Enhanced Optical Transmission in Multilayer Nanoslit Structures – Theory and Simulation

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Abstract

- Enhance optical transmission through a metal-insulator-metal plasmonic waveguide through impedance matching design procedures from the microwave/radio frequency regime.
- Applying tapered, quarter-wavelength, and binomial impedance matching techniques and numerical simulations using finite-difference time-domain computational analysis, we report tunability and increase in optical transmission.
- Primarily, the thickness of the waveguide affects the wavelength of light transmitted. Thinner gold films allow higher transmission of light in the visible range and increasing the thickness causes a new peak to form in the NIR region, that continues to redshift as the thickness increases.
- Adding secondary and tertiary structures increase the transmission at desired wavelengths.

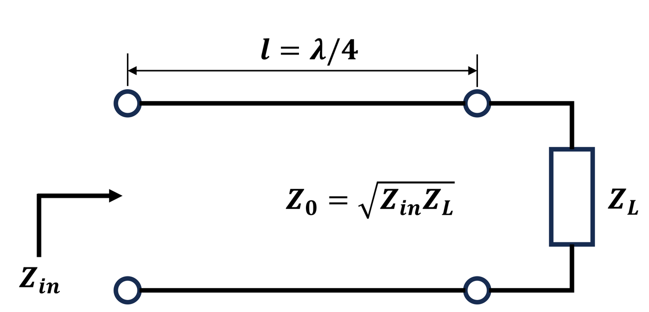
Introduction

- The phenomena of light waves coupling with the electron sea along the surface of metal dielectric interfaces is called surface plasmon polaritons. Designing devices that harness this plasmonic coupling can have significant applications in solid-state beam steering, highly integrated optical circuits, bio-chemical sensors, and more. The metal-insulator-metal (MIM) structure is a simple, yet effective structure for studying this coupling behavior.
- We extend impedance matching techniques from transmission line theory, such as tapered, quarter-wavelength, and multi-section impedance matching, while accounting for the penetration of electromagnetic fields through the metal regions.

Methods

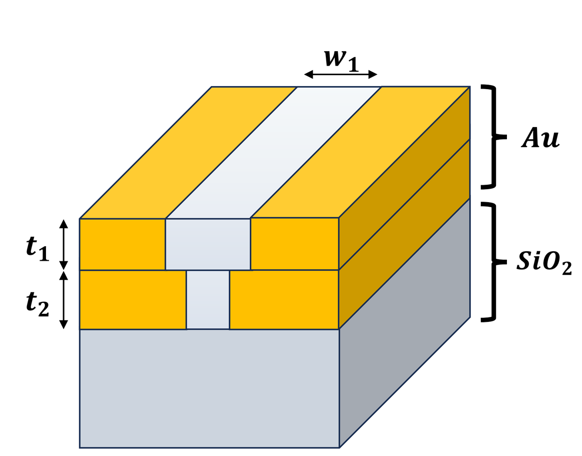
Quarter-Wavelength Transformer

- The quarter-wavelength transformer is an impedance matching technique between the load (free space) and the transmission line.



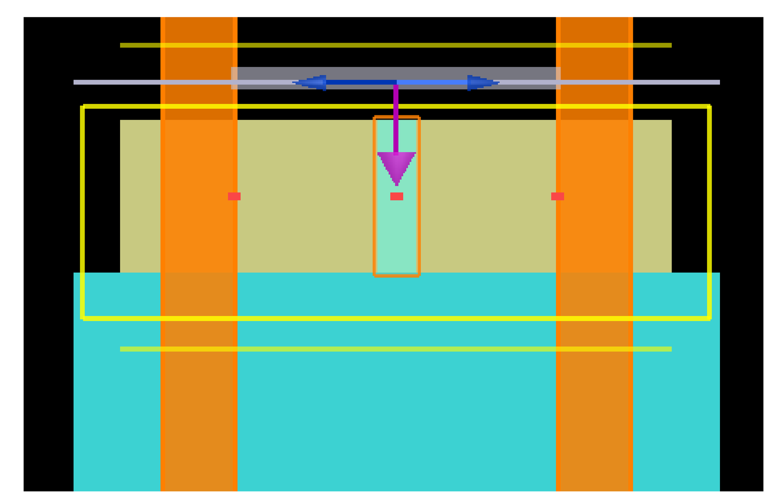
Finite Difference Time Domain (FDTD) Simulation

- Plane-wave source of 400-1400nm normal incident.
- Perfectly matched layers to simulate a single nanohole
- Mesh size of 1nm.
- Transmission monitored below MIM structure.
- MIM (gold-glass-gold) structure with varying width between 50nm and 125nm. A multilayer structure introduces sections of shorter width below the main waveguide.



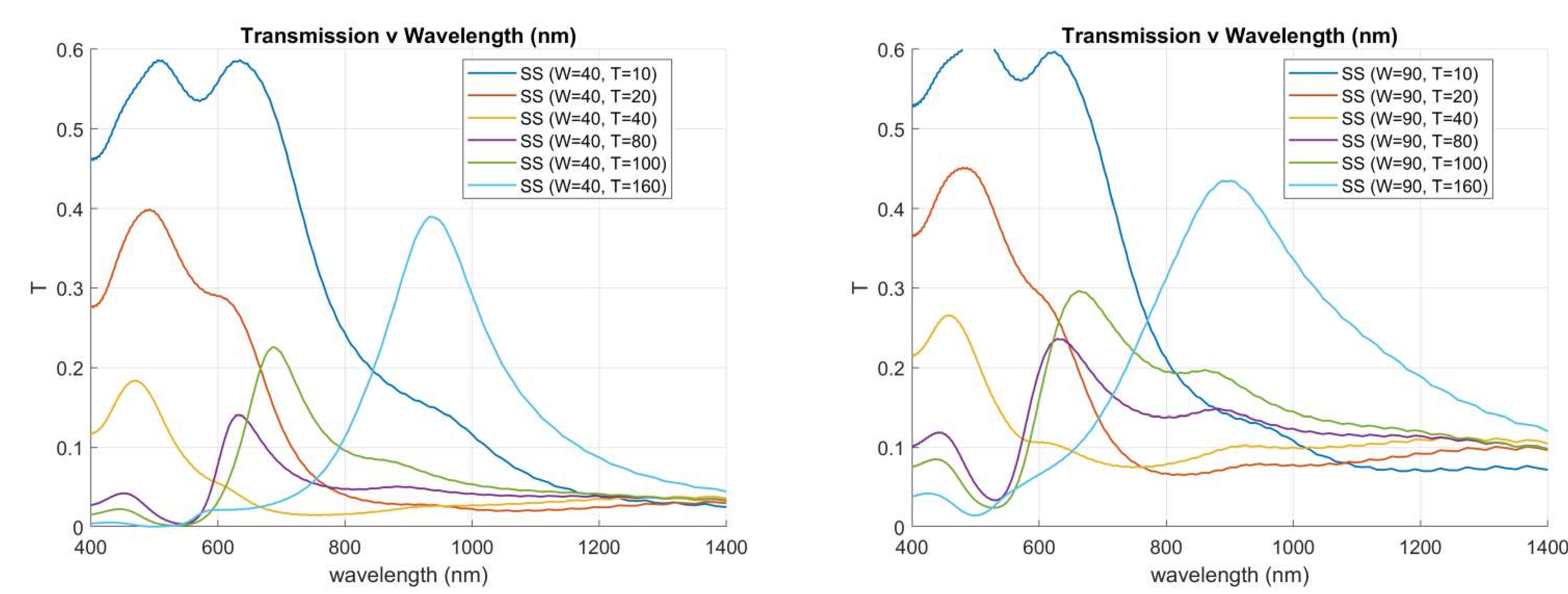
FDTD Simulation Results

Single Layer MIM Structure:

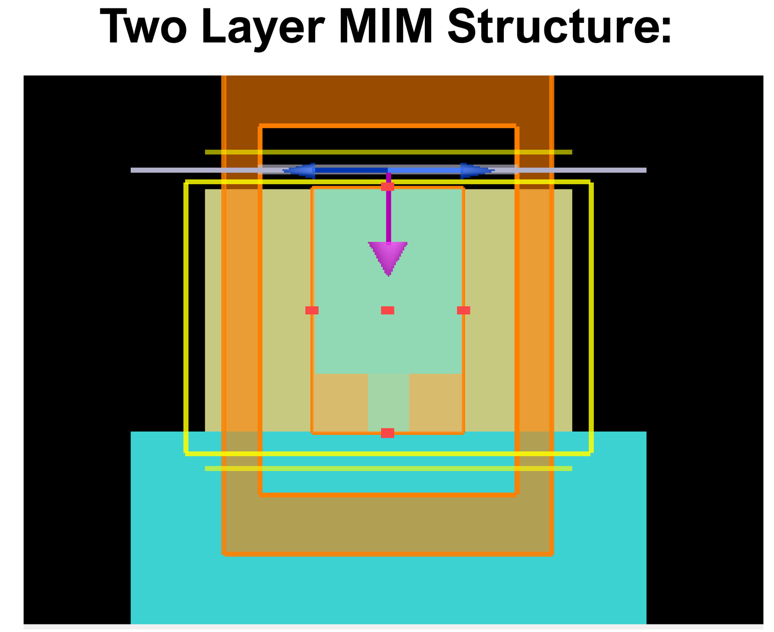


- Optical transmission through a single nanoslit as a function of slit width and thickness is investigated. As the width increases from 40 to 90, the transmission pattern changes slightly, with a larger hole demonstrating slightly higher transmission and slightly more broadband response.
- As the thickness increases, the large peak around 400-600nm shrinks as a new narrow peak forms around 600nm, which redshifts towards 1000nm as the thickness continues to increase.

Transmission vs Wavelength for Single-Layer MIM (Left: 40nm thick, Right: 90nm thick)

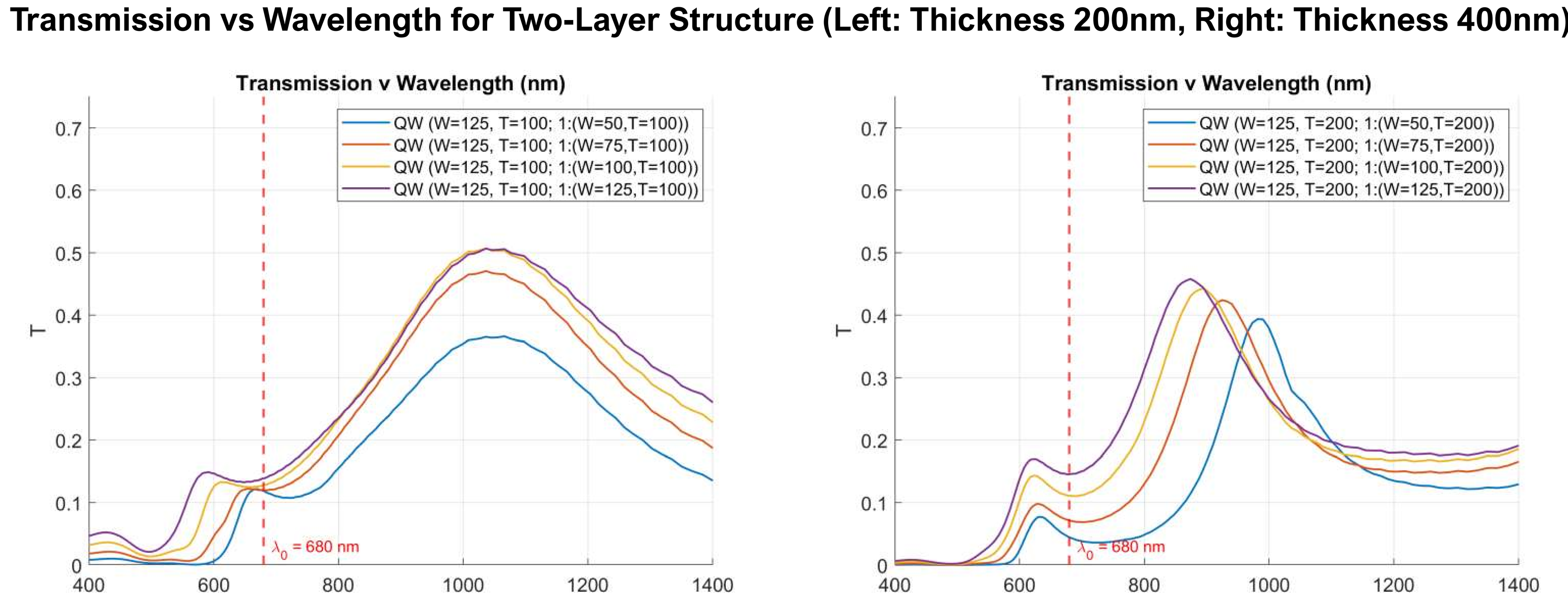


Two Layer MIM Structure:



- The two layer MIM structure takes advantage of the larger transmission from the larger hole and the high confinement in the smaller hole.
- We approach the smaller hole dimensions using a quarter wave impedance matching technique, further, comprehensive numerical modeling provides additional insight.
- Results from the simulations demonstrate the possibility of tuning the transmission peak to a desired wavelength.

Transmission vs Wavelength for Two-Layer Structure (Left: Thickness 200nm, Right: Thickness 400nm)



- Total Thickness of 200nm primarily redshifts the lower peak. Increasing the total thickness to 400nm shifts the upper peak.

Conclusion

- **Single-layer MIM structure simulations demonstrate high correlation between wavelength dependent transmission and total thickness of the waveguide.** Gold thin film introduces a large transmission in the visible range, decreasing with increasing thickness. A new peak in the NIR region emerges as the thickness increases that continues to redshift and grow.
- **Simulation results indicate promising enhanced transmission for a two-layer MIM structure.** The findings suggest that achieving a minimum reflection coefficient for MIM structures is possible by carefully selecting the appropriate gap width and thickness of the nanohole. This optimization is crucial for enhancing the efficiency and performance of the transformer.
- **Calculating the dimensions for the impedance matching section proves to be complex.** When calculating the impedance of the matching section to create a quarter wave matching section, field profile results suggest the high coupling at the boundary between the waveguide and free space is more complicated than the simple assumptions made in our calculations. Accounting for the coupling to of light to SPP wave at top and bottom surfaces may produce results closer to the simulation.

Future Work

- **Multi-section transformers and tapered line impedance matching will be explored.** Increasing the number of sections introduces additional parameters for finer tuning. The behavior between MIM structures may follow microwave impedance matching techniques, proving to be an easy way to further enhance transmission. Meanwhile, a tapered MIM structure may be an employed for broadband operation.
- **Further understanding of the MIM waveguide at the free space boundaries must be explored.** Currently, numerical results demonstrate the potential for creating structures analogous to quarter wave or multi-section transformer structures that are well studied in the microwave regime. However, our model often undershoots the dimensions we see providing significant coupling. We aim to further study the boundary conditions between our waveguide and free space.
- **Extend the design into periodic structures for extraordinary optical transmission.** Periodic nanohole structures demonstrate the ability to transmit beyond Bethe's small aperture theory. By extending our results to periodic structures, we may be able to observe additional coupling.

Acknowledgments

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