

Article

Analytical-Numerical Modeling of Filling-Fraction-Dependent Plasmonic Coupling in Nanostructured Metasurfaces Under Kretschmann Configuration

Karan K. Singh ¹, Guillermo E. Sánchez-Guerrero ¹, Perla M. Viera-González ¹,
Carlos A. Fuentes-Hernández ², María T. Romero de la Cruz ³, Eduardo Martínez-Guerra ⁴,
Rodolfo Cortés-Martínez ^{1,*} and Edgar Martínez-Guerra ^{1,*}

¹ Facultad de Ciencias Físico-Matemáticas, Universidad Autónoma de Nuevo León, Pedro de Alba S/N, San Nicolás de los Garza 66451, Mexico; kishor.singh@uanl.edu.mx (K.K.S.); guillermo.sanchezgr@uanl.edu.mx (G.E.S.-G.); perla.vieragn@uanl.edu.mx (P.M.V.-G.)

² ITS Sur de Guanajuato, Tecnológico Nacional de México, Av. Educación Superior 2000, Uriangato 38982, Mexico; ca.fuentes@itsur.edu.mx

³ Facultad de Ciencias Físico-Matemáticas, Universidad Autónoma de Coahuila, Unidad Campo Redondo Edificio A, Saltillo 25280, Mexico; teresa.romero.cruz@uadec.edu.mx

⁴ CIMAV-Subsede Monterrey, Centro de Investigación en Materiales Avanzados, Av. Alianza Norte 202 Parque de Investigación e Innovación Tecnológica, Apodaca 66628, Mexico; eduardo.martinez@cimav.edu.mx

* Correspondence: rodolfo.cortesm@uanl.edu.mx (R.C.-M.); edgar.martinezgrr@uanl.edu.mx (E.M.-G.); Tel.: +52-81-83-294030 (E.M.-G.)

Abstract

Surface plasmon resonance (SPR) sensors based on nanostructured metasurfaces offer enhanced sensitivity through engineered electromagnetic responses. In this study, we present an analytical and numerical investigation of the plasmonic behavior of gold nanopillar (Au-NP) and nanohole (Au-NH) arrays under both *p*- and *s*-polarized illumination, employing the Effective Medium Theory (EMT) in combination with the Transfer Matrix Method (TMM). The study combines Effective Medium Theory (EMT) and the Transfer Matrix Method (TMM) to describe the macroscopic optical response of multilayer plasmonic systems. For *p*-polarization, the nanostructure geometry strongly modulates the real and imaginary parts of the effective permittivity, with nanoholes supporting stronger SPR coupling and reduced optical losses compared to nanopillars. Under *s*-polarization, the effective permittivity remains largely invariant, primarily driven by the filling fraction. The analysis reveals that polarization-dependent behavior arises from boundary-condition-mediated coupling mechanisms governing surface plasmon excitation, aligning with classical plasmonic theory. Benchmarking against analytical dispersion relations and published experimental data for Au/BK7 systems shows close agreement within $\pm 2^\circ$, confirming the physical consistency of the EMT–TMM framework. These results provide a systematic description of how polarization and filling fraction jointly modulate SPR coupling. The results offer a foundation for the rational design of plasmonic coatings and SPR-supporting metasurfaces by elucidating macroscopic coupling trends; however, no quantitative sensor performance metrics, such as refractive index sensitivity or figure of merit, are evaluated in this work.

Keywords: Au Nanopillars (Au-NPs); Au Nanoholes (Au-NHs); nanostructured metasurfaces; effective permittivity; filling fraction



Academic Editors: Luciana R. P. Kassab, Raul Rangel-Rojo and Rafael Salas-Montiel

Received: 17 December 2025

Revised: 27 February 2026

Accepted: 6 March 2026

Published: 24 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Surface plasmon resonance (SPR) remains a central mechanism in nanophotonics due to its sensitivity to interfacial dielectric perturbations and its widespread implementation in optical sensing platforms. In particular, the Kretschmann configuration continues to serve as a practical and scalable architecture for surface plasmon polariton (SPP) excitation, enabling angularly resolved interrogation of metal-dielectric interfaces. While the SPR response of continuous noble-metal films is well understood, the extension of this framework to nanostructured metasurfaces remains nontrivial, especially when subwavelength patterning disrupts lateral continuity [1–14].

Recent advances in plasmonic metasurfaces have emphasized localized resonances supported by nanopillars, nanoholes, and hybrid architectures [15–20], often analyzed through full-wave numerical simulations or near-field characterization. Although these approaches provide detailed spatial information, they are computationally intensive and offer limited analytical insight into how global design parameters, such as filling fraction and polarization, collectively govern macroscopic coupling conditions in multilayer SPR systems. As a result, a systematic analytical description linking nanostructural geometry to Kretschmann-type SPR excitation has not yet been comprehensively developed.

In this context, effective medium-based descriptions, when applied within clearly defined validity limits, offer a complementary perspective. Rather than resolving localized near-field effects, effective medium theory (EMT) enables the extraction of averaged optical parameters that determine momentum-matching, damping, and angular reflectance minima in stratified plasmonic systems. When combined with the transfer matrix method (TMM), EMT provides a physically consistent framework for analyzing filling fraction-dependent trends in reflectance without performing full-wave simulations. This formulation lays a theoretical foundation for the rational design of metasurfaces supporting Kretschmann-type SPR excitation by controlling macroscopic resonance conditions; the present study does not address sensor optimization, refractive-index sensitivity, or figure-of-merit calculations. Despite its widespread use in metamaterial optics, the combined EMT–TMM approach has seen limited systematic benchmarking for nanostructured plasmonic layers operating under Kretschmann excitation. The present work addresses this gap by developing and validating an analytical/numerical EMT–TMM framework to investigate polarization and filling fraction-dependent plasmonic coupling in gold-based metasurfaces. The study focuses on three representative geometries, nanopillars, nanoholes, and hollow nanopillars, treated as homogenized layers characterized by an effective permittivity determined by their volumetric filling fraction. The present framework focuses on macroscopic coupling behavior in stratified plasmonic systems. The objective of this work is to systematize how nanostructural geometry modifies classical SPR coupling conditions. By benchmarking EMT–TMM predictions against analytical dispersion relations and previously reported experimental data for Au/BK7 systems, we establish quantitative consistency within $\pm 2^\circ$ in the predicted resonance angle. This validation supports the use of the framework as a design-oriented analytical tool for assessing how polarization and filling fraction jointly modulate SPR coupling efficiency. Importantly, polarization-resolved analysis reveals that geometry-dependent effects arise primarily under *p*-polarized illumination, where boundary condition-driven coupling governs the excitation of SPP-like modes. In contrast, *s*-polarized responses are largely insensitive to detailed nanostructural topology and depend mainly on volumetric metal content. This distinction provides a physically transparent explanation for polarization-dependent stability and tunability in metasurface-based SPR sensors. Overall, this study delivers a concise, validated analytical framework for interpreting SPR coupling in nanostructured metasurfaces under the Kretschmann configuration. By delineating the applicability range of EMT,

the study establishes a consistent analytical basis for interpreting polarization-dependent coupling in nanostructured metasurfaces, bridging the gap between continuous film SPR theory and nanostructured plasmonic architectures. The present work provides a systematic application of established EMT and TMM formulations to periodic gold nanopillar and nanohole geometries under Kretschmann excitation. Instead, its contribution lies in the systematic application and clarification of established theoretical approaches, namely EMT and TMM, for periodic gold nanopillar and nanohole geometries under the Kretschmann configuration. The framework enables the identification of macroscopic, polarization-dependent design trends relevant to metasurface-based SPR architectures.

2. Materials and Methods

2.1. Optical Configuration

Calculations were performed for multilayer structures in the Kretschmann configuration consisting of a BK7 substrate, an optional Ti adhesion layer, a gold layer (continuous or nanostructured), and an air superstrate. Optical constants for Au, Ti, and BK7 were taken from literature-reported values at the operating wavelengths. Angularly resolved reflectance was computed at fixed wavelength under *p*- and *s*-polarized illumination.

2.2. Transfer Matrix Calculations

Angular reflectance spectra were calculated using the transfer matrix method (TMM) for planar, isotropic, laterally homogeneous layers. Each layer is characterized by its complex refractive index n_i and thickness d_i . Wave propagation inside the layer is described by the propagation matrix.

$$P_i = \begin{pmatrix} e^{ik_{z,i}d_i} & 0 \\ 0 & e^{-ik_{z,i}d_i} \end{pmatrix}, \quad k_{z,i} = k_0 n_i \cos \theta_i. \quad (1)$$

where, $k_0 = \frac{2\pi}{\lambda_0} = \frac{\omega}{c}$, λ_0 is the free space wavelength, ω the angular frequency, and θ_i is the propagation angle inside the layer. Interfaces between adjacent layers are described using Fresnel reflection and transmission coefficients, combined into the interface matrix:

$$T_{i,i+1} = \frac{1}{t_{i,i+1}} \begin{pmatrix} 1 & r_{i,i+1} \\ r_{i,i+1} & 1 \end{pmatrix}. \quad (2)$$

The global transfer matrix is obtained by sequential multiplication of all interface and propagation matrices. The reflectance is calculated from the resulting reflection coefficient at the prism interface (Figure 1). The implementation was validated by reproducing the surface plasmon resonance (SPR) angle of reference Au/BK7 systems, with agreement within $\pm 2^\circ$ compared to reported analytical and experimental data (Figure 2).

2.3. Effective Medium Approximation for Nanostructured Layers

Nanostructured gold metasurfaces (nanopillars, nanoholes, and hollow nanopillars) were modeled as homogenized layers characterized by an effective complex permittivity. The filling fraction was defined as follows:

$$f = \frac{V_{\text{inclusion}}}{V_{\text{unit cell}}}, \quad (3)$$

The effective permittivity was estimated using the Maxwell–Garnett relation,

$$\epsilon_{\text{eff}} = \epsilon_h \frac{(1 + 2f)\epsilon_i + 2(1 - f)\epsilon_h}{(1 - f)\epsilon_i + (2 + f)\epsilon_h}, \quad (4)$$

where ε_i is the permittivity of gold, and ε_h is the host permittivity. This effective medium description was used exclusively to capture averaged optical trends associated with variations in filling fraction and geometry. Given that feature sizes (160–250 nm) approach the operating wavelength, the extracted effective permittivity ε_{eff} values are employed to analyze relative optical trends across geometries. Because the investigated nanostructures do not satisfy the strict quasistatic condition, the EMT–TMM framework is employed to analyze macroscopic coupling trends in the effective optical response. Phenomena such as localized surface plasmon resonances and near-field enhancement are explicitly excluded from the scope of the present analysis, in accordance with the objective of developing an analytical/numerical framework for effective plasmonic behavior. Within this framework, Equations (6) and (7) correspond to Rayleigh’s formulation and the linear mixing rule for p - and s -polarized excitation, respectively, and are used as polarization-specific macroscopic approximations consistent with the qualitative use of EMT adopted in this work. Consequently, results derived from EMT–TMM analyses describe filling-fraction-dependent macroscopic coupling behavior within the homogenization approximation. Previous numerical benchmarks and experimental [21,22] indicate that the Maxwell–Garnett effective medium theory remains quantitatively reliable when the structural feature size is smaller than approximately $\lambda/8$. For larger inclusions approaching $\lambda/3$, deviations between EMT-predicted and full-wave-calculated permittivities can reach 25–30. Accordingly, the reported results enable identification of relative permittivity trends and polarization-dependent coupling conditions within the EMT approximation. This quantified boundary establishes the operational domain of the EMT–TMM framework applied throughout the present study. It is further emphasized that classical Maxwell–Garnett-type effective medium formulations are rigorously valid only in the dilute inclusion regime, typically for volume fractions not exceeding approximately $f \leq 0.3$. In the present work, filling fractions exceeding this threshold are intentionally explored solely to examine qualitative, macroscopic trends and polarization-dependent behavior in the effective optical response, rather than to claim quantitative accuracy of the homogenized parameters. Accordingly, results obtained for $f > 0.3$ extend the EMT-based analysis to higher filling fractions for comparative evaluation of macroscopic optical response, consistent with the stated objective of analyzing macroscopic effective optical behavior rather than exact homogenization or device-level performance. Within this context, Equations (6) and (7), corresponding to Rayleigh’s formulation and the linear mixing rule for p - and s -polarized excitation, respectively, are employed as polarization-specific macroscopic approximations appropriate for qualitative trend analysis.

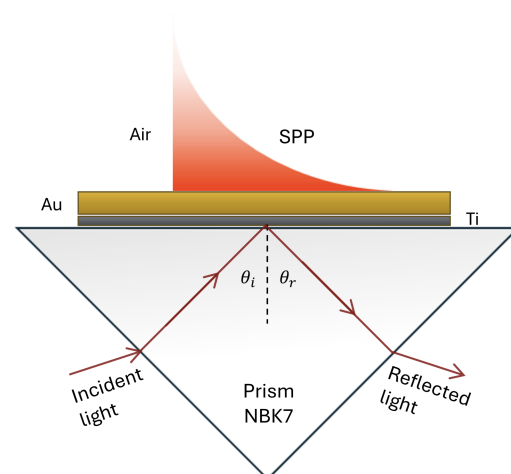


Figure 1. Schematic representation of the Kretschmann configuration used for surface plasmon resonance (SPR) excitation. A p -polarized light beam is incident at an angle θ_1 through a BK7 glass

prism, undergoing total internal reflection at the prism/metal interface. A thin titanium (Ti) adhesion layer and a gold (Au) film form the plasmon supporting multilayer atop the prism. The reflected light exhibits an angular dip in intensity corresponding to resonant coupling of the incident photons to surface plasmon polaritons (SPPs) at the Au/air interface. This configuration enables momentum matching between the incident evanescent field and the plasmon mode.

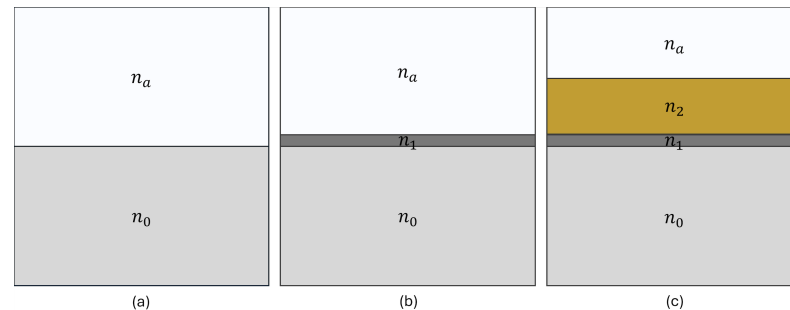


Figure 2. (a) BK7/air, (b) BK7/Ti/air, and (c) BK7/Ti/Au/air configurations illustrating increasingly complex multilayer plasmonic systems. The schematic represents the refractive indices of each layer as n_0 (BK7 substrate), n_1 (Ti layer), n_2 (Au layer), and n_a (air superstrate).

2.4. Polarization Treatment

Reflectance spectra were computed independently for p - and s -polarized incident light. Only p -polarized illumination was considered for surface plasmon polariton (SPP) coupling analysis. The angular resonance condition was identified from reflectance minima satisfying

$$k_0 n_p \sin \theta = \text{Re}(k_{\text{SPP}}), \quad (5)$$

where n_p is the prism refractive index; for non-magnetic media, the dielectric constant is related to the refractive index by $\epsilon_j = n_j^2$. Results obtained under s -polarization were used as a reference to evaluate geometry-insensitive, volumetric optical responses. The EMT-TMM framework employed here is restricted to far-field reflectance and macroscopic coupling behavior. Localized surface plasmon resonances, near-field distributions, and strong-coupling effects are not resolved within this model. The results offer a foundation for the rational design of plasmonic coatings and SPR-supporting metasurfaces by elucidating macroscopic coupling trends; however, no quantitative sensor performance metrics such as refractive-index sensitivity or figure of merit are evaluated in this work. The computational analysis is based on analytical EMT-TMM formulations assuming homogenized, laterally uniform layers. The EMT-TMM approach is analytical and numerical, assuming homogenized, laterally uniform layers. Accordingly, the modeling setup is fully defined by the specified material permittivities, layer thicknesses, wavelength range, angle of incidence, polarization state, and filling fraction, without the use of numerical solvers, meshing procedures, or convergence parameters. Therefore, while it provides physically consistent reflectance and effective permittivity trends, with Equations (6) and (7) implementing Rayleigh's formulation and a linear mixing rule for p - and s -polarized excitation as polarization-specific macroscopic approximations, the formulation evaluates far-field reflectance and effective permittivity trends without resolving spatial field distributions [23].

$$\epsilon_{\text{eff}}^p = \epsilon_h \frac{\epsilon_f(1 + f_1) + \epsilon_h(1 - f_1)}{\epsilon_f(1 - f_1) + \epsilon_h(1 + f_1)}, \quad (6)$$

$$\epsilon_{\text{eff}}^s = \epsilon_h(\lambda)(1 - f_1) + f_1\epsilon_f(\lambda), \quad (7)$$

The polarization state of the incident light plays a critical role in determining the feasibility of SPR excitation. Only transverse magnetic (TM) or p -polarized light possessing

an electric field component normal to the metal/dielectric boundary satisfies the boundary conditions for coupling to SPPs [11,14,17]. Throughout this work, *p*-polarization (TM) is defined as having the electric field in the plane of incidence, whereas *s*-polarization (TE) corresponds to an electric field perpendicular to the plane of incidence. The plane of incidence is defined by the incident wavevector and the surface normal of the planar multilayer stack. This principle, well established in classical plasmonic theory and verified experimentally in numerous nanostructured systems [11,14], underpins the design strategy adopted here. The nanostructured layers are treated as laterally homogeneous effective media; therefore, no specific in-plane structural orientation with respect to the plane of incidence is considered. By examining both *p*- and *s*-polarized light responses, the study assesses how anisotropic geometries and polarization-dependent field distributions influence the real and imaginary parts of the effective permittivity, offering new insights into how metasurfaces can replicate or enhance the SPR behavior of continuous thin films. Material dispersion and optical losses are treated consistently throughout all calculations by employing wavelength-dependent complex permittivities for all constituent materials in both the EMT and TMM formulations. These complex permittivities are applied uniformly in the evaluation of reflectance, effective permittivity, and polarization-dependent response. Therefore, while it provides physically consistent reflectance and effective permittivity trends, with Equations (6) and (7) incorporating the same dispersive and lossy material parameters as polarization-specific macroscopic approximations, it does not capture near field distributions or localized resonance features that would be accessible through full wave numerical models. It is further emphasized that the effective medium relations employed in this work provide an averaged homogenized description of the nanostructure geometry within Maxwell–Garnett formalism. In particular, classical formulations derived for spherical inclusions, as well as shape-modified models developed for ellipsoidal, disk-like, or cylindrical inclusions, cannot rigorously represent the complex, non-spherical morphologies of the nanopillar and nanohole arrays investigated here.

3. Results

This section presents a systematic study of the plasmonic response in gold-based thin films and metasurface configurations, progressing from conventional surface plasmon resonance (SPR) phenomena to the optical behavior of nanostructured systems. The objective is to clarify how variations in material composition, geometry, and layer thickness influence plasmonic coupling, damping, and resonance conditions. The first part examines SPR excitation in planar gold films of different thicknesses within the Kretschmann configuration. Reflectance spectra are analyzed to determine the conditions for efficient coupling, highlighting the balance between electromagnetic field confinement and optical losses. This provides a quantitative reference for the dependence of plasmonic response on film thickness. The second part investigates the effect of titanium as an adhesion layer, focusing on how Ti thickness alters resonance efficiency and damping. The analysis identifies practical limits that ensure adequate film adhesion while minimizing optical degradation, acknowledging that ultrathin Ti layers may exhibit discontinuity. The third section considers the combined BK7/Ti/Au multilayer configuration, evaluated using the transfer matrix method (TMM). This model explores the interplay between layer thickness, refractive index contrast, and resonance strength. Finally, gold-based metasurfaces comprising nanopillar and nanohole arrays are discussed. Their periodic structure introduces propagating plasmonic modes, which are analyzed using effective medium and TMM approaches to reveal general spectral trends within their valid physical range. Overall, this structured progression from thin films to metasurfaces provides a coherent theoretical framework for understanding and guiding the design of gold-based plasmonic systems.

3.1. SPP Modes Supported by Gold Thin Films

The excitation of surface plasmon polaritons (SPPs) in metallic thin films depends sensitively on film thickness, which governs both optical field penetration and coupling efficiency at the metal/dielectric interface. To clarify this dependence, the reflectance response of planar gold (Au) films with thicknesses of 250, 125, 100, 80, and 75 nm was calculated using the transfer matrix formalism under *p*-polarized illumination (Figure 3).

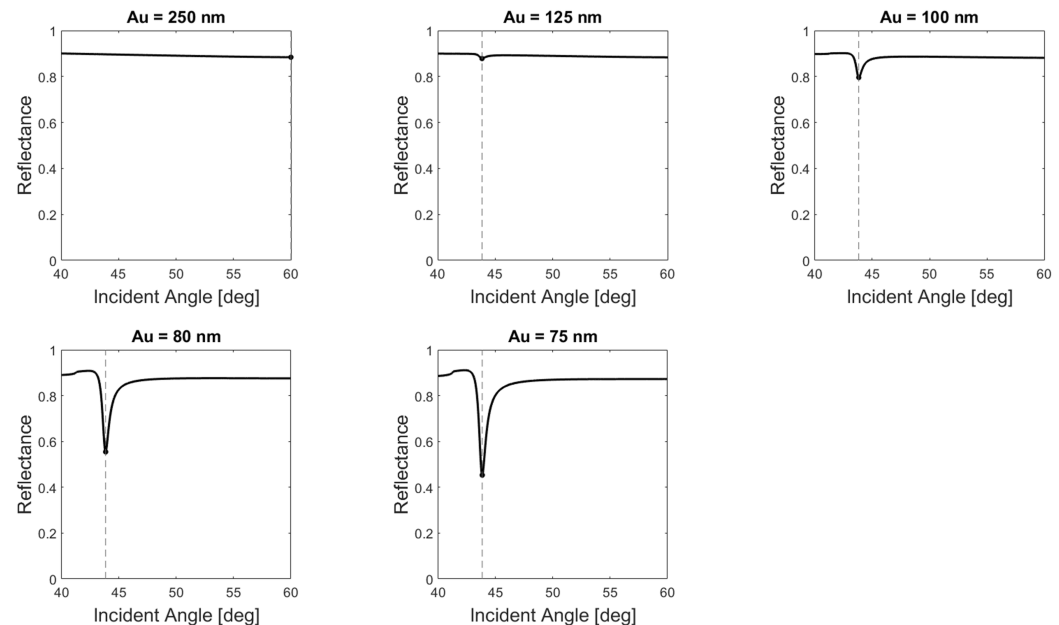


Figure 3. Reflectance as a function of incidence angle for gold thin films of thicknesses 250, 125, 100, 80, and 75 nm. The deepening of the reflectance minimum with decreasing film thickness indicates enhanced coupling to the surface plasmon polariton mode.

These simulations aim not to predict localized plasmon or extraordinary optical transmission effects, which require full-wave electromagnetic models, but rather to identify the angular conditions supporting classical Kretschmann-type SPP excitation. The computed reflectance spectra exhibit a progressive evolution of the plasmonic response as the Au film thickness decreases. For the 250 nm film, the reflectance remains nearly constant across the incident angle range, confirming that the evanescent field generated at the prism/metal boundary does not effectively reach the outer interface to excite an SPP. A shallow and broad reflectance minimum appears in the 125 nm film, indicating the onset of partial coupling between the incident mode and the surface plasmon. At 100 nm, the dip becomes more pronounced, revealing enhanced field overlap. The strongest and sharpest minimum occurs for the 75 nm film, where the reflectance approaches a local minimum but remains finite, consistent with partial, not complete, plasmonic absorption. To assess the accuracy of the implemented Transfer Matrix Method (TMM) formulation, reflectance spectra were compared with reported experimental trends for Au films in the Kretschmann configuration [22,24]. For a 50–80 nm Au layer on BK7 glass, the present model predicts a reflectance minimum at incidence angles between 43° and 45°, in close agreement (within $\pm 2^\circ$) with measured resonance angles reported in Refs. [22,24]. This consistency confirms that the analytical formalism correctly reproduces the canonical surface plasmon resonance (SPR) response of continuous Au films. Hence, subsequent results for multilayer and metasurface geometries can be interpreted as physically consistent extrapolations of this validated baseline. These results align with established experimental and theoretical reports showing that efficient SPP coupling in Au films occurs for thicknesses between approximately 45 nm and 80 nm, depending on the refractive indices

of the substrate and sensing medium [22,25]. The present data confirm that reducing Au thickness enhances coupling strength and angular sensitivity, while thicker layers suppress plasmon excitation due to insufficient field penetration. The choice of a 75 nm gold thickness in this study reflects a design compromise rather than an optimization claim. In practice, films below 60 nm often suffer from discontinuities or island formation, particularly when deposited over a titanium adhesion layer. Because ultrathin (1–2 nm) Ti films may not form continuous, optically homogeneous layers, their contribution is treated here as an interfacial boundary condition rather than a uniform optical spacer. A slightly thicker Au film thus ensures structural continuity and reproducible optical characteristics without compromising SPP visibility. This thickness range (70–80 nm Au with 1–3 nm Ti) corresponds to standard values employed in experimental Kretschmann-type configurations, where it provides an optimal compromise between field penetration depth (≈ 200 nm in glass) and reflectance minimum contrast [24,26,27]. These parameters also guarantee good adhesion and surface smoothness under typical magnetron-sputtering or thermal-evaporation conditions [27]. The interpretation of Figure 3 is therefore limited to identifying the qualitative dependence of reflectance on film thickness within the validity range of the transfer matrix method. No claims are made regarding localized plasmon modes, extraordinary transmission, or strong coupling effects, which require full-wave modeling for rigorous confirmation. The trends predicted nonetheless provide a consistent framework for selecting Au thicknesses that balance plasmonic sensitivity with fabrication reliability in Ti/Au-based Kretschmann configurations.

3.2. Titanium-Induced Losses and Their Effect on SPR Excitation

The influence of titanium (Ti) thickness on surface plasmon resonance (SPR) excitation was systematically analyzed through reflectance simulations as a function of incident angle for BK7/Ti/Au (75 nm)/air multilayer systems (Figure 4). These calculations reveal a pronounced dependence of the plasmonic coupling efficiency on the optical absorption of the Ti adhesion layer. Titanium is commonly employed to promote adhesion between gold (Au) and dielectric substrates due to its mechanical stability; however, its intrinsic losses can significantly attenuate the surface plasmon polariton (SPP) mode. The range of Ti thicknesses considered in this study (1–40 nm) covers realistic deposition values from minimal adhesion layers (1–3 nm) to intentionally thicker interlayers used to modulate damping and adhesion in experimental studies. Varying the Ti layer within this interval allows assessment of optical losses across the full practical spectrum of Ti/Au interfaces employed in plasmonic sensors.

The results indicate a monotonic broadening and suppression of the SPR dip with increasing Ti thickness. For Ti layers thicker than approximately 20 nm, the characteristic reflectance minimum is no longer evident, indicating that excessive absorption inhibits efficient plasmonic coupling. This behavior aligns with previously reported observations in multilayer SPR systems, where nonradiative damping in the adhesion layer reduces field confinement and resonance contrast [28]. For intermediate thicknesses (5–10 nm), a shallow resonance feature is still predicted, though the reflectance remains relatively high, confirming that damping losses persist. In contrast, when the Ti layer is reduced to 1 nm, the simulation exhibits a distinct and well-defined reflectance minimum, consistent with efficient SPR excitation. While this result suggests that minimizing Ti thickness can enhance plasmonic performance, it must be interpreted with caution, as at such ultrathin scales, Ti films are often discontinuous and may form island-like morphologies rather than continuous layers. Consequently, the optical response predicted by the transfer matrix method (TMM) should be considered an approximation rather than a physically complete representation of the experimental system [27,28]. The high imaginary component of Ti's

dielectric function accounts for its strong optical absorption, which introduces nonradiative energy dissipation and reduces the effective propagation length of SPPs. Therefore, any increase in Ti thickness inevitably leads to greater ohmic losses. The simulations support the general conclusion that maintaining the adhesion layer within the nanometer range minimizes these losses, in agreement with previous studies on Ti- and Cr-based adhesion layers [27–29]. However, the present results do not constitute an optimization in a strict sense, as no systematic parameter fitting or experimental verification was performed. Overall, the reflectance analysis demonstrates the competing roles of Ti; while it ensures mechanical stability at the Au substrate interface, it simultaneously introduces optical losses that can deteriorate the plasmonic response. Reducing Ti thickness improves SPR definition by maintaining stronger field localization at the metal–dielectric boundary. These findings underscore the necessity of balancing structural adhesion and optical performance in multilayer plasmonic designs rather than prescribing an absolute “optimal” thickness. Further experimental studies or full-wave simulations (e.g., finite-element or finite-difference time-domain methods) would be required to validate the trends predicted in this simplified modeling framework.

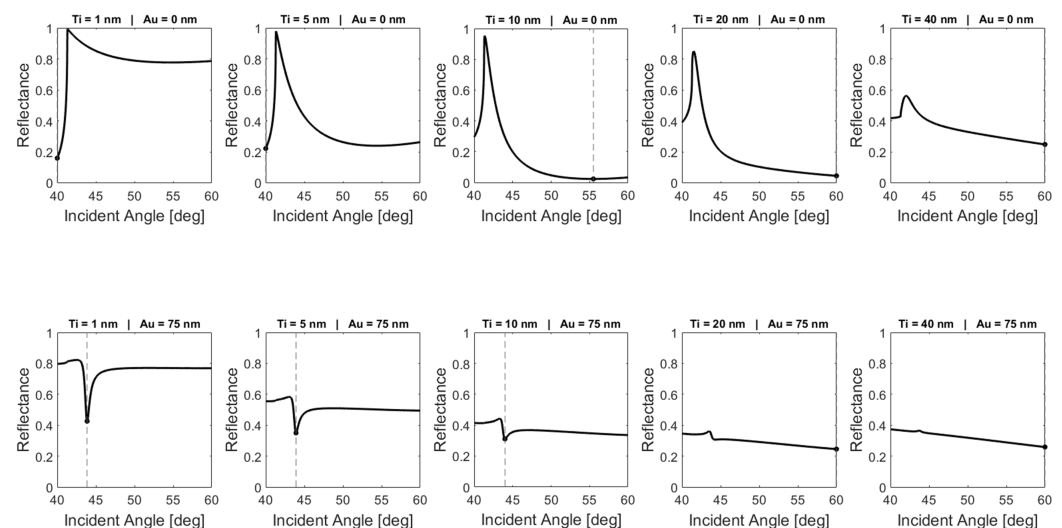


Figure 4. Simulated reflectance spectra for isolated Ti layers (top row) and for BK7/Ti/Au (75 nm)/air configurations (bottom row) at Ti thicknesses of 1, 5, 10, 20, and 40 nm.

3.3. Models: Nanopillars (NPs), Nanoholes (NHs), and Hollow Nanopillars (HNPs)

The plasmonic behavior of metasurfaces composed of gold nanostructures, specifically nanopillars (NPs), nanoholes (NHs), and hollow nanopillars (HNPs), was investigated with emphasis on how geometry influences their collective optical response rather than on absolute resonance prediction (Figure 5). These structures were considered representative periodic metallic/dielectric systems that support surface plasmon resonances (SPRs), and their effective optical properties were evaluated using a simplified analytical approach. While full-wave electromagnetic simulations would provide a more rigorous description of localized field distributions, the present analysis employs the Effective Medium Theory (EMT) and the Transfer Matrix Method (TMM) to offer first-order, qualitative insights into the effective permittivity (ϵ_{eff}) behavior as a function of structural filling factor. The limitations of EMT are acknowledged, since the nanostructure dimensions (160–250 nm) are not negligible compared to the operational wavelengths (500–1500 nm), and therefore quasistatic assumptions may not strictly apply. The filling factor defined as the ratio of the metallic cross-sectional area to the unit cell area was identified as a key parameter governing the average metallic contribution within the metasurface. For a periodic array with 250 nm pitch, varying the nanopillar diameter between 160 nm and 250 nm changes the

filling factor from approximately 0.32 to 0.79, resulting in a systematic increase in both the real and imaginary components of the effective permittivity. These variations reflect the gradual transition from sparse to dense metallic coverage, which modulates the average plasmonic response of the metasurface. Consequently, the trends predicted here should be interpreted qualitatively and used to support the discussion of structural-optical correlations rather than as quantitative predictions of resonance conditions. The predicted dependence of ϵ_{eff} on the filling factor aligns with previously reported analytical and experimental studies on plasmonic metamaterials [22] and nanostructured gold surfaces [12], where decreasing metal coverage reduces the effective polarizability and induces a blue-shift of the overall plasmonic response.

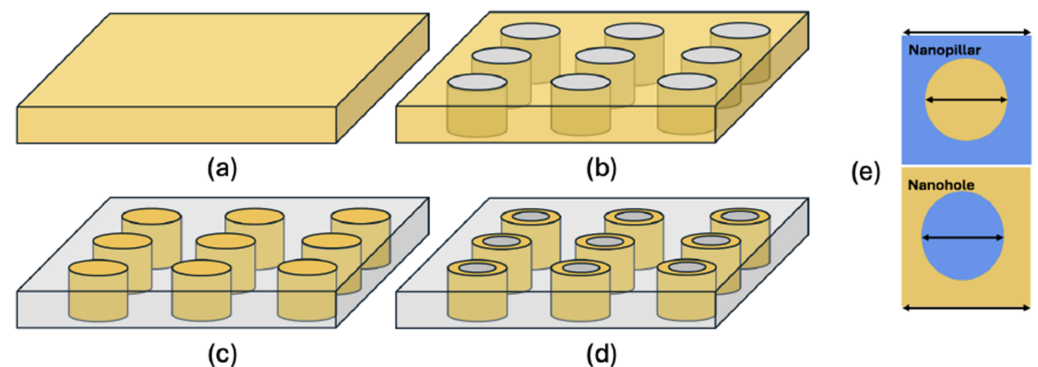


Figure 5. Nanostructural configurations: (a) a continuous gold film supporting extended surface plasmon polaritons (SPPs); (b) a nanohole array, where periodic voids enable localized and waveguide-assisted plasmonic modes; (c) a nanopillar array embedded in a dielectric medium supporting strong near-field localization at the metal–dielectric interfaces; and (d) a nanohollow array consisting of concentric metallic rings that can sustain hybridized plasmonic modes. Panels (e) provide top views defining the geometric configurations corresponding to nanoholes and nanopillars, respectively.

In future work, the integration of full-wave electromagnetic simulations and experimental validation will be essential to confirm the qualitative permittivity trends predicted here and to quantitatively identify the corresponding plasmonic resonance modes.

3.4. Nanopillars (NPs)

In this study, all nanopillars were designed with a 75 nm height, a dimension chosen primarily for fabrication feasibility and consistency with standard lithographic constraints, rather than for achieving a specific surface plasmon resonance (SPR) response. This thickness represents a compromise between structural robustness and optical tunability commonly used in nanofabricated gold metasurfaces.

For the highest filling factor (0.785) (Figure 6a), where the nanopillars nearly form a continuous metallic layer, the effective permittivity obtained from the Effective Medium Theory (EMT) model reaches $\epsilon_{\text{eff}} = 25.877 + 6.487i$. This value suggests a predominantly metallic effective behavior; however, given that the pillar dimensions (160–250 nm) are comparable to optical wavelengths, the quasistatic assumptions underlying EMT are only approximate. Consequently, the computed ϵ_{eff} should be regarded as a qualitative descriptor of average optical response rather than a quantitative indicator of localized plasmonic activity. The corresponding reflectance spectrum exhibits a dip that can be interpreted as a guided mode-like feature within the EMT framework. Although a higher metallic filling factor increases effective permittivity and enhances field overlap within the gold region, the accompanying imaginary component indicates stronger absorption losses. This trade-off can lead to reduced resonance sharpness when damping dominates, consistent with the general plasmonic behavior reported in the metasurface literature [22].

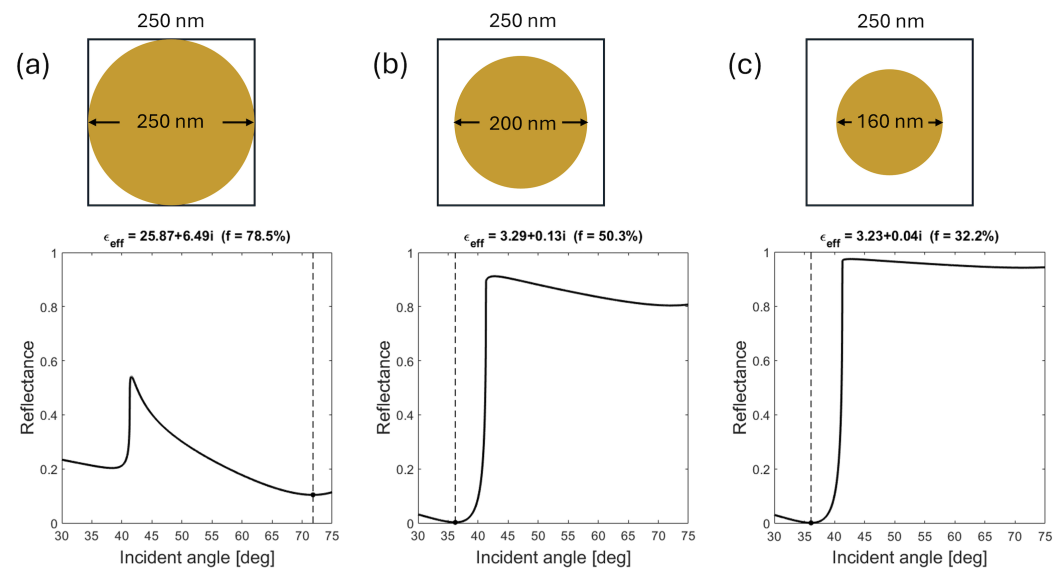


Figure 6. Schematic representation and reflectance spectra of gold nanopillar metasurfaces with varying filling factors. The nanopillars have a fixed height of 75 nm and diameters of 250 nm, 200 nm, and 160 nm, corresponding to filling factors of 0.785, 0.503, and 0.322, respectively. (a) high filling factor (0.785, 250 nm diameter), (b) intermediate filling factor (0.503, 200 nm), and (c) low filling factor (0.322, 160 nm).

As the filling factor decreases to 0.503 (Figure 6b) ($\epsilon_{\text{eff}} = 3.293 + 0.132i$), the reflectance response shows a gradual reduction in metallic character, indicating weaker near-field coupling between neighboring pillars and a transition toward partially confined optical modes. In this intermediate configuration, the structure behaves as a weakly modulated reflective surface where plasmonic and photonic effects coexist but are not strongly coupled. At the lowest filling factor (0.322) (Figure 6c), where the nanopillars are sparsely distributed, the effective permittivity decreases further to $\epsilon_{\text{eff}} = 2.23 + 0.36i$, approaching values typical of dielectric-like media. In this regime, the metasurface primarily supports leaky or weakly guided modes, and the optical field localization at the surface is considerably reduced.

These findings illustrate that within the limits of the TMM-EMT model, reducing the filling factor leads to a progressive transition from a metallic to a quasi-dielectric effective response. However, because EMT does not resolve spatial field variations or account for scattering from individual pillars, phenomena such as LSPR, epsilon-near-zero (ENZ) behavior, or Fabry–Pérot resonances cannot be conclusively inferred from this analysis. A more accurate description of these effects would require full-wave numerical simulations (e.g., finite difference time domain or finite element methods) or experimental validation. Therefore, the present EMT-based results are intended to provide qualitative insight into how geometric parameters influence the average optical properties of nanopillar metasurfaces rather than to predict localized plasmonic resonances. This approach highlights the trend of decreasing optical confinement with lower metallic coverage, consistent with the general behavior of periodic nanostructures but without implying the direct excitation of true SPR modes.

3.5. Hollow Nanopillars (HNPs)

3.5.1. Case Study I—Solid Gold Nanopillar

To examine the electromagnetic response of the nanopillar metasurface, the effective permittivity of gold (Au) nanopillars was estimated using the Maxwell–Garnett relation. This approach was adopted as a first-order analytical approximation to qualitatively assess the volumetric influence of metallic inclusions embedded in a dielectric environment. However, it must be emphasized that for structural dimensions on the order of 160–250 nm

and operating wavelengths around 630 nm, the quasi-static assumptions underlying the Effective Medium Theory (EMT) are qualitative indicators of optical trends.

As can be seen in Figure 7, the dimensions of the unit cell are $L_c = 250$ nm and $H_c = 250$ nm, giving a total volume $V_c = 1.563 \times 10^7$ nm³. The gold nanopillar has a diameter $D_{Au} = 133$ nm (including the rim thickness) and height $H_{Au} = 250$ nm, leading to a volume $V_{Au} = 4.243 \times 10^6$ nm³. The corresponding filling fraction is $f = 0.272$.

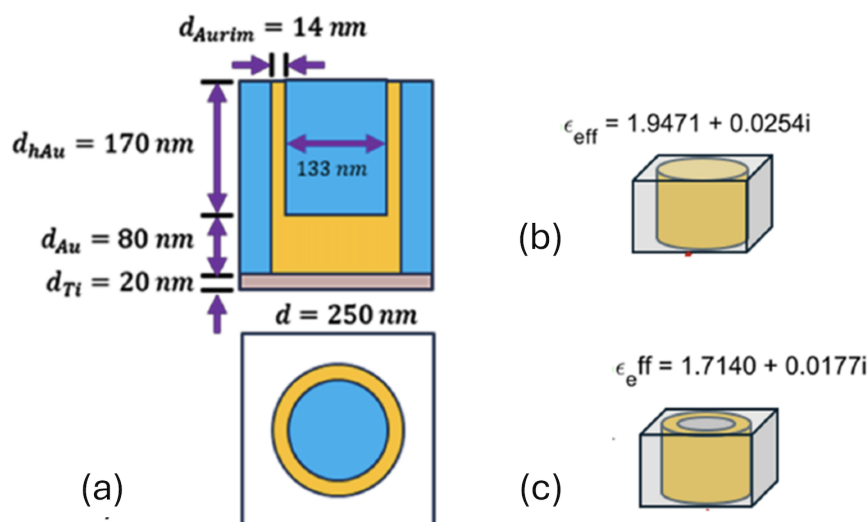


Figure 7. Au Hollow Nanopillar (Au-HNP). (a) Dimensional geometry. (b) Hollow nanopillar (Au-HNP). (c) Solid nanopillar (NP).

The effective permittivity ϵ_{eff} is obtained by substituting the filling fraction into the Maxwell-Garnett equation [23], with air as the host medium ($\epsilon_d = 1$) and the gold permittivity at $\lambda = 630$ nm given as $\epsilon_m = 11.74 + 1.2611i$. The calculation yields $\epsilon_{\text{eff}} = 1.9471 + 0.0254i$ (Figure 7b). The real part of ϵ_{eff} corresponds to the averaged refractive behavior of the composite medium, while the imaginary part is associated with dissipative optical losses within the metallic component. Although this analytical estimate does not capture retardation or localized surface plasmon resonances, it provides a reference for evaluating the relative optical response between solid and hollow geometries.

3.5.2. Case Study II—Hollow Gold Nanopillar

In the second configuration, illustrated in Figure 7c, the same unit-cell dimensions are considered ($L_c = 250$ nm, $H_c = 250$ nm), but the nanopillar incorporates a hollow core. This geometry allows us to qualitatively explore how the reduction in metal volume and the introduction of a dielectric cavity influence the effective permittivity of the composite.

The gold volume is evaluated in two sections: (1) a bottom solid base of height $H_{Au1} = 80$ nm and outer diameter $D_{\text{ex}} = 147$ nm, with volume $V_{Au1} = 1.358 \times 10^6$ nm³; and (2) a hollow cylindrical shell of height $H_{Au2} = 170$ nm, outer diameter $D_{\text{ex}} = 147$ nm, and inner diameter $D_{\text{in}} = 76$ nm. The total gold volume is $V_{Au} = 3.472 \times 10^6$ nm³, corresponding to a filling fraction $f = 0.22$. Using the same permittivities for gold and air, the Maxwell–Garnett relation yields $\epsilon_{\text{eff}} = 1.7140 + 0.0177i$.

The decrease in both the real and imaginary parts of ϵ_{eff} relative to Case I results from the lower gold filling fraction and the enhanced contribution of the dielectric cavity. Physically, the hollow structure supports stronger field localization at the inner and outer boundaries due to curvature-induced charge accumulation; however, these localized effects lie beyond the descriptive capacity of EMT. Therefore, the calculated effective permittivity should be regarded only as a macroscopic average that qualitatively reflects

material composition rather than actual plasmonic resonance behavior. It is important to note that EMT provides a homogenized optical response, which neglects spatial field variations, phase retardation, and coupling between adjacent nanostructures. Given that the characteristic dimensions of the nanopillars are not deeply subwavelength, the use of EMT serves merely as a simplified analytical framework rather than a rigorous predictive tool. Accordingly, the present EMT-based results are intended to illustrate qualitative differences between solid and hollow configurations in terms of effective optical density and absorption characteristics.

3.6. Nanoholes (NHs)

The plasmonic response of gold nanohole metasurfaces was analyzed by varying the hole diameter from 250 nm to 160 nm within a 250 nm periodic array (Figure 8), leading to filling factors of 0.785, 0.503, and 0.322, respectively. In this section, the analysis based on Effective Medium Theory (EMT) and the Transfer Matrix Method (TMM) is employed only to provide a qualitative interpretation of the optical response, since the structural dimensions are comparable to the excitation wavelength. Consequently, the retrieved effective permittivity values should be regarded as phenomenological indicators rather than physically rigorous quantities.

Unlike nanopillar arrays (Figure 6), which transition toward dielectric-like behavior as the filling factor decreases, nanohole arrays exhibit the opposite trend; the effective permittivity (ϵ_{eff}) becomes more negative as the metallic coverage increases. This opposite dependence arises from the complementary optical behavior of holes and pillars, consistent with Babinet's principle in plasmonic systems [12,22]. In such complementary structures, metallic continuity enhances delocalized surface plasmon coupling, while the presence of apertures favors coupling to propagating surface modes. For the highest filling factor (0.785), where the metallic coverage is nearly continuous, the effective permittivity is $\epsilon_{\text{eff}} = -0.415 + 0.153i$. Although the real part is slightly negative, the near-zero magnitude implies weak field confinement, which correlates with the absence of a pronounced dip in the reflectance spectrum. At this limit, the response remains dominated by bulk-like optical reflection rather than resonant excitation. As the hole diameter increases, reducing the filling factor to 0.503 ($-2.97 + 0.42i$), the negative permittivity becomes more pronounced, indicating enhanced plasmonic coupling and a distinct reflectance minimum near 52° . This dip is interpreted as a signature of improved coupling to surface plasmon polariton-like (SPP-like) modes, although the EMT-based approach cannot resolve their spatial distribution. At the lowest filling factor (0.322), the permittivity reaches $-5.255 + 0.65i$, corresponding to the strongest coupling regime predicted in this study. The reflectance spectrum exhibits a well-defined resonance dip, suggesting that reduced metallic coverage promotes conditions favorable for collective plasmonic resonances. However, due to the limitations of the analytical model, these features cannot be unambiguously ascribed to localized or propagating SPPs without full-wave simulation or experimental confirmation.

Overall, the results indicate a qualitative correlation between decreasing filling factor and enhanced plasmonic coupling in nanohole metasurfaces. The trend contrasts with nanopillar arrays, where reduced metallic content leads to diminished plasmonic behavior, further emphasizing the complementary nature of both geometries. It should be emphasized that the present conclusions are restricted to the optical trends obtained from EMT/TMM modeling. Quantitative predictions of field localization, resonance strength, or extraordinary optical transmission require validation through high fidelity numerical simulations (e.g., finite difference time domain or finite element methods) or experimental data.

Previous studies on periodic plasmonic nanohole arrays [12,28] have demonstrated the coexistence of extended SPPs, localized surface plasmon resonances (LSPRs), and hybrid waveguide-coupled modes depending on the interplay between hole size, periodicity, and dielectric environment. The present results are consistent with this framework at a qualitative level, showing that decreased hole size (and hence lower filling factor) enhances the negative real part of the effective permittivity and promotes stronger angular-dependent reflectance minima.

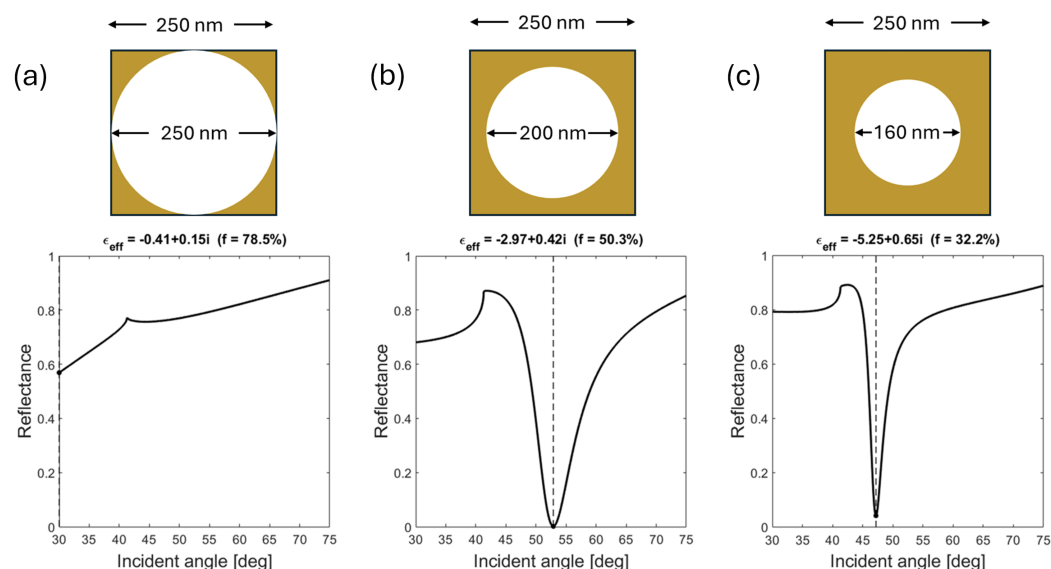


Figure 8. Figure 7 illustrates the geometric configurations and corresponding reflectance spectra of gold nanohole metasurfaces with varying filling factors. The nanoholes have a fixed height of 75 nm and diameters of 250 nm, 200 nm, and 160 nm, corresponding to filling factors of 0.785, 0.503, and 0.322, respectively. (a) high filling factor (0.785, 250 nm diameter), (b) intermediate filling factor (0.503, 200 nm), and (c) low filling factor (0.322, 160 nm).

3.7. Effect of *s*- and *p*-Polarized Light

The optical response of plasmonic metasurfaces under different light polarizations remains a subject of continued interest due to its implications for surface plasmon resonance (SPR) sensing and tunable optical functionalities. Although the use of polarization to modulate plasmonic coupling has been reported extensively, a systematic comparison between nanohole (NH), nanopillar (NP), and hollow nanopillar (HNP) architectures provides additional insight into the polarization-dependent effective medium behavior of such composite systems. In this study, we aim to clarify the limits and applicability of the Effective Medium Theory (EMT) and Transfer Matrix Method (TMM) for describing these phenomena, recognizing that the dimensions of the nanostructures (160–250 nm) approach the quasi-static limit of EMT validity. Therefore, the results discussed below should be interpreted as qualitative indicators of effective optical trends rather than absolute quantitative predictions. Hamouleh-Alipour demonstrated a metal dielectric metal (MDM) metasurface exploiting plasmon-induced absorption (PIA) to enhance SPR sensitivity, where polarization control enabled resonance tuning at near-infrared wavelengths (1133 and 1698 nm) [30]. Building on this and related studies, we analyze polarization-dependent permittivity behavior using simplified analytical formulations derived from the Maxwell–Garnett model for *p*- and *s*-polarized light, Equations (6) and (7), respectively.

Effective Medium Modeling

The effective permittivity ϵ_{eff} depends on the filling fraction f_1 , ranging from 0 (no inclusions) to 1 (full inclusion). At small f_1 , the response approximates that of the host

medium (ϵ_h), while at large f_1 , it approaches the permittivity of the inclusion (ϵ_f). This behavior illustrates the transition from dielectric-dominated to metal-dominated regimes, which is qualitatively consistent with plasmonic field confinement trends but not quantitatively predictive of resonance conditions.

To approximate the optical response, we applied the EMT and TMM frameworks to nanohole and nanopillar geometries. Although these techniques neglect microscopic field variations, they provide a homogenized description of the composite medium and allow comparative evaluation between polarization states. Figure 9 depicts the real and imaginary parts of the effective permittivity as a function of filling fraction for both nanohole and nanopillar arrays under p - and polarized light.

In p -polarization (Figure 9a,b), the nanohole array shows a zero crossing of the real permittivity near a filling fraction of $\sim 85\%$, while the nanopillar array exhibits a pole at a similar filling ratio. These features correspond to the effective medium's transition between dielectric and metallic responses rather than direct evidence of physical resonances. Under s -polarization (Figure 9c,d), both arrays exhibit monotonic trends in real and imaginary permittivity, with reduced sensitivity to geometry, consistent with the symmetric distribution of the electric field relative to the surface.

However, these observations should not be interpreted as direct demonstrations of ENZ or EOT phenomena. Instead, they highlight that polarization primarily influences the averaged dielectric response through anisotropic field distributions rather than through distinct resonant coupling mechanisms. The complementary trends between NH and NP structures under s -polarization suggest that polarization can modulate the effective refractive index in a controlled but limited manner. For sensing applications, the relatively uniform response under s -polarization implies higher stability and repeatability, whereas p -polarization remains more sensitive to geometry and material dispersion, offering tunability at the cost of greater variability. Thus, polarization control rather than structural redesign can serve as a practical means to optimize the optical response of metasurface-based SPR sensors within the valid range of the EMT approximation.

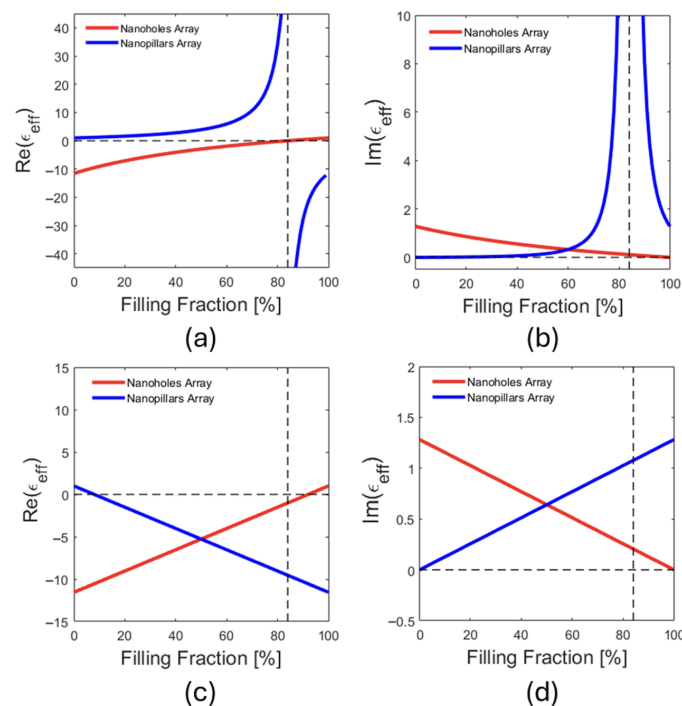


Figure 9. Effective permittivity trends for nanohole and nanopillar metasurfaces as a function of filling fraction under different polarization states. Panels (a,b) show the real and imaginary parts

of the effective permittivity under *p*-polarized illumination, respectively. Panels (c,d) display the corresponding values under *s*-polarized illumination. The nanohole array (red) and nanopillar array (blue) exhibit complementary trends, with dashed lines indicating reference levels.

These results are obtained using the Maxwell–Garnett effective medium approximation and are intended to illustrate qualitative polarization-dependent trends rather than exact resonance conditions.

4. Discussion

The EMT/TMM framework established here has been benchmarked against classical SPR data and offers a coherent analytical basis for describing filling-fraction-dependent plasmonic behavior in nanostructured Au metasurfaces. The EMT/TMM formalism established herein constitutes a fully analytical–numerical framework that reproduces canonical surface plasmon resonance (SPR) conditions within the resolution of the adopted model. The consistency of the predicted resonance angles and reflectance profiles with established analytical and experimental data reported in Refs. [22,24] supports the physical consistency of the present approach. The chosen Au and Ti thicknesses, therefore, represent realistic parameters for Kretschmann-type architectures, indicating that the analytical conclusions are consistent with experimentally accessible fabrication parameters. Within its analytical scope, the study establishes a self-consistent theoretical framework for interpreting filling-fraction-dependent SPR coupling in nanostructured metasurfaces.

Future extensions involving full-wave modeling and device fabrication will enable further quantitative assessment of the analytical trends identified here. Nevertheless, the homogenization assumption limits its quantitative accuracy for structures with features approaching the optical wavelength. To validate the current analytical trends, future work will integrate full-wave electromagnetic simulations, including finite-difference time-domain (FDTD) and finite-element (FEM) methods, to resolve near-field distributions and compare angular reflectance minima with those predicted here. In parallel, angle-resolved reflectance and transmission spectroscopy will be performed on fabricated Ti/Au thin films and nanopillar/nanohole arrays to experimentally verify the predicted shifts in resonance angle and effective permittivity trends. This combined analytical, numerical, and experimental program may establish quantitative bounds for the EMT/TMM approach and enable predictive modeling of metasurface-based SPR sensors.

5. Conclusions

In this work, we investigated the plasmonic behavior of gold-based metasurfaces composed of nanoholes and nanopillars, employing the Effective Medium Theory (EMT), the Transfer Matrix Method (TMM), and polarization-resolved analysis. Our results demonstrate that both the real and imaginary parts of the effective permittivity are strongly governed by the geometric parameters and the volume filling fraction of the nanostructures.

For *p*-polarization, nanoholes and nanopillars exhibit distinct plasmonic responses due to their respective cavity-like and protruding geometries. Nanohole arrays exhibit stronger effective coupling and a transition toward negative effective permittivity, with comparatively lower optical losses at small filling fractions, supporting conditions compatible with Kretschmann-type surface plasmon resonance. In contrast, nanopillar arrays, while capable of supporting partially confined optical modes, present higher optical losses due to the increased imaginary part of the effective permittivity at larger filling fractions. Under *s*-polarized illumination, both nanohole and nanopillar arrays show monotonic and nearly overlapping effective permittivity trends, reflecting the symmetric distribution of the electric field relative to the surface. In this regime, the electromagnetic response is primarily determined by the volumetric gold content, rendering the effective optical

behavior largely independent of the detailed structural topology. This polarization-induced symmetry yields a stable and repeatable optical response, indicating that s-polarization provides a comparatively stable effective optical response and geometry-insensitive SPR sensing. Overall, the results indicate that polarization control can be used as a practical and non-structural tuning parameter for optimizing plasmonic coupling in metasurface-based SPR sensors. This work establishes a coherent analytical framework for interpreting how polarization and filling fraction jointly govern effective permittivity and macroscopic optical response in nanostructured gold metasurfaces.

The analytical framework operates within the homogenization assumptions of EMT, associated with the effective medium description, including the quasistatic approximation underlying the EMT formulation and the absence of full-wave electromagnetic simulations or experimental validation. Accordingly, the reported results describe macroscopic optical trends rather than as quantitative predictions of localized field enhancement or sensor performance metrics. Future extensions may incorporate full-wave numerical modeling and experimental reflectance measurements to assess the quantitative limits of the EMT/TMM framework and to explore regimes beyond the quasistatic approximation.

Author Contributions: Conceptualization, R.C.-M. and E.M.-G. (Edgar Martínez-Guerra); methodology, R.C.-M. and E.M.-G. (Edgar Martínez-Guerra); software, K.K.S., P.M.V.-G. and G.E.S.-G.; validation, E.M.-G. (Eduardo Martínez-Guerra), E.M.-G. (Edgar Martínez-Guerra) and R.C.-M.; formal analysis, E.M.-G. (Edgar Martínez-Guerra) and R.C.-M.; investigation, C.A.F.-H. and R.C.-M.; resources, E.M.-G. (Eduardo Martínez-Guerra); data curation, C.A.F.-H. and M.T.R.d.l.C.; writing original draft preparation, E.M.-G. (Edgar Martínez-Guerra); writing—review and editing, E.M.-G. (Edgar Martínez-Guerra) and R.C.-M.; visualization, C.A.F.-H.; supervision, R.C.-M.; project administration, E.M.-G. (Eduardo Martínez-Guerra) and R.C.-M.; funding acquisition, E.M.-G. (Edgar Martínez-Guerra). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Basic Scientific Research Grant 475 A1-S-13587.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: E.M.-G. and M.T.R.C. gratefully acknowledge the computing time granted by LANCAD and CONACyT on the supercomputer Yoltla/Miztli/Xiuhcoatl at LVSP UAM-Iztapalapa/DGTIC-UNAM/CGSTIC-CINVESTAV through Projects No. LANCAD-UAM-38-2026 and LANCAD-UNAM-11-2026. During the preparation of this study, the authors used OpenAI GPT-4 to assist in refining the manuscript's English. The authors have critically reviewed and edited all outputs and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Senanayake, P.; Hung, C.H.; Shapiro, J.; Lin, A.; Liang, B.; Williams, B.S.; Huffaker, D.L. Surface Plasmon-Enhanced Nanopillar Photodetectors. *Nano Lett.* **2011**, *11*, 5279–5283. [[CrossRef](#)]
2. Nakamoto, K.; Kurita, R.; Niwa, O. Arrays of Metallic Nanopillars in Holes for Plasmonic Devices. In Proceedings of the 15th International Conference on Miniaturized Systems for Chemistry and Life Sciences (MicroTAS), Seattle, WA, USA, 2–6 October 2011; pp. 1786–1788.
3. Parsons, J.; Hendry, E.; Burrows, C.P.; Auguie, B.; Sambles, J.R.; Barnes, W.L. Localized Surface-Plasmon Resonances in Periodic Nondiffracting Metallic Nanoparticle and Nanohole Arrays. *Phys. Rev. B* **2009**, *79*, 073412. [[CrossRef](#)]
4. Eftekhari, F.; Escobedo, C.; Ferreira, J.; Duan, X.; Girotto, E.M.; Brolo, A.G.; Gordon, R.; Sinton, D. Nanoholes as Nanochannels: Flow-Through Plasmonic Sensing. *Anal. Chem.* **2011**, *81*, 4308–4311. [[CrossRef](#)]
5. Lesuffleur, A.; Im, H.; Lindquist, N.C.; Lim, K.S.; Oh, S.H. Laser-Illuminated Nanohole Arrays for Multiplex Plasmonic Microarray Sensing. *Opt. Express* **2008**, *16*, 219–224. [[CrossRef](#)]

6. Lospinoso, D.; Colombelli, A.; Lomascolo, M.; Rella, R.; Manera, M.G. Self-Assembled Metal Nanohole Arrays with Tunable Plasmonic Properties for SERS Single-Molecule Detection. *Nanomaterials* **2022**, *12*, 380. [\[CrossRef\]](#)
7. Kotlarek, D.; Fossati, S.; Venugopalan, P.; Quilis, N.G.; Slabý, J.; Homola, J.; Lequeux, M.; Amiard, F.; Lamy de la Chapelle, M.; Jonas, U.; et al. Actuated Plasmonic Nanohole Arrays for Sensing and Optical Spectroscopy Applications. *Nanoscale* **2020**, *12*, 9756–9768. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Wang, W.; Cui, Y.; Fung, K.H.; Zhang, Y.; Ji, T.; Hao, Y. Comparison of Nanohole-Type and Nanopillar-Type Patterned Metallic Electrodes Incorporated in Organic Solar Cells. *Nanoscale Res. Lett.* **2017**, *12*, 538. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Najiminaini, M.; Ertorer, E.; Kaminska, B.; Mittler, S.; Carson, J.J. Surface Plasmon Resonance Sensing Properties of a 3D Nanostructure Consisting of Aligned Nanohole and Nanocone Arrays. *Analyst* **2014**, *139*, 1876–1882. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Escobedo, C.; Vincent, S.; Choudhury, A.I.K.; Campbell, J.; Brolo, A.G.; Sinton, D.; Gordon, R. Integrated Nanohole Array Surface Plasmon Resonance Sensing Device Using a Dual-Wavelength Source. *J. Micromech. Microeng.* **2011**, *21*, 115001. [\[CrossRef\]](#)
11. Xiang, G.; Zhang, N.; Zhou, X. Localized Surface Plasmon Resonance Biosensing with Large Area of Gold Nanoholes Fabricated by Nanosphere Lithography. *Nanoscale Res. Lett.* **2010**, *5*, 818–822. [\[CrossRef\]](#)
12. Correia-Ledo, D.; Gibson, K.F.; Dhawan, A.; Couture, M.; Vo-Dinh, T.; Graham, D.; Masson, J.F. Assessing the Location of Surface Plasmons Over Nanotriangle and Nanohole Arrays of Different Size and Periodicity. *J. Phys. Chem. C* **2012**, *116*, 6884–6892. [\[CrossRef\]](#)
13. Bicket, I.C.; Bellido, E.P.; McRae, D.; Kapetanovic, V.; Lagugné-Labarthe, F.; Botton, G.A. Surface Plasmon Resonance Mode Behaviour in Sierpinski Fractal Triangles and New Plasmonic Materials. *Microsc. Microanal.* **2019**, *25*, 636–637. [\[CrossRef\]](#)
14. Jones, D.; Liu, N.; Corbett, B.; Lovera, P.; Quinn, A.J.; O’Riordan, A. Surface Plasmon Assisted Extraordinary Transmission in Metallic Nanohole Arrays and Its Suitability as a Bio-Sensor. *J. Phys. Conf. Ser.* **2011**, *307*, 012005. [\[CrossRef\]](#)
15. GuHuangjian, P.; LiHaiqiang, Y.; Chen, Z.; Zhang, Z.; YanChaojun, Z.; T.C., L. High-Q and Intense Lattice Plasmon Resonance in Hexagonal Nonclose Packed Thin Silver Nanoshells Array. *J. Phys. Chem. C* **2024**, *128*, 6431–6437. [\[CrossRef\]](#)
16. Zhao, D.; Wang, X.; Chen, Y.; Rao, X.; Gao, J.; Qi, Y.; Yang, H.; Zheng, X. Quasi-BIC mode and refractive index sensing by asymmetric silicon nanodisk arrays. *J. Phys. Chem. C* **2025**, *596*, 132421. [\[CrossRef\]](#)
17. Gao, J.; Wang, X. Chen, Y.; Zhao, D.; Qi, Y.; Yang, H. Triple Fano resonances induced by a square-elliptical cavity coupled with an MIM waveguide for high-sensitivity gas refractive index sensing. *J. Opt. Soc. Amer. B* **2025**, *42*, 742748–742754. [\[CrossRef\]](#)
18. Dadoenkova, Y.; Glukhov, I.; Moiseev, S.; Svethukin, V.; Shukov, A.; Zolotovskii, I. Optical generation in an amplifying photonic crystal with an embedded nanocomposite polarizer. *Opt. Commun.* **2017**, *389*, 1–4. [\[CrossRef\]](#)
19. Aly, A.; Elsayed, H.; Malek, C. Optical properties of one-dimensional defective photonic crystal containing nanocomposite material. *J. Nonlinear Opt. Phys. Mater.* **2017**, *26*, 1750007. [\[CrossRef\]](#)
20. Moiseev, S.; Ostatochnikov, V. Influence of the size-dependent permittivity of metal inclusions on the optical characteristics of a one-dimensional photonic crystal with a nanocomposite defect. *Opt. Quantum Electron.* **2015**, *47*, 3197–31200. [\[CrossRef\]](#)
21. Collin, S. Nanostructure Arrays in Free-Space: Optical Properties and Applications. *Rep. Prog. Phys.* **2014**, *77*, 126402. [\[CrossRef\]](#)
22. Maier, S.A. *Plasmonics: Fundamentals and Applications*; Springer: New York, NY, USA, 2007.
23. Sareni, B.; Krähenbühl, L.; Beroual, A.; Brosseau, C. Effective dielectric constant of periodic composite materials. *Appl. Phys.* **1996**, *80*, 1688–1696. [\[CrossRef\]](#)
24. Gwon, H.R.; Lee, S.H. Spectral and Angular Response of Surface Plasmon Resonance Based on the Kretschmann Prism Configuration. *Mat. Trans.* **2010**, *51*, 1150–1155. [\[CrossRef\]](#)
25. Sarid, D.; Challener, W. *Modern Introduction to Surface Plasmons: Theory, Mathematica Modeling, and Applications*; Cambridge University Press: Cambridge, UK, 2010.
26. Barnes, W.L.; Dereux, A.; Ebbesen, T.W. Surface plasmon subwavelength optics. *Nature* **2003**, *424*, 824–830. [\[CrossRef\]](#)
27. Mulyanti, B.; Wulandari, C.; Mohamad, N.R.; Rifaldi, E.; Hasanah, L.; Menon, P.S. Bimetallic Ag/Au Thin Films in Kretschmann-Based Surface Plasmon Resonance Sensor for Glucose Detection. *Optoelectron. Adv. Mater. Rapid Commun.* **2020**, *14*, 487–493.
28. Kim, W.M.; Kim, S.H.; Lee, K.S.; Lee, T.S.; Kim, I.H. Titanium Nitride Thin Film as an Adhesion Layer for Surface Plasmon Resonance Sensor Chips. *Appl. Surf. Sci.* **2012**, *261*, 749–752. [\[CrossRef\]](#)
29. Khairulazdan, N.B.; Mohamed, R.; Berhanuddin, D.D.; Menon, P.S. Characterisation of Nano-Thin Film GO/TiO₂ Layers for Kretschmann-Based Surface Plasmon Resonance Visible Sensing Using FDTD Method. *Opt. Appl.* **2021**, *51*, 579–587. [\[CrossRef\]](#)
30. Hamouleh-Alipour, A.; Forouzehshfard, M.; Vafapour, Z. Blood hemoglobin concentration sensing by optical nano biosensor-based plasmonic metasurface: A feasibility study. *IEEE Trans. Nanotechnol.* **2022**, *21*, 620–628. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.