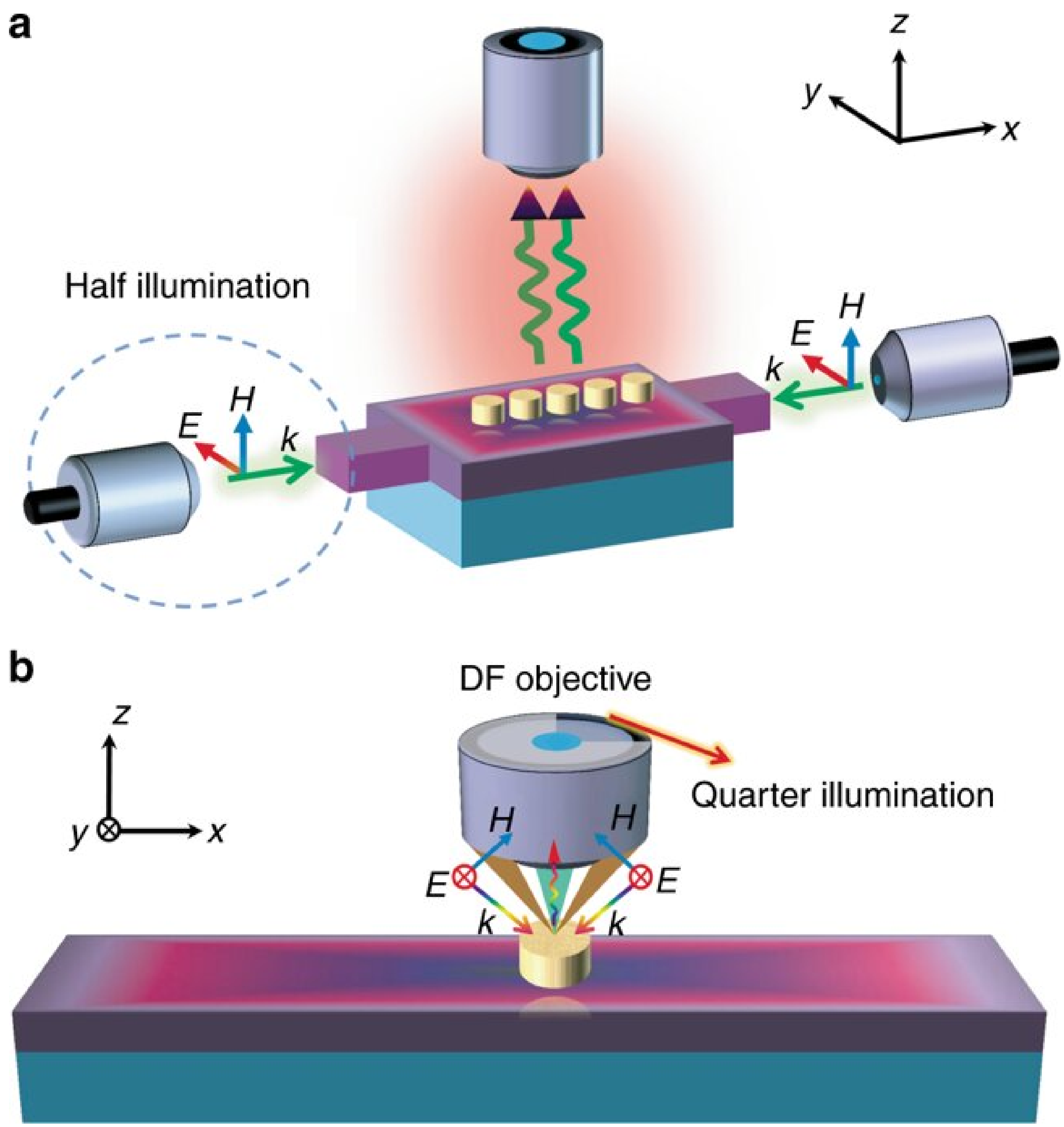
In-plane coherent control of plasmon resonances for plasmonic switching and encoding

March 11 2019, by Thamarasee Jeewandara



Schematic diagrams of two setups for in-plane coherent control of plasmon resonances. a Fiber-waveguide interferometer. b Dark-field (DF) confocal microscope, where quarter illumination can be satisfied by blocking 3/4 area of the annular aperture. Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-019-0134-1

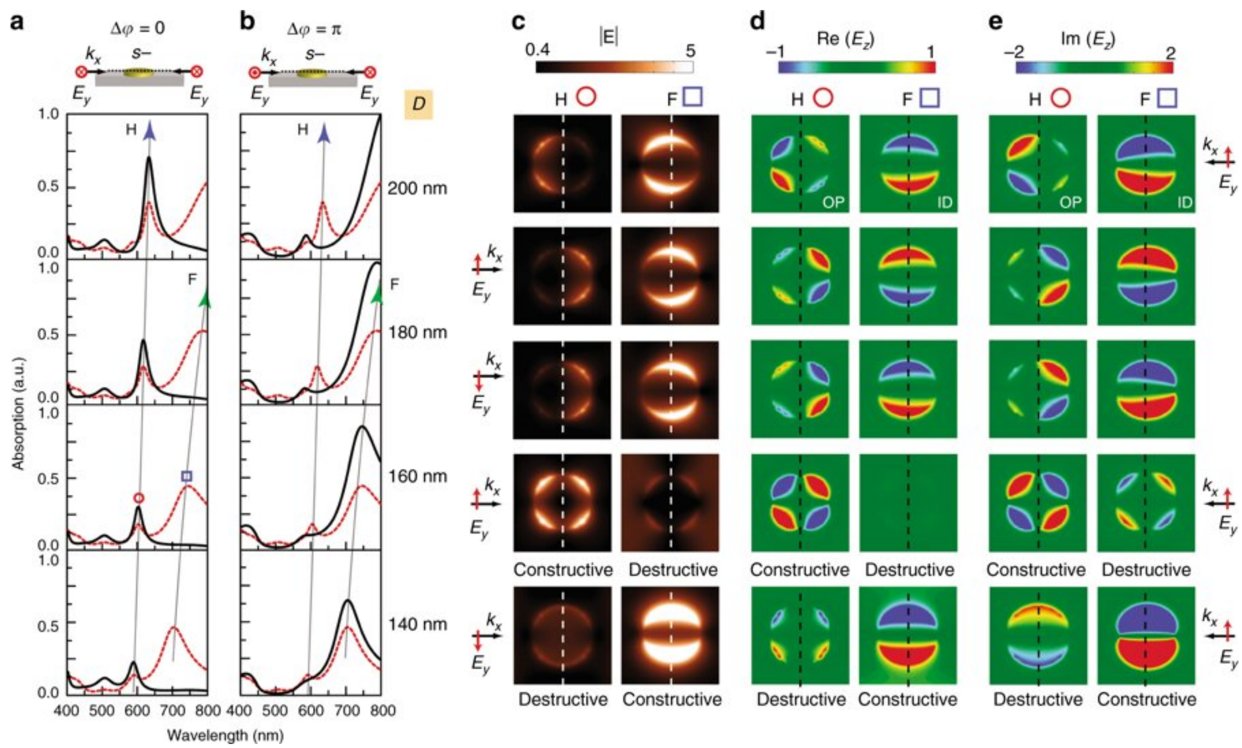
Light incident on metallic nanoparticles can initiate the collective motion of electrons, causing a strong amplification of the local electromagnetic field. Such plasmonic resonances have significant roles in biosensing with ability to improve the resolution and sensitivity required to detect particles at the scale of the single molecule. The control of plasmon resonances in metadevices have potential applications in all-optical, light-with-light signal modulation and image processing. Reports have demonstrated the out-of-plane coherent control of plasmon resonances by modulating metadevices in standing waves. In optical devices, light can be transferred along the surfaces for the unprecedented control of plasmons. When oscillations in conducting electrons are coupled with light photons, localized surface plasmon resonances (LSPR) can act as information carriers for nano-sized optical sensors and in computers.

In a recent study, Liyong Jiang and co-workers at the Nanjing University of Science and Technology demonstrated two methods for in-plane illumination of LSPRs as a proof-of-principle in gold nanodisks. The results of their work showed that the LSPRs could be switched into different states by adjusting the incident light to encode logical data into chains in a manner that was hitherto not possible with out-of-plane illumination. The results are now published in *Light: Science & Applications*.

Significant efforts in the past decade were devoted to study light-matter interactions at the nanoscale in plasmonic systems. The ability to control LSPR has led to many practical applications, including pioneering examples such as:

1. Surface-enhanced Raman Scattering
2. Plasmon waveguides
3. Molecular rulers
4. Biosensing and bioimaging
5. Nanolasers

6. [Plasmonic holography]
7. [Tunnel junctions], and
8. [Metalens].

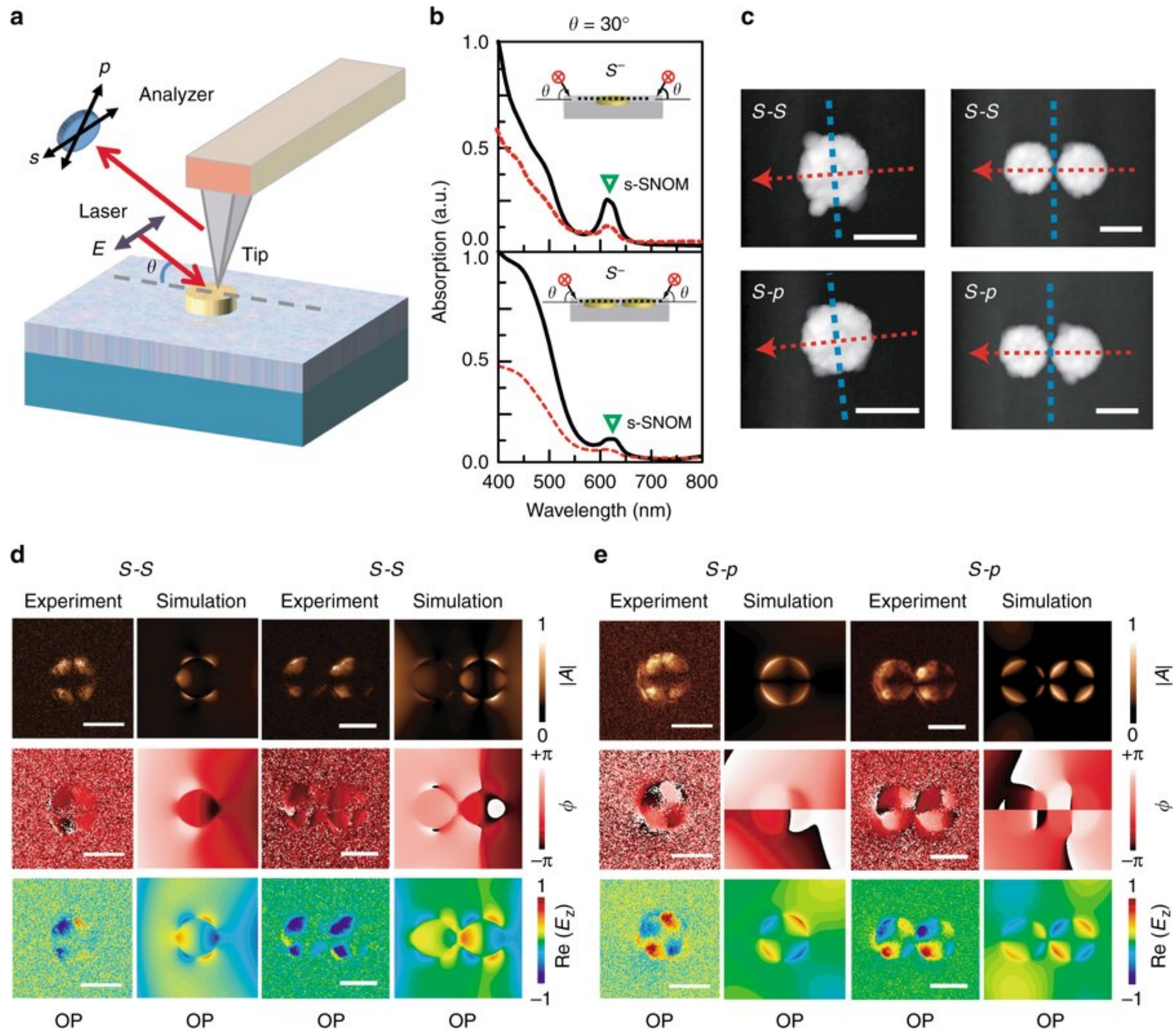


In-plane coherent control of plasmon resonances in gold nanodisk monomers. a, b Calculated normalized absorption spectra of gold nanodisk monomers with a diameter ranging from 140 to 200 nm for s-polarized in-plane plan wave coming from the right side (dashed line) or both sides (solid line) without phase delay, or with a phase delay of π. “F” and “H” represent fundamental and high-order plasmon resonances. c–e The corresponding spatial distributions of electric-field amplitude |E|, real part Re(Ez), and imaginary part Im(Ez) for the “F” and “H” modes (square and circle signs) of the representative gold nanodisk monomer (D = 160 nm) under asymmetrical and symmetrical in-plane illumination. Under symmetrical in-plane illumination, we can observe phase delay-dependent destructive/constructive interference for the “F” and “H” modes. Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-019-0134-1

During the initial stages of development, scientists focused on controlling LSPR by designing configurations of the plasmonic nanostructures. They understood the size- and shape-dependent LSPR of single plasmonic nanoparticles and coupled plasmonic systems based on the classical Mie theory and well-established plasmonic hybridization models. Additionally, the light beam typically illuminated the sample surface from one direction in conventional optical studies of single and coupled nanoantennas.

Although the ability to control plasmon resonances via out-of-plane illumination has opened a new path to modulate signals, the process has shown limitations. As a result, Jiang et al. reported on in-plane coherent control of plasmon resonances in typical metallic nanoantennas. The scientists provided a proof-of-principle demonstration of plasmonic switching and encoding applications for single and coupled gold nanodisks.

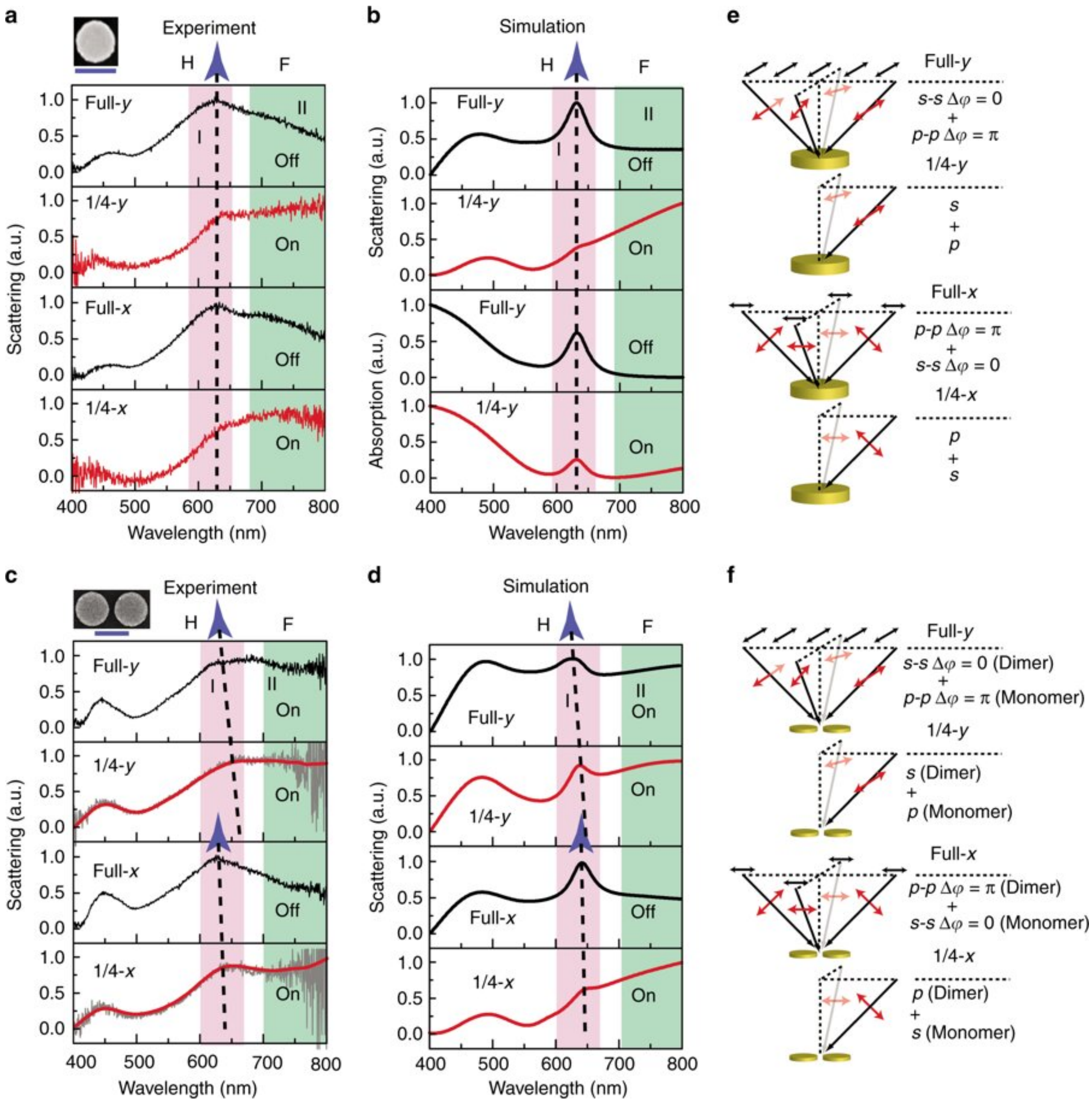
To accomplish in-plane coherent control of plasmon resonances in the lab, the scientists proposed two possible experimental setups. One was based on a fiber-waveguide interferometer, which faced challenges during experiments. In comparison, the second method included a more convenient, widely used dark-field confocal microscopy setup. In this, the condition of completely symmetric in-plane illumination could be satisfied early when the input light focused onto the center of the sample. To construct asymmetric in-plane illumination, the scientists blocked three-fourth of the area of the annular aperture. Jiang et al. showed that the setup was suited to study plasmonic nanostructures with sizes comparable to the focused spot size of the incident light beam.



Demonstration of electrical-field distribution rule for the 200 nm gold nanodisk monomer and dimer by s-SNOM. a Schematic of the s-SNOM measurement for s–s and s–p excitation–collection configurations. The wavelength of the excitation laser is 633 nm and the incidence angle with respect to the plane of the substrate is 30°. b Calculated normalized absorption spectra of 200 nm gold nanodisk monomer and dimer at incidence angle 30° under asymmetrical (dashed line) or symmetrical (solid line) illumination without phase delay. The gap size in the dimer is 30 nm. c Atomic-force microscopic (AFM) images of gold nanodisk monomer and dimer for s–s and s–p measurements. The red arrow represents the incidence direction of the laser and the blue dashed line represents the central axis of the nanodisk. d, e Experimental and simulated spatial distributions of the amplitude |A|, phase ϕ, and real part of electric-field component Ey in s–s measurement and Ez in s–p measurement for 200 nm gold nanodisk monomer and dimer. Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-019-0134-1

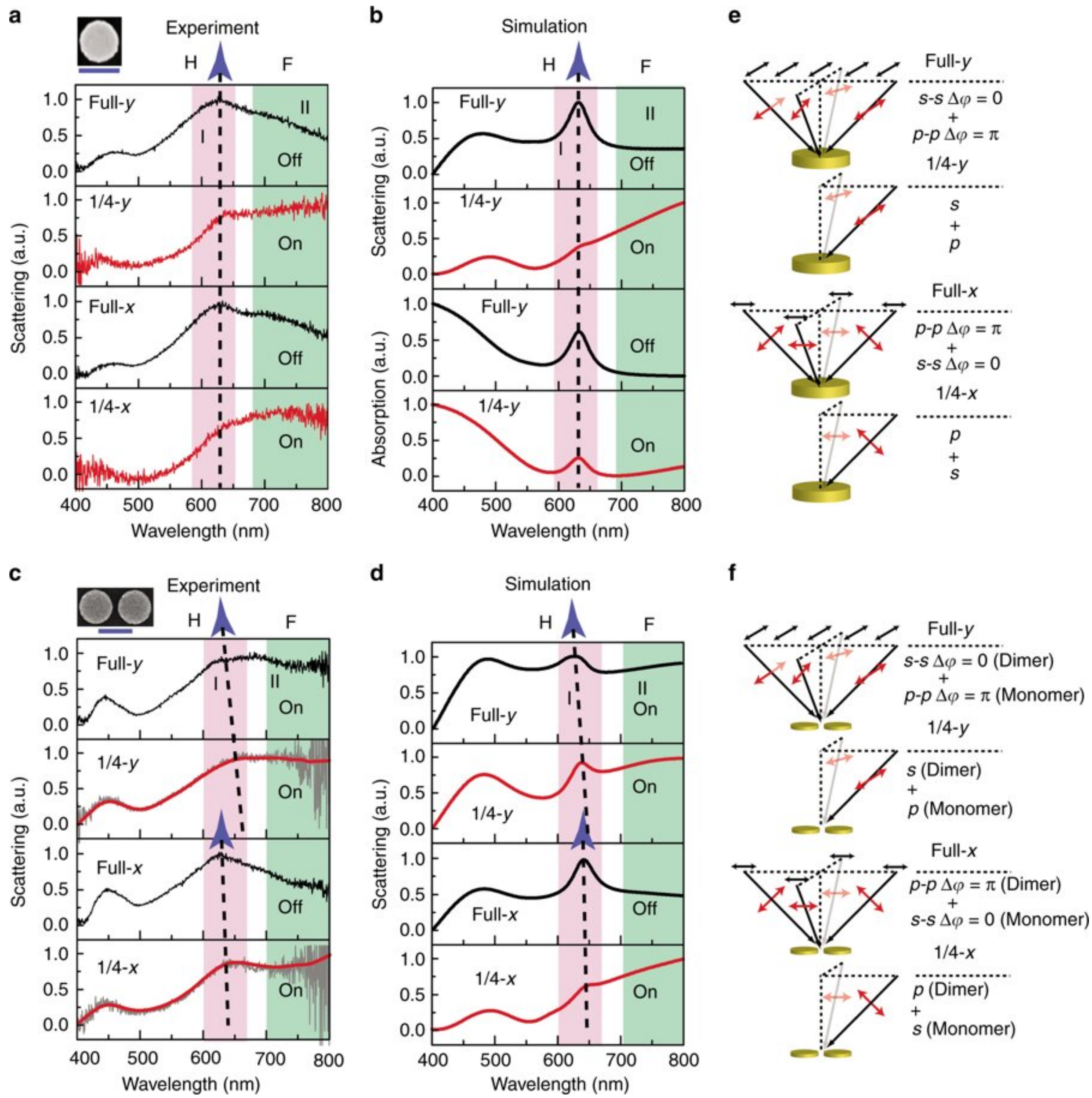
To engineer the gold nanodisk samples on silicon dioxide/silica (SiO_2/Si) substrates, Jiang et al. used electron-beam lithography (EBL) alongside a lift-off process. They completed the fabrication process by coating the substrate surface with a gold film and an underlying chromium (Cr) adhesion layer using electron-beam evaporation. The scientists then studied in-plane coherent control of plasmon resonances in the gold nanodisks and calculated the absorption spectra of gold nanodisk monomers ranging from diameters of 140 to 200 nm; fabricated on the SiO_2/Si substrate surface.

In the work, they established and experimentally verified the distribution rule of electrical-field components to realize destructive and constructive plasmon resonances in an axisymmetric plasmonic nanostructure. They showed how the in-plane coherent control of plasmon resonances strongly relied on the configuration and symmetry of plasmonic nanostructures, compared with out-of-plane coherent control. This feature can allow freedom in tailoring and engineering multiple plasmon resonances in other axisymmetric plasmonic structures, which include nanospheres, nanorod, nano bowtie and nanostructure polymers.



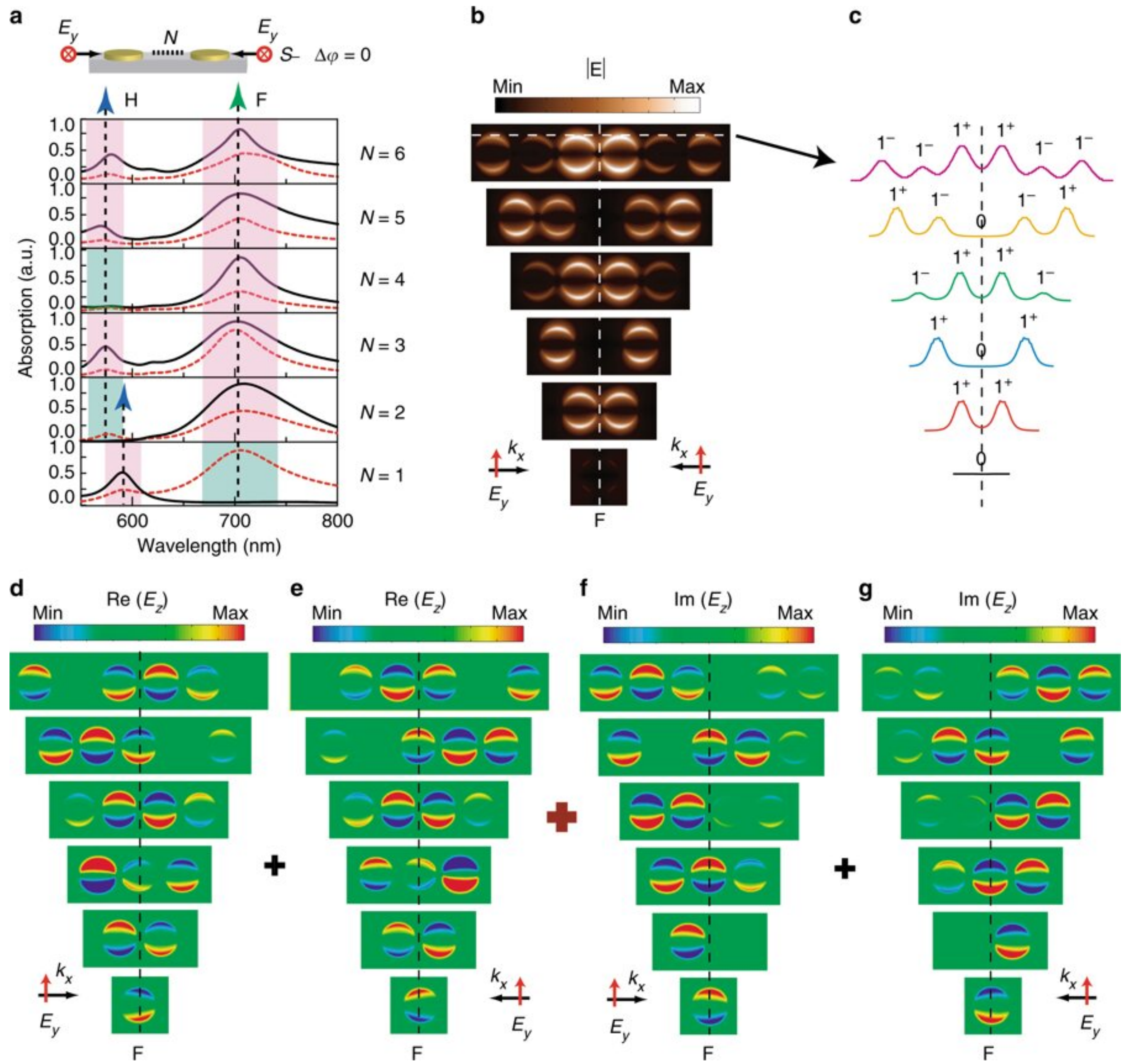
Demonstration of plasmonic switching by dark field (DF) scattering measurement of gold nanodisk monomer and dimer. a Normalized DF scattering spectra of gold nanodisk monomer with a diameter of 200 nm (SEM image) under full and quarter illumination. b The corresponding normalized simulated scattering and absorption spectra. c, d Normalized measured and simulated DF scattering spectra of gold nanodisk dimer with a diameter of 200 nm and a gap size of 30 nm (SEM image) under full and quarter illumination. The red solid curves in c are the smoothing results. The scale bar in SEM images is 200 nm. e, f Polarization diagrams of full and quarter illumination in the DF scattering measurement and simulation for gold nanodisk monomer and dimer. In both experiment and simulation, the excitation is s- or p-polarized and the collection is unpolarized. The black and red double-headed arrows represent the initial polarization and the polarization after focusing, respectively. Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-019-0134-1

To image the plasmon resonance modes in gold nanodisks the scientists used a polarization-sensitive s-SNOM technique, which can detect light at the nanometer scale regions directly beneath the tip of the atomic force microscopic (AFM) probe. The scientists used an s-s/s-p geometry scheme and engaged a dielectric (Si) tip for measurements. They illuminated the sample using laser radiation with an incident light of 30^0 relative to the plane of the substrate. Jiang et al. measured the amplitude and phase of the scattered signal based on the fourth harmonic of the tip-tapping frequency of the AFM tip. They used an analyzer in front of the detector to select the s- or p- polarized component of the scattered light.



Demonstration of plasmonic switching by dark field (DF) scattering measurement of gold nanodisk monomer and dimer. a Normalized DF scattering spectra of gold nanodisk monomer with a diameter of 200 nm (SEM image) under full and quarter illumination. b The corresponding normalized simulated scattering and absorption spectra. c, d Normalized measured and simulated DF scattering spectra of gold nanodisk dimer with a diameter of 200 nm and a gap size of 30 nm (SEM image) under full and quarter illumination. The red solid curves in c are the smoothing results. The scale bar in SEM images is 200 nm. e, f Polarization diagrams of full and quarter illumination in the DF scattering measurement and simulation for gold nanodisk monomer and dimer. In both experiment and simulation, the excitation is s- or p-polarized and the collection is unpolarized. The black and red double-headed arrows represent the initial polarization and the polarization after focusing, respectively. Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-019-0134-1

Jiang et al. also demonstrated plasmonic switching with dark field (DF) scattering measurements of a gold nanodisk monomer or dimer. In the experimental setup they used a confocal Raman microscopy system to measure the scattering spectra. They then used commercially available software packages to conduct numerical simulations in the study. The simulations included electrical-field distributions, absorption and scattering spectra for gold nanodisks. They simulated the complex electromagnetic parameters for gold and chromium incorporated in the experimental setup, based on previous publications.



Plasmonic encoding in gold nanodisk chains. a Calculated absorption spectra of gold nanodisk chains consisting of different numbers of nanodisks illuminated by the s-polarized in-plane plan wave coming from right side (dashed line) or both sides (solid line). The diameter of the nanodisk is 140 nm and the separation distance is 30 nm. The destructive and constructive plasmon resonances are represented by green and red colors, respectively. b Spatial distributions of electric-field amplitude |E| for the “F” plasmon resonances (peak position) under symmetrical illumination. c Sliced electric-field amplitude distributions along the chain’s edge (the white dashed line in b). d–g Corresponding spatial distributions of real and imaginary part of Ez when the s-polarized in-plane plan wave comes from the left side (d, f) and right side (e, g) respectively. Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-019-0134-1

In this way, Jiang et al. demonstrated proof-of-principle plasmonic switching and encoding in the study. They expect more potential applications based on the demonstrated ability for in-plane coherent control of plasmon resonance. For instance, scientists can use the method to study selective surface-enhanced spectra, where the photoluminescence or Raman signal of multiple molecules can be selectively enhanced. This will allow control of the on/off state of multiple plasmon resonances in a common nano-antenna. The scientists propose extending the plasmonic encoding scheme demonstrated in the study to plasmonic imaging, nano lasing and optical communication in nanocircuits. For instance, scientists can combine plasmonic nanostructure chains with different encoding characteristics to build logic gates (for Boolean logic operations) as well as design multichannel waveguides for all-optical information storage and processes.

More information: Liyong Jiang et al. In-plane coherent control of plasmon resonances for plasmonic switching and encoding, *Light: Science & Applications* (2019). DOI: 10.1038/s41377-019-0134-1

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