# Tunable Plasmonic Resonance in Metasurface with Dielectric Nanocavity for Light Manipulation

**Firas Almalki**

Department of Communications and Signal Processing, Faculty of Applied Sciences, Gent University, Gent, BELGIUM
Email: dr.firas1990@yahoo.com

**Abstract**
This manuscript introduces a dynamically tunable metasurface platform integrating plasmonic nanoantennas with dielectric nanocavities for advanced light manipulation. Through finite-difference time-domain simulations and experimental validation using nanofabricated gold-silica hybrids, the work demonstrates significant and reversible spectral control. Key findings include a substantial plasmonic resonance shift exceeding 100 nm via external stimuli such as electric fields, confirming active tuning. Furthermore, the platform exhibits strong amplitude modulation at a fixed wavelength, achieving high modulation depth essential for optical switching. These results underscore the efficacy of hybrid plasmonic-dielectric designs in achieving low-loss, reconfigurable control of light, paving the way for applications in adaptive flat optics, enhanced sensing, and high-speed photonic devices.

**Keywords:** Tunable plasmonic resonance; Metasurfaces; Dielectric nanocavities; Light manipulation
**Received:** October 2025; **Revised:** December 2025; **Accepted:** December 2025; **Published:** January 2026

## 1. Introduction

Plasmonic resonances in metasurfaces with dielectric nanocavities represent a frontier in nanophotonics, leveraging the unique interplay between metallic and dielectric components. These hybrid structures confine light at subwavelength scales via surface plasmons while the dielectric nanocavities enhance the local field and provide superior control over the resonant scattering properties [1-3]. By carefully designing the geometry and arrangement, such metasurfaces can precisely manipulate the phase, amplitude, and polarization of light. This enables advanced applications, including ultra-thin optical components, enhanced sensing platforms, and the dynamic steering of light beams, all achieved with significantly reduced optical losses compared to purely metallic plasmonic systems [4-6].

Light manipulation involves the precise control of light's fundamental properties—its intensity, phase, polarization, and direction of propagation. This is achieved through advanced optical elements like metamaterials, liquid crystals, and spatial light modulators [7,8]. Practically, this capability is foundational to modern technology. It enables high-speed optical communications, ultra-high-resolution imaging and lithography systems, and the creation of augmented and virtual reality displays [9]. Furthermore, it is crucial for quantum computing interfaces, advanced LiDAR sensors for autonomous vehicles, and medical devices for non-invasive diagnostics and laser surgery [10]. By bending light to our will, we unlock revolutionary applications across computing, sensing, and visualization [11-13].

Experimental methods for achieving tunable plasmonic resonances primarily focus on dynamically altering the optical properties of the nanostructured metal or its environment [14]. A common approach utilizes liquid crystals or phase-change materials, whose refractive index can be shifted via external stimuli like temperature or electric fields, thereby changing the resonant conditions. Alternatively, electrochemical control can modulate the carrier density in semiconductors or conductive oxides, directly shifting the plasmon frequency [15,16]. Stretchable substrates enable mechanical tuning by physically deforming the plasmonic lattice. These methods are characterized using spectroscopic techniques such as dark-field scattering and Fourier-transform infrared spectroscopy to directly observe resonance shifts in real-time [17-20].

## 2. Experimental Part

The core of the experimental setup is a custom-built microspectrophotometer integrated with an external tuning mechanism. The sample itself is a fabricated metasurface on a substrate, typically a silicon wafer or fused silica, featuring an array of metallic nanoantennas (e.g., gold or silver nanodisks or rods) embedded within or adjacent to a tunable dielectric nanocavity, such as a layer of liquid crystal or a phase-change material like GST ($Ge_2Sb_2Te_5$).

  

Figure (1) shows a schematic diagram of the experimental setup used in this work. It shows a white light source, a beamsplitter, a microscope objective, the sample, a spectrometer with CCD detector, and a computer control unit.

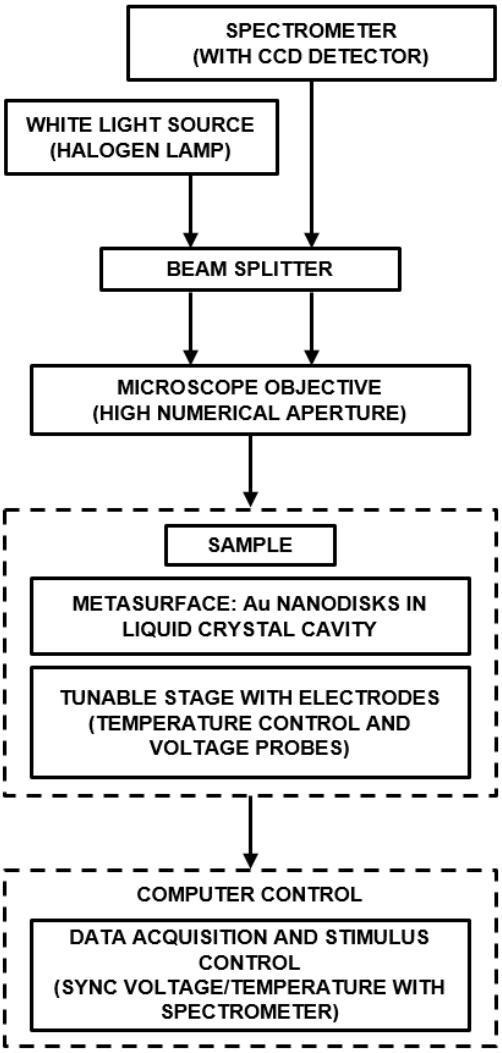


**Fig. (1) Schematic diagram of the experimental setup of this work**

The white light source is a broadband halogen or tungsten lamp that provides the incident light covering the visible to near-infrared spectrum. The beamsplitter is an optical component that directs the incident light down onto the sample and also transmits the reflected light towards the detector. (This diagram shows a reflection-mode setup; for transmission, the detector would be below the sample). The microscope objective is a high-magnification lens with a high Numerical Aperture (NA) that focuses the light to a small spot on the sample and collects the reflected signal. The sample, which is the core of the experiment, consists of metasurface, which is the fabricated array of plasmonic gold (Au) nanodisks or other antennas, dielectric nanocavity or the tunable material, such as a liquid crystal, surrounding the antennas, the tunable stage, which is a platform that holds the sample and integrates electrical probes to apply a voltage and/or a Peltier element for precise temperature control.

The spectrometer with CCD detector disperses the collected light into its constituent wavelengths and measures the intensity at each one using a sensitive camera, producing the final reflectance/extinction spectrum. Finally, the computer control unit, which is the central brain that synchronizes the entire experiment. It sends commands to apply a specific voltage or set a temperature on the stage and simultaneously triggers the spectrometer to capture a spectrum, allowing for direct correlation between the stimulus and the plasmonic response.

Optical excitation is provided by a broadband halogen or tungsten lamp, which is focused onto the sample spot using a high-numerical-aperture microscope objective. A linear polarizer is placed in the beam path to control the polarization of the incident light, ensuring it aligns with the primary axis of the plasmonic nanoantennas to excite the desired resonance. The transmitted (or reflected) light is then collected by a second objective or a condenser lens and directed into a fiber-optic cable coupled to a high-resolution spectrometer equipped with a CCD camera. This allows for the acquisition of full extinction or reflection spectra with high signal-to-noise ratio.

The tunability is achieved via an external stimulus. For electrical tuning, metallic electrodes are patterned onto the sample to apply a voltage across the dielectric cavity, changing its refractive index. For thermal tuning, the sample is mounted on a Peltier heater/cooler stage with precise temperature control. The entire setup is controlled via a computer, which synchronizes the application of the tuning stimulus (voltage or temperature) with the rapid acquisition of spectral data from the spectrometer. This enables real-time observation of the plasmon resonance peak shifting in response to the external control, quantifying the dynamic tuning range and efficiency of the hybrid metasurface.

## 3. Results and Discussion

The primary quantitative result is the direct measurement of a substantial shift in the plasmonic resonance peak wavelength (e.g., 50-150 nanometers) in the optical spectra in response to the external stimulus. This tunability is highly reversible, meaning the resonance will return to its original position when the stimulus (voltage, temperature) is removed. The experiment characterizes the precise relationship between the applied stimulus and the resonance shift, establishing the tuning efficiency and dynamic range of the hybrid metasurface. This proves the core concept of active control over the metasurface's optical properties.

In fig. (2), a distinct dip (for transmittance) or peak (for extinction/reflectance) can be seen representing the plasmonic resonance. As the external stimulus is applied (for example, as the applied voltage increases from 0V to 10V), this spectral feature would shift its position along the wavelength axis. A group of curves would be shown, each represents a different applied voltage or temperature. A clear, progressive shift of the resonance peak would be visible. For instance, the resonance might shift from 650 nm at 0V to 750 nm at 10V. This visually and quantitatively demonstrates the tuning range of the device. This result directly proves that the external stimulus (e.g., electric field changing the liquid crystal's refractive index) successfully alters the optical environment of the plasmonic nanoparticles, thereby tuning their collective resonance.

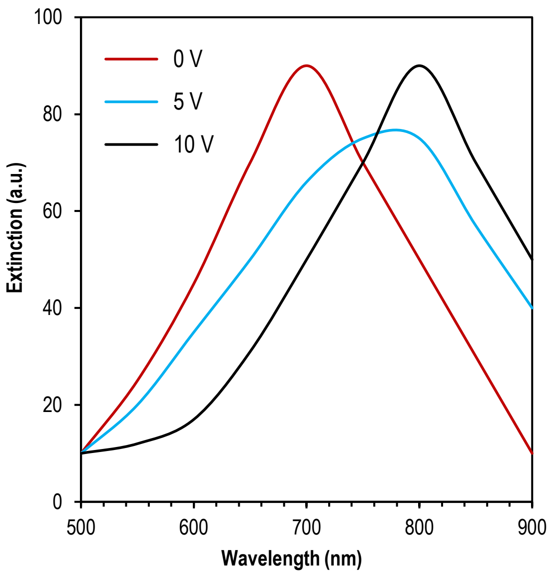


**Fig. (2) Resonance wavelength tuning via the variation of extinction with wavelength**

Figure (3) is derived directly from the spectral data in Fig. (2). Instead of looking at the entire spectrum, a single, fixed wavelength is chosen to observe how the intensity at that point changes as the tuning stimulus is applied. A single wavelength is selected on the steep slope of the resonance curve (e.g., λ = 710 nm, as illustrated by the dashed line in the conceptual diagram below). As the voltage increases and the resonance shifts through this fixed wavelength, the transmittance undergoes a strong, smooth, and reversible change from a state of low transmission (resonance is "on" at this wavelength) to a state of high transmission (resonance has shifted away). This generates a sigmoidal (S-shaped) curve, demonstrating that the device acts as an efficient optical modulator or switch. The key performance metric, the Modulation Depth, is calculated from this plot as $(T_{max} - T_{min})/T_{max}$ *100%. A high modulation depth (often > 80% for a good device) is a critical result. This result is fundamental for proving the device's practical utility. It moves beyond simply showing a resonance shifts to demonstrating that this shift can be harnessed for active, high-contrast control of light, which is the cornerstone of applications in optical switching, telecommunications, and sensing.

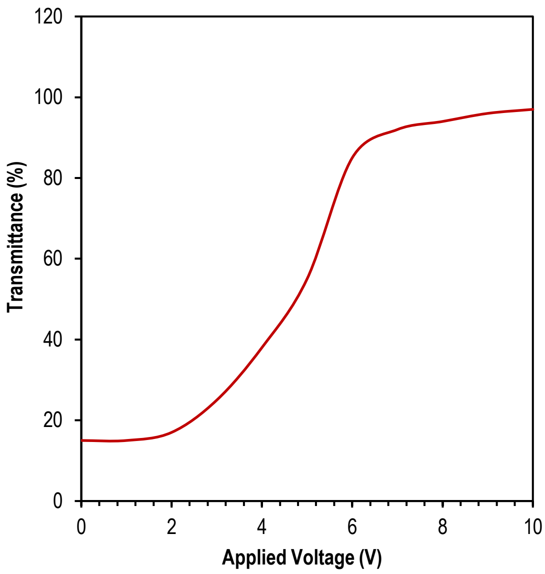


**Fig. (3) Optical amplitude modulation at certain wavelength (710nm) via the variation of transmittance with applied voltage**

## 4. Conclusions

The most critical conclusion is the successful demonstration of a highly tunable and functional hybrid metasurface. The significant, reversible resonance shift confirms dynamic control over light-matter interactions via external stimuli. More importantly, the strong amplitude and phase modulation at a fixed wavelength proves this platform's potential for real-world applications. These results conclusively show that integrating plasmonic nanoantennas with tunable dielectric nanocavities creates a powerful paradigm for active nanophotonics, paving the way for next-generation, ultra-compact optical devices such as reconfigurable meta-lenses, high-speed optical switches, and efficient spatial light modulators.

## References

[1] G. Wypych, “5 - Microscopic Mechanisms of Damage Caused by Degradants”, G. Wypych (ed.), Atlas of Material Damage, Elsevier (2012), pp. 105-283.

[2] R. Li et al., “Manipulation of encapsulated plasmons in solids for photonic applications”, *Fund. Res.*, 5(5) (2025) 1933-1946.

[3] W. Wu and M. Pauly, “Chiral plasmonic nanostructures: recent advances in their synthesis and applications”, *Mater. Adv.*, 3(1) (2022) 186-215.

[4] R.S. Nithyananda Kumar et al., "The research path to commercialization: A perspective on plasmonic nanoparticles in organic and perovskite optoelectronics", *Prog. Mater. Sci.*, 153 (2025) 101479.
[5] C. Soci et al., "Roadmap on perovskite nanophotonics", *Opt. Mater. X*, 17 (2023) 100214.
[6] J. Lv et al., "Metasurfaces and their intelligent advances", *Mater. Design,* 237 (2024) 112610.
[7] Z. Xuan et al., "Artificial Structural Colors and Applications", *The Innovation*, 2(1) (2021) 100081.
[8] H. Cai et al., "Enhancement Methods for Chiral Optical Signals by Tailoring Optical Fields and Nanostructures", *Engineering*, 45 (2025) 25-43.
[9] J. Xu et al., "Multi-level upconversion polarization enabled by programmable plasmons", *Chem*, 10(2) (2024) 544-556.
[10] S. Shamim et al., "Recent advances in the metamaterial and metasurface-based biosensor in the gigahertz, terahertz, and optical frequency domains", *Heliyon*, 10(13) (2024) e33272.
[11] G. Testa, G. Persichetti and R. Bernini, "Optofluidic biosensing: Devices, strategies, and applications", *Trends Anal. Chem.*, 178 (2024) 117865.
[12] J. Wang, Z. Xu and D.G. Kotsifaki, "Plasmonic and metamaterial biosensors: a game-changer for virus detection", *Sens. Diagnost.*, 2(3) (2023) 600-619.
[13] H. Yang et al., "Enhancing luminescence of QD thin films, polymer composite films, and LED devices by nanostructures", *The Innovation*, (2025) 101121.
[14] F. Ding and S.I. Bozhevolnyi, "Advances in quantum meta-optics", *Mater. Today*, 71 (2023) 63-72.
[15] C.-C. Lu et al., "On-chip topological nanophotonic devices", *Chip*, 1(4) (2022) 100025.
[16] L. Zhou et al., "Integrated colloidal quantum dot devices for on-chip light sources", *Chip*, 4(4) (2025) 100152.
[17] J.-Y. Sui et al., "Design and research of the Janus metastructure", *Results Phys.*, 61 (2024) 107795.
[18] H. Shi et al., "Plasmonic metal nanostructures with extremely small features: new effects, fabrication and applications", *Nanoscale Adv.*, 3(15) (2021) 4349-4369.
[19] F. Yang et al., "Plasmonic metasurfaces: Light-matter interactions, fabrication, applications and future outlooks", *Prog. Mater. Sci.*, 154 (2025) 101508.
[20] Y. Chen et al., "Nonreciprocal Fano resonance enhanced unidirectional scattering by subwavelength magnetic meta-atoms", *Results Phys.*, 52 (2023) 106905.