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Exploring the Optical Behavior of Light Through Periodic Slits in Thick Silver Films: A Stimulation Based Approach in Vision Sciences

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ABSTRACT

Background and Objectives: The interaction of light with metallic nanostructures has opened new frontiers in photonics and optoelectronics. Silver, with its unique optical properties and minimal loss in the visible spectrum, enables phenomena like surface plasmon polaritons (SPPs) and extraordinary optical transmission (EOT). These effects offer significant potential for advancing applications in sensing, imaging, and nanophotonics. This study aims to investigate the optical behavior of light through periodic arrays of slits in thick silver films, focusing on the influence of geometric parameters and surface plasmonic effects on transmission efficiency and electric field enhancement.

METHODOLOGY: Finite element method (FEM)-based numerical simulations were conducted using COMSOL Multiphysics. Silver films with slit widths ranging from 10 nm to 100 nm were modeled under transverse magnetic (TM) polarized light. Parameters such as electric field enhancement, power flow, and slit periodicity were analyzed across wavelengths from 430 nm to 720 nm.

RESULTS: Simulations revealed that slit periodicity and geometry significantly impact transmission efficiency, with optimal configurations resulting in enhanced electric fields due to SPP excitation. At periodicities matching the SPP wavelength, transmission was reduced, highlighting the role of constructive and destructive interference. Peak power flow occurred at shorter wavelengths, aligning with enhanced plasmonic activity.

CONCLUSION: The study demonstrates that by tailoring the geometry of periodic slits in silver films, it is possible to control light-matter interactions for advanced applications in nanophotonics, sensing, and energy harvesting. The findings contribute to a deeper understanding of plasmonic phenomena and their practical implications.

KEYWORDS: Surface plasmon polaritons, localized surface plasmon resonance, silver nano slits, finite element method, nanophotonics, extraordinary optical transmission.

INTRODUCTION

The interaction of light with materials, particularly at the nanoscale, forms the foundation of many modern optical and photonic technologies. Among these materials, silver stands out as a preferred choice due to its remarkable optical and electrical properties, including its ability to support low-loss surface plasmon resonances in the visible and near-infrared spectrum. These characteristics have made silver a cornerstone in the study of plasmonics and nanophotonics, where understanding light behavior at subwavelength scales is critical. This paper delves into how light interacts with periodic arrays of slits in thick silver films and the resulting extraordinary optical effects.

Periodic slit arrays in metallic films generate phenomena such as extraordinary optical transmission (EOT). This occurs when light passes through subwavelength apertures more efficiently than predicted by classical theory. The excitation of surface plasmon polaritons (SPPs), collective oscillations of electrons at the metal-dielectric interface, plays a vital role in EOT. These oscillations not only enhance the electric field near the surface but also allow light to travel through nanoscale apertures, making it possible to manipulate optical properties at dimensions smaller than the wavelength of light (1).

A significant feature of EOT is its sensitivity to geometric parameters like slit width, periodicity, and film thickness. By carefully designing these parame

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ters, the transmission of light can be enhanced or suppressed. For instance, the periodicity of the slits can align with the SPP wavelength to produce constructive or destructive interference, controlling the intensity and directionality of transmitted light. This interplay between light and nanostructures enables the creation of advanced optical devices such as filters, waveguides, and sensors (2).

Silver's exceptional properties make it ideal for exploring these phenomena. Compared to other metals, silver exhibits the lowest optical losses in the visible range, which is crucial for applications requiring high efficiency and precision. Its high conductivity and plasmonic response allow for strong field enhancements and better energy localization, essential for sensing, imaging, and energy harvesting applications (3).

The advent of advanced computational tools has significantly enhanced the ability to study and optimize these effects. Finite element modeling, for example, allows for precise simulations of light behavior in complex geometries (4) This study leverages COMSOL Multiphysics, a leading simulation tool, to explore the influence of geometric parameters on the optical properties of periodic silver slits. The focus is on transverse magnetic (TM) polarization, which is particularly effective in exciting SPPs and achieving extraordinary optical transmission (5).

By investigating the transmission efficiency, electric field enhancement, and power flow in various configurations, this research contributes to the broader understanding of light-matter interactions at the nanoscale (8). The findings not only provide insights into the fundamental physics of plasmonics but also highlight practical applications in photonics, including sensors, waveguides, and other integrated optical devices (13-15). As the demand for miniaturized and efficient optical components grows, studies like this one pave the way for innovations that bridge fundamental research and technological advancements (6).

METHODOLOGY

This study employed numerical simulations to investigate the optical properties of light passing through periodic arrays of silver slits. The finite element method (FEM), implemented in COMSOL Multiphysics, was used to model and analyze the interactions of electromagnetic waves with the slit structures. Silver films with slit widths ranging from 10 nm to 100 nm were considered, with periodicities varied to evaluate their effect on light transmission. The dielectric properties of silver were modeled based on established data from Johnson and Christy to ensure accuracy in simulating its optical behavior.

A monochromatic plane wave, propagating in the –z direction, was used to illuminate the silver film. The surrounding medium was air, and boundary conditions were defined to accurately simulate wave interactions at the interfaces (9). The study specifically focused on transverse magnetic (TM) modes, which are known for their significant field enhancements and their ability to excite surface plasmon polaritons (SPPs). TM polarization was chosen to investigate its influence on transmission efficiency and field enhancement within the periodic slit arrays (7).

The analysis encompassed key parameters such as electric field enhancement, magnetic field distribution, and power flow across wavelengths ranging from 430 nm to 720 nm. The electric field's background magnitude was set at 1 V/m to standardize the simulations (10). To validate the results, numerical outcomes were compared with analytical solutions and existing experimental data from the literature. This approach ensured the reliability of the simulation model and its findings.

By employing FEM and leveraging the advanced capabilities of COMSOL Multiphysics, the study systematically explored how variations in slit geometry and periodicity influence the transmission characteristics of light through thick silver films (16-18). The results provide valuable insights into optimizing nanoscale structures for applications in photonics and optoelectronics (19).

RESULTS

Simulations demonstrated significant electric field enhancement near the slit edges. This enhancement was attributed to the excitation of surface plasmon polaritons (SPPs), which concentrated electromagnetic energy within the subwavelength apertures. Maximum enhancement occurred at specific slit widths and periodicities, aligning with the effective wavelength of the guided mode. These findings suggest that geometric tuning of the slits can optimize light confinement and enhance device performance (12).

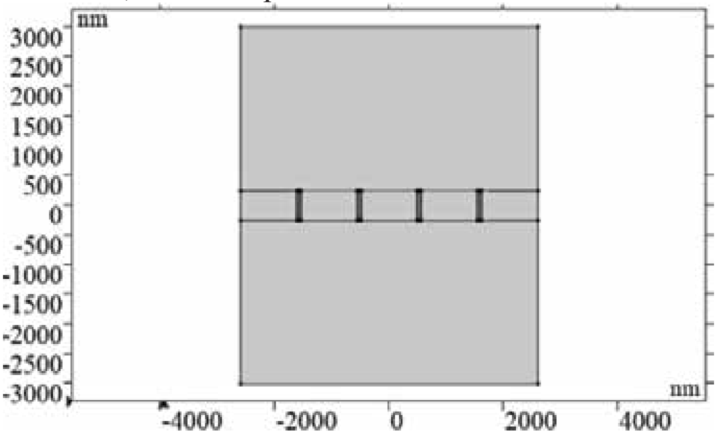
The transmission efficiency exhibited a quasi-periodic dependence on slit periodicity and film thickness. When the periodicity equaled integer multiples of the SPP wavelength, destructive interference reduced transmission to near-zero (20). Conversely, optimal transmission was observed at half the effective wavelength of the guided mode. These results align with theoretical models, demonstrating the potential for precise control of light transmission through nanoscale engineering.

Localized surface plasmon resonance (LSPR) effects were evident in the silver nano slits, characterized by enhanced electromagnetic fields confined to subwavelength scales. LSPR sensitivity to environmental changes underscores its potential for biosensing and chemical detection applications. By leveraging these resonances, the study highlights opportunities for real-time, label-free detection technologies.

Periodic Array of Slits

A periodic array of slits gives to a regular arrangement of elongated openings, narrow or gaps in a material or area. These slits are normally arranged in a repeating pattern which has equal spacing among them. The array can be one-dimensional, where the slits are aligned in a straight line, or two-dimensional, where the slits form a grid-like pattern. In nanophotonics and plasmonics, periodic arrays of subwavelength slits or apertures in metallic films can be used to create surface plasmon resonances, enabling the confinement and manipulation of electromagnetic fields at the nanoscale.

The purpose of creating a periodic array of slits is to manipulate the interaction of light or other electromagnetic waves with the structure. The periodicity determines the behavior of light when passes through nanoslit. These arrays can display intriguing optical characteristics and offer the chance to regulate light transmission, reflection, and absorption.



Periodic Array of Slit

To accomplish certain optical effects like improved transmission, selective filtering, or plasmonic resonances, the slits size, shape, and spacing can be adjusted. Periodicity

determines the behaviour of light when it passes through the nanoslits. Periodic arrays of slits find applications in various fields Including optics, photonics, and nanotechnology. They are used in areas such as sub wavelength imaging, surface-enhanced spectroscopy, metasurfaces, optical sensors, and integrated photonic devices. The interaction of light with the slits can lead to phenomena like diffraction, surface plasmon polaritons, and enhanced electromagnetic field confinement.

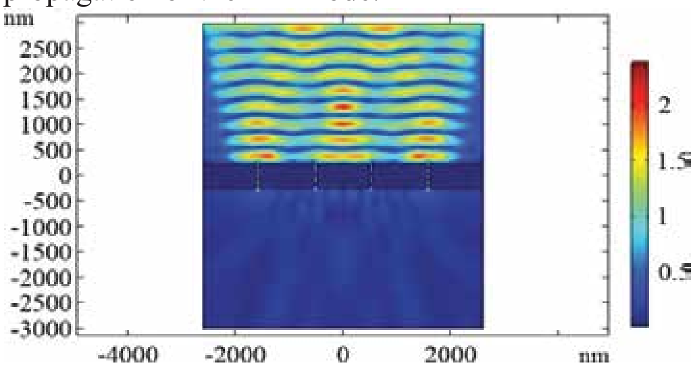
Parameters for Periodic Array of Silver Slits

The parameters that used for periodic array of silver slits are given in table Parameters for Periodic Array of Silver Slits.

Name	Expression	Value
Width	5200	1500
Height	6000	3000
Slit width	50	50
h_slit	500	500
Lambda	633	633

Under E (TM) Illumination, the Cutoff for Sub-Wavelength Slits

Under E (TM) illumination, the cutoff for a sub-wavelength silver slits array refers to the minimum width of the slits at which the transmission of the TM-polarized electromagnetic wave is significantly reduced or completely blocked. In other words, it is the threshold width below which the slits can no longer support the propagation of the TM mode.

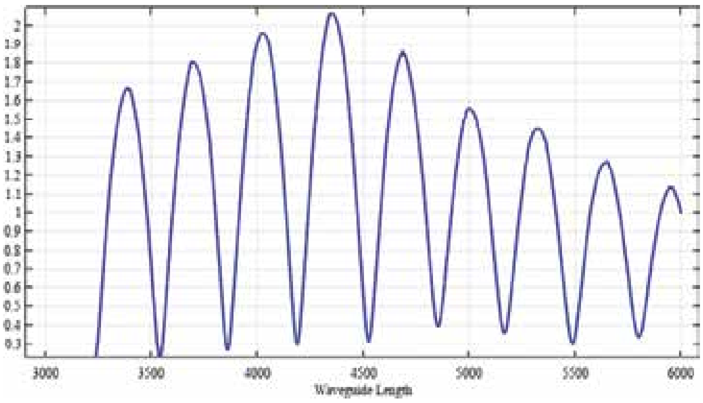


TM Mode for Silver Slits

The cutoff for sub-wavelength slits is influenced by several factors, including the

incident wavelength, the refractive index of the surrounding medium, and the properties of the silver film. As the slit width decreases and approaches the sub-wavelength regime, the interaction between the incident wave and the slits becomes more pronounced.

When the width of the slits is larger than the incident wavelength, the TM mode can propagate through the slits with relatively low losses. However, as the width of the slits decreases and approaches the sub-wavelength scale, the confinement of the electric field within the slits becomes stronger, leading to increased scattering and absorption losses. At a certain critical width, the TM mode cannot effectively propagate through the slits, resulting in a cutoff in transmission.



Electric Field

The cutoff behavior can be studied using computational methods such as numerical simulations, including finite-difference time-domain (FDTD) or finite element methods (FEM). These simulations can provide insights into the relationship between the slit width, incident wavelength, and transmission characteristics of the sub-wavelength silver slits array under E (TM) illumination.

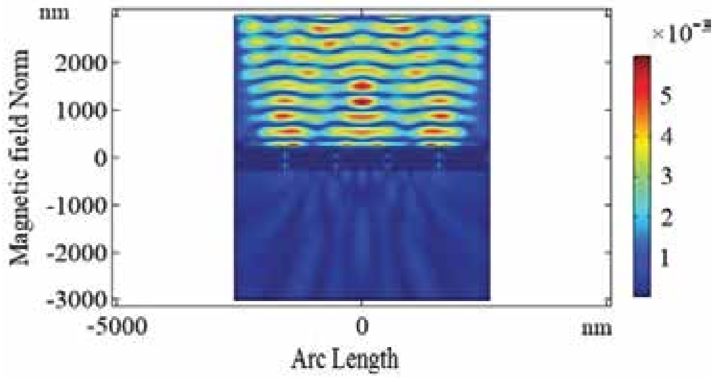
By understanding the cutoff behavior, researchers can optimize the design and dimensions of sub-wavelength silver slits arrays for specific applications such as plasmonic sensing, enhanced light-matter interactions, or sub-wavelength imaging. The cutoff width can serve as a critical parameter in tailoring the optical properties of such structures and achieving desired functionalities based on the specific requirements of the application.

The cutoff for a sub-wavelength silver slits array under E (TM) illumination refers to the minimum size or maximum spacing at which significant transmission of TM polarized electromagnetic waves can occur. Understanding and controlling the cutoff is important for designing and optimizing plasmonic devices and structures for applications in nanophotonics, sensing, and integrated optics.

(TE) Light Transmission through Sub-Wavelength Slits

When considering (TE) light transmission by a sub-wavelength silver slits array, the interaction between the transverse electric (TE) mode and the nanostructured silver film becomes the focus of investigation. This scenario presents unique optical phenomena that arise from the interplay between the incident light and the sub-wavelength features of the slits array.

The transmission of (TE) light through an array of sub-wavelength silver slits is effected by numerous factors, containing the width and periodicity of the slits, the incident wavelength, and the properties of the silver film. As the incident light interacts with the slits, several optical effects such as diffraction, plasmonics, and resonances come into play

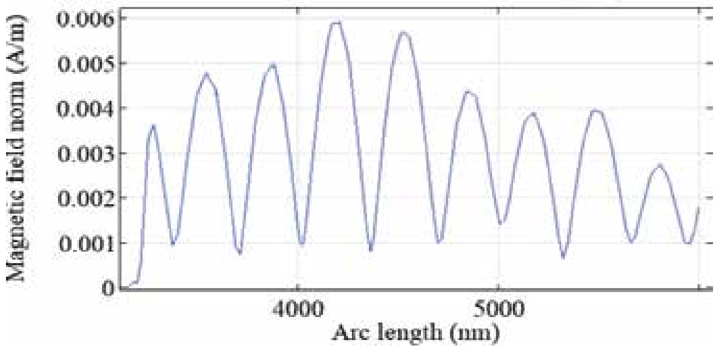


TE Mode for Silver Slits

Diffraction effects play a significant role in the transmission of (TE) light through the slits. When the width of the slits is smaller than the wavelength of the incident light, the diffracted light waves propagate through the slits and contribute to the transmission. The diffraction pattern is influenced by the size and spacing of the slits, leading to interference and scattering effects that impact the transmission spectrum. The results of this study show that the response of the nanoslit can be tailored by optimizing the parameters, including the refractive index of the surrounding medium, permittivity and permeability of the materials and subwavelength parameters of the nanoslit (20).

The presence of silver as the material for the slits introduces plasmonic effects into the system. The surface plasmons of the silver film can be excited by the incident (TE) light, leading to enhanced transmission or absorption at specific wavelengths.

The interface between the incident light and plasmons results in localized electromagnetic field enhancements within the slits, influencing the overall transmission characteristics. Resonant phenomena also occur in sub-wavelength silver slits arrays, where specific slit geometries and incident wavelengths can lead to resonant modes within the structure. These resonances can lead to transmission peaks or dips in the spectrum, and their positions are influenced by the slit dimensions, the surrounding medium, and the plasmonic properties of the silver film. By tuning the slit parameters, it is possible to engineer the resonant modes and tailor the transmission properties for desired applications.



Magnetic Field

The research of (TE) sub-wavelength of light transmission of silver slits arrays often combines experimental and numerical approaches. Experimental techniques such as spectroscopy, microscopy, and near-field measurements can be utilized to characterize the transmission spectrum, study the field distribution, and validate the performance of the array. Numerical simulations using methods like finite-difference time-domain (FDTD) or finite element analysis (FEA) provide a deeper understanding of the underlying physics, enabling the exploration of parameter variations and optimization of the slits array design.

The investigation of (TE) light transmission through sub-wavelength silver slits arrays has significant implications for various applications, including plasmonic sensing, sub- wavelength imaging, and optical filtering. By manipulating the slit dimensions, the periodicity, and the plasmonic properties of the silver film, it is possible to achieve tailored transmission properties that suit the specific requirements of these applications.

In this simulation, strong transmission of light was observed. Enhancement in electric field was also observed. We can measure the enhancement in electric field by color bar. In this case of TM mode, when the incident wave come from the top and travel downwards it will hit the interface. Due to difference in permittivity, reflection and transmission of light occurs. Because both of these propagations are in opposite direction, due to interference phenomena, standing waves were formed. These standing waves were formed in only upward and downward sides of the slit but not inside the slabs. Because the electrons move over the surface, edges block the movement of electron and do not allow to going inside the slabs. So these edges oppose the smooth movement of electrons. That's why charges of opposite polarity will accumulate at the edges as result dipoles are formed. So when the incident light beams will pass, charges accommodate and field moves in outside directions (four directions are left, right, top and bottom) only.

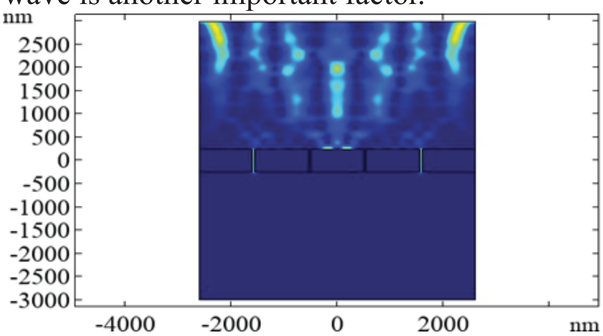
The result of this research of (TE) light transmission through sub-wavelength silver slits arrays involves analyzing the interplay between, plasmonics diffraction, and resonances. By carefully designing the slits array and optimizing the slit parameters,

researchers can control and enhance the transmission properties for applications in nanophotonic, sensing, and imaging. The combination of experimental techniques and numerical simulations provides valuable insights into the underlying physics and aids in the development of advanced devices and systems.

Power Flow through Silver Nano Slit

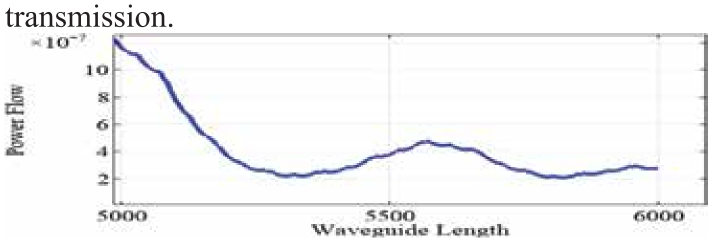
The transport of electromagnetic energy through a silver nano slit array is referred to as the power flow. In the context of silver nano slit arrays, the power flow is influenced by several factors including the incident wavelength, the width and periodicity of the slits, the surroundings and silver film characteristics. When light interacts with a silver nano slit array, it undergoes transmission, reflection & absorption processes. The power flow through the structure can be analyzed by considering the transmitted power, reflected power and absorbed power.

The transmitted power represents the portion of incident power that passes through the nano slit array and emerges on the other side. It depends on factors such as the width and periodicity of the slits, the incident angle, and the polarization of the incident light. The transmission efficiency, which is the ratio of transmitted power to incident power, provides insights into the effectiveness of power transfer through the array. The incident wavelength also plays a significant role in the power flow. The polarization of the incident wave is another important factor.



Power Flow for Silver Nano Slits

By matching the wavelength to the resonant modes of the slit, the transmission efficiency can be maximized. Resonant effects, such as localized surface plasmon resonances, can enhance the transmission through the nano slit, leading to increased power flow. The power flow through the nano slit can vary depending on whether the incident wave is TE (transverse electric) or TM (transverse magnetic) polarized. The polarization determines the electric field distribution and the interaction with the slit, thereby influencing the power transmission.



Power Flow

The reflected power corresponds to the portion of incident power that is reflected back into the same medium. Reflectivity, which is the ratio of reflected power to incident power, quantifies the amount of power that is reflected by the nano slit array.The absorbed power refers to the power that is converted into heat within the structure. In silver nano slit arrays, absorption occurs due to various mechanisms, including ohmic losses in the silver film and absorption in the surrounding medium.

The absorbed power can contribute to heating effects and should be considered in applications where thermal management is crucial. These methods allow for the calculation of the electric and magnetic fields, enabling the determination of the transmitted, reflected, and absorbed powers.

Understanding the power flow through silver nano slit arrays is essential for optimizing their performance in various applications. For instance, in plasmonic sensing, maximizing the transmitted power while minimizing reflection and absorption can enhance the sensitivity and signal-to-noise ratio. In energy harvesting or photovoltaic applications, optimizing the power flow can lead to improved light absorption and energy conversion efficiency.

In conclusion, the power flow through a silver nano slit array is determined by the interplay of transmission, reflection, and absorption processes by carefully designing the slit geometry, choosing appropriate materials, and considering the incident conditions, researchers can control and optimize the power flow for specific applications in areas such as sensing, energy harvesting, and integrated photonic devices. Numerical simulations, such as finite-difference time-domain (FDTD) can be used to study the power flow through silver nano slits. Computational simulations provide valuable insights into the power distribution within the structure, aiding in the design and optimization process.

Comparison of Electric Field, Magnetic Field and Power Flow at Different Wavelengths

The value of slit width kept fixed i.e. 50 nm for different wavelengths. Values of Electric Field, Magnetic Field and Power Flow at Different Wavelengths

Wavelength	Slit size	Electric field	Magnetic field	Power flow
400	50	3.5	10×10^{-3}	40×10^{-6}
450	50	2.5	7×10^{-3}	25×10^{-7}
580	50	2.5	4×10^{-3}	30×10^{-7}
633	50	2	5×10^{-3}	20×10^{-7}
675	50	4.5	12×10^{-3}	18×10^{-6}

Demonstrates various values for the visible region's five different visible wavelengths of the power flow, electric field, and magnetic field. Finally, we examined the, magnetic field, power flow and electric field values in this model at various wavelengths. Notably, power flow exhibits its largest value at the lowest wavelength, 400 nm, whereas electric field exhibits its lowest value at 633 nm, the wavelength at which it is employed at its peak, or 675 nm. The lowest values of the magnetic field and power flow are at wavelengths of 580 nm and 675 nm, respectively.

Power flow analysis revealed peak efficiency at shorter wavelengths (around 400 nm), with efficiency diminishing at longer wavelengths. The interaction between light and subwavelength features created interference patterns that influenced energy density within the slits. The results suggest that precise control over slit geometry can enhance light harvesting and optical energy management in photovoltaic and sensing applications (11).

The study's findings were compared to previous research, validating the simulation outcomes and reinforcing the importance of slit periodicity and width in determining optical properties. The ability to modulate light transmission through structural parameters highlights the versatility of silver as a material for plasmonic and photonic applications.

CONCLUSION

This research elucidates the impact of slit geometry and periodicity on the optical properties of light interacting with thick silver films. By harnessing surface plasmon polaritons and localized surface plasmon resonance phenomena, it is possible to achieve tailored optical responses for applications in nanophotonics, sensing, and energy harvesting. The findings contribute to a deeper understanding of light-matter interactions at the nanoscale, paving the way for advancements in next-generation optical devices and technologies.

The study of light-matter interactions at the nanoscale holds significant relevance for the fields of optometry and optics. Understanding how light behaves when it interacts with periodic nanostructures, such as slits in metallic films, has direct implications for the development of advanced optical technologies. This research explores the transmission of light through silver films with periodic slit arrays, focusing on phenomena like surface plasmon polaritons (SPPs) and extraordinary optical transmission (EOT). These findings offer valuable insights into designing enhanced optical systems for vision science, imaging, and light manipulation.

For optometry, precise manipulation and control of light are crucial for advancing diagnostic tools, corrective lenses, and vision-related devices. The ability to harness plasmonic phenomena enables the development of ultra-sensitive optical sensors and imaging systems that can operate at resolutions beyond the diffraction limit. Applications include wavefront sensing in refractive surgery, high-resolution retinal imaging, and the creation of optical filters and lenses with superior light-guiding capabilities.

In optics, the ability to control light transmission and field enhancement through subwavelength structures is fundamental for the design of photonic devices. The findings of this research can inform the development of advanced optical coatings, holographic systems, and adaptive optics. By tailoring the geometry and periodicity of nanostructures, it is possible to optimize the performance of devices used in medical imaging, spectroscopy, and optical communication systems. This work also complements ongoing efforts in photonic integration, where compact, high-performance optical components are essential for technological innovation.

Recommendations

Future research should expand on the parameter space by exploring other metals and alloys with distinct plasmonic properties to compare their efficacy against silver. Investigating multi-layered structures or hybrid configurations incorporating dielectric materials could further enhance transmission efficiencies and field confinement. Additionally, experimental validation of the simulation results will be critical to bridge theoretical and practical applications. Applying these findings in real-world optical sensing, energy harvesting, and waveguiding devices could demonstrate their practical significance.

Understanding light interaction with nanostructures, such as periodic slits in metallic films, is vital for advancing optical and optometric technologies. This study examines silver slit arrays and their phenomena, including surface plasmon polaritons (SPPs) and extraordinary optical transmission (EOT), with implications for enhancing imaging, diagnostic tools, and vision correction systems.

Plasmonic phenomena can enable high-resolution imaging systems for retinal and corneal diagnostics, improve wavefront sensing in refractive surgery, and lead to contact lenses with embedded optical filtering properties. Additionally, optical coatings using plasmonic materials could reduce glare and enhance UV protection for eyewear. This work also informs advanced photonic device designs, essential for medical imaging and light manipulation in optometry.

- Develop high-resolution imaging tools using plasmonic behaviors for precise retinal diagnostics.
- Enhance wavefront sensing for real-time optical aberration measurements in surgeries.
- Create contact lenses with embedded nanoscale filters for therapeutic applications.
- Integrate advanced coatings on eyewear for glare reduction and UV protection.
- Improve ophthalmic imaging systems by incorporating nanoscale light control.

Limitations

While this study provides insights into the effects of slit geometry and periodicity, it is limited to a simulation-based approach that assumes idealized conditions, such as perfect material homogeneity and no manufacturing imperfections. In real-world scenarios, factors like material defects, surface roughness, and non-ideal boundary conditions may impact performance. Furthermore, the scope was restricted to silver as the plasmonic material, and results may vary with other materials. These limitations suggest the need for experimental studies to corroborate and refine the findings.

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Authors Contributions:

Nimra Fatima: Substantial contributions to the conception and design of the work.

Umme Farwa: Design of the work and the acquisition. Drafting the work.

Muhammad Asfar Zaman: Final approval of the version to be published.

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