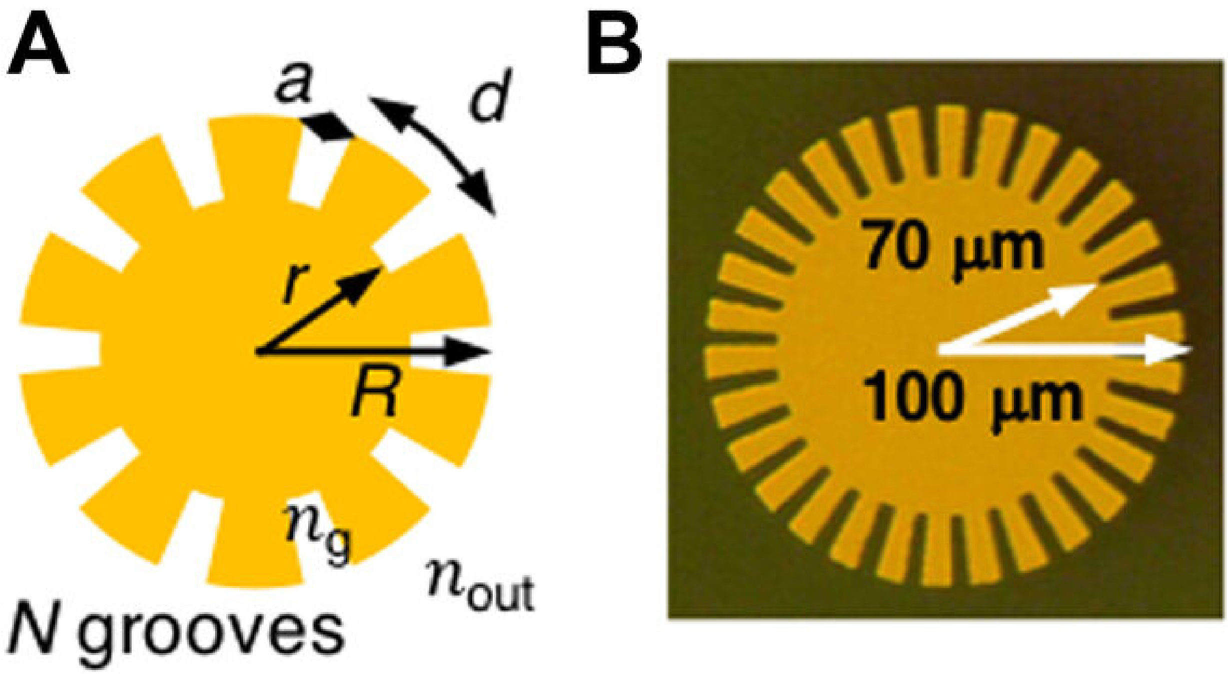
Transferring orbital angular momentum of light to plasmonic excitations in metamaterials

June 23 2020, by Thamarasee Jeewandara



Metamaterial structure for OAM transfer. (A) Schematic view with the following structural parameters: inner radius (r), outer radius (R), periodicity (d), groove width (a), and number of grooves (N). The refractive indices inside the groove and outside the disk are given by ng and nout, respectively. (B) Optical image of the sample made of gold (r = 70 µm, R = 100 µm, N = 30, and a/d = 0.4). The thickness is around 100 nm. Chromium (10 nm thick) is deposited under the gold as an adhesion layer. Credit: Science Advances, doi: 10.1126/sciadv.aay1977

The vortex beam with orbital angular momentum (OAM) is a new and ideal tool to selectively excite dipole forbidden states through linear optical absorption. The emergence of the vortex beam with OAM provides intriguing opportunities to induce optical transitions beyond the framework of electric dipole interactions. The unique feature arose from the transfer of OAM from light-to-material as demonstrated with electronic transitions in atomic systems .

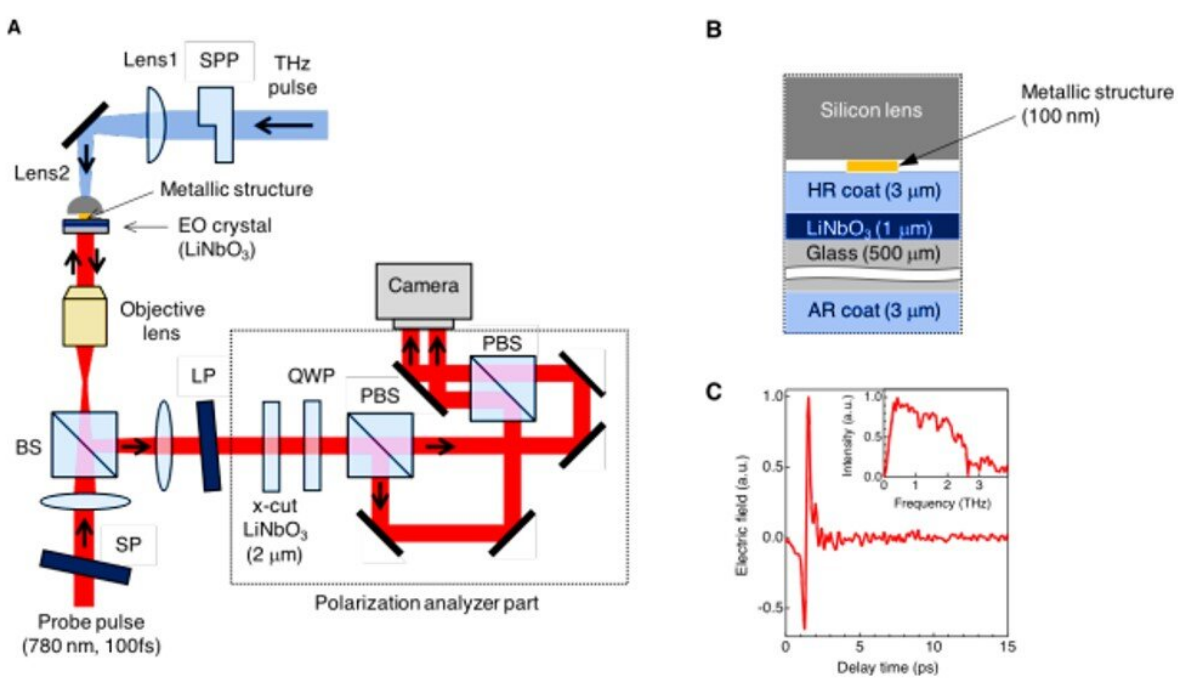
In a new report on *Science Advances*, T. Arikawa and a team of researchers in physics, electrical engineering and cell materials science in Japan and Canada, detailed OAM transfer to electrons in solid-state systems. They used metamaterials to show how multipolar modes of surface electromagnetic excitations, also known as 'spoof' localized surface plasmons, could be selectively induced through the terahertz vortex beam. Spoof surface plasmons are a type of surface plasmon polariton (SPP) that typically propagates across dielectric and metallic interfaces at infrared and visible frequencies. However, since such polaritons cannot naturally occur in terahertz or microwave frequencies, spoof surface plasmons require artificial metamaterials for propagation in such frequencies.

The selection rules of the study were governed by the conservation of total angular momentum, which Arikawa et al. confirmed using numerical simulations. The efficient transfer of light orbital angular momentum to elementary excitations at room temperature in solid-state systems can expand the potential for experimental OAM manipulation to construct OAM-based applications, including quantum memories and OAM-based sensors.

Light-matter interactions are governed by spatial-temporal structures of a light field and via material wave functions. Researchers have used nonlinear optical methods such as two-photon absorption to selectively excite a specific dark mode, in the presence of strong light sources. The

OAM (orbital angular momentum) provides a new method to selectively excite dipole-forbidden states through linear optical absorption, while deriving different selection rules. Scientists can explore such selectivity, relative to OAM transfer from light to a material, although such transitions are very small to record. In this work, Arikawa et al. investigated electrons in solids with extended wave functions as an ideal platform to study vortex light-matter interactions.

Recent studies in electromagnetic field analysis had predicted efficient OAM transfer from vortex beams to localized surface plasmons (LSPs) in a metallic disk. During simulations, multipolar modes with large angular momentum, i.e. quadrupole, hexapole, etc., can be selectively excited as a result of OAM transfer.

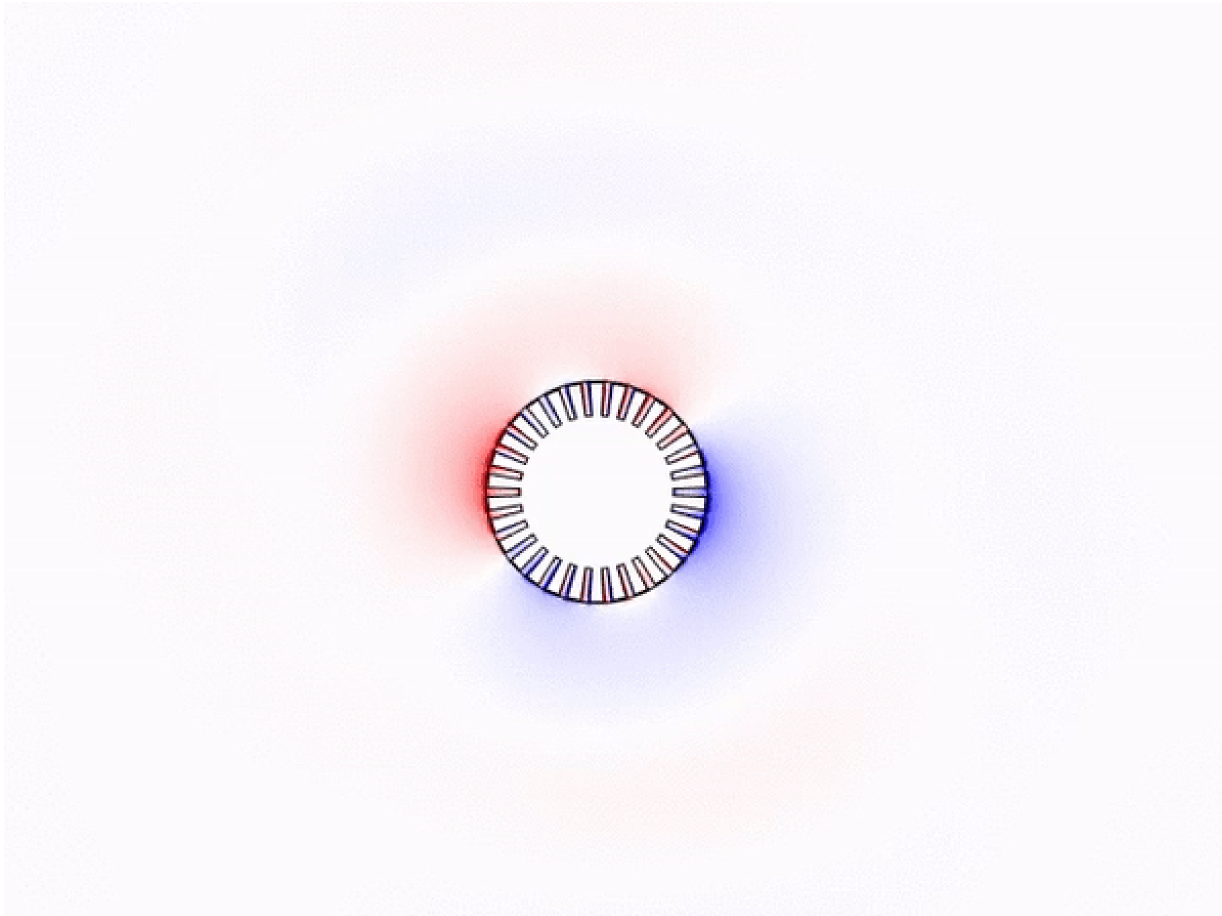


Experimental setup. (A) Schematic of the experimental setup. BS: beam splitter, QWP: quarter wave plate, PBS: polarizing beam splitter. (B) Magnified view of around the EO crystal (side view). (C) Electric field waveform of the incident

Gaussian THz pulse. The inset shows its frequency spectrum. Credit: Science Advances, doi: 10.1126/sciadv.aay1977

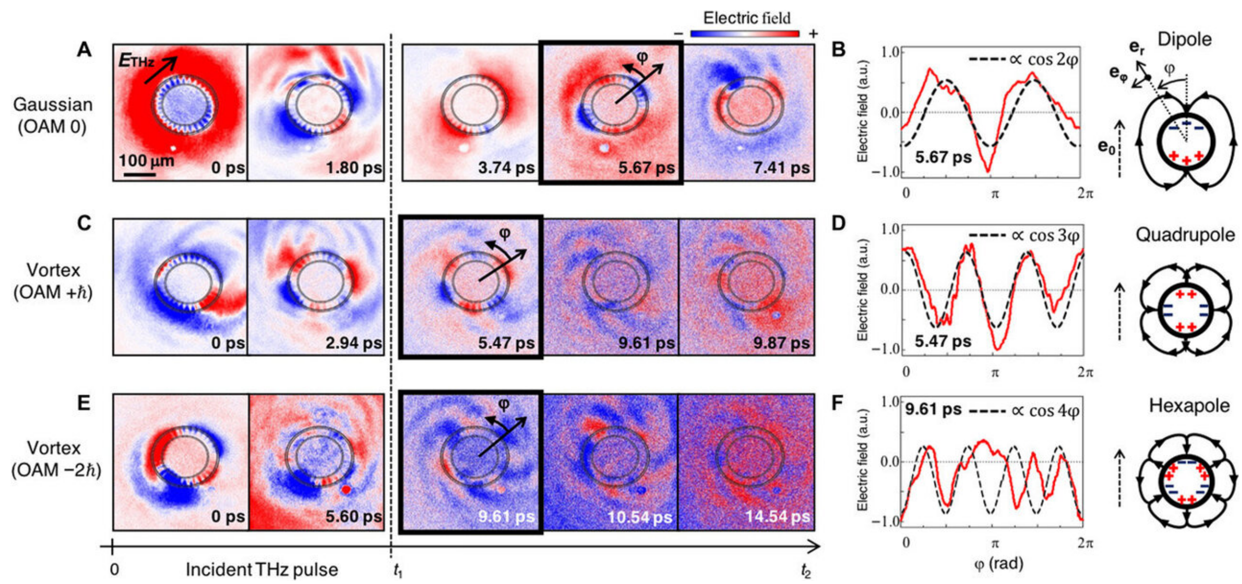
In this work, the team experimentally showed selective excitation using spoof LSP (a low-frequency analog of LSP) that can exist around the surface of a periodically textured metallic disk. They built the metamaterial structure to bring the resonance frequencies down to the terahertz (THZ) frequency range for non-destructive imaging. The experimental setup allowed the scientists to visualize the characteristic patterns surrounding the corrugated disk and identify spoof LSP modes excited in the sample. To visualize near-field patterns due to LSPs, Arikawa et al. engineered corrugated gold disks on the top surface of a terahertz (THZ) detector crystal, to sample the electric field that formed a few microns away from the metallic structure. They performed the experiments at room temperature and obtained five snapshots of the THZ electric field around the sample after excitation by a linearly polarized Gaussian beam.

Time-resolved near-field imaging and mode expansion analysis.



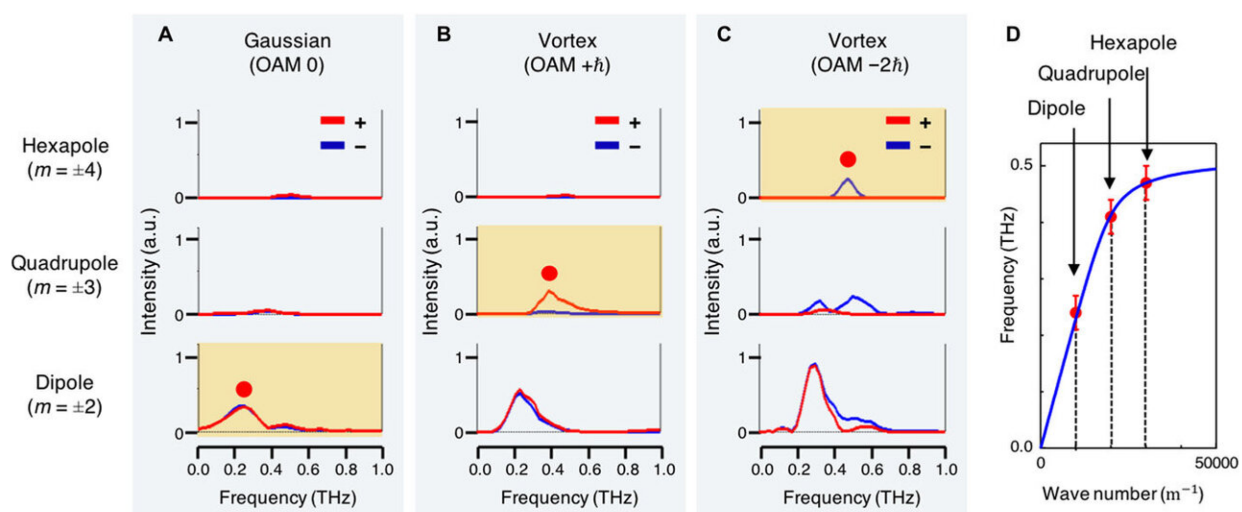
Simulations for the vortex beam (OAM +ħ) excitation exhibit the characteristic field distribution (six zero crossing points) unique to the clockwise quadrupole mode, similar to the experimental result. Credit: Science Advances, doi: 10.1126/sciadv.aay1977

After the incident terahertz pulse passed through the sample, the team observed an electric field oscillation localized around the outer circle of the sample as a resonant excitation of spoof LSP, representing the expected electric field pattern. The work confirmed the excitation of the dipole mode by the Gaussian beam and that multiple spoof LSPs could be excited by vortex beams. To illustrate this point, Arikawa et al. performed additional analyses by focusing on the electric field along the outer circle of the sample to represent the frequency spectrum of each LSP mode. The results showed the efficient and selective excitation of multipolar modes based on the OAM of light, allowing the scientists to identify all spoof LSP modes excited in the sample.



Selective excitation of multipole spoof LSPs. Selected snapshots of the near-field evolution around the sample excited by (A) Gaussian beam, (C) vortex beam (OAM +ħ), and (E) vortex beam (OAM −2ħ). The double circle represents the position of the sample (inner and outer radius). The time origin (0 ps) is the time when the first positive peak of the incident pulse comes. The color scales are optimized at each frame for the sake of clarity. (B, D, and F) The electric field taken along the outer circle of the sample as a function of the azimuthal angle φ (red curves). The error bars are almost the same as the thickness of the traces. The dashed cosine curves are expected electric field patterns when the modes depicted on the right are excited. The solid arrows schematically represent the quasi-static electric field around each mode. The cosine functions are obtained by projecting the quasi-static field onto the polarization axis (e0, dashed up arrow) detected in the experiment. er and eφ are cylindrical unit vectors introduced to calculate quasi-static fields. a.u., arbitrary units. Credit: Science Advances, doi: 10.1126/sciadv.aay1977

The analysis additionally revealed the resonance frequency of each mode, allowing them to draw the dispersion relation i.e. the relation between the optical frequency and the propagation constants of surface plasmon polariton modes. The dispersion relation of the spoof LSPs depended on the geometrical parameters of the metallic structures, providing the scientists a powerful tool to control the resonance frequencies. The team performed additional experiments and analyses on samples with diverse dimensions of corrugation to demonstrate resonance frequency control. The results allowed them to deduce the selection rules in the system to excite multiple spoof LSPs. The observations strongly supported that the selection rules were governed by the conservation of total angular momentum (TAM), which the team then numerically confirmed for spoof LSPs using similar electromagnetic field analyses.



Mode decomposition of near-field distributions. Frequency spectra of the dipole [E(±2, f)], quadrupole [E(±3, f)], and hexapole [E(±4, f)] modes excited in the sample illuminated by (A) Gaussian beam, (B) vortex beam (+ħ), and (C) vortex beam (−2ħ). (D) Dispersion relation of the spoof LSP. The red dots represent the resonance frequencies determined in (A) to (C). The blue curve is a theoretical fitting. Credit: Science Advances, doi: 10.1126/sciadv.aay1977

In this way, T. Arikawa and colleagues observed traveling surface waves with low electron scattering to enable coherent collective motion of electrons across the entire sample. The frequency tunability of the corrugated metallic disk geometry allowed it to be a very versatile OAM receiver with wide ranging frequencies as long as the scattering in the experimental setup was sufficiently low. The team expect the OAM to transfer across to other elementary excitations in solids including Rydberg excitons, skyrmions and phonons, although they will need focusing techniques beyond the diffraction limit in such instances. The work on efficient OAM exchange between light and elementary excitations in solid-state systems will be foundational to generate novel solid-state devices for OAM applications.

More information: T. Arikawa et al. Transfer of orbital angular momentum of light to plasmonic excitations in metamaterials, *Science Advances* (2020). DOI: 10.1126/sciadv.aay1977

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