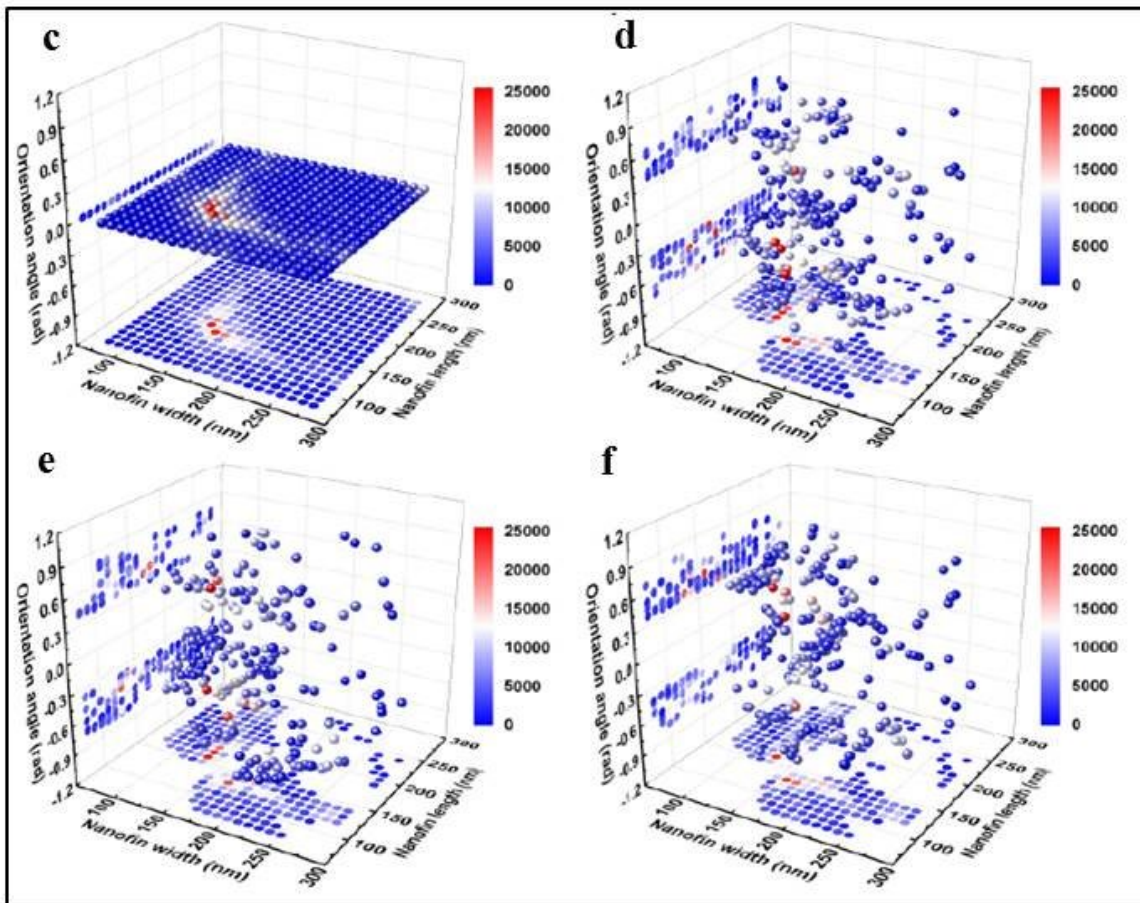
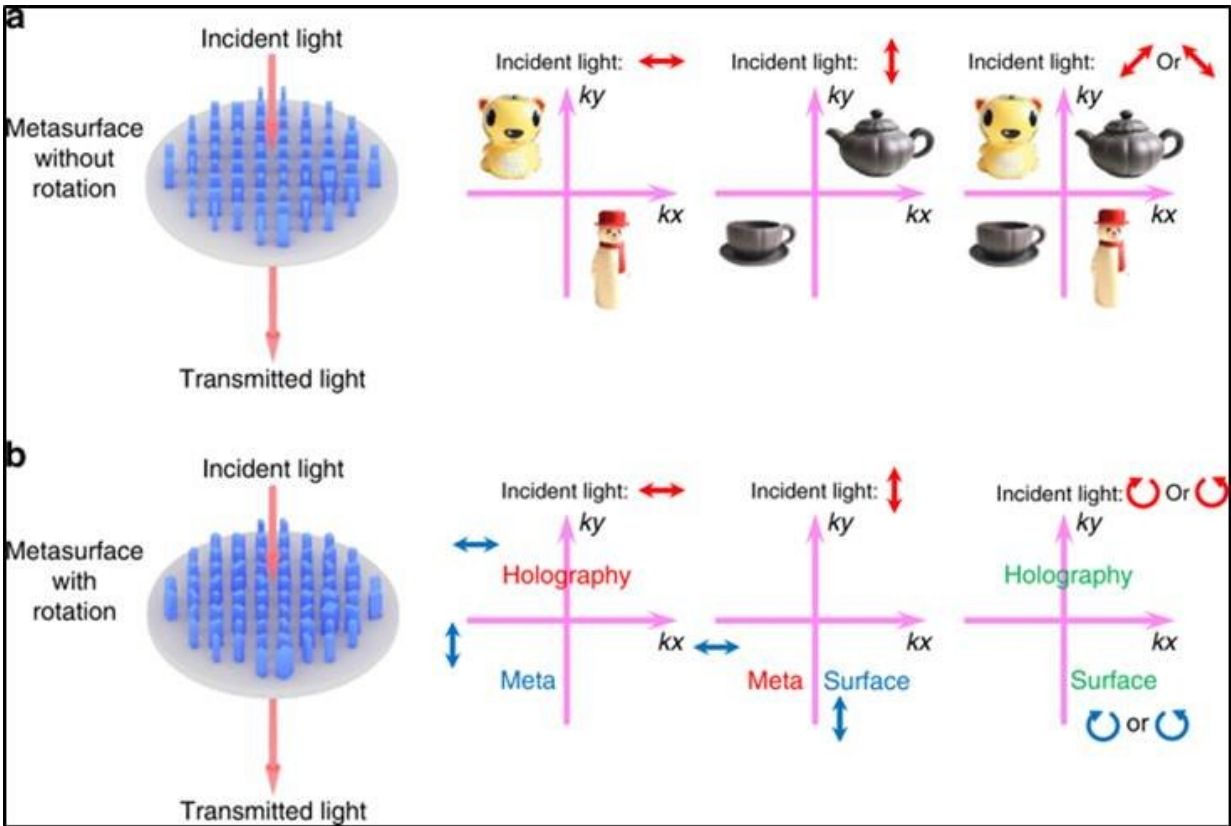


Multichannel vectorial holographic display and encryption

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Principle of the metasurface holography design and statistical results of the number of each nanofin (different cross-sections and orientation angles) contained in the designed metasurface holograms. Schematic illustrations of polarization multiplexed holograms based on dielectric metasurfaces. The red and blue arrows indicate the polarization of the incident light and the transmission axis of the polarizer placed behind the metasurface sample. The red, blue, and green color of the reconstructed images (the words “holography”, “meta”, and “surface”) represent components of the output light, respectively. a) Two channel polarization and an angle multiplexed hologram based on metasurfaces composed of nanofins with different cross-sections but fixed orientation angles, which can be used to reconstruct two sets of off-axis images. b) Multichannel polarization multiplexed hologram based on metasurfaces composed of nanofins with different cross-sections and orientation angles, which can be used to reconstruct three independent images and all combinations of these images (12 channels in total). c) Two-channel polarization- and angle-multiplexed hologram (enables appearance of “cartoon tiger”, “cartoon snowman”, “teapot”, “cup”), b) Multichannel polarization-multiplexed hologram (appearance of the word “holography”, “meta”, “surface”) c) Multichannel polarization-multiplexed hologram (appearance of “dice”) d) Multichannel polarization-multiplexed hologram (appearance of a “cartoon person”). Credit: Light: Science & Applications, doi: 10.1038/s41377-018-0091-0.

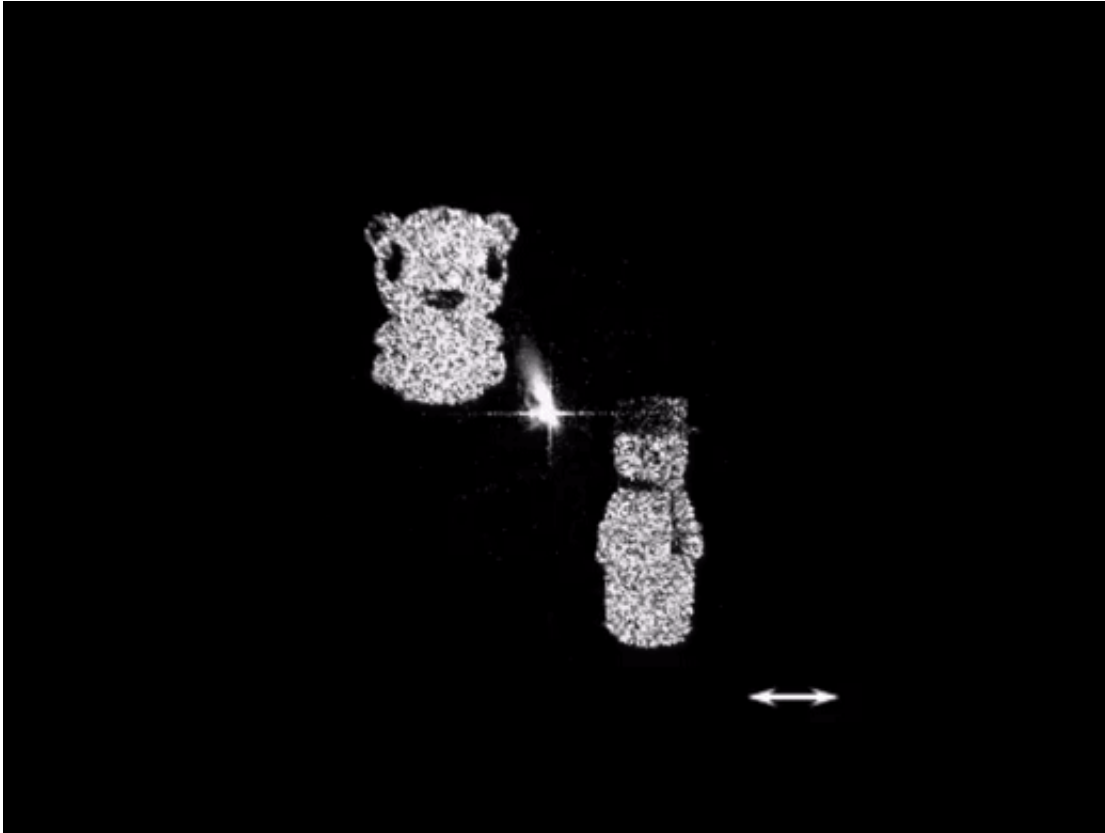
Holography is a powerful tool that can reconstruct wavefronts of light and combine the fundamental wave properties of amplitude, phase, polarization, wave vector and frequency. Smart multiplexing techniques (multiple signal integration) together with [metasurface designs](#) are currently in high demand to explore the capacity to engineer information storage systems and enhance optical encryption security using such metasurface holograms.

Holography based on metasurfaces is a promising candidate for

applications in optical displays/storage with enormous [information bearing capacity](#) alongside a [large field of view](#) compared to traditional methods. To practically realize [metasurface](#) holograms, holographic profiles should be encoded on [ultrathin nanostructures](#) that possess [strong light-matter interactions](#) ([plasmonic](#) interactions) in an ultrashort distance. Metasurfaces can control light and acoustic waves in a manner not seen in nature to provide a flexible and compact platform and realize a variety of vectorial holograms, with high dimensional information that surpass the limits of [liquid crystals](#) or optical photoresists.

Among the existing techniques employed to achieve highly desired optical properties, [polarization multiplexing](#) (multiple signal integration) is an attractive method. The strong cross-talk associated with such platforms can, however, be prevented with [birefringent metasurfaces](#) (two-dimensional surfaces with two different refractive indices) composed of a single meta-atom per unit-cell for optimized [polarization](#) multiplexing.

Nevertheless, the full capacity of all polarization channels remains to be explored for improved information storage capacity within metasurface holograms and in holographic optical devices. In a recent study, Ruizhe Zhao and co-workers demonstrated a new method to realize multichannel vectorial holography for dynamic display and high-security applications. In the study, birefringent metasurfaces were explored to control polarization channels and process very different information through rotation. The reconstructed vectorial images could be switched from one form to another with negligible cross-talk by selecting a combination of input/output polarization states. The results are now published in *Light: Science & Applications*.

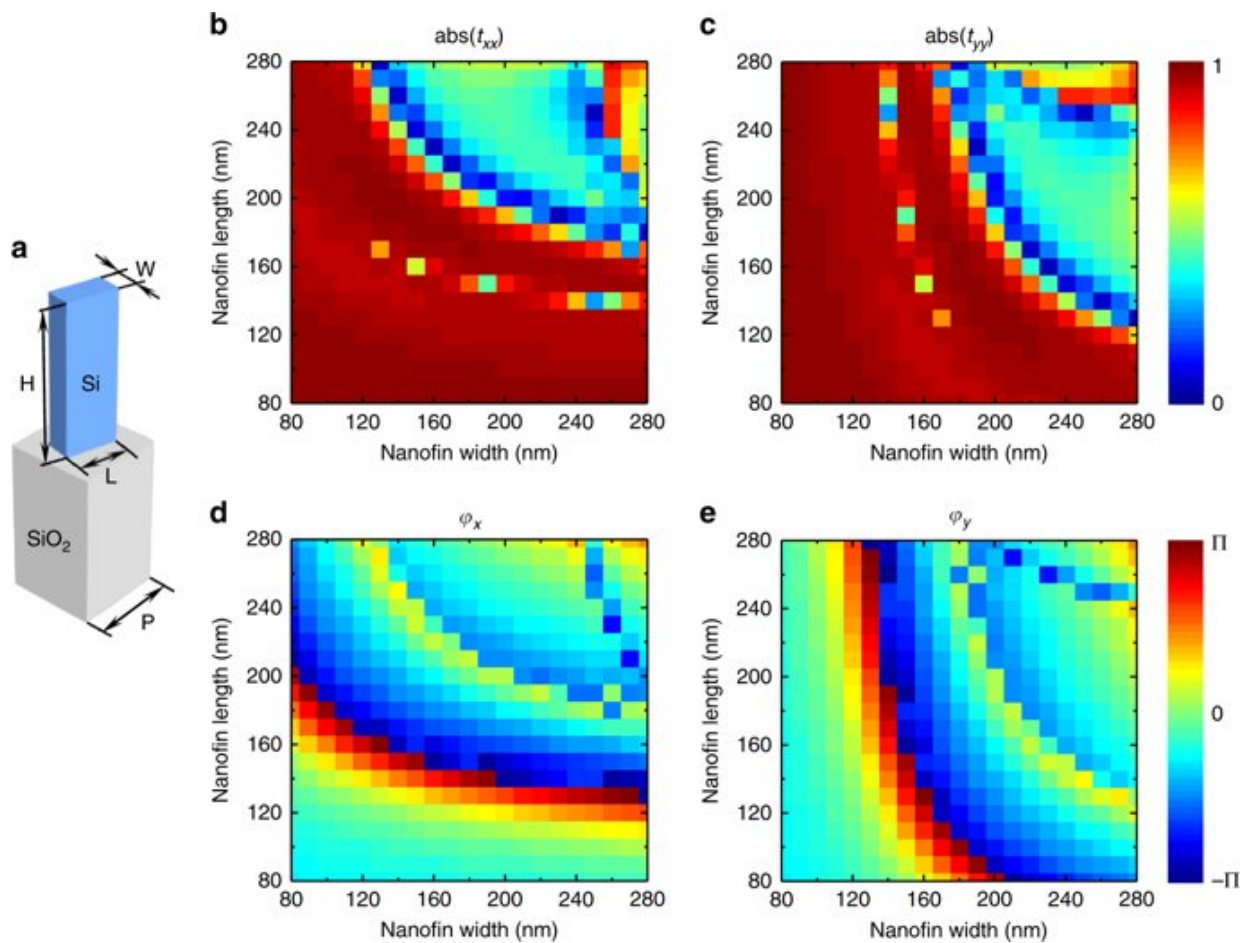


The two-channel polarization and angle-multiplexed hologram represents a cartoon tiger, cartoon snowman, teapot and teacup. Credit: Light: Science & Applications, doi: 10.1038/s41377-018-0091-0.

The scientists first derived a multiplexing algorithm to support the dynamic vectorial holographic display and encryption process. By using the correct polarization keys, the receiver could obtain the exact information delivered. By increasing the complexity of such images, even higher flexibility was obtained alongside detailed analysis of the reconstructed vectorial image properties. Since the device containing metasurfaces is compact in size, in practice, it can be easily transported with encoded information.

To pattern the design of interest, Zhao et al. engineered several dielectric

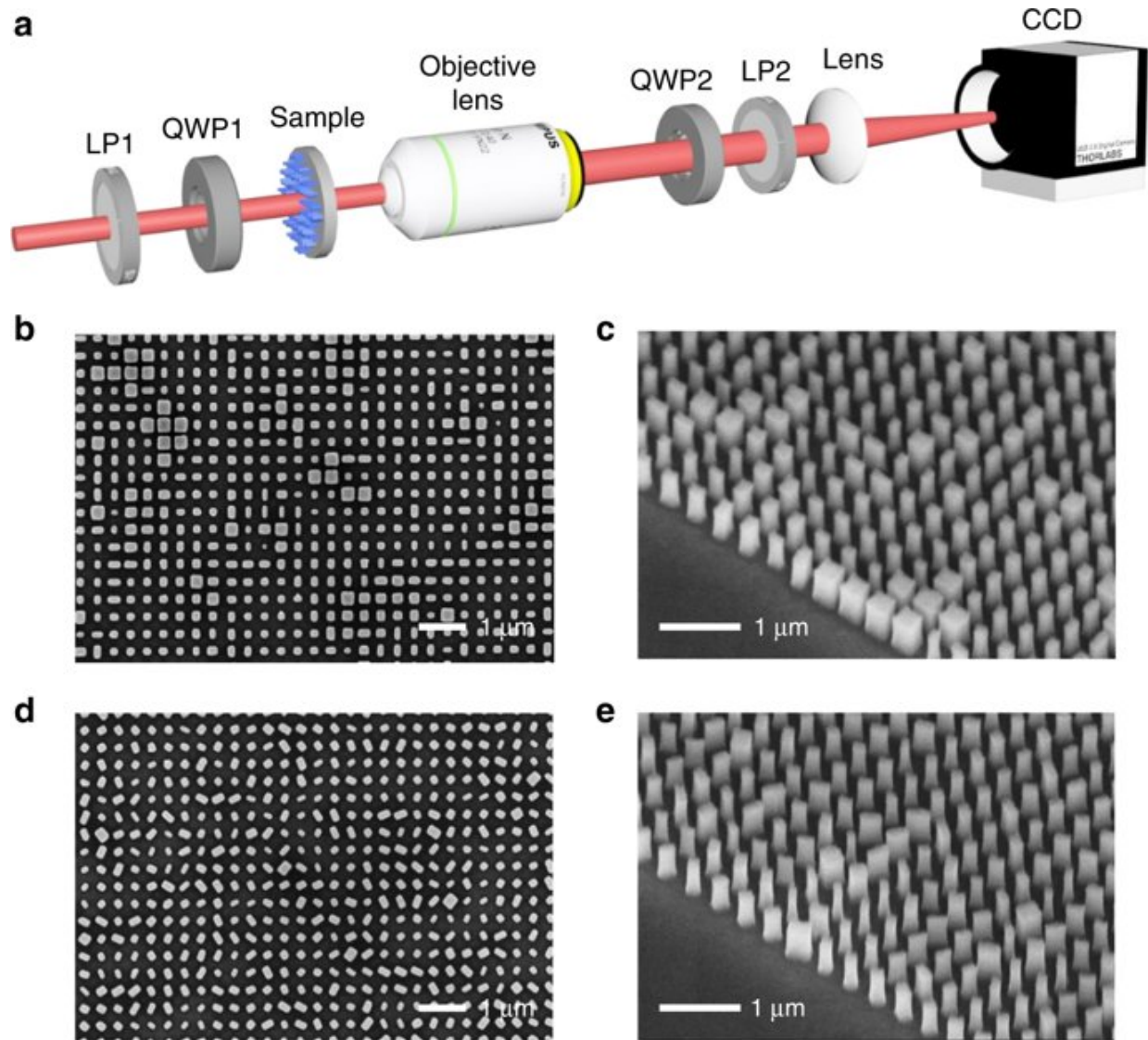
silicon metasurfaces on top of a glass substrate using plasma etching, followed by electron beam lithography. The metasurfaces were composed of 1000 x 1000 nanofins, i.e. nanostructures with the ability to augment heat transfer via surface area enhancement and liquid-solid-interactions. The researchers studied two schemes of multiple polarization channels; with or without rotation using the birefringent dielectric metasurfaces—to realize the holograms.



a) Schematic illustration of an amorphous silicon nanofin positioned on a glass substrate. The metasurface will be composed of a periodic arrangement of such unit-cells. b–e) Simulation results for the amplitude and phase of the transmission coefficients t_{xx} and t_{yy} shown for a 2D parameter optimization by using a rigorous coupled wave analysis method. The length and width of the

nanofin are both swept in the range of 80–280 nm at an incident wavelength of 800 nm. Credit: Light: Science & Applications, doi: 10.1038/s41377-018-0091-0.

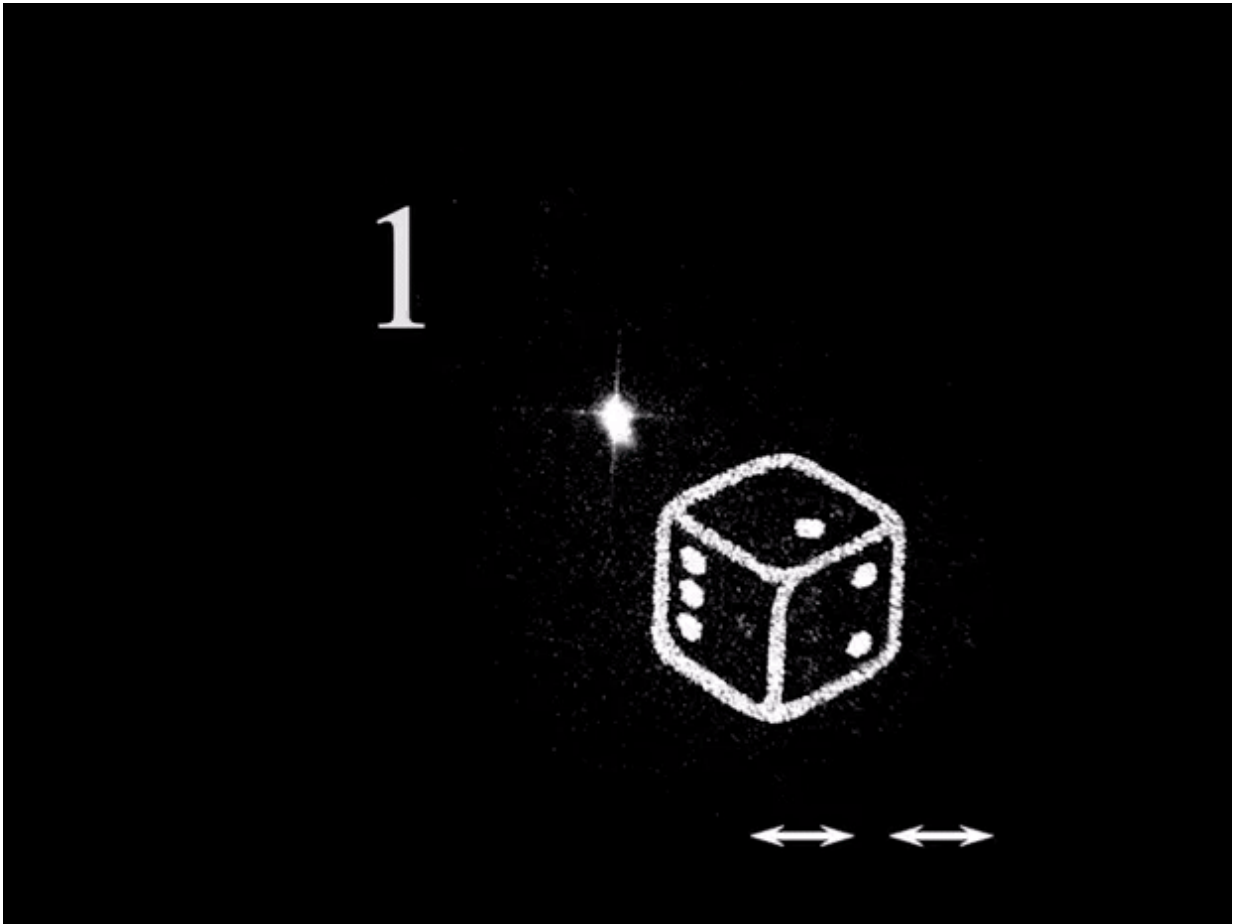
The birefringent dielectric metasurfaces were designed using silicon nanofins on top of a glass substrate. To achieve the desired phase shifts, 2-D parameter optimization was conducted using a rigorous coupled wave analysis (RCWA) method. The RCWA semi-analytical method is typically applied in computational electromagnetics to solve scattering from periodic dielectric structures. The length L and width W of the nanofin were in the range of 80 to 280 nm, height at 600 nm and period size P at 400 nm. The values were carefully selected to ensure the phase of the output light eliminated any undesired orders of diffraction. For the simulation, the nanofin was placed on a glass substrate and subjected to a fixed wavelength of incident light at 800 nm. Simulation results indicated the amplitude of transmission for most nanofins with diverse cross-sections were beyond 90 percent efficiency. The scientists determined orientation angles of the nanofins using equations derived in the study to experimentally demonstrate multichannel polarization multiplexing.



Experimental setup and scanning electron microscopy images of the fabricated metasurface samples. a) The experimental setup for the observation of the holographic images. The two linear polarizers (LP1, LP2) and two quarter-wave plates (QWP1, QWP2) are used to set the precise polarization combination for the incident/transmitted light. The lens images the back focal plane of the microscope objective lens ($\times 40/0.6$) to a CCD camera. b–e) Scanning electron microscopy images of two typical fabricated silicon metasurface samples shown with a top and side view. The metasurface holograms are composed of 1000×1000 nanofins with different cross-sections and orientation angles. Credit: Light: Science & Applications, doi: 10.1038/s41377-018-0091-0.

For optical characterization of the metasurface holograms, Zhao et al. used an [experimental setup](#). The magnifying ratio and numerical aperture of the objective lens were carefully chosen to collect all the diffraction light from the sample and reconstruct holographic images in the Fourier plane. The scientists used a second objective/lens to capture the Fourier plane on a CCD camera. They also separately observed two scanning electron microscopy images of the samples with or without rotation to characterize the engineered surface.

As a proof-of-principle, using the metasurfaces, Zhao et al. constructed holographic images of a cartoon tiger and a snowman that appeared with high fidelity and high resolution when illuminated by x-polarized light. When the incident light was switched to y-polarization, the reconstructed images changed to a teapot and a teacup. In this experiment, only two polarization channels were available in the setup, with both pairs of the holographic images reconstructed and made to disappear simultaneously by rotating the polarizer behind the sample. The [experimental results](#) were in agreement with the simulation to confirm the study's fundamental design principle. The net diffraction efficiency of the hologram was defined as the ratio of intensity of the single reconstructed image to the power of incident light.



Multichannel polarization-multiplexed holograms (“Dice”). Credit: Light: Science & Applications, doi: 10.1038/s41377-018-0091-0.

The scientists were able to design and construct more complex multiplexing functionalities with 12 channels using the same principles of design thereafter. The vectorial images were viewed as holographic reconstructions with the input/output polarization combinations developed as proposed. The technique could also be used to encrypt different images at the same spatial location. In encryption, such superposition can convey a different meaning on reconstruction. As an example, the scientists chose the image of a die with six representative surfaces, and by using different combinations of input/output

polarization states, encoded up to six images for viewing.

The multiplexing algorithm derived in the study aided the dynamic vectorial holographic display and the encryption of images encoded on birefringent dielectric metasurfaces. By using the correct polarization keys, a receiver could obtain the exact information delivered. Higher flexibility could be obtained by increasing the complexity of the image and changing the medium of encryption to titanium dioxide (TiO₂) or silicon nitride (SiN). The correct polarization combination secured the information for enhanced complexity during decryption.

The multichannel hologram maintained a relatively large working bandwidth since the reconstructed images could be observed away from the designed wavelength of 800 nm. The study established a design and engineering technique that combined birefringent properties of simple nanofins used as the building blocks, with extra-design freedom of rotation matrix and smart multiplexing algorithms. The results enabled high-dimensional multichannel polarization multiplexed holograms, with up to 12 polarization channels. In this way, efficient light-based encryption and integrated multichannel holographic display techniques can pave the way for advanced communication in high security applications.

More information: Ruizhe Zhao et al. Multichannel vectorial holographic display and encryption, *Light: Science & Applications* (2018). [DOI: 10.1038/s41377-018-0091-0](https://doi.org/10.1038/s41377-018-0091-0)

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