

Shared-aperture geometric phase metasurfaces

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The shared-aperture phased antenna array and geometric phase concepts are combined in a novel technique to obtain photonic spin-controlled multifunctional devices.

Shared-aperture multifunctional planar systems (in which a number of tasks are performed concurrently) have recently been introduced in the field of phased array antennas, for radar applications.¹ Indeed, these shared-aperture phased antenna arrays—see Figure 1(a)—are a promising way to increase functionality in photonics. Recent achievements in the fast-growing field of metasurfaces (i.e., metamaterials of reduced dimensionality) are particularly relevant because they provide a route to developing virtually flat optics. Such metasurfaces consist of a dense arrangement of small-scale resonant optical antennas. For example, in a phased antenna array, phase accumulators are arranged so that they form a wavefront (because of phase differences across the array). Light–matter interactions of individual nanoantennas therefore allow local light scattering properties to be controlled with these arrays.

The local phase pickup in a phased antenna array can be manipulated by changing the antenna material, size, shape, and environment (known as antenna resonance shaping), or via the geometric phase concept. The latter concept is fundamental to geometric phase metasurfaces (GPMs), in which the phase pickup originates from space-variant orientations of the anisotropic nanoantennas that compose the metasurface. In addition, the geometric phase concept is an efficient way to achieve spin-controlled phase modulation, whereas the photon spin is associated with the intrinsic angular momentum of light.^{2–8} GPMs can also be used to transform incident circularly polarized light into a beam of opposite helicity (imprinted with a geometric phase).

In our work,⁹ we have used a new technique to synthesize shared-aperture phased antenna arrays. We combine these arrays with the geometric phase concept to realize multifunctional GPM photonic arrays. In addition, we have incorporated

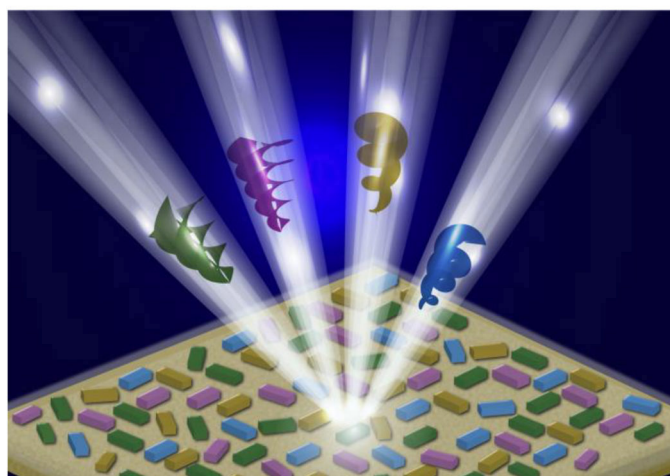
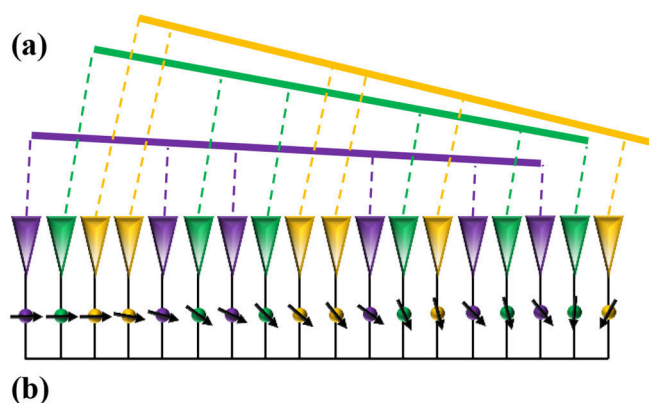


Figure 1. Schematic illustrations of (a) the shared-aperture concept and (b) structured wavefronts emerging from an interleaved geometric phase metasurface. In (a) each wavefront is represented by a different color. The wavefronts are illustrated with solid lines and the dashed lines indicate the propagation directions.

spin-controlled 2D optics (based on gap-plasmon nanoantennas) to produce interleaved nanoantenna matrices, as shown in Figure 1(b). We have also demonstrated various functionalities on a single GPM, which is applicable for use in medicine and chemistry.

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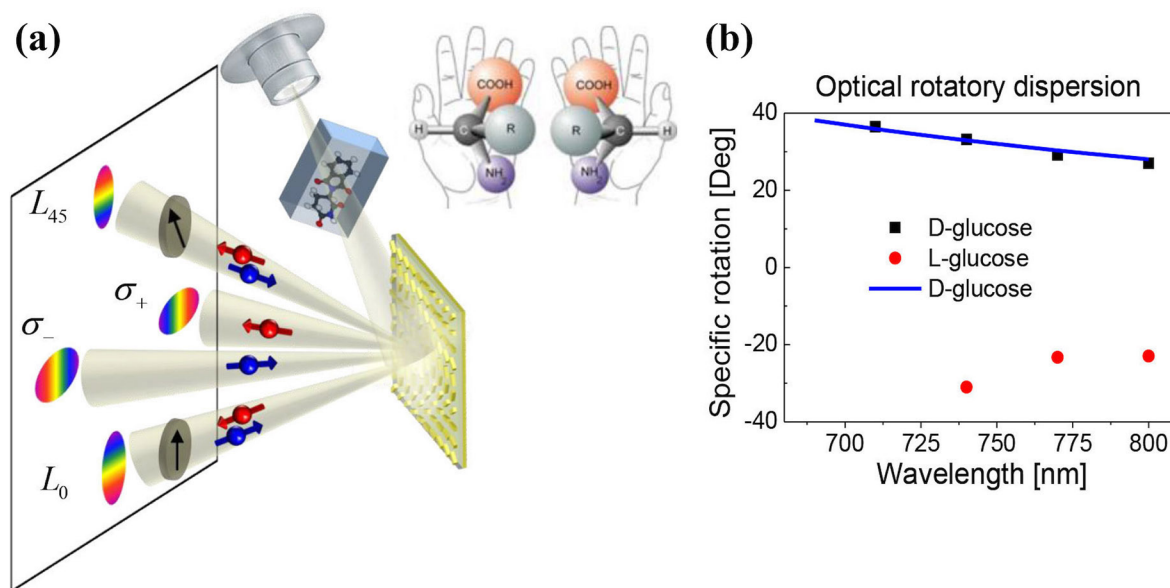


Figure 2. Illustration of the spectropolarimeter metasurface (SPM). (a) The measurement setup for the device. The SPM is illuminated by a continuum light that passes through a cuvette (with a chemical solvent). Four beams (L_{45} , L_0 , σ_+ , and σ_-) with different intensities are then reflected toward a CCD camera. L_{45} and L_0 are projections of the reflected beam upon linear polarization at 45 and 0°, respectively. σ_+ and σ_- are projections of the reflected beam onto the right- and left-circular polarization states, respectively. The building block of this metasurface is a gap-plasmon nanoantenna.¹⁰ The inset shows the left- and right-handed versions of a chiral molecule, where R represents the stereocenter configuration of the compound. (b) The optical rotatory dispersion (ORD) for specific rotation of D- and L-glucose (i.e., right- and left-handed glucose), measured using the SPM. The blue line shows D-glucose ORD literature values.

We designed our photonic GPM, with spatially interleaved phase profiles, by randomly mixing optical nanoantenna subarrays. Each of these subarrays provides a different phase function, in a spin-dependent manner. With this approach we take advantage of the peculiar characteristic of random patterns for yielding extraordinary information capacities. We also use the geometric phase concept to control the polarization helicity. Furthermore, in our harmonic response approach, we exploit the expansion of a complex function to its harmonics so that we can generate multiple wavefronts. We have thus applied both these techniques to nanoantenna arrays to obtain multiple wavefronts, e.g., vortex beams that carry orbital angular momentum information.⁹

Metasurfaces with well-established sub-wavelength interleaved phased arrays based on multiplexed GPMs are now being developed for real-world applications. For instance, we have created a novel device for the simultaneous determination of the polarization state and spectrum of light. This device—known as the spectropolarimeter metasurface (SPM)—is illustrated schematically in Figure 2(a). The SPM measurement setup involves a continuum light beam passing through a cuvette (with a chemical solvent) to illuminate the device. Four light

beams, with different intensities, are then reflected toward a CCD camera for measurement.

We have successfully used our SPM to measure the optical rotatory dispersion of L-glucose and D-glucose (i.e., left and right chiralities) and to thus characterize and differentiate between these two enantiomer types, as shown in Figure 2(b). Distinguishing between these two types of glucose is important because mammals have enzymes that break down D-glucose, but not L-glucose (i.e., only the D enantiomer is biologically active). Moreover, because most biological molecules are chiral, enantiomeric distinctions have widespread implications for the pharmaceutical and food industries. For example, the drug thalidomide was based on a chiral molecule. One of its enantiomers can relieve the effects of morning sickness, but the other enantiomer harms fetal development. Our SPM has a size of 50 μm and can thus be integrated into advanced small diagnostics systems in medicine and chemistry.

In summary, we have developed a technique in which the geometric phase concept and shared-aperture antenna arrays can be combined. This work paves the way for spin-enabled

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multifunctional wavefront shaping, with the use of a single, broadband, and sophisticated nano-optic device. Our shared-aperture metasurface platform also opens a path toward novel types of nanophotonic functionality. For example, we have developed a device that enables integrated on-chip spectropolarimetric analyses. In the next stage of our work we plan to extend the shared-aperture metasurfaces to different spectral domains by making sophisticated nanoantenna designs.

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References

1. D. M. Pozar and S. D. Targonski, *A shared-aperture dual-band dual-polarized microstrip array*, **IEEE Trans. Antennas Propag.** **49**, pp. 150–157, 2001.
2. N. M. Litchinitser, *Photonic multitasking enabled with geometric phase*, **Science** **352**, pp. 1177–1178, 2016.
3. Z. Bomzon, V. Kleiner, and E. Hasman, *Pancharatnam–Berry phase in space-variant polarization-state manipulations with subwavelength gratings*, **Opt. Lett.** **26**, pp. 1424–1426, 2001.
4. Z. Bomzon, G. Biener, V. Kleiner, and E. Hasman, *Space-variant Pancharatnam–Berry phase optical elements with computer-generated subwavelength gratings*, **Opt. Lett.** **27**, pp. 1141–1143, 2002.
5. G. Biener, A. Niv, V. Kleiner, and E. Hasman, *Formation of helical beams by use of Pancharatnam–Berry phase optical elements*, **Opt. Lett.** **27**, pp. 1875–1877, 2002.
6. E. Hasman, V. Kleiner, G. Biener, and A. Niv, *Polarization dependent focusing lens by use of quantized Pancharatnam–Berry phase diffractive optics*, **Appl. Phys. Lett.** **82**, pp. 328–330, 2003.
7. N. Dahan, Y. Gorodetski, K. Frischwasser, V. Kleiner, and E. Hasman, *Geometric doppler effect: spin-split dispersion of thermal radiation*, **Phys. Rev. Lett.** **105**, p. 136402, 2010. doi:10.1103/PhysRevLett.105.136402
8. D. Lin, P. Fan, E. Hasman, and M. L. Brongersma, *Dielectric gradient metasurface optical elements*, **Science** **345**, pp. 298–302, 2014.
9. E. Maguid, I. Yulevich, D. Veksler, V. Kleiner, M. L. Brongersma, and E. Hasman, *Photonic spin-controlled multifunctional shared-aperture antenna array*, **Science** **352**, pp. 1202–1206, 2016.
10. A. Pors, O. Albrektsen, I. P. Radko, and S. I. Bozhevolnyi, *Gap plasmon-based metasurfaces for total control of reflected light*, **Sci. Rep.** **3**, p. 2155, 2013. doi:10.1038/srep02155