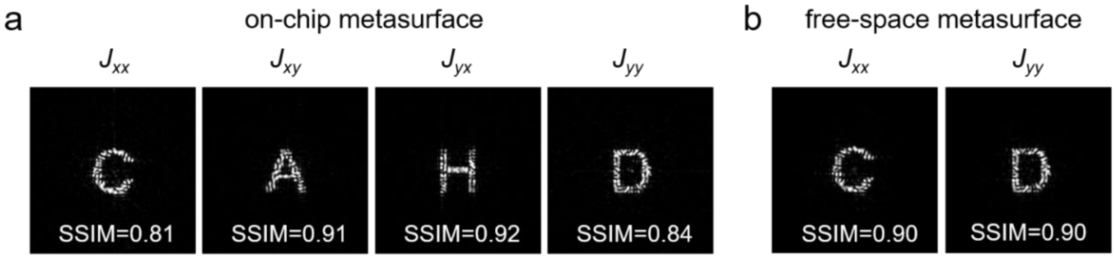


Fig. R4 Comparison of the holographic images generated by (a) on-chip metasurface and (b) free-space metasurface. SSIM: Structural Similarity.

3. The concept of full-parameter control of Jones Matrix is proposed in the free space by composite phase control in multi-atom structures (Nat. Commun. 13, 7550 (2022)). It is intentional to introduce some new mechanisms from free space into on-chip platforms. Whether it is possible to achieve generalized geometric phase on the on-chip platform? (Phys. Rev. Lett. 126, 183902 (2021)).

Authors reply:

We appreciate the reviewer for this valuable suggestion. It is indeed that the new mechanisms in free-space metasurface could be introduced into on-chip platforms.

According to the reviewer's advice, we expand the generalized geometric phase in free space (referred to Phys. Rev. Lett. 126, 183902 (2021)) into on-chip platform through numerical simulations. Without loss of generality, we choose a C3 symmetric three-pointed star nanostructure with feature size of r_1=300 nm, r_2=40 nm for on-chip modulation, as plotted in Fig. R5a. According to the full-parametric modulation design, the Jones matrix of C3 structure could be written as

$$J=\begin{bmatrix} J_{xx} & J_{yx} \\ J_{xy} & J_{yy} \end{bmatrix}=\sum_{k=1}^{4}\begin{bmatrix} e^{i2\pi\cdot(\delta_{yk}/\mathrm{P_y})} & 0 \\ 0 & e^{i2\pi\cdot(\delta_{xk}/\mathrm{P_x})} \end{bmatrix} R(3\theta_k)\begin{bmatrix} a_{x0}\cdot e^{i\varphi_{x0}} & 0 \\ 0 & a_{y0}\cdot e^{i\varphi_{y0}} \end{bmatrix} R(-3\theta_k). \quad \text{(R2)}$$

For simplicity, we consider the phase modulation of four elements to acquire four independent deflection beams in the far-field. Figure R5b exhibits the generated four deflection beams with deflection angles (θ_x, θ_y) of (-5°, -10°), (5°, -10°), (-10°, -5°), (-10°, 5°), corresponding to the four independent parameters J_{xx}, J_{xy}, J_{yx}, J_{yy}. Therefore, the simulated results validate the feasibility of applying generalized geometric phase from free space onto on-chip platform.

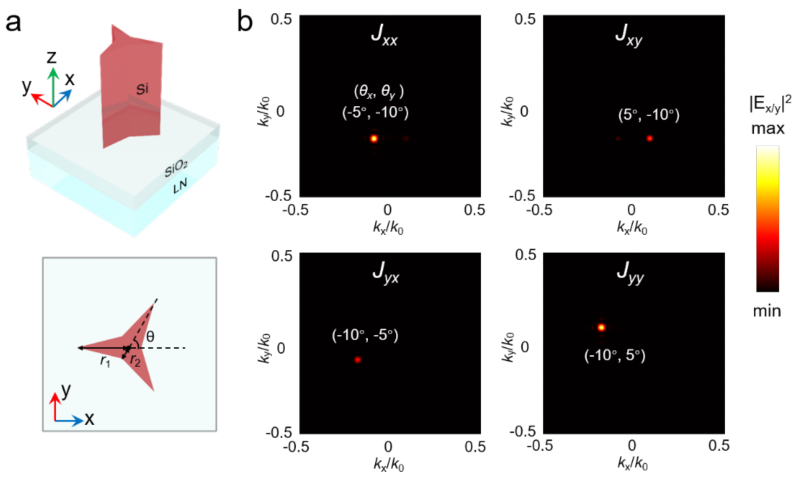


Fig. R5 Demonstration of on-chip generalized geometric phase. (a) Schematic of the C3 symmetric three-pointed star nanostructure. (b) The simulated far-field deflection beams with deflection angles (θ_x, θ_y) under +x and +y direction guided wave illuminations.

4. Considering the whole device is a static one and does not involve dynamic modulation, why the authors chose the LNOI platform rather than the SOI platform with lower loss and fabrication cost. In the manuscript, Eqs. (3) and (4) indicate the relationship between the Jones matrices of the subunits and supercells. To demonstrate the accuracy of these equations, the authors should present a comparison between the theoretical results and full-wave simulation results.

Authors reply:

Thank you for this valuable comment. As for the selection of material, one of our major motivations is dynamic control of on-chip guided wave radiation so as to promote more practical applications, in view of most existing metasurfaces are static and lack of tunability. Owing to the excellent electro-optic (EO) effect, LNOI has emerged as an EO integrated photonics platform with ultra-high modulation speed and low power consumption, which provides a promising scheme for dynamic control of on-chip guided wave radiation (which has been demonstrated in our recent work in Adv. Photonics 6, 016005 (2024)). However, it should be mentioned that the fabrication process of integrating LN devices and metasurfaces is not entirely mature and usually undergoes a long processing cycle. Hence, in this work, we established our on-chip metasurface by emphasizing the Jones matrix modulation capability to lay a foundation for fully dynamic modulation in LNOI platform.

To demonstrate the accuracy of Eqs. (3) and (4) in the main text, we have performed full-wave simulations to compare with the theoretical results after genetic algorithm optimization for full-parametric and direction-multiplexed modulation, as presented in Fig. R6 and Fig. R7. It is obvious that the simulation results are in good agreement with the theoretical ones, which verifies the accuracy of Eqs. (3) and (4).

In the revised Supplementary material, we have added the theoretical results through optimization and the relevant simulated results in Supplementary Note 4.

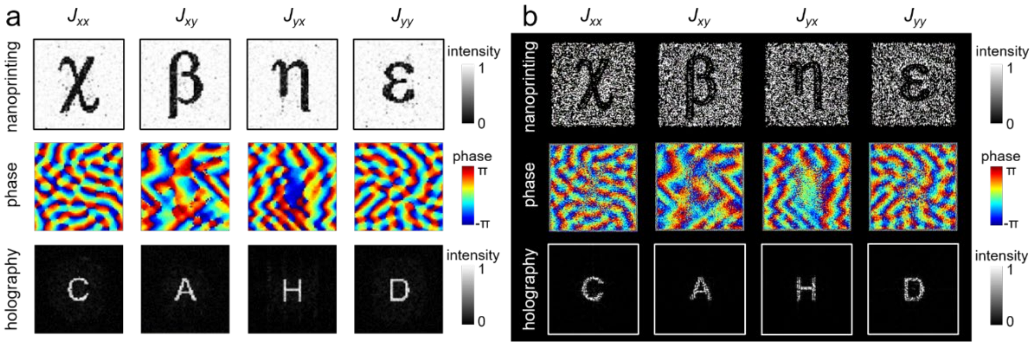


Fig. R6 Comparison between (a) the theoretical and (b) the full-wave simulation results for full-parametric modulation of Jones matrix.

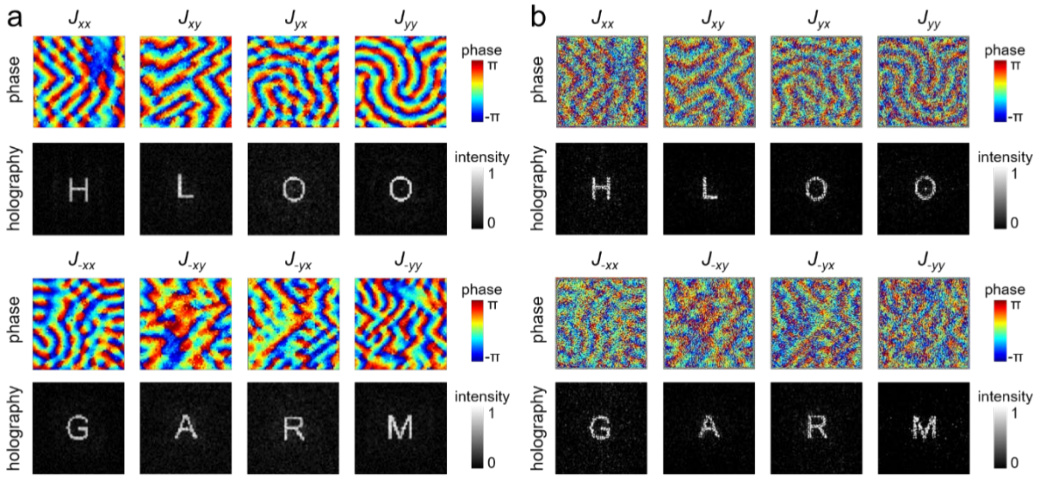


Fig. R7 Comparison between (a) the theoretical and (b) the full-wave simulation results for direction-multiplexed modulation of Jones matrix.

5. The study utilizes a grating coupler to excite the TE mode within the waveguide. The authors should state the coupling efficiency of the grating coupler and describe the calculation method in detail.

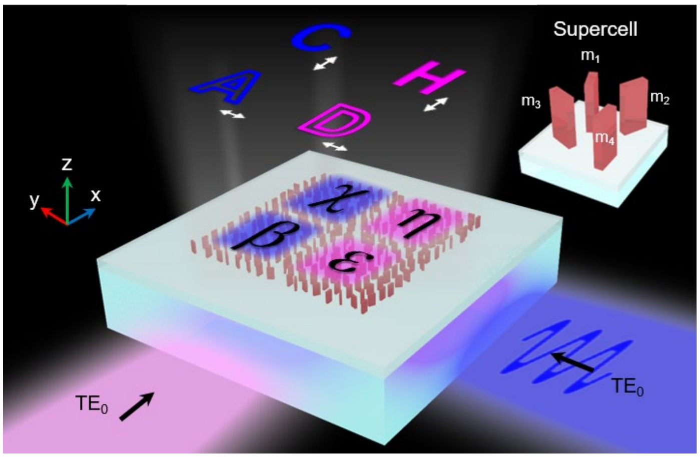
Authors reply:

Thank you for raising this point. The coupling efficiency of the grating coupler is measured to be -8 dB in experiments. To characterize the coupling efficiency, two referenced grating couplers with distance of 600 μm were fabricated on top of LN waveguide. Through focusing the illumination beam onto one grating coupler (input grating), the guided mode can be excited in LN waveguide. While the other grating coupler (output grating) are utilized to decouple the guided mode into free-space light. By measuring the input power P_{in} onto the input grating and the power P_{out} decoupled by output grating, the insertion loss (IL) could be calculated by $IL=10lg(P_{out}/P_{in})$ to be -16 dB. Since the propagation loss within the LN waveguide is of a magnitude low enough to be negligible, the coupling efficiency of each grating coupler η_g could be approximately estimated to be $\eta_g=IL/2$, namely -8 dB.

6. Figure 1 illustrates the nanoprinting is a “Yang” shape, i.e., the letter is bright and the background is dark. However, the nanoprinting in Fig. 3 is a “Yin” shape, i.e., i.e., the letter is dark and the background is bright. I suggest the authors to change the figure 1 or further added similar “Yang” shape results in Fig. 3. If both the nanoprinting and holographic images are “Yang” shape, how about the crosstalk between the channels. More results are suggested to be given.

Authors reply:

Thank the reviewer for their careful evaluation of our work. We have followed the reviewer’s suggestion to correct the nanoprinting images in Fig.1 as “Yin” shapes, which are in accordance with the experimental ones in Fig.3.



Revised Fig. 1

In the case of “Yang” shape design, most of the “dark” pixels could not provide any phase profile for holographic images due to the amplitude of zero, only leaving the “bright” pixels (i.e., effective pixels) for phase modulation. To investigate the influence of number of effective pixels (EP) on the quality of holographic images, we theoretically analyze three “Yang” shape images with different EP (with total pixels of 60×60) through Gerchberg–Saxton algorithm. As presented in Fig. R8, the quality of the generated holographic image, which is evaluated by correlated coefficient (cc) with the target, improves as the number of EP increases. Therefore, for a “Yang” shape design, sufficient number of EP should be guaranteed to generate a high-quality holographic image.

As a supplementary, we have devised full-parametric modulation in the form of nano-printing and holographic images with both “Yang” shapes, see simulation results displayed in Fig. R9. Here, the shapes of four nano-printing images are designed to be the four suits of playing cards with averaged EP of ~1250 (within total pixels of 60×60). It is observed that there is no apparent crosstalk between all the eight channels, almost identical to the “Yin” shape design, which demonstrates the feasibility of “Yang” shape design.

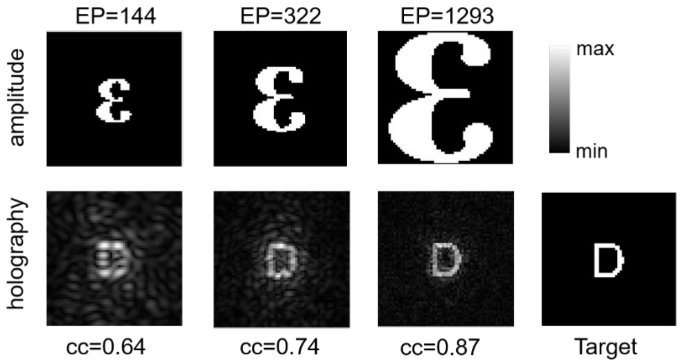


Fig. R8 Theoretical analysis of the quality of holographic images with different number of EP. EP: effective pixels. cc: correlated coefficient.

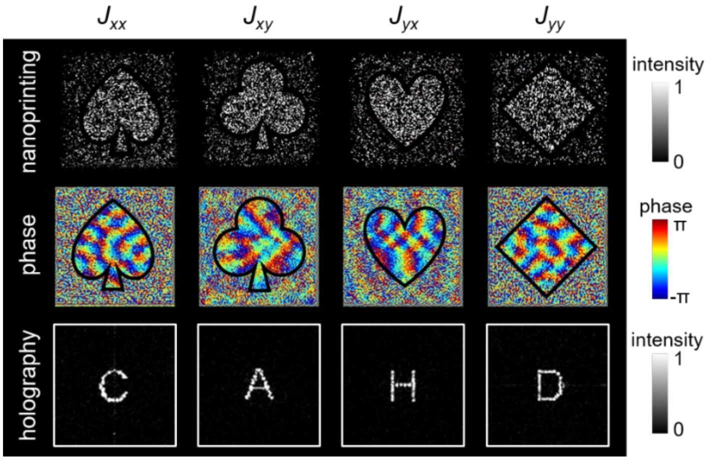


Fig. R9 The simulated results of “Yang” shape design with the nano-printing images, phase distributions and holographic images. The black lines outline the region of EP.

7. I recommend that the authors include a schematic diagram of the experimental setup to

enhance clarity.

Authors reply:

We thank the reviewer's valuable suggestion. A schematic illustration of the experimental setup and the corresponding description have been added in Supplementary Note 5, as shown below.

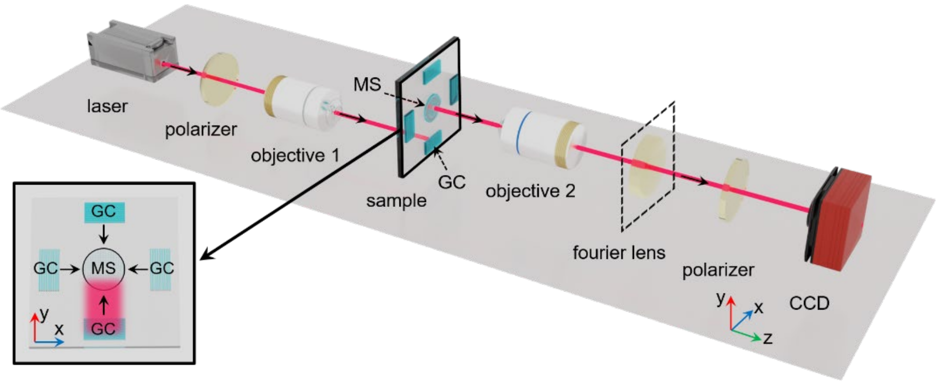


Fig. S7 Illustration of measurement setup in experiments. The inset shows the diagram of the sample and the guided wave propagating along y direction excited through one GC. GC: grating coupler. MS: metasurface. CCD: charge coupled device.

8. Some references about composite phase control in freespace are provided for authors.

(1) Li X, Chen QM, Zhang X, Zhao RZ, Xiao SM et al. Time-sequential color code division multiplexing holographic display with metasurface. Opto-Electron Adv 6, 220060 (2023). doi: 10.29026/oea.2023.220060.

(2) Y. Guo, S. Zhang, M. Pu et al., Spin-Decoupled Metasurface for Simultaneous Detection of Spin and Orbital Angular Momenta Via Momentum Transformation, Light Sci. Appl. 10, 63 (2021).

(3) Nan T, Zhao H, Guo JY et al. Generation of structured light beams with polarization variation along arbitrary spatial trajectories using tri-layer metasurfaces. Opto-Electron Sci 3, 230052 (2024). doi: 10.29026/oes.2024.230052.

(4) F. Zhang, Y. Guo, M. Pu et al., Meta-Optics Empowered Vector Visual Cryptography for High Security and Rapid Decryption, Nat. Commun. 14, 1946 (2023).

(5) Z. L. Deng, M. Jin, X. Ye et al., Full-Color Complex-Amplitude Vectorial Holograms Based

on Multi-Freedom Metasurfaces, Adv. Funct. Mater. 30, 1910610 (2020).

Authors reply:

We appreciate the reviewer for this recommendation. We have added the related references in the revised manuscript:

"*16. Guo, Y. et al. Spin-decoupled metasurface for simultaneous detection of spin and orbital angular momenta via momentum transformation. Light Sci. Appl.* ***10****, 63 (2021).*

17. Zhang, F. et al. Meta-optics empowered vector visual cryptography for high security and rapid decryption. Nat. Commun. ***14****, 1946 (2023).*

18. Li, X. et al. Time-sequential color code division multiplexing holographic display with metasurface. Opto-Electronic Advances. ***6****, 220060-220060 (2023).*

19. Nan, T., Zhao, H., Guo, J., Wang, X., Tian, H. & Zhang, Y. Generation of structured light beams with polarization variation along arbitrary spatial trajectories using tri-layer metasurfaces. Opto-Electronic Science ***3****, 230052-230052 (2024).*

59. Deng, ZL. et al. Full-Color Complex-Amplitude Vectorial Holograms Based on Multi-Freedom Metasurfaces. Adv. Funct. Mater. ***30****, 1910610 (2020).*"

Reviewer #2:

In the manuscript entitled "On-chip multifunctional metasurfaces with full-parametric multiplexed Jones matrix", the authors demonstrated an on-chip metasurface design on lithium niobate on an insulator platform to realize modulation of Jones matrix for guided wave radiation. Through four-element supercell arrangement and the joint modulation of geometric phase and detour phase, the amplitude and phase of extracted guided waves can be manipulated to achieve four nano-printing and four holographic images under the guided waves propagating along x- and y-directions. Furthermore, by joint modulation of the detour phase, geometric phase, and propagation phase, the on-chip metasurface can eliminate the conjugated effect under forward- and backward-propagating guided wave illuminations for direction-multiplexed modulation.

On-chip metasurfaces have garnered increasing attention, spanning both academia and industry, and they represent a pivotal solution for the construction of compact photonic devices. Given that the topic of this work is a recent emerging trend, it would be of interest and significance to a broad range of readers for Nature Communications. The manuscript is mostly clear to understand and presents notable progress in developing high-capacity multiplexing and multifunctional on-chip meta-optics. Overall, I would recommend it for consideration to be published in NC. However, there are some noted issues that need to be addressed.

Authors reply:

We appreciate the reviewer for concise summary of our work and the positive comments. A point-by-point response to the reviewer's comments has been prepared and our manuscript has been revised accordingly.

1. In this work, the authors proposed the design strategy of a four-element supercell arrangement based on the detour phase and geometric phase and attempted to achieve full-parametric modulation of the Jones matrix. Similar Jones matrix modulation has been reported in the free-space scheme before [Science Advances, 2021, 7(25): eabh0365]. However, I kindly suggest the authors reconsider if it is appropriate to claim as a full-parametric modulation of the Jones matrix here.

For the guided wave propagating along the x-direction, the authors demonstrated the parameter modulation of J_{yy} and J_{yx} of the Jones matrix; For along the y-direction, the author demonstrated the corresponding parameter modulation of J_{xx} and J_{xy}, (Figure 3c). That means it changes the illumination condition (direction), which is not applicable to the full parameter modulation of the Jones matrix. In my humble opinion, full-parametric modulation of the Jones matrix should keep the illumination condition unchanged rather than changing any of the illumination conditions (such as incident angle/directions) except polarization.

For instance, to compare with the previous work [Science Advances, 2021, 7(25): eabh0365], they realize the parameter modulation of three components J_{yy}, J_{yx}/J_{xy}, and J_{xx} in free-space under the same illumination condition (oblique along one orthogonal direction), and it does not realize the decoupling of J_{yx} and J_{xy}, which is reasonably the upper-limit for a single-layer metasurface. Therefore, it should be super careful to claim as the full parameter modulation of the Jones matrix by a single-layer metasurface. Overall, I would suggest the author make corresponding explanations or remove the statement of full parameter modulation.

Authors reply:

We would thank the reviewer for raising this question.

Strictly speaking, it is true that full-parametric modulation of the Jones matrix should keep the illumination condition unchanged except polarization. However, it is a different case in on-chip scheme and there are two following points need to be taken into consideration.

First, as stated in the previous work (Science Advances, 2021, 7(25): eabh0365), the upper limit number of controllable parameters in Jones matrix for a single-layer metasurface in free space is six, due to the constraints on symmetry of Jones matrix. It means that full-parametric modulation of Jones matrix requires the introduction of new physical mechanisms and extra modulation space. While on-chip scheme, which involves guided wave illumination, provides a practical platform to take advantage of detour phase along two orthogonal directions as additional modulation parameters. To this end, we adopt on-chip scheme and utilize the detour phase induced in guided wave illuminations propagating along x and y directions to break the limitations in free-space metasurface, so as to makes full-parametric modulation achievable through a single-layer on-chip metasurface.

Second, under such guided wave illumination condition, the physical framework of on-chip scheme is different from that of free-space metasurface, both in terms of the illumination mode and the definition of polarization states. For guided wave illumination associated with phase accumulation during propagation, detour phase would inherently be introduced in the successive interaction process between guided wave and metasurface, distinguished from that in free-space metasuface. Meanwhile, it might not be appropriate to regard TE and TM modes in on-chip scheme as x- and y-linearly polarized light in free space, since the in-plane electric filed components of TE and TM modes are not of the same order of magnitude. That is to say, switching TE mode to TM mode under the same guided wave illumination direction is not actually equivalent to changing polarization states in free-space illumination. Also, it is difficult to synthesize arbitrary exact polarization state through linear superposition of TE and TM modes like two polarization bases in free-space case. On the contrary, guided waves propagating along two orthogonal directions could be considered as two orthogonal states and serve as two polarization bases (see the pioneering work in Light Sci. Appl. 4, e330 (2015)). The feasibility of such definition has also been validated in recent works of on-chip metasurfaces (Nanophotonics 11, 1923-1930 (2021), Adv. Photonics 6, 016005 (2024)).

Frankly speaking, the definition of Jones matrix of on-chip metasurface is not strictly identical to that of free-space metasurface since the on-chip scheme associated with guided wave illumination brings new modulation mechanism and addition modulation DOF. Thus, we humbly believe that the defined Jones matrix in our work for guided wave illumination might be more suitable and proper to illustrate the optical response and multiplexing capability of guided wave driven metasurface.

To avoid misunderstanding, we have stated the definition of two bases of Jones matrix for on-chip metasurface, and emphasized the difference of on-chip scheme with guided wave illumination in the revised manuscript in page 6, lines 99-105 "*It should be noted that the definition of Jones matrix for on-chip metasurface is different from that for free-space metasurface. For on-chip scheme, guided wave illuminations along x and y directions could inherently introduce detour phase as two additional modulation DOFs, which beaks the limitation in modulation of Jones matrix. To this end, we define the input* TE_0 *modes propagating along y and x directions, which are equivalent to a pair of orthogonal polarization states, as two bases of Jones matrix for on-chip metasurface.*"

2. As mentioned in Comment 1, in Figure 3, for the guided wave propagating along the x-direction, the demonstration of the parameter modulation of J_{xx} is lacking. This is because the input TE_0 mode propagating along the x-direction is equivalent to y-linearly polarized light, so there is a lack of x-linearly polarized incident light along the x-direction. In [Optics Express, 2019, 27(24): 35631-35645], polarization-selective metamaterial waveguide holograms have been demonstrated by illuminating the grating coupler with two different polarization beams (TE and TM). By referring to this work, is it possible to generate TM mode guided waves by coupling x-polarized free-space incident light into a waveguide through a grating, thus achieving x-linearly polarized incident light along the x-direction? In this case, is it possible to achieve the parametric modulation of the Jones matrix component J_{xx} for the same illumination condition (along the x-direction)?

Authors reply:

Thank you for raising this critical question. With reference to the work (Optics Express, 2019, 27(24): 35631-35645), it is practical to generate TM$_0$ mode guided waves via x-polarized free-space incident light through grating coupler and achieve parametric modulation of J_{xx}. According to the Eq. (3) in the main text, we can derive the equivalent Jones matrix J^{TM} for TM mode illuminations along x and y directions as

$$\begin{aligned} J^{TM} &= \begin{bmatrix} J^{TM}_{xx} & J^{TM}_{yx} \\ J^{TM}_{xy} & J^{TM}_{yy} \end{bmatrix} = \sum_{k=1}^{4} \begin{bmatrix} e^{i2\pi\cdot(\delta_{xk}/\mathrm{P_x})} & 0 \\ 0 & e^{i2\pi\cdot(\delta_{yk}/\mathrm{P_y})} \end{bmatrix} R(\theta_k) \begin{bmatrix} a^{TM}_{x0}\cdot e^{i\varphi^{TM}_{x0}} & 0 \\ 0 & a^{TM}_{y0}\cdot e^{i\varphi^{TM}_{y0}} \end{bmatrix} R(-\theta_k) \\ &= \sum_{k=1}^{4} \begin{bmatrix} \cos^2\theta_k\cdot a^{TM}_{x0}\cdot e^{i(\varphi^{TM}_{x0}+2\pi\cdot\delta_{xk}/\mathrm{P_x})} + \sin^2\theta_k\cdot a^{TM}_{y0}\cdot e^{i(\varphi^{TM}_{y0}+2\pi\cdot\delta_{xk}/\mathrm{P_x})} & \sin\theta_k\cdot\cos\theta_k\cdot(a^{TM}_{x0}\cdot e^{i\varphi^{TM}_{x0}} - a^{TM}_{y0}\cdot e^{i\varphi^{TM}_{y0}})\cdot e^{i2\pi\cdot(\delta_{yk}/\mathrm{P_y})} \\ \sin\theta_k\cdot\cos\theta_k\cdot(a^{TM}_{x0}\cdot e^{i\varphi^{TM}_{x0}} - a^{TM}_{y0}\cdot e^{i\varphi^{TM}_{y0}})\cdot e^{i2\pi\cdot(\delta_{xk}/\mathrm{P_x})} & \sin^2\theta_k\cdot a^{TM}_{x0}\cdot e^{i(\varphi^{TM}_{x0}+2\pi\cdot\delta_{yk}/\mathrm{P_y})} + \cos^2\theta_k\cdot a^{TM}_{y0}\cdot e^{i(\varphi^{TM}_{y0}+2\pi\cdot\delta_{yk}/\mathrm{P_y})} \end{bmatrix} \end{aligned} \qquad \text{(R3)}$$

It should be mentioned that due to the detour phase (δ_x and δ_y) induced by TM mode propagating along two orthogonal directions, the Eq. (R3) under TM mode illuminations could also realize full-parameter modulation of Jones matrix in principle, similar to TE mode illuminations. In reference to the Eqs. (3) and (R3), the combined Jones matrix for the same illumination condition (along the x-direction) of TM$_0$ and TE$_0$ modes could be written as follows.

$$\begin{aligned} J &= \begin{bmatrix} J^{TM}_{xx} & J^{TE}_{yx} \\ J^{TM}_{xy} & J^{TE}_{yy} \end{bmatrix} \\ &= \sum_{k=1}^{4} \begin{bmatrix} \cos^2\theta_k\cdot a^{TM}_{x0}\cdot e^{i(\phi^{TM}_{x0}+2\pi\cdot\delta_{xk}/\mathrm{P_x})} + \sin^2\theta_k\cdot a^{TM}_{y0}\cdot e^{i(\phi^{TM}_{y0}+2\pi\cdot\delta_{xk}/\mathrm{P_x})} & \sin\theta_k\cdot\cos\theta_k\cdot(a_{x0}\cdot e^{i\phi_{x0}} - a_{y0}\cdot e^{i\phi_{y0}})\cdot e^{i2\pi\cdot(\delta_{xk}/\mathrm{P_x})} \\ \sin\theta_k\cdot\cos\theta_k\cdot(a^{TM}_{x0}\cdot e^{i\phi^{TM}_{x0}} - a^{TM}_{y0}\cdot e^{i\phi^{TM}_{y0}})\cdot e^{i2\pi\cdot(\delta_{xk}/\mathrm{P_x})} & \sin^2\theta_k\cdot a_{x0}\cdot e^{i(\phi_{x0}+2\pi\cdot\delta_{xk}/\mathrm{P_x})} + \cos^2\theta_k\cdot a_{y0}\cdot e^{i(\phi_{y0}+2\pi\cdot\delta_{xk}/\mathrm{P_x})} \end{bmatrix} \end{aligned} \qquad \text{(R4)}$$

According to Eq. (R4), we conduct numerical simulations of phase modulation of J^{TM}_{xx}, J^{TM}_{xy}, J^{TE}_{yx} and J^{TE}_{yy} for demonstration. Figure R10 exhibits the generated four holographic images under TM$_0$ and TE$_0$ modes illuminations along x direction. It is observed that J^{TM}_{xx} is independent on the other three parameters and the parametric modulation of J^{TM}_{xx} could thus be validated. However, under such circumstance, both TM and TE modes would experience the same detour phase, the DOF of detour phase (especially for δ_y) could not be fully utilized, which leads to $J_{xy}^{TM} = J_{yx}^{TE}$ and two identical holographic images of letter "A" (a slight shift in frequency spectrum due to the different propagation constants of TM_0 and TE_0 modes). Hence, the symmetry of Jones matrix could not be broken, which results in only three controllable parameters J_{xx}^{TM}, J_{yx}^{TE} and J_{yy}^{TE}. This is the reason why we introduce guided wave illuminations along two orthogonal directions to realize full-parametric modulation rather than guided wave illuminations along only one direction with TE and TM modes.

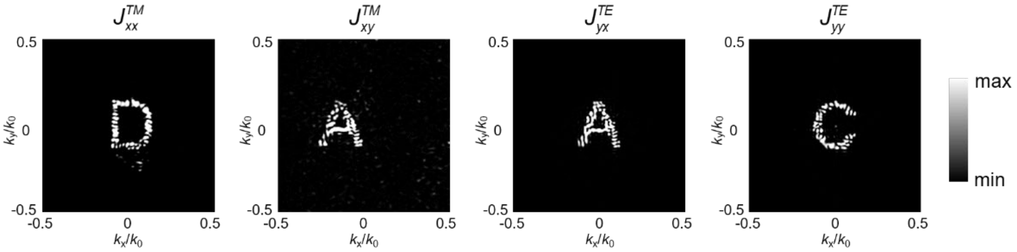


Fig. R10 The simulated holographic images under TM_0 and TE_0 mode illuminations, corresponding to the parametric modulation of J_{xx}^{TM}, J_{xy}^{TM}, J_{yx}^{TE} and J_{yy}^{TE}.

3. Following Comment 2, here, the input TE_0 modes propagating along the x-direction are actually equivalent to y-polarized light. I am curious that if propagating as TM guided mode, it can be regarded as which polarization state. In addition, for grating coupling in Fig. 3a, what is the polarization state of the incident light to generate the TE_0 guided mode?

Authors reply:

Thank you for raising this question. Since the TM guide wave along x-direction has E_x polarization component, it could be roughly viewed as a quasi in-plane x-linearly polarized light. Nevertheless, TM guided mode is not appropriate to be combined with TE guided mode to form a set of polarization bases, compared with x- and y-linearly polarized states in free space, since the in-plane polarization components of TM and TE modes are not of the same order of magnitude.

In regard to the polarization state of incident light in experiments, we utilized y-linearly incident light to excite TE_0 guided mode along x-direction while x-linearly incident light to excite TE_0 guided mode along y-direction to make sure the maximum modal overlapping between free-space light and TE_0 guided modes.

4. In the Introduction section, the authors mention that the “harmonic strategy” was proposed and utilized to improve the multiplexing capability. I advise the authors to add the corresponding explanation regarding the concept of “harmonic strategy.”

Authors reply:

We thank the reviewer’s kind advice. As far as we know, in multi-dimensional design of metasurface, harmonic strategy generally refers to the design strategy in which a complex superposition of multiple phase profiles is mapped onto a single meta-atom for multi-channel multiplexing (Adv. Mater. 2020, 32, 1805912 and Laser Photonics Rev. 2022, 16, 2200351).

According to the reviewer’s suggestion, we have added the corresponding explanation in Introduction section: In page 3, line 55 “*To address this issue, the combination of detour phase and geometric phase*[51,52]*, harmonic strategy (complex superposition of multiple phase profiles)*[48,53] *and other mechanisms*[54] *were proposed and attempted to improve the multiplexing capability.*”

5. Owing to the on-chip propagation scheme, on-chip metasurfaces enjoy the unique merits of no zero-order diffraction, which makes it promising for practical high-quality display applications such as augmented reality (AR). I recommend that the authors briefly mention this advantage and the AR applications in the introduction, possibly by referring to some latest peer works in the field.

Authors reply:

Thank you for the kind reminder of this point.

The related statement of the advantage of on-chip metasurface in no zero-order diffraction and its application in AR applications have been added in the Introduction, along with the recent peer works. In page 3, lines 46-48 “*Owing to the on-chip optical propagation scheme, such guided wave driven metasurfaces are featured with no zero-order diffraction, which is promising for high-quality images in augment reality (AR) projection and optical displays*[42-44].”

"*42. Li, Z., Shi, Y., Dai, C. & Li, Z. On-Chip-Driven Multicolor 3D Meta-Display. Laser Photonics Rev. 2301240 (2024).*

*43. Shi, Y., Dai, C., Wan, S., Wang, Z., Li, X. & Li, Z. Electrical-Driven Dynamic Augmented Reality by On-Chip Vectorial Meta-Display. ACS Photonics **11**, 2123-2130 (2024).*

*44. Wan, S. et al. Multidimensional Encryption by Chip-Integrated Metasurfaces. ACS Nano **18**, 18693-18700 (2024).*"

6. The simulated extraction efficiency of T_x and T_y can reach up to ~ 0.25. How about the up-extraction efficiency of the on-chip metasurface in the experiment? In addition, there is a 100 nm spacing layer of SiO2 between the LNOI waveguide and Si nanopillars. What is its function? Utilized as a buffer layer? Would it reduce the efficiency of extracting light from the waveguide?

Authors reply:

We thank the reviewer for raising this question. As the simulated parameter sweep results shown in Fig. S1, the maximum extraction efficiency T_x and T_y of a single meta-atom is 0.25 while the averaged extraction efficiency of single meta-atoms with L and W ranging from 50 nm to 400 nm is about 0.02. Note that such extraction efficiency is calculated under the mode source with small size in the parameter sweep model. In fact, the simulated extraction efficiency of the total on-chip metasurface is about 8.3%. While in experiments, the extraction efficiency of the on-chip metasurface, which is defined as the ratio of the power of the extracted radiation to the power of input guided wave, has been measured to be ~6.5% in average.

In this work, a 100 nm spacing layer of SiO_2 is placed between LN waveguide and silicon metasurface to ensure weak interaction process. It is intended to balance the efficiency of extraction light during guided wave radiation.

In the revised manuscript, the extraction efficiency of the on-chip metasurface in experiments and the relevant description of the function of SiO_2 spacing layer has been added in page 10, lines 194-196 as "Here, the extraction efficiency of the on-chip metasurface, which is defined as the ratio of the power of the generated holographic images to the power of input guided waves, is experimentally measured to be ~6.5%."

and in page 5, lines 96-97 as "*A 100 nm spacing layer of silicon dioxide is placed between LN* *waveguide and silicon metasurface to ensure weak interaction process.*".

7. There might be some minor mistakes to correct.

(i) In the Numerical Simulation section of the Methods, we agree that a perfectly matched layer (PML) can be utilized as a boundary condition along the on-chip propagation direction (y- or x-direction). However, why do the authors apply periodic boundary conditions along the z-direction (page 13, line 250)? Is that a mistake or not? The authors should clarify this or correct it.

(ii) In addition, the mention of Figures 4a-4d in the main text (page 12, lines 219-220) does not match the figure sequence label. Please carefully check the format and language to further improve the manuscript.

Authors reply:

Thank the reviewer for pointing out these two mistakes.

(i) We are sorry for this mistake. Actually, perfectly matched layer (PML) is applied along the z-direction in our simulations. In the revised manuscript, we have corrected this error in the Methods section. "*Periodic boundary condition was applied along x direction (y direction) while perfectly matched layer (PML) conditions were utilized as boundary conditions along y and z directions (x and z directions).*"

(ii) The description of Figures 4a-4d has been corrected. The corresponding format and language have also been checked and polished in the revised manuscript.

Reviewer #3:

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Authors reply:

We thank the reviewer for his/her co-review of our manuscript.

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List of major changes (marked as red color in the main text)

1. We have stated the definition of two bases of Jones matrix for on-chip metasurface, and emphasized the difference of on-chip scheme with guided wave illumination in the principle section.
2. The description of AR applications of on-chip metasurface and corresponding references have been added in the revised manuscript.
3. We have corrected the nanoprinting images in Fig.1 as “Yin” shapes in the revised manuscript.
4. The statement of experimental efficiency of the device has been provided in the revised manuscript.
5. The theoretical results through genetic algorithm and full-wave simulation results for full-parametric modulation and direction-multiplexed modulation have been appended in Supplementary Note 4.
6. The schematic of experimental setup and the related description have been provided in Supplementary Note 5.
7. We have added the numerical simulations on combination of direction-multiplexed modulation with harmonic strategy and z-plane spatial multiplexing in Supplementary Note 8.

REVIEWERS' COMMENTS

Reviewer #1 (Remarks to the Author):

The authors have made a careful revision. The revised version has solved the reviewers' concerns and the manuscript quality has been greatly improved, which statify the high standard of NC. I suggest it can be accepted now.

Reviewer #2 (Remarks to the Author):

The authors have mostly addressed the noted issues to the best of their ability. At this point, I think it is ready to be accepted for publication in Nature Communications.

Reviewer #3 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.