

People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
Mohamed Boudiaf University of M'Sila

Faculty of Technology
Department of Electronics



FIELD: Science and Technology
MAJOR: Electronics
SPECIALIZATION: Telecommunications
Engineering

**Master's Thesis Submitted in Fulfillment of the
Requirements for the Degree of Academic Master**

Prepared by:

Benchohra Hadjer

Lahlali Wiam

Thesis Title

**Design of a Band-Stop Filter Based on Metal–Insulator–Metal
(MIM) Plasmonic Structures**

Presented before the Examination Committee composed of :

Prof. Djamel KHEDROUCHE University of M'Sila **Chairman**

Prof. Abdesselam HOCINI University of M'Sila **Supervisor**

Prof. Harhouz Ahlam University of M'Sila **Reviewer**

2025 / 2026

Dedication

The journey was not short, the dream was not within easy reach, and the road was not paved with facilities and ease. Yet, I learned that every hardworking person has a share of success, and every patience bears its fruit.

To the one whose name I proudly carry with the most honorable title, the one who supported me without limits and devoted his life to building my future, the one who taught me that knowledge is the weapon of success and learning is the path to excellence, and who has always been, after God, my support, my strength, and my refuge...

To my pride and honor...

My beloved Father...

To the one under whose feet God placed Paradise, the one whose heart embraced me before her arms did, who spent countless sleepless nights for my comfort, eased the burdens of my life, and was a light in my darkest moments and a prayer behind every success...

My beloved Mother...

To the one who has been like a second father and an unwavering source of support, who surrounded me with kindness and care, treated me as his own daughter, and whose presence was a source of strength and reassurance. His encouragement motivated me to persevere and achieve success...

My dear Uncle...

To those who have always strengthened and supported me, who have been springs of hope and sources of happiness, from whom I draw strength and determination, and who shared with me both the difficult and joyful moments...

My Brothers and Sisters...

To everyone who has been a source of help and support along this journey, to my loyal friends and classmates who shared with me the moments of hard work, perseverance, and dedication...

To all those who stood by me in times of ease and hardship...

I dedicate to you this achievement, the fruit of years of effort and perseverance. Today, I reap its first rewards by the grace of Almighty God. All praise is due to God for His blessings, all praise is due to Him for His guidance and assistance, and all praise is due to Him by whose grace good deeds are accomplished.

Hadjer

2
0
2
6



Dedication

Praise be to Allah, and gratitude without measure. Had it not been for His grace and blessings, I would not have reached this point. Peace and blessings be upon the Prophet Muhammad.

Today, as I reap the fruits of my efforts, I dedicate this achievement to all those who supported me throughout this journey:

To my father, who taught me that knowledge is a treasure and learning is a weapon; to the one who sacrificed for my sake and whose name I carry with pride—may Allah protect him and grant him a long life.

To the one beneath whose feet lies Paradise, to the one whose prayers illuminated my path and whose endless support inspired me every day:

My beloved mother.

To those who stood by me, from my father's family to my mother's family, and to everyone who prayed for me and wished me success.

To my brothers and sisters, and my dear siblings.

To myself, for not giving up despite the difficulties and challenges.

To my classmates and friends who shared with me the years of study, effort, and ambition.

To my dear friends,

I dedicate this achievement to you all. Today, I stand where I am thanks to Allah first, and then to your support. All praise is due to Allah, who guided me and made this success possible.

wiam

2
0
2
6



Acknowledgements

First and foremost, we thank Almighty Allah for giving us the health, strength, and determination to undertake and complete this thesis.

This work would not have been possible without the guidance and support of **Prof. Abdesselam HOCINI**. We would like to express our sincere gratitude for his outstanding supervision, patience, rigor, and continuous availability throughout the preparation of this thesis.

We would also like to extend our sincere thanks to all the members of the jury for accepting to evaluate and examine this work.

Our special thanks go to **Mrs. Imane Zegaar** for her support and assistance throughout this work, as well as for her valuable advice and guidance, which greatly contributed to the successful completion of this thesis.

We would also like to express our gratitude to all our teachers who accompanied us throughout our years of study and contributed to our academic and professional development.

Finally, we would like to thank everyone who contributed, directly or indirectly, to the realization of this project through their moral or material support.

Thank you all.

Table of Contents

Table of Contents	V
List of Figures	IXX
List of Tables	X
List of Abbreviations	XI
GENERAL INTRODUCTION	1

Chapter 01: Fundamentals of Plasmonics

1.Introduction.....	4
2. Theoretical Foundations and Physical Principles	6
2.1 Surface Plasmons: Definition and Nature	6
2.2 Surface Plasmon Polaritons (SPP).....	7
2.3 Localized Surface Plasmons (LSPR)	9
2.4 Resonance Mechanisms and Field Amplification	11
3. Plasmonic Materials	12
3.1 Noble Metals: Gold and Silver.....	12
3.2 Other Plasmonic Materials	13
3.3 Geometries and Nanostructured Architectures	13
4. Plasmonic Metamaterials	14
4.1 Negative Refractive Index.....	15
4.2 Applications in Optical Cloaking	15
4.3 Tunable Metamaterials.....	16
5. Plasmonic Nanostructures and Their Optical Properties.....	17
5.1 Nanospheres	17
5.2 Nanorods	19
5.3 Core-Shell Nanoparticles	21
6. Fabrication Methods of Plasmonic Nanostructures	24
6.1 Chemical Fabrication Methods	25
6.1.1 Seed-Mediated Growth Method.....	26
6.1.2 Chemical Reduction Method	26
6.1.3 Template-Assisted Synthesis	26

6.2 Physical (Top-Down) Fabrication Methods	27
6.2.1 Electron Beam Lithography (EBL)	27
6.2.2 Thin Film Deposition and Thermal Annealing	27
6.2.3 Nanoimprint Lithography.....	28
7. Conclusion	28

Chapter 02: Plasmonic Devices and Applications

1.Introduction.....	31
2. Optical Properties.....	31
2.1 Plasmonic Resonance and Spectral Tunability	31
2.2 Electromagnetic Field Amplification.....	32
2.3 Diffusion and Absorption	33
3. Plasmonic Sensors (SPR / LSPR)	34
3.1 Surface Plasmon Resonance (SPR)	34
3.2 Localized Surface Plasmon Resonance (LSPR)	34
3.3 Advantages of Plasmonic Sensors	35
4. Plasmonic Optical Devices.....	35
4.1 Waveguides.....	36
4.2 Resonators	36
4.3 Advantages of Plasmonic Devices	36
5. Filters	37
6. Plasmonic Filters	38
6.1 Definition	38
6.2 Types of Plasmonic Filters	38
6.2.1 Nanoparticle-based Filters	38
6.2.2 Nanohole Array Filters	39
The way they work depends on the size and arrangement of the holes. They are used in sensing and systems[153].	39
6.2.3 Plasmonic Grating Filters	39
6.2.4 Resonator-based Filters.....	39
6.3 Spectral Response of Plasmonic Filters	40
6.3.1 Band-pass Filters	40

6.3.2 Band-stop Filters	40
6.3.3 Low-Pass Filters	41
6.3.4 High-Pass Filters	41
6.4 Working Principle	42
6.5 Advantages of Plasmonic Filters.....	42
6.6 Limitations of Plasmonic Filters.....	43
7. Works.....	43
8. Applications in Detection and Bio-sensing.....	43
8.1 SPR and LSPR sensors	43
8.2 Surface Enhanced Raman Spectroscopy (SERS).....	44
9. Design Parameters of Plasmonic Filters	45
10. Materials Used in Plasmonic Filters.....	46
11. Performance Metrics of Plasmonic Filters.....	47
12. Comparison with Conventional Filters	47
13. Fabrication Techniques of Plasmonic Filters.....	48
13.1 Electron Beam Lithography (EBL)	48
13.2 Focused Ion Beam (FIB)	48
13.3 Nanoimprint Lithography (NIL).....	49
13.4 Other Techniques	49
14. Spectral Response of Plasmonic Filters.....	49
14.1 Resonance Peaks	49
14.2 Transmission Spectrum	49
14.3 Bandwidth.....	50
14.4 Factors Affecting Spectral Response	50
14.5 Spectral Tunability	50
15. Effect of Geometry on Filtering Performance	50
15.1 Nanoparticle Shape.....	50
15.2 Size Effect.....	50
15.3 Spacing and Periodicity	50
15.4 Extraordinary Optical Transmission	51
15.5 Optimization	51
16. Loss Mechanisms in Plasmonic Filters.....	51
16.1 Absorption Losses	51
16.2 Scattering Losses	51

16.3 Radiative Losses	51
16.4 Surface Roughness	51
16.5 Ohmic Losses	52
16.6 Strategies to Reduce Losses	52
17. Future Perspectives	52
18. Conclusion.....	52

Chapter 03: Design and Study of a Plasmonic Filter

1. Introduction.....	56
2. Structure of the Proposed Filter.....	56
2.1 General Structure	56
2.2 Dimensions of the Structure	57
2.3 Working Principle.....	58
3. Simulation Method Using RSoft.....	58
3.1 Introduction to RSoft	58
3.2 Numerical Method(FDTD)	59
4. Discussion of results	60
4.1 Study of Metal Selection and MIM Waveguide Fundamentals	60
Table 3.1. Transmission values for metals, at the reference wavelength.....	61
4.2 Study of Waveguide Thickness	62
4.3 study of the Single-Cavity Structure	63
4.4 Study of the Double-Cavity Structure.....	65
4.5 Study of the Triple-Cavity Structure	67
4.6 Study of the Four-Cavity Structure	68
5. Comparison of Different Structures	70
6. Conclusion	71
GENERAL CONCLUSION.....	72
Références.....	73

List of Figures

Chapter 01: Fundamentals of Plasmonics

Figure 1.1. Propagation and Electromagnetic Field Confinement of Surface Plasmon Polaritons (SPPs) at a Metal–Dielectric Interface

Figure 1.2. Surface Plasmon Propagation on an Electrically Insulating Metal Interface

Figure 1.3. Surface Plasmon Polariton Propagation at a Metal–Dielectric Interface

Figure 1.4. Dispersion Curve for SPP Compared to the Light Line

Figure 1.5. Localized Plasmon Resonance Generated by a Metallic Nanoparticle

Figure 1.6. Absorption Spectrum (LSPR)

Figure 1.7. Negative Refraction of Electromagnetic Waves in a Plasmonic Metamaterial

Figure 1.8. Principle of Optical Cloaking Using Plasmonic Metamaterials

Figure 1.9. Tunable Response of Plasmonic Metamaterials Under External Stimuli

Figure 1.10. Localized Surface Plasmon Resonance (LSPR) in Metallic Nanospheres

Figure 1.11. Plasmonic Modes in Gold Nanorods: Transverse and Longitudinal Resonances

Figure 1.12. Core–Shell Nanoparticles Structure (Au–SiO₂ Example)

Figure 1.13. Fabrication Methods of Plasmonic Nanostructures (Chemical and Physical Approaches)

Chapter 02: Plasmonic Devices and Applications

Figure 2.1. Illustration of SPR and LSPR Phenomena

Figure 2.2. Plasmonic Waveguide Illustrating Subwavelength Light Confinement

Figure 2.3. Extraordinary Optical Transmission Through a Plasmonic Nanohole Array

Figure 2.4. Working Principle of a Plasmonic Filter Based on Resonance Effects

Figure 2.5. Electromagnetic Hotspots Generated Between Metallic Nanoparticles

Chapter 03: Design and Study of a Plasmonic Filter

Figure 3.1. A Diagram of the Basic MIM Plasmonic Waveguide

Figure 3.2. Transmission Spectrum of the Reference MIM Waveguide for Metal Claddings

Figure 3.3. Transmission Spectra of the MIM Waveguide as a Function of Channel Width (W)

Figure 3.4. Transmission Spectrum of a Single-Cavity Plasmonic Structure for Various Lengths (L)

Figure 3.5. Transmission Spectrum of the Double-Cavity Configuration Under Different Separation Distances (D)

Figure 3.6. Transmission Spectrum of the Triple-Cavity Structure

Figure 3.7. The Optimized Four-Cavity Plasmonic Filter

Figure 3.8. Comprehensive Comparison Across the Multi-Cavity Evolutionary Designs

List of Tables

Table 1.1. Comparison of Plasmonic Nanostructures (Nanospheres, Nanorods, Core–Shell Nanoparticles)

Table 3.1. Transmission Values for Metals at the Reference Wavelength

List of Abbreviations

SPP :	Surface Plasmon Polariton
SPR :	Surface Plasmon Resonance
LSPR :	Localized Surface Plasmon Resonance
MIM :	Metal–Insulator–Metal
FDTD :	Finite-Difference Time-Domain
FEM :	Finite Element Method
EM :	Electromagnetic
TM :	Transverse Magnetic
TE :	Transverse Electric
RI :	Refractive Index
QF :	Quality Factor
FWHM :	Full Width at Half Maximum
EOT :	Extraordinary Optical Transmission
Au :	Gold
Ag :	Silver
Al :	Aluminum
SiO ₂ :	Silicon Dioxide
UV :	Ultraviolet
VIS :	Visible Spectrum
NIR :	Near-Infrared
THz :	Terahertz
nm :	Nanometer
μm :	Micrometer

GENERAL INTRODUCTION

The rapid development of optical communication systems, integrated photonic circuits, and nanoscale sensing technologies has created an increasing demand for compact and high-performance optical devices. Conventional photonic components are often limited by the diffraction limit of light, which restricts the miniaturization of optical systems and their integration into highly dense photonic platforms.

Plasmonics has emerged as a promising field capable of overcoming these limitations by exploiting the interaction between electromagnetic waves and free electrons at metal–dielectric interfaces. This interaction gives rise to surface plasmon modes that enable the confinement and manipulation of light at dimensions significantly smaller than the wavelength of the incident radiation. As a result, plasmonic structures have attracted considerable attention for applications in optical communications, biosensing, imaging, energy harvesting, and integrated nanophotonic systems.

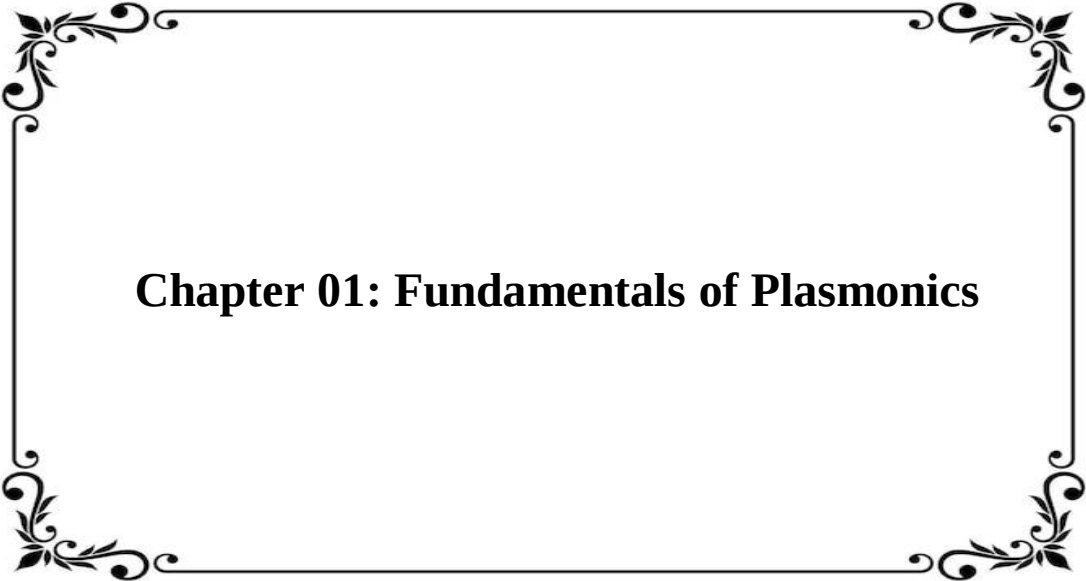
Among the various plasmonic devices, plasmonic filters play a crucial role in wavelength selection and spectral control. In particular, Metal–Insulator–Metal (MIM) waveguide structures offer strong electromagnetic confinement, compact dimensions, and compatibility with integrated photonic circuits. By introducing resonant cavities into MIM waveguides, it becomes possible to obtain highly selective transmission characteristics and enhanced filtering performance.

The main objective of this work is to design and optimize a high-performance plasmonic band-pass filter based on MIM waveguides and resonant cavities. Different configurations have been investigated, starting from a single-cavity structure and progressively evolving toward multiple-cavity architectures. The influence of geometrical parameters on the transmission spectrum, resonance behavior, and filtering characteristics has been analyzed in order to achieve improved performance and better spectral selectivity.

This manuscript is organized into three chapters. The first chapter presents the fundamental concepts of plasmonics, including plasmonic materials, nanostructures, metamaterials, and fabrication techniques. The second chapter focuses on plasmonic devices and applications, with particular emphasis on plasmonic filters, their operating principles, performance parameters, and practical applications. The third chapter is devoted to the design, simulation,

optimization, and comparative analysis of the proposed plasmonic filter structures, leading to the final optimized configuration.

The results obtained demonstrate that the introduction of multiple resonant cavities significantly improves the spectral response of the filter, enhances resonance quality, and contributes to the development of compact and efficient plasmonic devices for future integrated photonic applications.



Chapter 01: Fundamentals of Plasmonics

1.Introduction

Plasmonics is an interdisciplinary research field situated at the intersection of nanotechnology, optics, and materials science. It studies the interaction between electromagnetic radiation and the free electrons present at the surface of metallic materials, particularly at the nanoscale. This interaction leads to the excitation of collective electron oscillations known as surface plasmons.

One of the most important characteristics of plasmonic phenomena is their ability to confine electromagnetic energy below the diffraction limit of light. This exceptional confinement allows strong enhancement of the local electromagnetic field near metallic nanostructures, making plasmonics highly attractive for a wide range of scientific and technological applications .

Depending on the nature of the excitation and the geometry of the metallic structure, plasmonic modes are generally classified into two main categories: Surface Plasmon Polaritons (SPPs), which propagate along metal–dielectric interfaces, and Localized Surface Plasmon Resonances (LSPRs), which are confined around metallic nanoparticles [1].

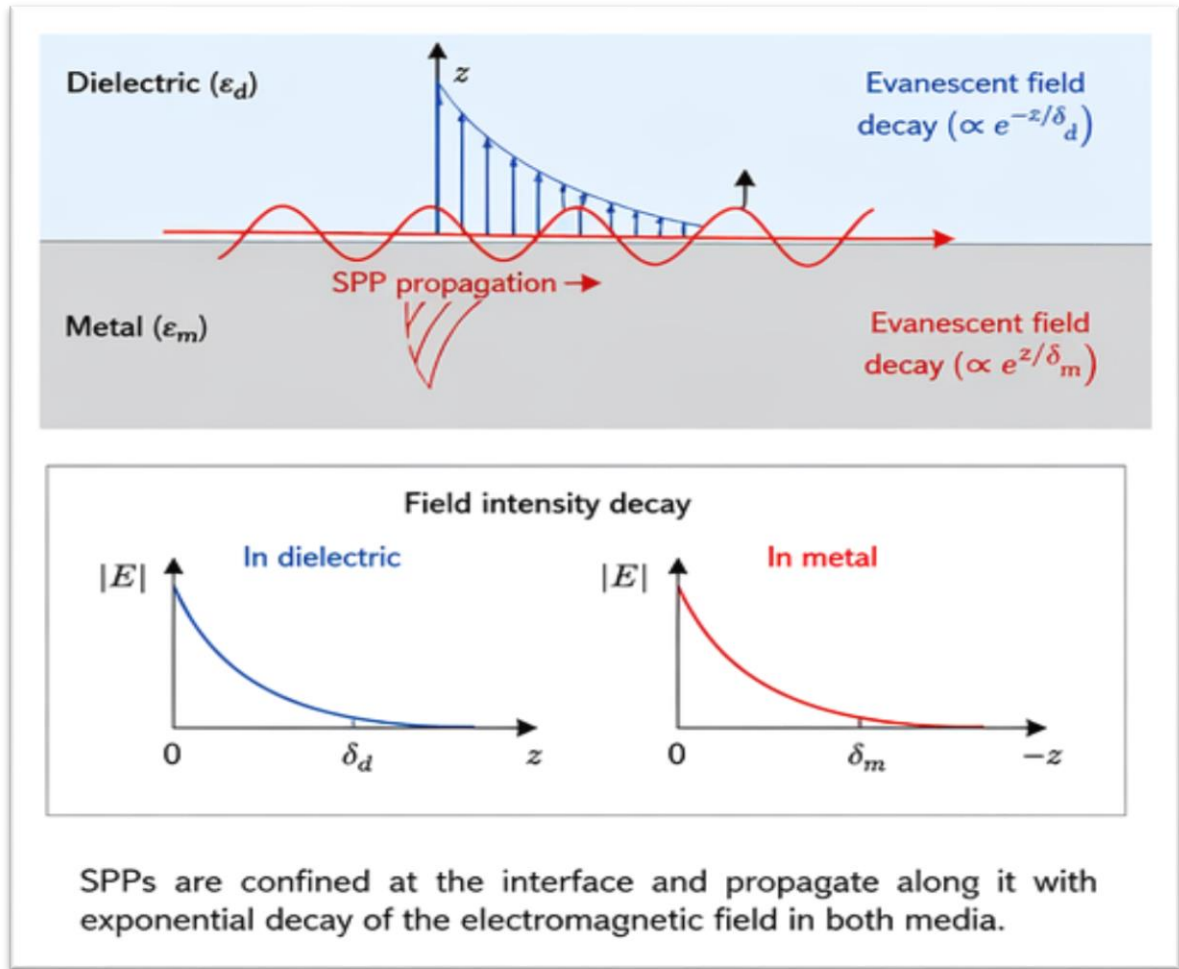


Figure 1.1. Propagation and Electromagnetic Field Confinement of Surface Plasmon Polaritons (SPPs) at a Metal–Dielectric Interface.

The optical response of these modes strongly depends on several parameters, including the dielectric properties of the material, the surrounding environment, and the morphology of the nanostructure.

Recent progress in nanofabrication techniques has enabled precise control over the size, shape, and composition of plasmonic nanostructures such as nanospheres, nanorods, nanoshells, and hybrid architectures. These advances have considerably expanded the applications of plasmonics in biosensing, nanophotonics, medical imaging, photovoltaics, optical communication, and energy harvesting systems. In addition, plasmonic metamaterials have introduced new possibilities for manipulating light in unconventional ways, including negative refraction and tunable optical responses.

The objective of this chapter is to present the fundamental principles of plasmonics and to introduce the main plasmonic materials, nanostructures, metamaterials, and fabrication methods commonly used in this field. Particular attention is given to the relationship between nanostructure geometry and optical behavior, which plays a key role in the design of advanced plasmonic devices [2].

2. Theoretical Foundations and Physical Principles

2.1 Surface Plasmons: Definition and Nature

Surface plasmons represent coherent collective oscillations of free electrons on the surface of a metal, coupled with an electromagnetic field . These oscillations occur at the interface between a negative dielectric constant material (typically a metal) and a positive dielectric constant material (dielectric or air) . When an incident electromagnetic field interacts with this interface, it induces charge separation and dipole oscillation aligned with the electric field of light.

The plasmonic phenomenon relies on the collective response of conduction electrons in metals. Unlike individual electron transitions, plasmons involve the coordinated movement of a large number of electrons, thus creating charge density waves that propagate along the metal-dielectric interface or remain confined within metallic nanostructures . This collective nature gives plasmons their unique amplification and electromagnetic field confinement properties [3].

2.2 Surface Plasmon Polaritons (SPP)

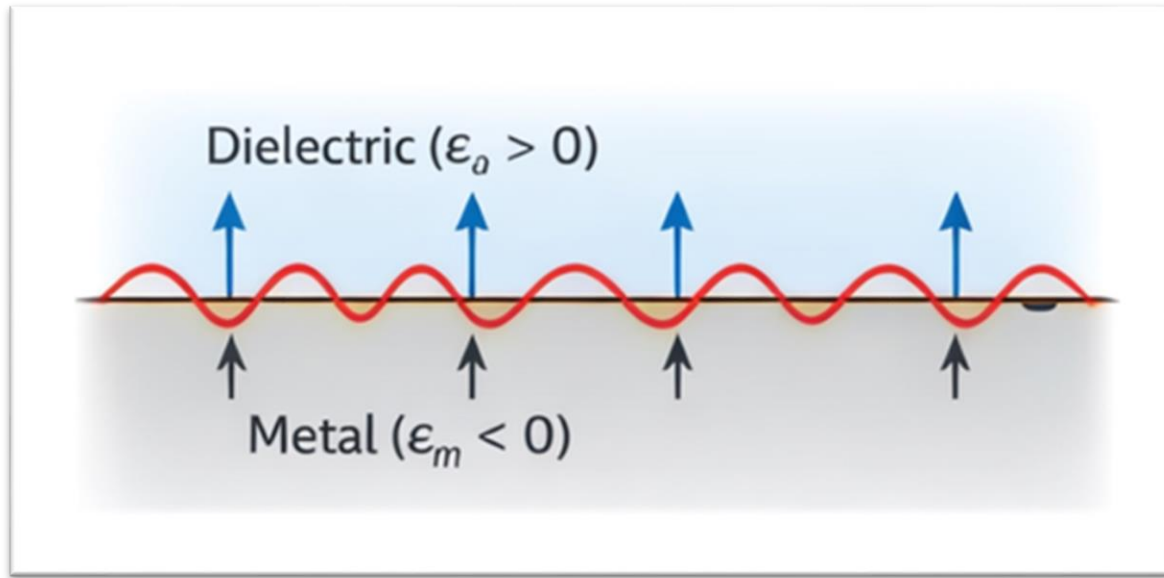


Figure .12: Surface plasmon propagation on an electrically insulating metal interface

Surface plasmon polaritons (Surface Plasmon Polaritons, SPP) are propagative electromagnetic modes that form when the surface plasmons and incident photons are coupled. These modes propagate along the metal-dielectric interface with a wave vector greater than that of light in the dielectric medium, which confines them near the interface .

To better understand the propagation and confinement properties of Surface Plasmon Polaritons, the SPP wave vector at a metal–dielectric interface is expressed by the following equation:

$$K_{spp} = K_0 \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}}$$

where:

- K_{spp} is the propagation wave vector of the SPP,
- K_0 is the free-space wave vector,
- ϵ_m is the dielectric permittivity of the metal,
- ϵ_d the dielectric permittivity of the surrounding dielectric medium.

This equation shows that the SPP wave vector is larger than that of light propagating in the dielectric medium, which explains the strong electromagnetic confinement near the interface

SPPs exhibit several remarkable features. Firstly, they possess an electric field component perpendicular to the interface that decays exponentially in both media, thus creating a spatial confinement of the field . Secondly, the scattering relation of SPPs differs from that of free light, allowing for modes at frequencies where propagation in the dielectric would be impossible. Thirdly, SPPs can be excited by various methods including prism coupling (Kretschmann configuration), gratings, or surface defects.

SPP applications include Surface Plasmon Resonance (SPR) sensors, where the refractive index sensitivity of the dielectric medium allows the detection of biomolecules with high accuracy . Optimized plasmonic nanoslides can achieve exceptional surface sensitivities, with S_s values = 70 nm/nm and figures of merit (FOM) of 1.5 nm^{-1} , representing the highest reported performance for plasmonic sensors [4].

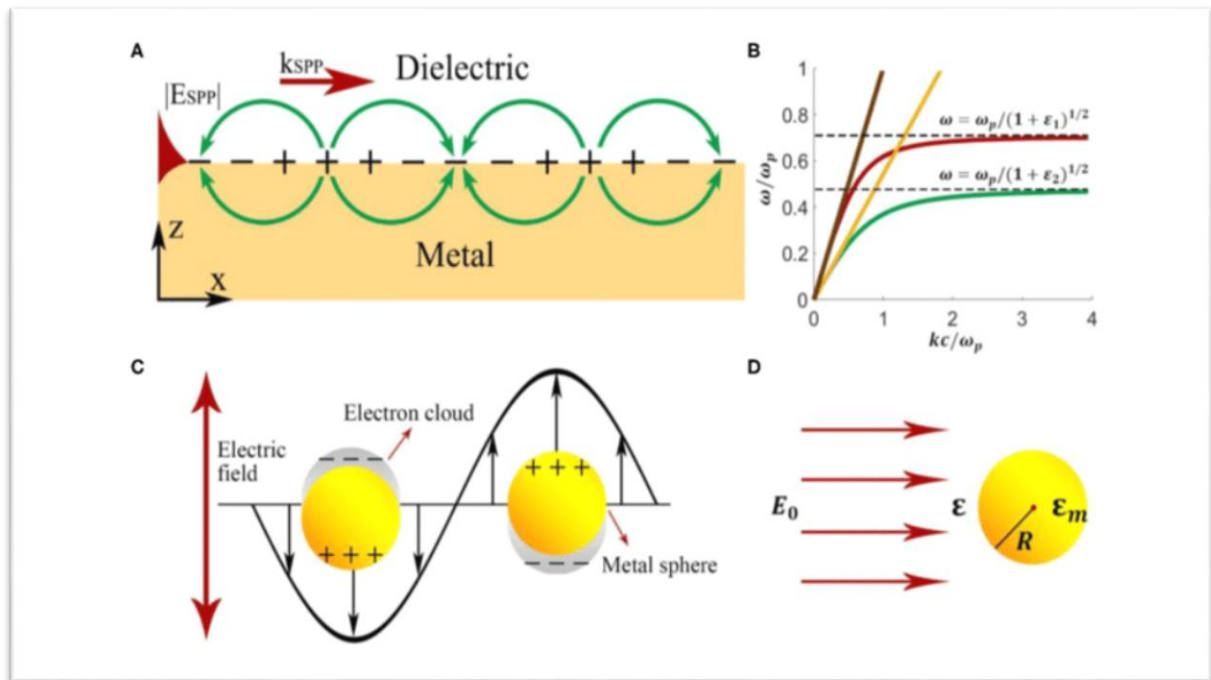


Figure 1.3. Surface Plasmon Polariton propagation at a metal–dielectric interface.

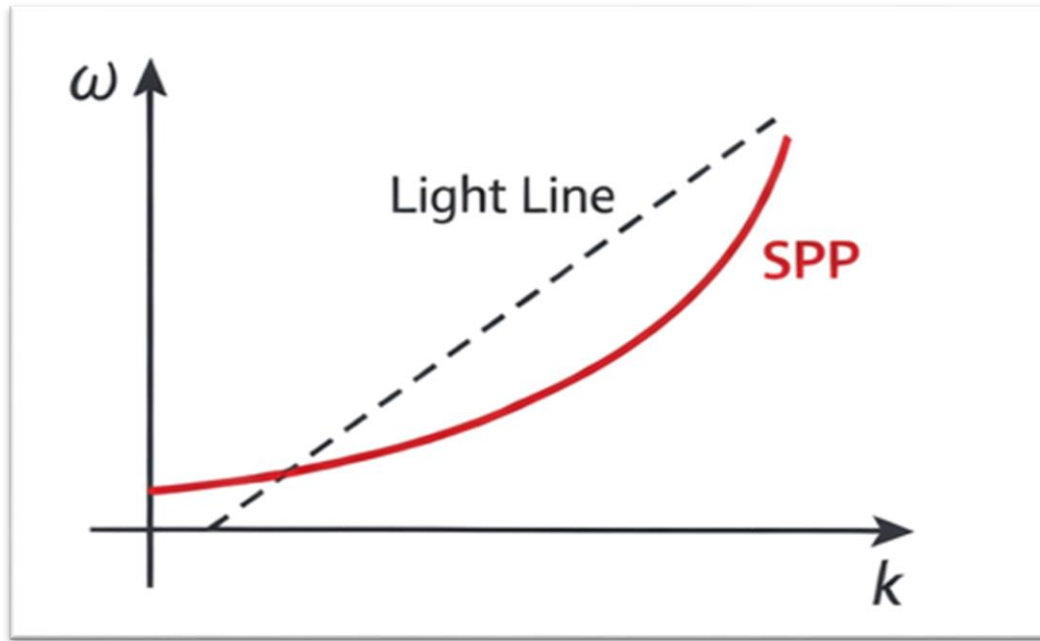


Figure 1.4. Dispersion curve for spp compared to the light line

2.3 Localized Surface Plasmons (LSPR)

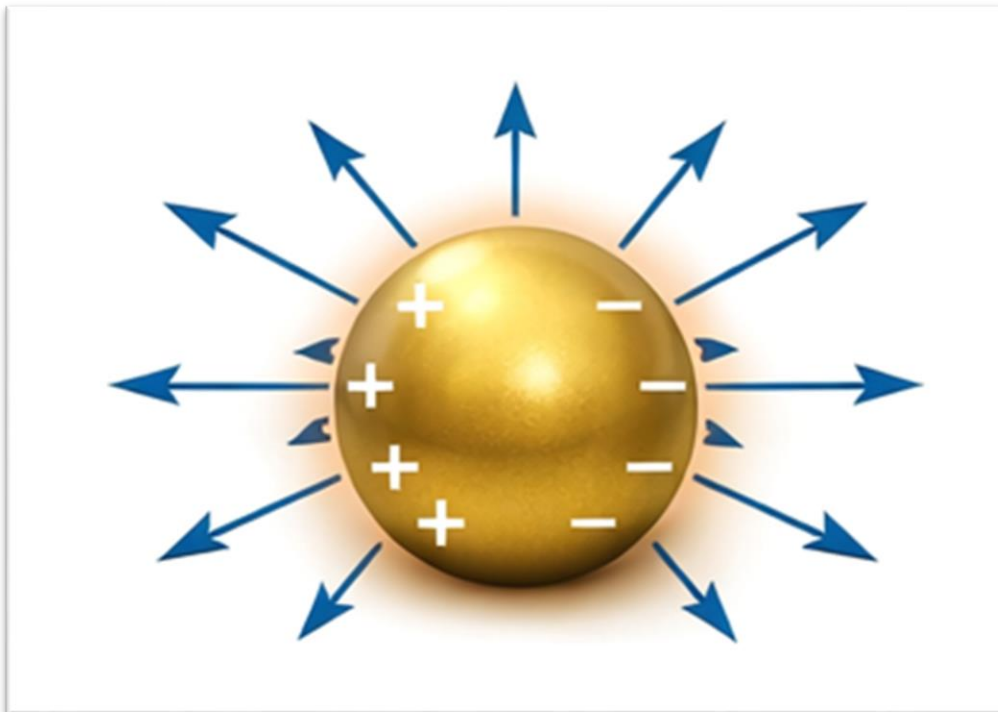


Figure .15. Localized plasmon resonance generated by a metallic nanoparticle

Localized Surface Plasmon Resonance (LSPR) occurs when light interacts with metallic nanoparticles whose dimensions are less than the incident wavelength. In this regime, conduction electrons collectively oscillate in phase, creating a dipolar (or multipolar for larger particles) resonance that confines the electromagnetic field within a nanometer-sized volume around the particle.

LSPR resonance is characterized by a specific resonant frequency that depends on several parameters: the composition of the metal, the size and shape of the nanoparticle, and the refractive index of the surrounding medium. This multi-parametric dependence offers great flexibility for optical property engineering. For example, gold nanoparticles can exhibit LSPR resonances ranging from visible to near-infrared depending on their geometry.

For small metallic nanoparticles, the resonance condition of Localized Surface Plasmon Resonance (LSPR) can be approximately described by the following relation:

$$\text{Re}(\epsilon_m) = -2\epsilon_d$$

where:

- ϵ_m is the dielectric permittivity of the metal,
- ϵ_d is the dielectric permittivity of the surrounding medium.

This relation explains why the plasmon resonance strongly depends on the optical properties of both the metallic nanoparticle and its surrounding environment.

The spatial confinement of LSPR is extremely high, limited only by nanoparticle size, allowing to reach sub-wavelength resolutions. This intense localization of the electromagnetic field, combined with the amplification of the field (up to 5-6 orders of magnitude), constitutes the physical basis for many applications in enhanced spectroscopy, ultra-sensitive detection and high-resolution imaging.

The theoretical models describing LSPR include Mie theory for spherical nanoparticles and Gans theory for ellipsoidal particles. These models allow to calculate the quenching, absorption and scattering cross sections, as well as to predict the maximum resonance wavelength depending on the aspect ratio of the nanostructures [5].

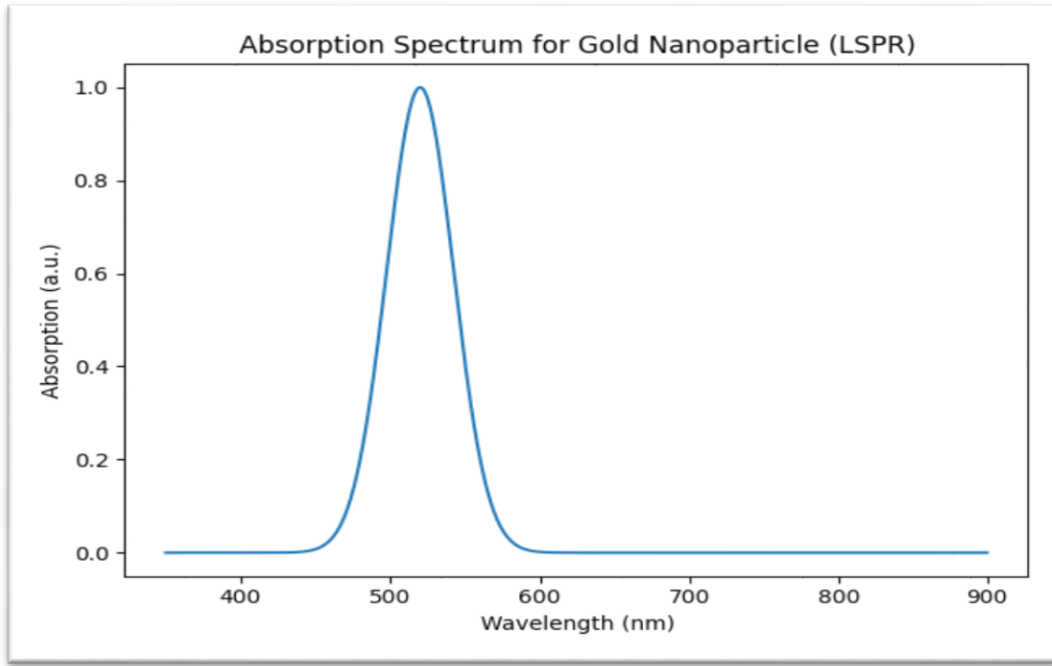


Figure .16: Absorption Spectrum (LSPR)

2.4 Resonance Mechanisms and Field Amplification

The amplification of the electromagnetic field constitutes one of the most remarkable properties of plasmonic systems. At plasmonic resonance, the local electric field strength can be amplified by several orders of magnitude with respect to the incident field. This amplification results from the concentration of electromagnetic energy in a nanometric volume, creating "hot spots" where light-matter interaction is considerably enhanced.

The physical mechanisms underlying this amplification include the collective resonance of conduction electrons, which accumulates the energy of the incident field, and the extreme spatial confinement that concentrates this energy in a reduced volume. In coupled structures, such as nanoparticle dimers, amplification can be even more important in the nanoscale interstices between particles, where the fields of the two particles constructively overlap.

Electromagnetic theory and numerical simulations by the finite difference method in the time domain (FDTD) confirm these exceptional amplifications. Calculations show that a three-fold increase in the electric field amplification can be achieved by optimizing the interface between the plasmonic nanostructure and the substrate. These amplifications are directly responsible for the exceptional performance observed in surface-enhanced Raman

spectroscopy (SERS), where amplification factors of 10^{14} - 10^{15} allow single molecule detection.

Non-local and quantum effects become significant when the characteristic dimensions of nanostructures (notably the interstices in the dimers) approach the nanometer or sub-nanometer. In this regime, classical models must be complemented by approaches taking into account non-local screening and electron tunneling. These effects modify the plasmonic response, with resonance wavelengths and peak intensities that exhibit smaller variations in non-local models compared to classical theory [6].

3. Plasmonic Materials

3.1 Noble Metals: Gold and Silver

Gold (Au) and silver (Ag) are the most widely used plasmonic materials due to their exceptional optical properties in the visible and near-infrared. These noble metals have a negative dielectric constant in this spectral range, a necessary condition for the existence of intense plasmonic resonances [1].

Silver offers the highest sensitivity to changes in refractive index, with performances 1.2 to 2 times higher than gold. Silver nanoparticles generate SERS amplification factors of up to 10^{10} , enabling label-free detection, rapid synthesis and enhanced antibacterial activity. The shape and size of silver nanostructures are controllable, which allows for fine tuning of resonance characteristics and SERS intensity.

Gold has the advantage of excellent biocompatibility and superior chemical stability, making it particularly suitable for biomedical applications. Gold and silver nanoparticles can be synthesized into a wide variety of shapes (nanospheres, nanobags, nanocages, nanostars, core-shell structures) by controllable synthetic approaches. The geometry of the particles, correlated with plasmonic properties, allows optimizing performance for specific biomedical applications.

Hybrid structures combining gold and silver, such as Ag@Au core-shell nanoparticles, offer an interesting compromise between the optical properties of silver and the stability of gold. These architectures allow to exploit the advantages of both metals while minimizing their respective limitations.

3.2 Other Plasmonic Materials

Beyond gold and silver, other metals exhibit interesting plasmonic properties for specific applications. Rhodium (Rh), platinum (Pt), aluminum (Al), gallium (Ga), magnesium (Mg), copper (Cu) and palladium (Pd) have been studied for their applications in optical detection and catalysis .

Aluminum is of particular interest for photovoltaic applications due to its low cost and its ultraviolet and visible plasmon resonance. Aluminum nanospheres can be used on the front surface of solar cells to improve plasmon scattering and light absorption.

Tungsten (W) was explored for high temperature plasmonic absorbers due to its high melting point. Circular tungsten nano-antennas, deposited on an aluminum nitride (AlN) dielectric spacer and a silver reflective layer, allow for absorption greater than 90% over a wide spectral band (400-1500 nm) for solar thermal photovoltaic applications [8].

Two-dimensional materials like graphene, transition metal oxides, and heavily doped semiconductors also support plasmonic resonances, offering extended spectral tunability from ultraviolet to far infrared . These emerging materials significantly expand the spectrum of applications for plasmonics.

3.3 Geometries and Nanostructured Architectures

The diversity of nanostructured geometries constitutes a major asset of plasmonics, allowing to finely adjust the optical properties for specific applications. The main architectures include:

Spherical nanoparticles: Nanospheres represent the simplest geometry, with optical properties well described by Mie theory . Their LSPR resonance mainly depends on the diameter and the surrounding environment.

Nanorods: These elongated structures have two distinct resonance modes (transverse and longitudinal), the longitudinal mode being particularly sensitive to the aspect ratio [1]. Gold nanorods of 80 nm × 30 nm with an absorption peak at 732 nm were used for nanoscale imaging without photobleaching.

Complex nanostructures: Nanocages, nanostars, nanowires and multi-branch structures offer advanced optical properties with multiple hotspots and increased field amplifications.

Core-shell structures: Architectures like ₂, ₂ @Pa and Ag@Au combine the properties of different materials to optimize performance.

Periodic gratings: Metal nanoslides, including non-uniform narrow groove arrays with rounded vertices and sloped walls, allow for direct light coupling and miniaturization of devices. Networks of nanodisks, nanocylinders and circular nano-antennas offer collective properties resulting from the coupling between adjacent structures.

Pyramidal structures: Pyramidal absorbing metamaterials composed of five alternating metal/dielectric layers (gold 10 nm thick each) form periodic arrays of quadrangular truncated pyramids, offering a spectral absorption of 76% and exceeding 90% in several bands between 400-1500 nm .

4. Plasmonic Metamaterials

Plasmonic metamaterials represent a class of sub-wavelength scale structured artificial materials, characterized by complex electrical permittivities and magnetic permeabilities that are not found in natural materials . These periodic structures of metal and dielectric components allow to control the propagation of light in an unprecedented way.

The pyramidal plasmonic metamaterial absorbers illustrate the capabilities of these structures. Composed of nanoplasmonic metal-dielectric multilayers forming quadrangular truncated pyramids, these devices offer resonant absorption characteristics at optical frequencies. Absorption depends on the induced resonances in the nanoplasmonic metasurface and the resonant interferences. Simulations using electromagnetic complete wave software allow modeling the absorption, reflection, and transmission of these structures.

Optimized performances include a spectral absorption of 76% and an absorption greater than 90% in multiple bands between 400-1500 nm . These features are useful for photodetection, thermal imaging, thermal emitters, solar cells, energy harvesting, stealth technologies, antennas and sensing applications. Narrow and sharp absorption peaks are particularly suitable for sensing applications .

Plasmonic metamaterials supported by periodic metal and dielectric structures allow to exploit plasmonic amplification processes to develop new generation biosensors with high performances [9]. These devices capitalize on the amplification of the electromagnetic field by several orders of magnitude to improve light-matter interactions.

4.1 Negative Refractive Index

One of the most remarkable properties of plasmonic metamaterials is their ability to exhibit a negative refractive index. In such materials, electromagnetic waves propagate in an unusual manner compared to conventional media. This phenomenon enables extraordinary optical effects such as superlensing and cloaking applications.

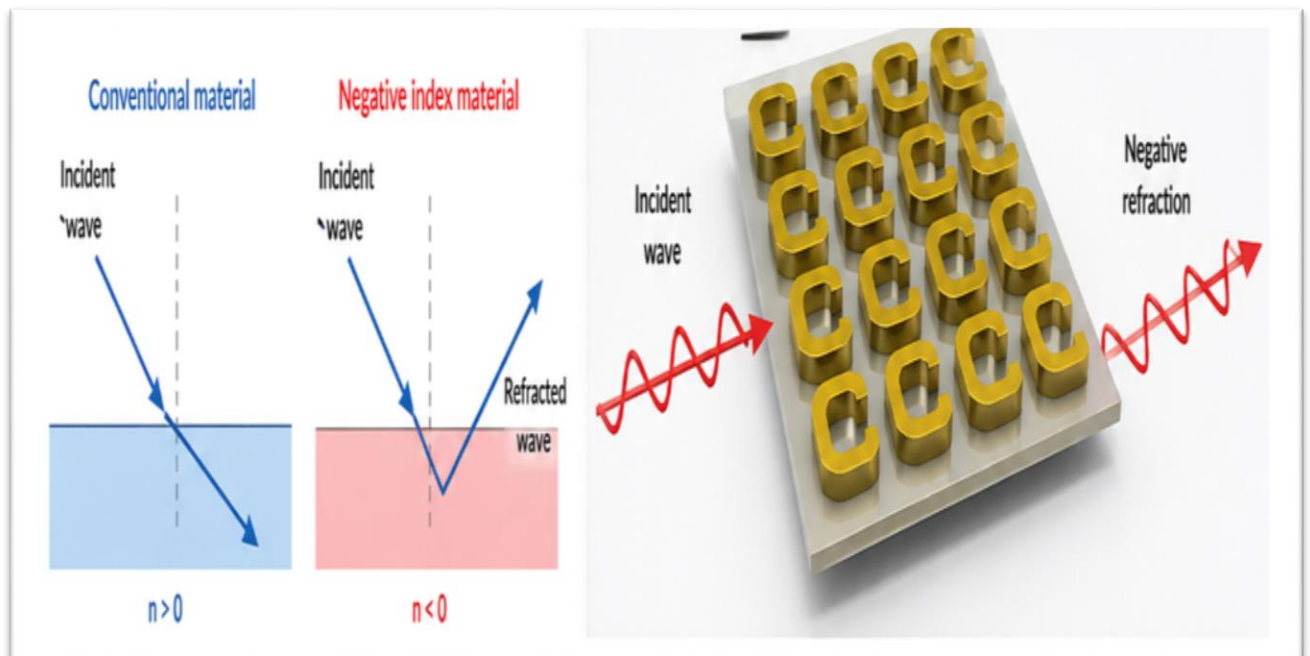


Figure 1.7. Negative Refraction of Electromagnetic Waves in a Plasmonic Metamaterial

4.2 Applications in Optical Cloaking

Plasmonic metamaterials are also investigated for optical cloaking devices capable of reducing the visibility of objects by guiding electromagnetic waves around them. Although still under development, these structures demonstrate the potential of metamaterials for advanced defense and photonic applications [10].

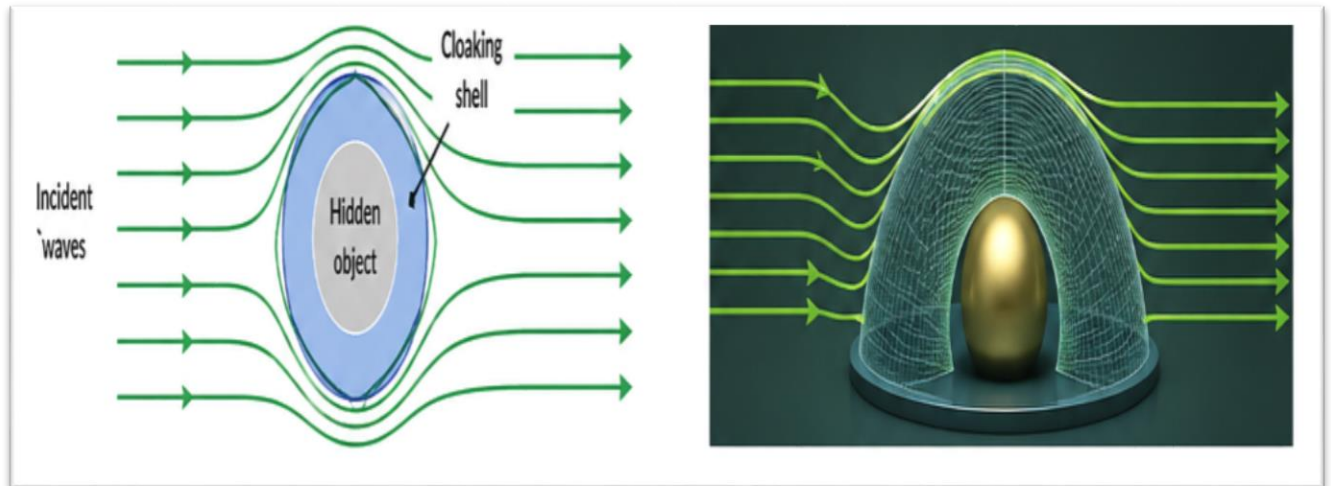


Figure 1.8. Principle of Optical Cloaking Using Plasmonic Metamaterials

4.3 Tunable Metamaterials

Recent studies focus on tunable plasmonic metamaterials whose optical response can be dynamically modified using external stimuli such as temperature, electric fields, or phase-change materials. These adaptive systems are promising for smart sensors and reconfigurable photonic devices [11].

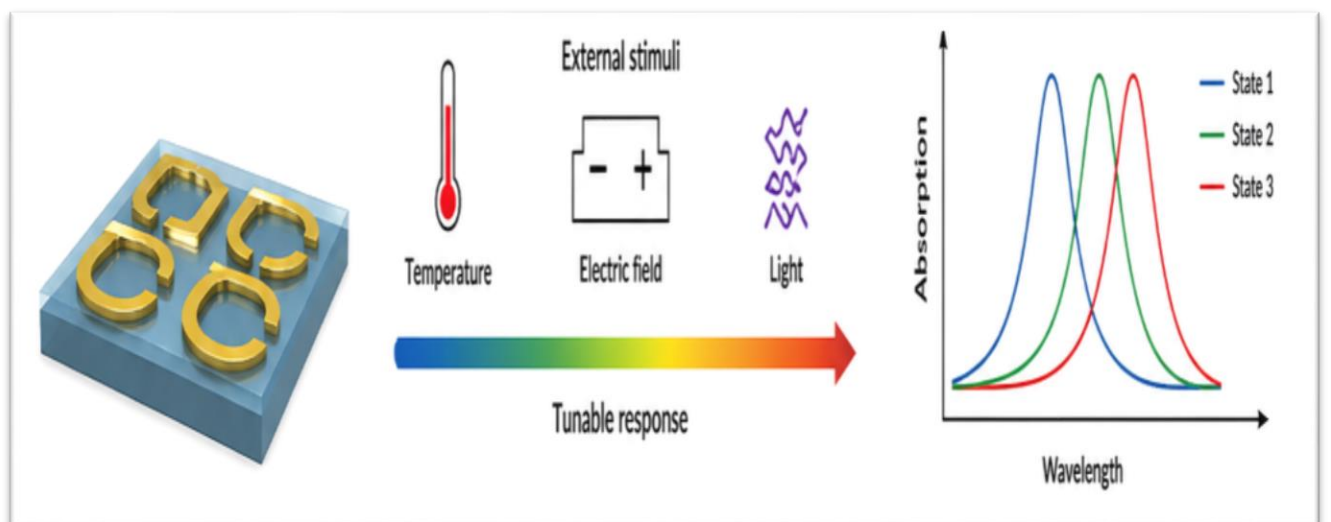


Figure 1.9: Tunable Response of Plasmonic Metamaterials Under External Stimuli

5. Plasmonic Nanostructures and Their Optical Properties

Plasmonic nanostructures are materials possessing at least one dimension in the nanometer range, generally between 1 and 100 nm. At this scale, the interaction between light and matter exhibits unique optical properties that differ significantly from those observed in bulk materials. These properties arise from the collective oscillation of conduction electrons at the surface of metallic nanostructures when excited by electromagnetic radiation.

The optical behavior of plasmonic nanostructures strongly depends on their size, shape, composition, and surrounding dielectric environment. By carefully controlling these parameters, it becomes possible to manipulate light at dimensions much smaller than its wavelength. This capability has led to major advances in nanoscale sensing, biomedical imaging, optical communication, surface-enhanced spectroscopy, and photothermal applications.

Among the various plasmonic nanostructures investigated in the literature, nanospheres, nanorods, and core-shell nanoparticles are the most commonly studied due to their tunable optical properties and relatively accessible fabrication methods [12].

5.1 Nanospheres

Definition : Nanospheres are spherical metallic nanoparticles generally composed of noble metals such as gold or silver. Because of their highly symmetric geometry, their optical response is nearly identical in all spatial directions [13].

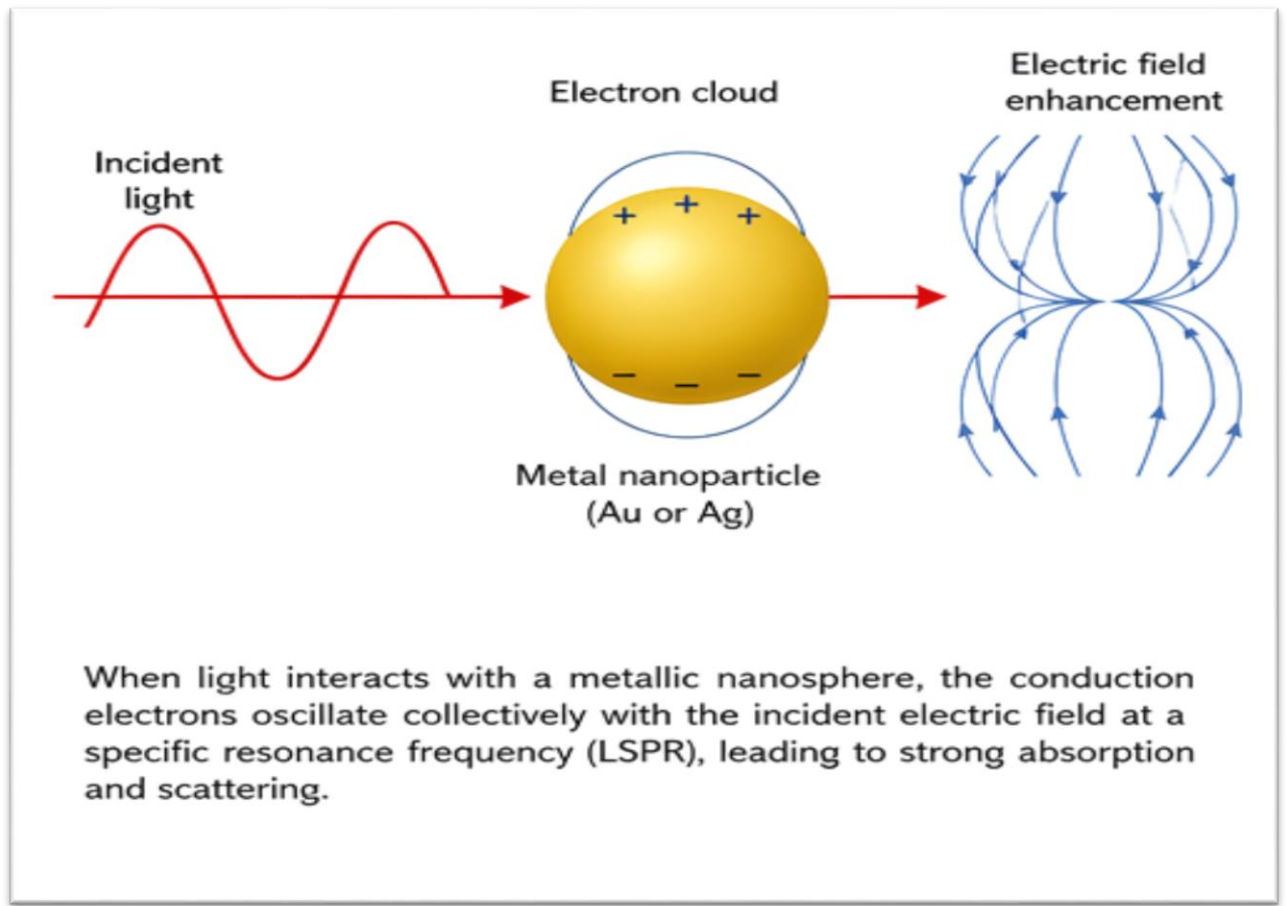


Figure 1.10. Localized Surface Plasmon Resonance (LSPR) in Metallic Nanospheres

Physical Mechanism (LSPR) : When electromagnetic radiation interacts with a metallic nanosphere, the free electrons oscillate collectively at a characteristic resonance frequency known as the Localized Surface Plasmon Resonance (LSPR) . This resonance produces strong absorption and scattering of light together with significant enhancement of the local electromagnetic field.

The resonance frequency mainly depends on:

- the particle size,
- the dielectric properties of the surrounding medium,
- and the nature of the metallic material.

Due to these properties, metallic nanospheres are widely employed in plasmonic sensing and optical detection systems.

Advantages : Metallic nanospheres present several advantages:

- simple and highly symmetric geometry,
- relatively easy chemical synthesis,
- good optical stability,
- and reproducible plasmonic behavior.

Limitations : Despite their advantages, nanospheres exhibit limited tunability compared to more complex nanostructures. Their plasmonic response mainly depends on particle size, which restricts the possibility of independently controlling multiple resonance modes [14].

Applications : Nanospheres are extensively used in:

- biosensing applications,
- Raman signal enhancement,
- drug delivery systems,
- biomedical imaging,
- and optical filtering technologies.

5.2 Nanorods

Definition : Nanorods are elongated metallic nanoparticles characterized by two principal dimensions: length and diameter. Unlike spherical nanoparticles, nanorods exhibit anisotropic optical properties due to their asymmetric geometry [15].

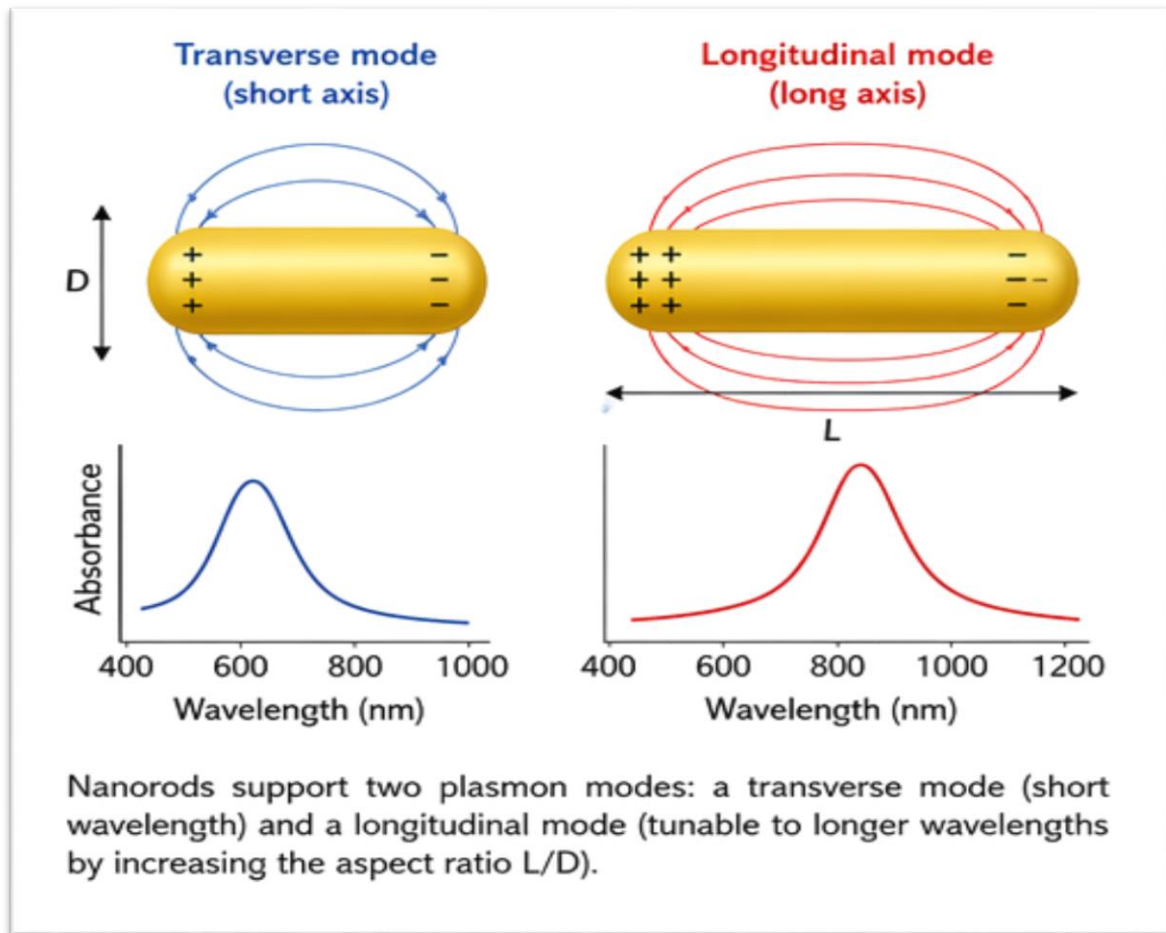


Figure 1.11. Plasmonic Modes in Gold Nanorods: Transverse and Longitudinal Resonances

Plasmon Resonance Modes : Metallic nanorods support two distinct plasmonic resonance modes:

1. **the transverse mode**, associated with electron oscillation along the short axis,
2. **and the longitudinal mode**, corresponding to oscillation along the long axis of the nanorod.

The longitudinal resonance mode is highly sensitive to the aspect ratio of the nanorod. Increasing the length-to-diameter ratio causes the resonance wavelength to shift toward the near-infrared region. This tunability makes nanorods particularly attractive for biomedical and photonic applications.

Advantages : Nanorods possess several important advantages:

- highly tunable optical response,
- strong electromagnetic field enhancement,
- improved sensitivity in sensing applications,
- and efficient light absorption in the near-infrared region.

Limitations : The synthesis of nanorods generally requires more complex fabrication procedures compared to spherical nanoparticles. In addition, their optical response is strongly influenced by orientation, aggregation effects, and environmental conditions [16].

Applications : Nanorods are widely used in:

- plasmonic sensors,
- photothermal therapy,
- solar energy conversion,
- optical antennas,
- and nanoscale imaging systems.

5.3 Core-Shell Nanoparticles

Definition : Core-shell nanoparticles consist of a central core surrounded by an outer shell made of a different material. This hybrid configuration enables the combination of multiple optical, chemical, and physical properties within a single nanostructure [17].

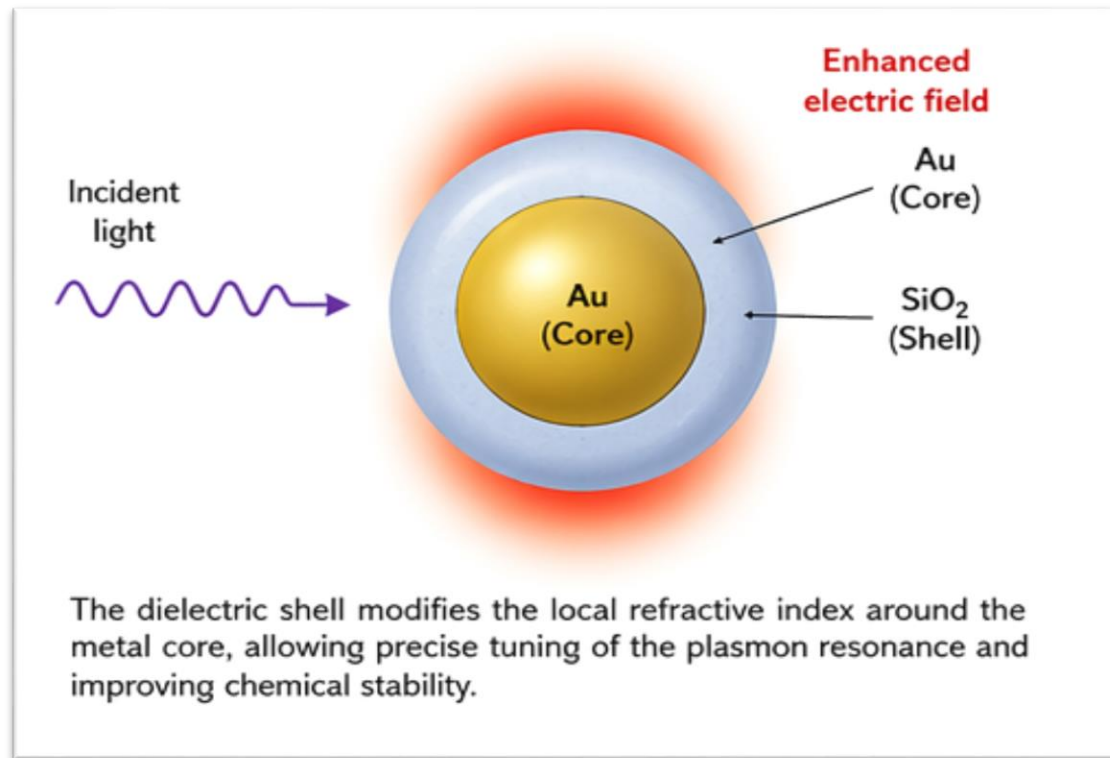


Figure 1.12. Core-Shell Nanoparticles Structure (Au-SiO₂ Example)

Working Principle : The optical properties of core-shell nanoparticles originate from the interaction between the plasmonic modes of the core and the shell. By adjusting the structural parameters of the nanoparticle, the plasmonic response can be precisely controlled.

The main parameters influencing the optical behavior are:

- core radius,
- shell thickness,
- and the combination of materials employed.

Several types of core-shell architectures have been investigated:

- metal core / dielectric shell structures,
- dielectric core / metal shell systems,
- and metal-metal hybrid nanoparticles.

Advantages : Core-shell nanostructures offer numerous advantages:

- high optical tunability,
- strong field confinement,
- improved chemical stability,
- and reduced optical losses.

Limitations : These nanostructures require highly controlled fabrication conditions at the nanometer scale, which increases the complexity of synthesis and characterization processes.

Applications : Core-shell nanoparticles are employed in:

- biosensing,
- photonic devices,
- photocatalysis,
- energy harvesting systems,
- and biomedical imaging applications.

➡ Comparative Analysis of Plasmonic Nanostructures

	Nanospheres	Nanorods	Core–Shell Nanoparticles
			
Geometry	Symmetric (isotropic)	Anisotropic	Hybrid Multilayer structure
Optical Tunability	Low	High	Very High
Resonance Modes	Single resonance	Transverse and Longitudinal	Multiple coupled resonances
Fabrication Complexity	Simple	Moderate	Complex

Table 1.1 Comparative Analysis of the Optical and Structural Characteristics of Plasmonic Nanostructures.

6. Fabrication Methods of Plasmonic Nanostructures

The fabrication of plasmonic nanostructures plays a fundamental role in determining their optical and physical properties. Parameters such as particle size, morphology, composition, and structural organization directly influence plasmonic resonance behavior and electromagnetic field enhancement [18]. Consequently, the development of reliable fabrication techniques is essential for the realization of high-performance plasmonic devices.

In general, fabrication approaches are classified into two main categories:

- chemical (bottom-up) methods,
- and physical (top-down) methods.

Bottom-up approaches rely on the assembly of atoms or molecules to form nanostructures, whereas top-down methods consist of reducing bulk materials into nanoscale architectures using advanced lithographic or deposition techniques.

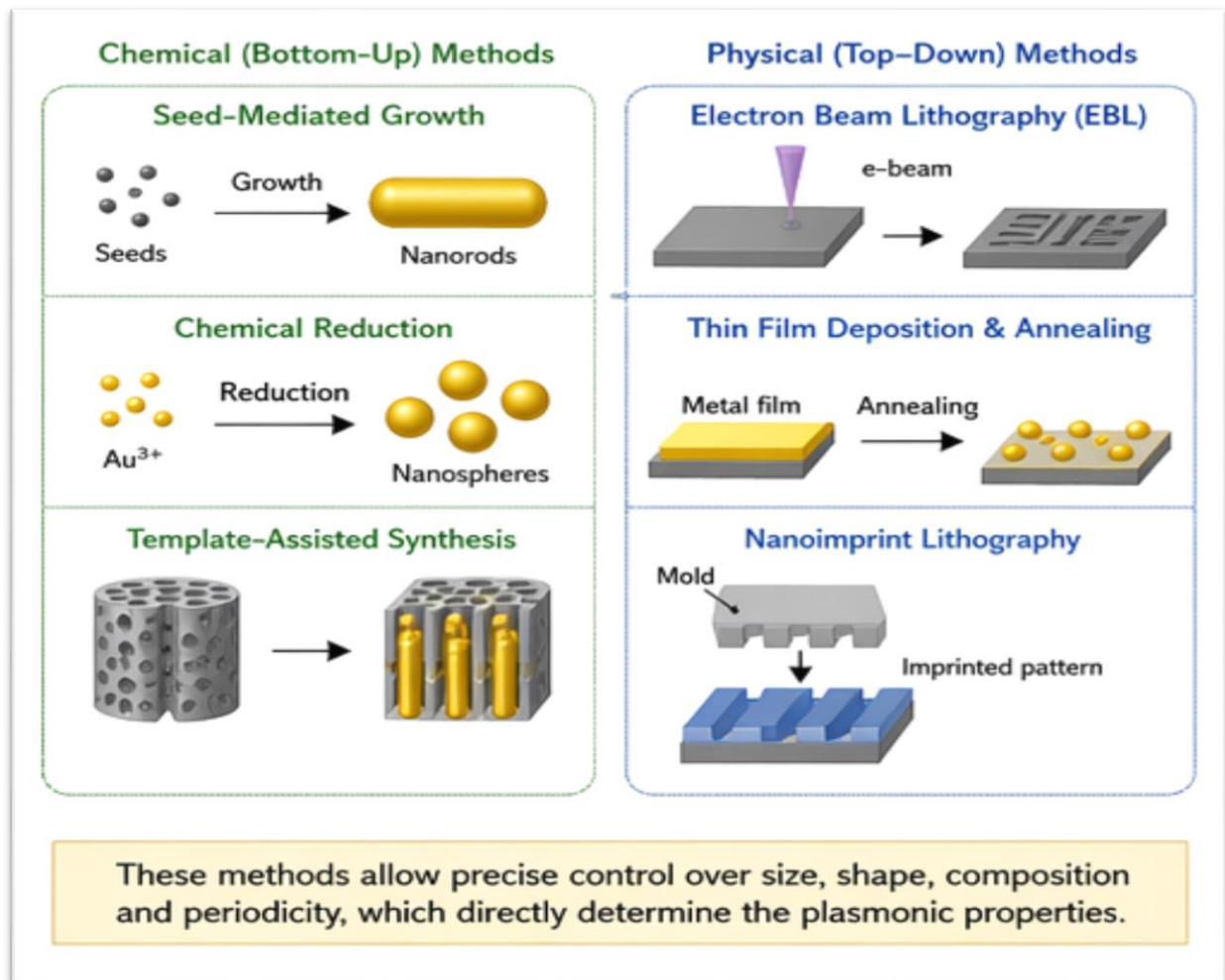


Figure 1.13. Fabrication Methods of Plasmonic Nanostructures (Chemical and Physical Approaches)

6.1 Chemical Fabrication Methods

Chemical synthesis methods are widely used for the fabrication of plasmonic nanoparticles due to their simplicity, relatively low cost, and ability to produce large quantities of nanostructures with controlled dimensions. These methods are based on chemical reactions occurring in solution, where metallic precursors are transformed into nanoparticles [19].

6.1.1 Seed-Mediated Growth Method

The seed-mediated growth method is one of the most commonly employed techniques for synthesizing anisotropic nanoparticles, particularly gold nanorods. In this approach, small metallic nanoparticles called “seeds” are first prepared and subsequently introduced into a growth solution containing metallic ions and surfactants.

The growth process is strongly influenced by synthesis conditions such as surfactant concentration, temperature, and reducing agents. Cetyltrimethylammonium bromide (CTAB) is frequently used to guide anisotropic growth and control the aspect ratio of nanorods .

This method provides excellent control over particle morphology and optical properties, making it highly suitable for plasmonic applications requiring tunable resonance wavelengths [20].

6.1.2 Chemical Reduction Method

The chemical reduction method consists of transforming metallic ions into neutral metallic atoms using reducing agents such as sodium citrate or sodium borohydride . One of the best-known procedures is the Turkevich method, commonly used for synthesizing gold nanoparticles.

This technique offers several advantages:

- simple experimental procedure,
- reproducibility,
- and good control over nanoparticle size.

Because of its simplicity and efficiency, chemical reduction remains one of the most widely used methods for preparing metallic nanoparticles for plasmonic applications [21].

6.1.3 Template-Assisted Synthesis

Template-assisted synthesis relies on the use of predefined templates or molds to guide the formation of nanostructures with controlled geometry. Templates may include porous membranes, nanostructured substrates, or patterned materials.

This method is particularly suitable for the fabrication of:

- nanorod arrays,

- nanoshell structures,
- and ordered plasmonic architectures.

Template-assisted approaches provide improved structural uniformity and enable precise control over nanoparticle dimensions and spatial organization.

6.2 Physical (Top-Down) Fabrication Methods

Physical fabrication methods involve the direct modification of bulk materials using advanced microfabrication and nanolithography techniques. These approaches offer excellent precision and are particularly useful for producing highly organized plasmonic structures.

6.2.1 Electron Beam Lithography (EBL)

Electron Beam Lithography (EBL) is a high-resolution nanofabrication technique that uses a focused electron beam to create nanoscale patterns on a resist-coated substrate.

After exposure and development processes, metallic layers are deposited to form plasmonic nanostructures with highly controlled geometries.

The main advantages of EBL include:

- extremely high fabrication precision,
- capability to produce complex nanostructures,
- and excellent reproducibility.

However, the technique remains relatively expensive and time-consuming, which limits its use for large-scale industrial production [22].

6.2.2 Thin Film Deposition and Thermal Annealing

This method involves depositing a thin metallic layer, generally gold or silver, onto a substrate followed by thermal annealing treatment.

During heating, the metallic film becomes unstable and reorganizes into isolated nanoparticles through a phenomenon known as dewetting. This process leads to the spontaneous formation of metallic nanospheres and nanoparticle clusters.

Thin film deposition combined with thermal annealing is commonly employed for:

- plasmonic substrates,

- random nanoparticle assemblies,
- and large-area plasmonic coatings.

6.2.3 Nanoimprint Lithography

Nanoimprint lithography is a cost-effective fabrication technique based on the mechanical imprinting of nanoscale patterns onto a polymer layer using a nanostructured mold.

This method offers several important advantages:

- low fabrication cost
- large-area production capability
- high pattern uniformity
- and compatibility with industrial-scale manufacturing.

Due to these characteristics, nanoimprint lithography has become a promising technique for the mass production of plasmonic and nanophotonic devices [23].

7. Conclusion

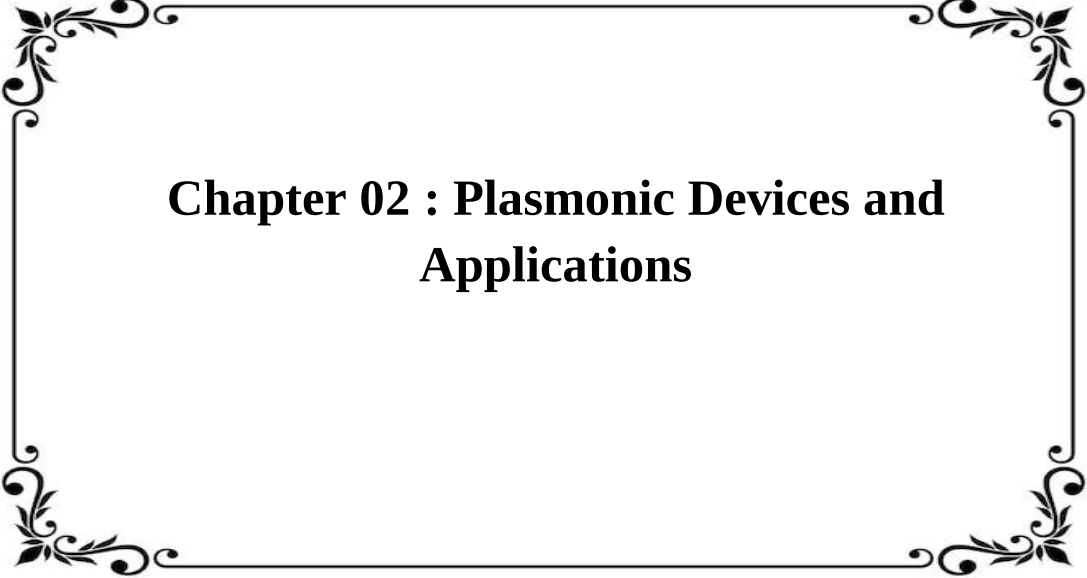
Plasmonics represents one of the most important research fields in modern nanophotonics due to its ability to manipulate and confine light at dimensions smaller than the diffraction limit. The interaction between electromagnetic waves and metallic nanostructures gives rise to remarkable optical phenomena such as Surface Plasmon Polaritons (SPPs) and Localized Surface Plasmon Resonances (LSPRs), which are responsible for strong electromagnetic field enhancement and nanoscale light confinement.

The optical behavior of plasmonic systems is strongly influenced by the properties of the materials employed, particularly noble metals such as gold and silver, as well as by the geometry of nanostructures. Different architectures including nanospheres, nanorods, and core-shell nanoparticles provide tunable plasmonic responses suitable for sensing, imaging, energy harvesting, and biomedical applications, [24].

In addition, recent advances in nanofabrication techniques have enabled the controlled synthesis of plasmonic nanostructures with precise dimensions and morphologies. Both chemical and physical fabrication methods contribute significantly to the development of high-performance plasmonic devices adapted to modern technological requirements.

Furthermore, plasmonic metamaterials have introduced new possibilities for controlling electromagnetic waves through engineered optical properties such as negative refractive index and tunable responses. These materials open promising perspectives for future applications in photonics, optical communication, sensing technologies, and reconfigurable nanodevices [25].

Overall, the continuous progress achieved in plasmonic materials, nanostructures, and fabrication technologies demonstrates the growing importance of plasmonics in both fundamental research and advanced technological applications.



Chapter 02 : Plasmonic Devices and Applications

1.Introduction

Plasmonic devices have attracted considerable attention in modern nanophotonics due to their remarkable ability to manipulate and confine electromagnetic waves at dimensions smaller than the diffraction limit of light. These devices are based on the interaction between incident electromagnetic radiation and the collective oscillation of free electrons at metal–dielectric interfaces, leading to phenomena such as Surface Plasmon Resonance (SPR) and Localized Surface Plasmon Resonance (LSPR) [26].

The unique optical properties of plasmonic structures, including strong electromagnetic field enhancement, spectral tunability, and subwavelength light confinement, have enabled the development of compact and high-performance optical components. As a result, plasmonic technologies have found important applications in sensing, imaging, optical communication, energy harvesting, and integrated photonic systems.

Among the various plasmonic devices, plasmonic filters represent a particularly important category because of their capability to selectively transmit or suppress specific wavelengths of light with high precision. Their optical response can be controlled through the geometry of nanostructures, material properties, and surrounding dielectric environment, which provides significant flexibility for advanced optical engineering [27].

In addition, plasmonic sensors based on SPR and LSPR mechanisms have demonstrated exceptional sensitivity for chemical and biological detection. The integration of plasmonic devices into nanoscale optical systems has also contributed to the miniaturization of photonic technologies and the improvement of device performance in modern applications.

This chapter presents the fundamental optical properties of plasmonic structures and discusses the main plasmonic devices and their applications. Particular attention is given to plasmonic filters, including their operating principles, types, fabrication techniques, spectral response, performance parameters, and applications in sensing and nanophotonic systems.

2. Optical Properties

2.1 Plasmonic Resonance and Spectral Tunability

Plasmonic resonance is manifested by characteristic absorption and scattering peaks in the optical spectrum, the position of which depends on multiple structural and environmental

parameters. This spectral tunability constitutes one of the most valuable properties of plasmonics, allowing to adapt nanostructures to specific applications.

For gold and silver nanoparticles, the resonance wavelength can be adjusted by changing the shape and size of the particles. Design strategies include control of geometry (spheres, rods, cubes, cages, stars), composition (core-shell structures), and dielectric environment. This correlation between geometry, plasmonic properties and biomedical applications allows to optimize performance for detection, imaging and therapy [28].

Plasmonic resonances can be observed at various wavelengths, from ultraviolet to far infrared, depending on the properties and structures of the materials. Noble metals exhibit resonances in the visible and near infrared, while semiconductors and two-dimensional materials extend this spectral range.

The engineering of the substrate-nanostructure interface offers an additional way to modulate optical properties. The decoupling of optical fields close to the bulk substrate by creating gold nanodisks on silicon pillars induces a significant spectral shift towards the blue of the LSPR resonance. This approach allows to optimize plasmonic properties while facilitating nanofabrication [29].

2.2 Electromagnetic Field Amplification

The amplification of the electromagnetic field represents the most remarkable optical property of plasmonic systems. At resonance, the local electric field strength can be amplified by 5-6 orders of magnitude with respect to the incident field. This exceptional amplification results from the confinement of electromagnetic energy in nanometric volumes.

Localized surface plasmons (LSPR) generate significant amplification of the local electric field at resonance wavelength. This amplification is highly concentrated in the nanoparticle and decays rapidly as it moves away from the nanoparticle-dielectric interface. Localization implies that LSPRs possess a very high spatial frequency (sub-wavelength), limited only by the size of nanoparticles [30].

Coupled structures, such as dimers of nanoantennas, exhibit even greater amplifications in nanometric gaps. However, when the gap distance approaches nanometer and subnanometer, quantum effects like non-local screening and electron tunneling become significant. Non-

local models show that the resonance wavelength and peak intensity exhibit smaller variations compared to classical theory when geometric or material parameters vary.

The optimization of the interface between plasmonic nanostructures and the substrate allows to increase the electric field amplification by a factor three compared to disks on bulk silicon [31]. This improvement results in a significant increase in the SERS amplification factor, reaching the order of 10^6 .

2.3 Diffusion and Absorption

Plasmonic nanostructures exhibit scattering and absorption properties that can be independently controlled by adjusting their geometry and composition. The total extinction cross section breaks down into scattering and absorption contributions, the relative proportions of which depend on the size and shape of the nanoparticles.

Small nanoparticles (< 50 nm) mainly show absorption, while larger particles (> 80 nm) effectively scatter light. This property is exploited in different applications: absorption for photothermal therapy and solar cells, scattering for dark field imaging and enhancement of absorption in photovoltaic devices [32].

Periodic plasmonic nanostructures for GaAs thin-film solar cells use plasmon scattering by front surface aluminum nanospheres and back surface silver nanocylinders. This optimal configuration improves the short-circuit current density by 45.38% and efficiency by 46.83% compared to bare cells [33]. These improvements are attributed to plasmonic scattering and guided mode propagation at the metal-dielectric interface.

Broadband plasmonic absorbers, such as tungsten pyramidal structures, offer absorption greater than 90% over a wide spectral range (400-1500 nm). This performance results from the induction of localized plasmonic resonances by nano-antennas, allowing enhanced absorption through light-matter interactions. The ultra-compact and easily manufactured design features polarization insensitivity and super-bandwidth.

3. Plasmonic Sensors (SPR / LSPR)

Plasmonic sensors are among the most important applications of plasmonics due to their high sensitivity to variations in the surrounding environment. These sensors operate through the interaction between incident electromagnetic waves and free electrons located at metal–dielectric interfaces, producing plasmonic resonances that are strongly affected by refractive index changes near the metallic surface [34]. Compared with conventional optical sensors, plasmonic sensors provide several advantages including high sensitivity, real-time detection capability, label-free operation, and miniaturization. These properties make them highly suitable for chemical, biological, and environmental sensing applications.

3.1 Surface Plasmon Resonance (SPR)

Surface Plasmon Resonance (SPR) occurs when incident light couples with collective oscillations of free electrons propagating along a metal–dielectric interface. Under resonance conditions, a strong reduction in reflected light intensity is observed, making SPR extremely sensitive to refractive index variations close to the metallic surface. SPR-based sensors are widely employed in biosensing, molecular detection, and optical filtering applications because of their ability to detect very small environmental changes with high precision. In addition, SPR structures are frequently integrated into optical systems for wavelength-selective filtering and signal modulation [35].

3.2 Localized Surface Plasmon Resonance (LSPR)

Localized Surface Plasmon Resonance (LSPR) is generated in metallic nanoparticles such as gold and silver nanostructures. Unlike propagating surface plasmons, LSPR corresponds to localized oscillations of conduction electrons confined within nanoscale particles. The resonance wavelength strongly depends on nanoparticle size, geometry, composition, and surrounding dielectric environment. Consequently, LSPR structures exhibit excellent spectral tunability and strong electromagnetic field enhancement [36]. These characteristics make LSPR highly attractive for sensing, optical filtering, biomedical imaging, and photothermal applications. Furthermore, the intense scattering and absorption properties associated with LSPR contribute significantly to the development of compact and tunable plasmonic devices.

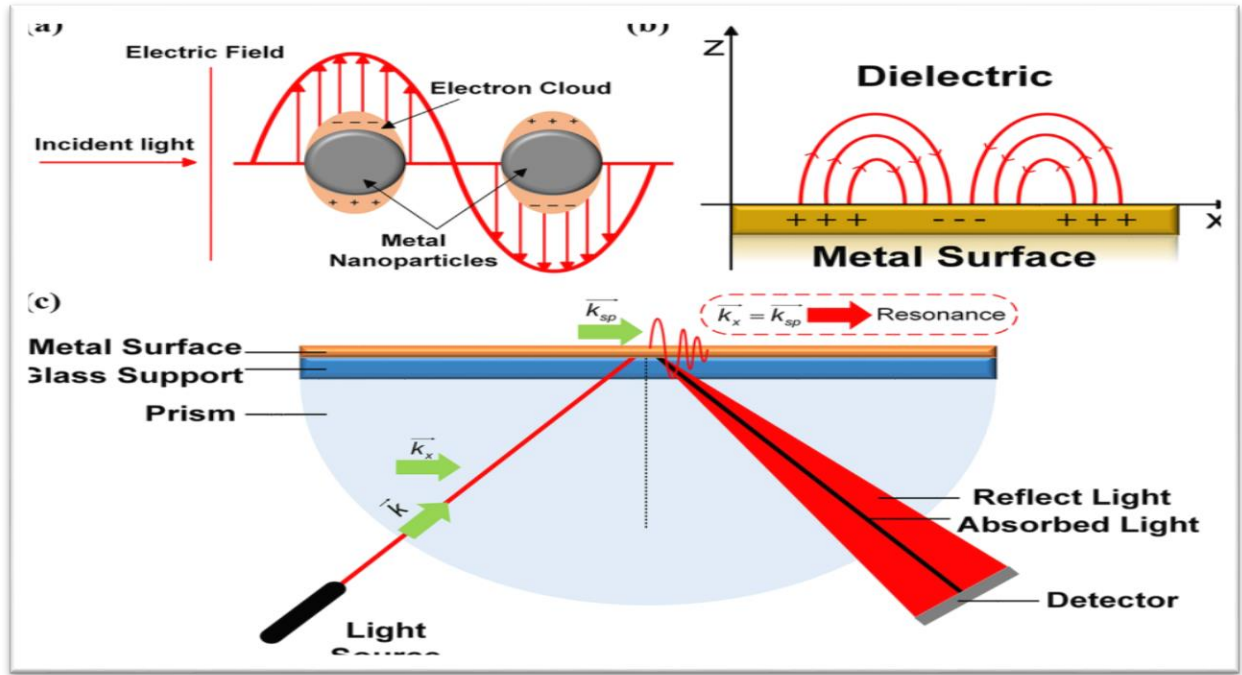


Figure 2.1. Illustration of SPR and LSPR phenomena

3.3 Advantages of Plasmonic Sensors

Plasmonic sensors offer several advantages compared with conventional optical sensing technologies. One of their most significant properties is their extremely high sensitivity to refractive index variations, enabling the detection of very low concentrations of chemical and biological species [37]. Another important advantage is their capability for real-time and label-free detection, which simplifies sensing procedures and reduces experimental complexity. Moreover, plasmonic sensors can be miniaturized and integrated into compact photonic and microfluidic systems, facilitating the development of portable sensing platforms. In addition, the strong localization and amplification of electromagnetic fields near metallic nanostructures considerably improve detection performance, particularly in applications involving biosensing, medical diagnostics, and environmental monitoring.

4. Plasmonic Optical Devices

Plasmonic optical devices are nanophotonic components designed to manipulate electromagnetic waves through the excitation of surface plasmons at metal–dielectric interfaces [38]. These devices enable light confinement beyond the diffraction limit, allowing

the realization of ultra-compact optical systems with enhanced performance. The exceptional ability of plasmonic structures to localize electromagnetic energy at the nanoscale has led to important applications in optical communication, sensing, imaging, and integrated photonic circuits. In addition, plasmonic devices provide a promising platform for bridging the size mismatch between photonic and electronic components.

4.1 Waveguides

Plasmonic waveguides are structures capable of guiding electromagnetic waves in the form of Surface Plasmon Polaritons (SPPs) along metal–dielectric interfaces. These waveguides provide strong optical confinement within subwavelength dimensions, which is difficult to achieve using conventional dielectric waveguides. Several plasmonic waveguide configurations have been developed, including metal–insulator–metal (MIM) and insulator–metal–insulator (IMI) structures. MIM waveguides provide excellent confinement but suffer from higher propagation losses, whereas IMI waveguides offer longer propagation distances with reduced confinement. Due to their nanoscale dimensions, plasmonic waveguides are highly suitable for integrated optical circuits, optical interconnects, and compact photonic systems.

4.2 Resonators

Plasmonic resonators are structures designed to confine and enhance electromagnetic energy at specific resonance frequencies [39]. These devices generate strong localized electromagnetic fields, particularly under resonance conditions. Different types of plasmonic resonators have been investigated, including nanoparticle resonators, nanocavities, and ring resonators. Their optical response depends strongly on structural geometry, material composition, and environmental conditions. Plasmonic resonators are extensively used in sensing applications because small environmental variations can induce measurable resonance shifts. Their high spectral selectivity and field enhancement capabilities also make them valuable for nanophotonic and optoelectronic applications.

4.3 Advantages of Plasmonic Devices

Plasmonic devices present several advantages over conventional optical systems. Their most important characteristic is the ability to confine light at dimensions significantly smaller than

the diffraction limit, enabling the fabrication of highly compact photonic components. Furthermore, plasmonic structures support ultrafast optical processes because of their strong interaction with high-frequency electromagnetic waves. This property is particularly advantageous for optical communication and signal processing technologies. Another major advantage is their compatibility with electronic components, facilitating the development of hybrid optoelectronic systems and integrated photonic circuits. In addition, the strong electromagnetic field enhancement associated with plasmonic resonances significantly improves device performance in sensing, imaging, and nonlinear optical applications

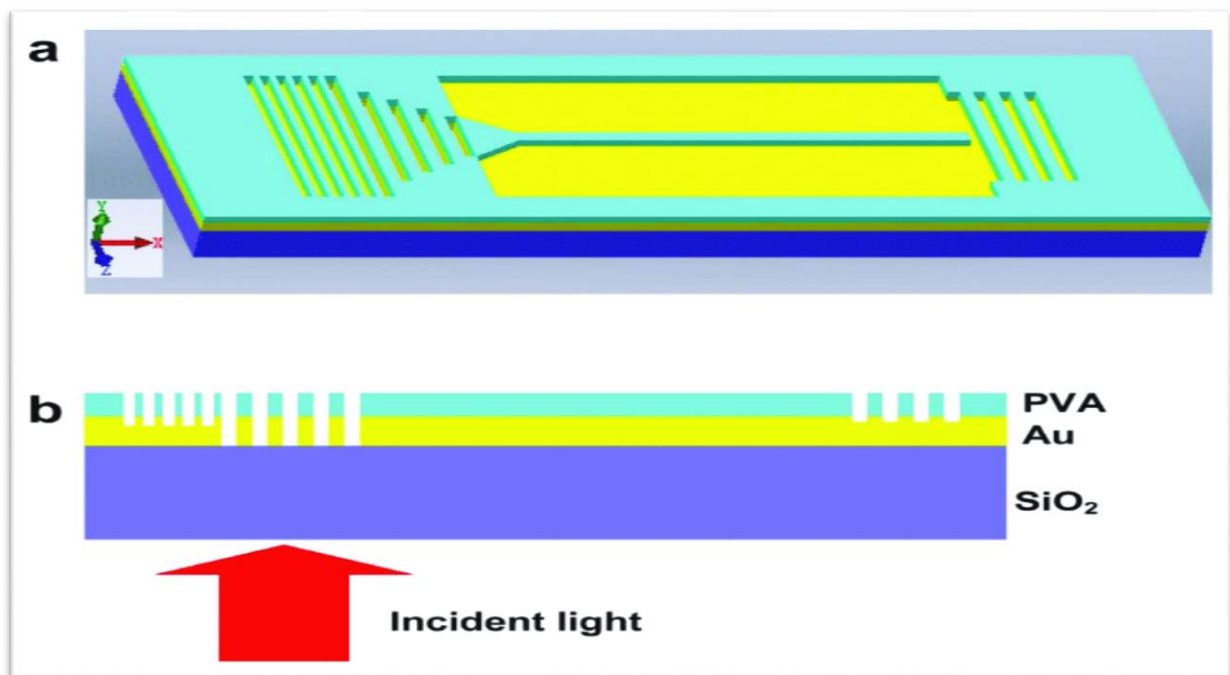


Figure 2.2. Plasmonic waveguide illustrating subwavelength light confinement

5. Filters

Optical filters are essential components in photonic systems because they selectively transmit or reject specific wavelength ranges from a broad optical spectrum. These devices play a fundamental role in optical communication, signal processing, sensing, and imaging technologies. Recently, plasmonic filters have attracted considerable attention due to their nanoscale dimensions, spectral tunability, and enhanced optical performance [40]. Unlike conventional optical filters, plasmonic filters exploit plasmonic resonances to manipulate

light within extremely confined regions, enabling compact and high-efficiency optical devices.

The operation of plasmonic filters is primarily based on resonance effects occurring at metal–dielectric interfaces. Under resonance conditions, specific wavelengths are selectively transmitted, absorbed, or reflected depending on the geometry of the nanostructure and the optical properties of the materials employed. Due to their compactness, tunability, and compatibility with integrated photonic systems, plasmonic filters have become promising candidates for advanced optical communication systems, biosensing platforms, and nanoscale photonic circuits.

6. Plasmonic Filters

6.1 Definition

Plasmonic filters are optical devices designed to selectively control the transmission, reflection, or absorption of electromagnetic waves through plasmonic resonance phenomena such as Surface Plasmon Resonance (SPR) and Localized Surface Plasmon Resonance (LSPR) [41]. The optical response of these filters depends strongly on nanostructure geometry, material composition, and surrounding dielectric environment. By carefully engineering these parameters, plasmonic filters can achieve highly selective wavelength filtering with tunable spectral characteristics. Their ability to operate at subwavelength dimensions makes plasmonic filters particularly attractive for integrated nanophotonic and optoelectronic applications.

6.2 Types of Plasmonic Filters

6.2.1 Nanoparticle-based Filters

These filters use metal particles. These particles react to light by vibrating. This vibration helps them filter light.

The way they work depends on the size and shape of the particles. They are good at detecting changes in the environment. They are used in sensing and color filtering[42].

6.2.2 Nanohole Array Filters

These filters have holes in a metal layer. Light goes through these holes in a way. This makes them good at filtering light.

The way they work depends on the size and arrangement of the holes. They are used in sensing and systems[43].

6.2.3 Plasmonic Grating Filters

These filters have a pattern on their surface. This pattern helps them light with special effects. This makes them good at filtering light.

The way they work depends on the pattern and material used. They are used in communications and signal processing[44].

6.2.4 Resonator-based Filters

These filters use cavities or rings. These cavities trap light. Make it interact with the material. This makes them good, at filtering light.

The way they work depends on the size and shape of the cavities. They are used in sensing and laser systems[45].

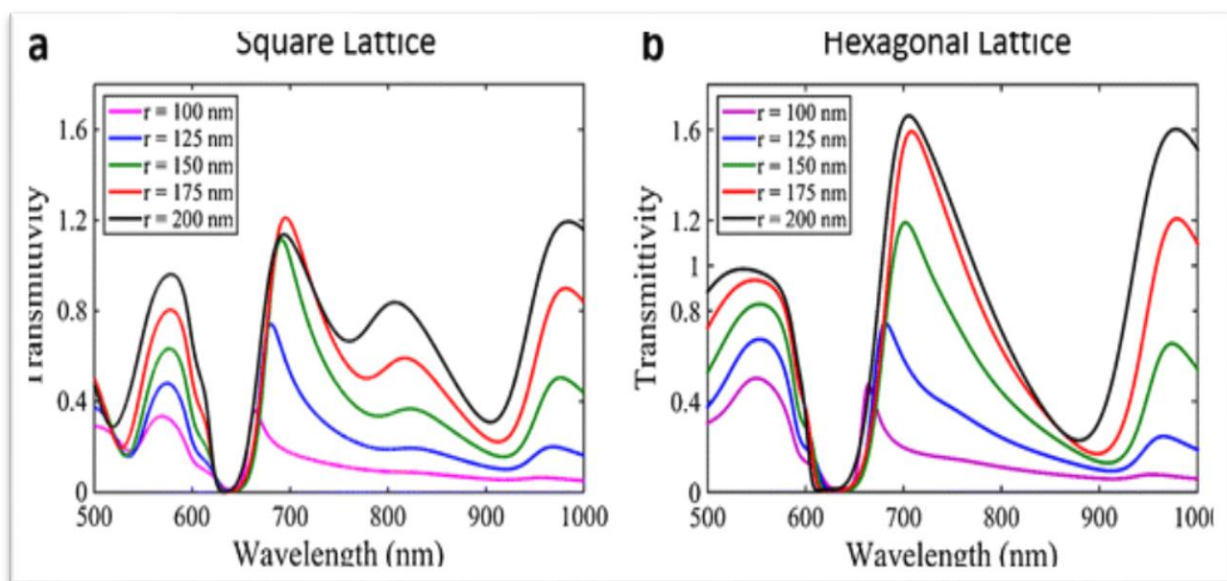


Figure 2.3. Extraordinary optical transmission through a plasmonic nanohole array

6.3 Spectral Response of Plasmonic Filters

filters can be classified by how they respond to different wavelengths of light. This is important to understand how these devices work in life especially in systems that help us communicate with light and in technologies that sense things[46].

The way a plasmonic filter responds to wavelengths of light is mainly because of resonance effects. These effects let some wavelengths of light pass through which we call the pass-band and block wavelengths, which we call the stop-band. This behavior depends on things like the shape of the structure the properties of the material it is made of and the properties of the medium around it.

6.3.1 Band-pass Filters

Band-pass plasmonic filters are designed to let only a certain range of wavelengths pass through. This range is called the pass-band. These filters block wavelengths that're not in this range. This is done by making the filter resonate in a way that helps light pass through in a narrow range of wavelengths.

The position and width of the pass-band depend a lot on how the plasmonic structure's designed. This includes things like the size, shape and how often the pattern repeats. Times these filters have sharp peaks where they let light through which means they are very good at filtering.

Band-pass filters are used a lot in systems that communicate with light especially when many signals are sent at the time on different wavelengths. They are also important in sensing applications, where small changes in the wavelength of the light that passes through can tell us a lot about what's around us[47].

6.3.2 Band-stop Filters

Band-stop plasmonic filters also called filters are designed to block a certain range of wavelengths. This range is called the stop-band. They let other wavelengths pass through.

This is usually done by making the filter absorb or reflect light strongly at the wavelengths it is designed to block. When the light that hits the filter has the wavelength as the resonance of the plasmonic structure the energy is either absorbed or scattered which means very little light passes through at those wavelengths.

Band-stop filters are very useful when we need to remove parts of the light. For example they can remove noise or interference from signals, which makes the signal better and the system work better. How well they work depends on how the stop-band is defined and how much the unwanted wavelengths are blocked[48].

6.3.3 Low-Pass Filters

Low-pass plasmonic filters let wavelengths of light that are longer than a certain cutoff pass through but they block wavelengths that are shorter. This is done by designing the filter so that the short wavelengths do not resonate or propagate well.

The cutoff wavelength is very important. Can be controlled by changing the size and material of the structure. Although these filters are not used much as band-pass filters in plasmonic systems they are still important in some applications.

They are very useful in systems where we need to remove high-frequency noise or unwanted short wavelengths. They also help smooth out the signal and make it more stable[49].

6.3.4 High-Pass Filters

High-pass plasmonic filters work the opposite way of low-pass filters. They let wavelengths that're shorter, than a certain cutoff pass through but they block longer wavelengths.

This is done by designing the filter so that only the wavelengths that satisfy the resonance or propagation conditions can pass through. The cutoff wavelength can be changed by modifying the shape and material of the filter.

High-pass filters are useful when we need to remove low-frequency components from the signal. This makes the signal clearer. The system work better especially in applications where we need high-resolution light information[50].

6.4 Working Principle

Plasmonic filters work based on resonance between free electrons in metals.

At resonance the electromagnetic field gets strongly enhanced.

Absorption or transmission changes a lot and only specific wavelengths are selected.

The filtering behavior depends on the material, geometry and surrounding medium.

This allows control of light at a small scale.

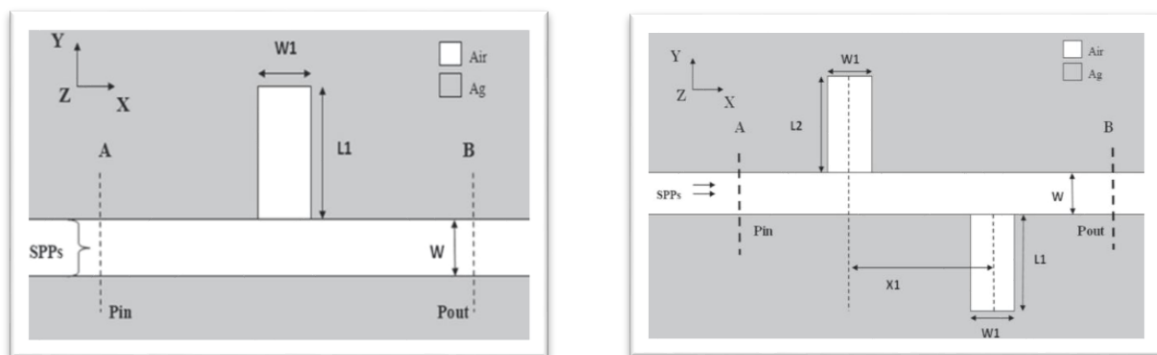


Figure 2.4. Working principle of a plasmonic filter based on resonance effects

6.5 Advantages of Plasmonic Filters

filters are better than traditional optical filters in many ways:

- They are very small.
- They can choose which light to let through precisely They can be adjusted by changing their shape or material.
- They work well with integrated systems.

These properties make Plasmonic filters very promising for modern optical technologies[51].

6.6 Limitations of Plasmonic Filters

Even though Plasmonic filters have advantages they also have some limitations. One big challenge is that they can lose light because of the metal they are made of. Making them at a small scale can also be complex and expensive[52].

Researchers are working to overcome these limitations by developing new materials and better designs.

7. Works

Several studies have looked into plasmonic filters for advanced optical applications.

A study on tiny hole arrays showed transmission efficiency making them suitable for optical filtering[53].

Research on gold nanoparticles found that adjusting their size and shape allows control of the resonance wavelength improving filter selectivity.

Another work on plasmonic gratings achieved wavelength- filtering with high precision useful in optical communication systems[54].

These studies highlight the potential of filters, for developing compact, tunable and high-performance optical devices.

8. Applications in Detection and Bio-sensing

8.1 SPR and LSPR sensors

Sensors based on surface plasmon resonance (SPR) and localized surface plasmon resonance (LSPR) represent bio-sensing tools of exceptional versatility and sensitivity. These sensors exploit the extreme sensitivity of plasmon resonance to changes in refractive index of the surrounding environment to detect bio molecules without labeling [55].

LSPR sensors offer labeling-free, portable, low-cost, real-time detection. Recent advances include the detection of biochemical markers in clinical and environmental contexts [56]. Detection strategies based on various nano structured platforms demonstrate their advantages and limitations, with potential strategies to improve detection performance [57].

Non-uniform narrow groove plasmonic nanoslides for SPR detection and imaging exhibit remarkable performance. These structures offer a maximum surface sensitivity (S_s) of 70 nm/nm and a figure of merit (FOMs) of 1.5 nm^{-1} , representing the highest reported values compared to previous plasmonic sensors [58]. Gold nano-gratings (GNG) and gold-coated silicon nano-gratings (GSNG) allow direct coupling of light, facilitating miniaturization and fabrication.

Silver-based sensors have a sensitivity to refractive index changes 1.2 to 2 times greater than that of gold. Applications include nano-photonics, super-resolution imaging, energy and sensor sensing (including food, environmental and biomedical sensing) [59]. Non-linear optical amplification, transmission amplification and high refractive index sensitivity enable label-free detection with SERS amplification factors up to 10^{10} [60].

Plasmonic sensors integrated into microfluidic systems and smartphone-based platforms represent the future of sensing. Future perspectives highlight the need to improve sensitivity, selectivity and stability to facilitate broader practical applications [61].

8.2 Surface Enhanced Raman Spectroscopy (SERS)

Surface-Enhanced Raman Scattering (SERS) is one of the most powerful applications of plasmonics, enabling single molecule detection through extraordinary Raman signal amplification [62]. Plasmons amplify the Raman signal and concentrate the incident electromagnetic field, modulating fluorescence emission in plasmon-enhanced fluorescence assays [63].

SERS amplification factors can reach 10^{14} - 10^{15} , with detection limits descending to 10 fM . These exceptional performances result from the amplification of the local electromagnetic field at plasmon resonance, which increases both Raman excitation and signal emission [64]. Silver nanoparticles generate SERS amplification factors of up to 10^{10} .

Design strategies for plasmonic amplification include optimizing the shape and structure of gold and silver nanoparticles. Nanostars, nanocages and core-shell structures create multiple hotspots where field amplification is maximal. The engineering of the substrate-nanostructure interface, such as gold nanodisks on silicon pillars, significantly increases the SERS amplification factor, reaching the order of 10^6 [65].

SERS applications cover a broad spectrum including molecular identification, detection of pathogens and environmental contaminants, cancer diagnosis and biomedical applications . In vivo tumor detection and improved catalytic activity demonstrate the practical potential of this technique [66]. SERS sensors embedded in polymer microfluidic devices and biosensors provide portable platforms for point-of-care applications .

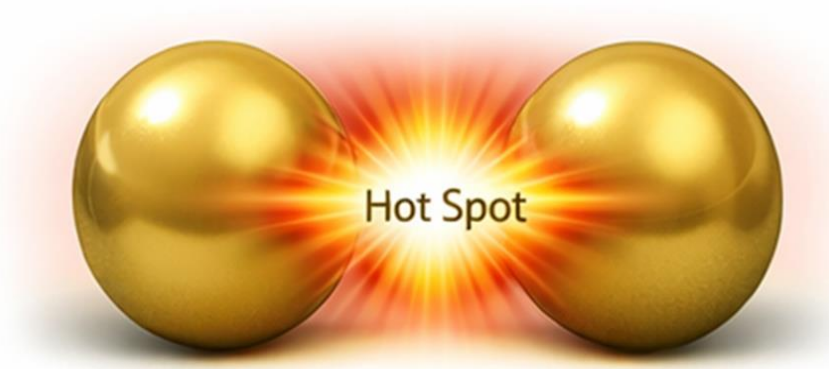


Figure 2.5. Electromagnetic hotspots generated between metallic nanoparticles.

9. Design Parameters of Plasmonic Filters

The performance of filters is really dependent on several design parameters that control how they resonate and select wavelengths.

Plasmonic filters have a lot to do with the size of the nanostructure[67].

The size of the nanostructure directly affects the resonance wavelength of filters.

When you increase the size of plasmonic filters it generally shifts the resonance toward wavelengths, which is called a red shift[68].

The shape of filters is also important.

Different shapes like spheres, rods and disks lead to plasmonic responses from plasmonic filters.

Complex shapes can really enhance field localization. Improve the filtering performance of plasmonic filters.

The material used for filters is another key factor.

The choice of metal such as gold or silver determines the response of plasmonic filters due to their different dielectric properties .

The refractive index of the environment around filters also plays a role.

Changes in the surrounding medium can shift the resonance wavelength of filters making plasmonic filters highly sensitive to environmental variations[69].

By optimizing these parameters you can design highly selective and tunable plasmonic filters [70].

10. Materials Used in Plasmonic Filters

filters are mainly made of metallic materials that support strong plasmonic resonance.

Gold is widely used for filters because it is chemically stable and has good optical properties in the visible and near-infrared regions[71].

Silver is another option for filters.

Silver offers optical losses and sharper resonance compared to gold making it suitable for high-performance plasmonic filters[72].

However silver is less stable and more sensitive to oxidation than gold.

Aluminum is also used for filters especially for ultraviolet applications and low-cost fabrication.

It is commonly used in large-scale plasmonic devices like plasmonic filters.

The selection of material for filters depends on the desired wavelength range, stability and application requirements of plasmonic filters[73].

11. Performance Metrics of Plasmonic Filters

The performance of filters is evaluated using several important parameters.

One of these parameters is transmission, which's the amount of light that passes through the plasmonic filter at a specific wavelength.

High transmission is desirable for filtering by plasmonic filters.

Another parameter is bandwidth which is the range of wavelengths transmitted by the plasmonic filter.

Narrow bandwidth indicates selectivity of plasmonic filters.

Efficiency is also important which represents how effectively the plasmonic filter transmits the desired wavelength while blocking others[74].

Sensitivity is a parameter, which measures how much the resonance wavelength of plasmonic filters shifts when the surrounding environment changes[75].

This is particularly important for sensing applications using plasmonic filters.

These metrics help in comparing plasmonic filter designs and optimizing their performance[76].

12. Comparison with Conventional Filters

filters have several advantages compared to conventional optical filters.

One advantage is size: plasmonic filters operate at the nanoscale while conventional filters are larger in size[77].

Another advantage is tunability: plasmonic filters can be easily tuned by modifying geometry or material properties whereas traditional filters have limited tunability[78].

Plasmonic filters are also highly sensitive to changes making them suitable for sensing applications.

Additionally plasmonic filters can be easily integrated into circuits unlike many conventional filters.

However plasmonic filters may suffer from optical losses due, to metal absorption, which remains a challenge compared to traditional filters[79].

13. Fabrication Techniques of Plasmonic Filters

The fabrication of filters requires special techniques to make very small structures. These techniques must be very accurate because the accuracy directly affects how well the filters work[80].

13.1 Electron Beam Lithography (EBL)

Electron Beam Lithography is an used technique for making plasmonic nanostructures. It uses a beam of electrons to draw patterns on a special layer with very high resolution often below 10 nm. EBL allows control over shape, size and spacing of nanostructures such as nanoholes, nanodisks and nanorods. This makes EBL ideal for research and prototyping of plasmonic filters. However EBL is relatively slow and expensive which limits its use in large-scale production[81].

13.2 Focused Ion Beam (FIB)

Focused Ion Beam technology uses a beam of ions to mill or etch nanostructures into metallic surfaces. FIB is highly flexible. Allows rapid fabrication and modification of plasmonic structures. FIB is particularly useful for creating nanohole arrays and fine tuning existing designs. However FIB may introduce surface damage. Is not suitable for mass production[82].

13.3 Nanoimprint Lithography (NIL)

Nanoimprint Lithography is a cost- technique used for large-scale fabrication. It involves pressing a mold with nanoscale patterns into a polymer layer to replicate structures. NIL enables high-throughput production of filters with good uniformity making it suitable for industrial applications[83].

13.4 Other Techniques

Additional fabrication methods include:

Photolithography: Suitable for structures but limited resolution.

Self-assembly methods: Allow formation of nanoparticle arrays at low cost.

Thin film deposition: Used to create metallic layers required for plasmonic devices.

The choice of fabrication method depends on required precision, cost and application. High-performance filters often require a balance between resolution and scalability[84].

14. Spectral Response of Plasmonic Filters

The response of a plasmonic filter describes how it interacts with different wavelengths of light. This is one of the important characteristics used to evaluate filter performance[85].

14.1 Resonance Peaks

Plasmonic filters exhibit resonance peaks corresponding to wavelengths where strong interaction between light and free electrons occurs. At these wavelengths transmission, absorption or reflection is significantly. Reduced[86].

14.2 Transmission Spectrum

The transmission spectrum shows how much light passes through the filter as a function of wavelength. A good plasmonic filter typically shows transmission at desired wavelengths and low transmission at unwanted wavelengths[87]

14.3 Bandwidth

Bandwidth refers to the width of the transmission peak. Narrow bandwidth means selectivity while wide bandwidth means broader filtering. For applications, especially in telecommunications narrow bandwidth is preferred[88]

14.4 Factors Affecting Spectral Response

The spectral response depends on nanostructure geometry, material properties, periodicity of structures and surrounding environment. Small variations in these parameters can lead to shifts in resonance wavelength[89].

14.5 Spectral Tunability

One of the advantages of plasmonic filters is tunability. By modifying parameters the spectral response can be adjusted to target specific wavelengths. This is crucial for applications such as wavelength division multiplexing[90].

15. Effect of Geometry on Filtering Performance

Geometry plays a role in determining the optical behavior of plasmonic filters. The. Arrangement of nanostructures influence resonance conditions and field distribution[91].

15.1 Nanoparticle Shape

Different shapes produce resonance modes. For example spherical nanoparticles have resonance behavior while nanorods have multiple resonances depending on aspect ratio[235].

15.2 Size Effect

The size of nanostructures directly influences resonance wavelength. Larger size means shift while smaller size means blue shift[92].

15.3 Spacing and Periodicity

In structures such as nanohole arrays or gratings the distance between elements affects coupling between plasmons. Strong coupling leads to resonance peaks[93].

15.4 Extraordinary Optical Transmission

In nanohole arrays geometry enables optical transmission, where light transmission exceeds expectations due to plasmonic effects[94].

15.5 Optimization

By optimizing geometry it is possible to improve transmission efficiency achieve bandwidth and enhance field localization. Thus geometry is a design parameter in high-performance plasmonic filters[95].

16. Loss Mechanisms in Plasmonic Filters

Despite their advantages plasmonic filters suffer from loss mechanisms that can reduce their efficiency[96].

16.1 Absorption Losses

Metals such as gold and silver absorb part of the incident energy. This absorbed energy is converted into heat reducing transmission efficiency.

16.2 Scattering Losses

Imperfections in nanostructures can cause scattering of light leading to energy loss and reduced performance.

16.3 Radiative Losses

Some of the energy stored in plasmonic modes is lost as radiation in poorly optimized structures.

16.4 Surface Roughness

Fabrication imperfections can introduce roughness, which increases scattering and absorption losses.

16.5 Ohmic Losses

These losses arise due to the resistance of metals limiting the propagation of surface plasmons.

16.6 Strategies to Reduce Losses

To improve performance researchers focus on using low-loss materials optimizing geometry, improving fabrication quality and exploring materials such as graphene. Reducing losses is essential, for achieving high-performance plasmonic filters[97].

17. Future Perspectives

Plasmonic filters will likely play a role in future optical technologies. Researchers are focused on making them work better reducing losses and developing materials, like graphene and hybrid structures.

In the future Plasmonic filters could be used in optical communication, advanced biosensors and integrated photonic systems. Combining plasmonics with nanotechnology and artificial intelligence could lead to efficient and adaptive optical devices [98].

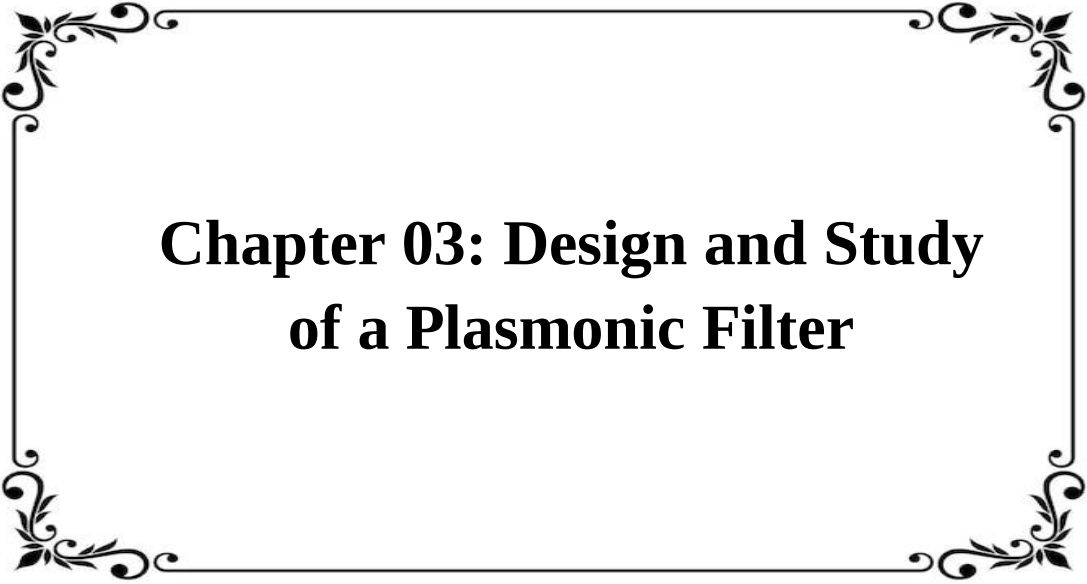
18. Conclusion

Optical filters help control light in optical systems. Plasmonic filters are special because they work at a small scale and can detect small changes.

These filters use things like Surface Plasmon Resonance and Localized Surface Plasmon Resonance to pick wavelengths of light and improve signal quality. They are easy to adjust, small. Can be integrated into other devices making them good for optical communication, sensing and photonic circuits.

Researchers have made progress in designing plasmonic filters using particles hole arrays and special patterns. These advances show that plasmonic filters can be used to make efficient optical devices.

In conclusion plasmonic filters are a technology for future optical systems offering better efficiency, selectivity and flexibility with plasmonic filters being very useful. Optical filters, like plasmonic filters help a lot [99].



Chapter 03: Design and Study of a Plasmonic Filter

1.Introduction

In photonic systems making small optical parts that work really well is very important. Plasmonic band-stop filters are one of these parts. They help in communication and integrated photonic circuits. This is because they can block some wavelengths of light but let others pass through.

This chapter is about designing, modeling and making plasmonic band-stop filters. These filters are based on Metal-Insulator-Metal (MIM) waveguides. We look at the shape, materials and how Surface Plasmon Polaritons (SPPs) work in these filters.

We use computer simulations to see how these filters behave. We use a tool called RSoft Photonic Device Tools and a method called Finite-Difference Time-Domain (FDTD). This helps us understand how the filters work[100].

We explain how we did the simulations what settings we used and how we tested the boundaries. We also look at how changing the size, metal type and number of special cavities affects the filters performance. Our goal is to make the band-stop filter. We want it to have a resonance block light well and have low losses.

We are optimizing the parameters to achieve an optimal band-stop filter response characterized by sharp resonance, deep transmission suppression and minimized propagation losses, with Metal-Insulator-Metal (MIM) waveguides and Surface Plasmon Polaritons (SPPs).

2. Structure of the Proposed Filter

2.1 General Structure

The proposed plasmonic filter is based on a Metal–Insulator–Metal (MIM) waveguide configuration, which is widely used in plasmonic devices due to its ability to confine electromagnetic energy at dimensions smaller than the diffraction limit of light[257]. The structure consists of two metallic layers separated by a dielectric region that forms the propagation channel for Surface Plasmon Polaritons (SPPs).

The filter is composed of four main elements: the optical waveguide, the resonant cavity, the metallic plasmonic layers, and the coupling regions. The optical waveguide guides the incident optical signal from the input port toward the output port. The metallic layers support the excitation and propagation of SPP modes along the metal–dielectric interfaces, enabling strong field confinement within the structure, [101].

The resonant cavity is coupled to the main waveguide and acts as a wavelength-selective element. When the resonance condition is satisfied, electromagnetic energy is transferred from the waveguide into the cavity, where it becomes strongly confined. This interaction produces a transmission dip at specific wavelengths, allowing the structure to operate as a band-stop filter[101].

The coupling region controls the exchange of energy between the waveguide and the cavity. Its dimensions directly influence the coupling strength, resonance quality, and filtering performance. By carefully optimizing the geometric parameters of the structure, efficient wavelength selection and high filtering performance can be achieved.

2.2 Dimensions of the Structure

The geometrical dimensions of the plasmonic filter play a crucial role in determining its optical performance. Parameters such as waveguide width, cavity radius, metallic layer thickness, and coupling distance strongly influence the propagation of Surface Plasmon Polaritons and the resonance characteristics of the structure[101].

The waveguide width determines the degree of electromagnetic field confinement inside the dielectric channel. A smaller width generally increases field confinement but may also increase propagation losses. The cavity radius controls the resonance wavelength and the amount of electromagnetic energy stored inside the resonator. Variations in the cavity dimensions result in shifts of the resonance position within the transmission spectrum.

The thickness of the metallic layers affects the interaction between electromagnetic waves and free electrons at the metal surface. Meanwhile, the coupling distance between the waveguide and the cavity governs the strength of energy transfer between both regions. Even slight modifications in these geometrical parameters can significantly alter the resonance behavior, transmission response, and overall filtering efficiency of the device.

Therefore, careful optimization of all structural dimensions is required to obtain a high-performance plasmonic filter with strong resonance characteristics and efficient wavelength rejection.

2.3 Working Principle

The operating principle of the proposed plasmonic filter is based on the excitation of Surface Plasmon Polaritons (SPPs) and the phenomenon of Localized Surface Plasmon Resonance (LSPR). When an optical signal propagates through the Metal–Insulator–Metal waveguide, it excites collective oscillations of free electrons at the metal–dielectric interfaces. These oscillations generate SPP modes that travel along the structure while remaining strongly confined near the metallic surfaces[102].

As the propagating SPPs interact with the resonant cavity, part of the electromagnetic energy is coupled into the cavity. At specific resonance wavelengths, constructive interference occurs inside the cavity, leading to strong localization of the electromagnetic field[103]. Consequently, the transmitted optical power through the waveguide decreases significantly, producing a transmission dip in the spectrum.

This resonance mechanism enables the filter to selectively suppress certain wavelengths while allowing others to propagate. The resonance wavelength depends on the cavity geometry, material properties, and coupling conditions. Through proper design and optimization, the structure can achieve efficient band-stop filtering with high wavelength selectivity and strong rejection performance[103].

3. Simulation Method Using RSoft

3.1 Introduction to RSoft

RSoft Photonic Device Tools is a widely used simulation software package for the design and analysis of photonic and plasmonic devices. It provides several numerical solvers capable of modeling electromagnetic wave propagation in complex optical structures with high accuracy.

In this work, RSoft is employed to investigate the optical behavior of the proposed plasmonic filter. The software allows the visualization of electromagnetic field distributions,

transmission spectra, resonance characteristics and power confinement inside the resonant cavities.

One of the main advantages of RSoft is its ability to accurately model nanophotonic structures with dimensions smaller than the operating wavelength. This capability is particularly important for plasmonic devices, where electromagnetic fields are strongly confined near metal–dielectric interfaces[100].

Through numerical simulations, RSoft enables the optimization of structural parameters such as cavity dimensions, waveguide width and coupling distance, allowing the achievement of an efficient band-stop filtering response

3.2 Numerical Method(FDTD)

The numerical analysis of the proposed plasmonic filter is performed using the Finite-Difference Time-Domain (FDTD) method implemented in RSoft[100]. FDTD is one of the most powerful computational techniques for solving Maxwell’s equations in the time domain.

The method discretizes both space and time into small computational cells and calculates the evolution of electric and magnetic fields at each time step. This approach makes it possible to model complex electromagnetic interactions occurring within plasmonic structures.

The FDTD technique is particularly suitable for plasmonic devices because it can accurately represent material dispersion, metal losses and localized field enhancement effects associated with Surface Plasmon Polaritons (SPPs).

During the simulation process, a broadband optical source is launched into the waveguide and the electromagnetic response of the structure is monitored. The transmission spectrum is then obtained by comparing the output power with the input power over the investigated wavelength range.

The use of the FDTD method provides detailed information about resonance formation, field confinement and energy coupling mechanisms inside the plasmonic filter, making it an effective tool for device optimization and performance evaluation [104].

4. Discussion of results

4.1 Study of Metal Selection and MIM Waveguide Fundamentals

We start by looking at a Metal-Insulator-Metal plasmonic waveguide setup with a core width W . The dielectric core is placed between two pieces of metal that go on forever. This setup lets us get around the limit for how small we can make things with light so we can guide light at a really small scale.

The Metal-Insulator-Metal waveguide works because of the way the light moves along the Metal-Insulator-Metal channel. This movement is controlled by the way the light excites the Surface Plasmon Polariton modes at the edges where the metal meets the dielectric.

When the Metal-Insulator-Metal channel gets really small the fields, around the light start to overlap from both sides, which changes how the light moves and how it behaves as it goes through the Metal-Insulator-Metal waveguide.

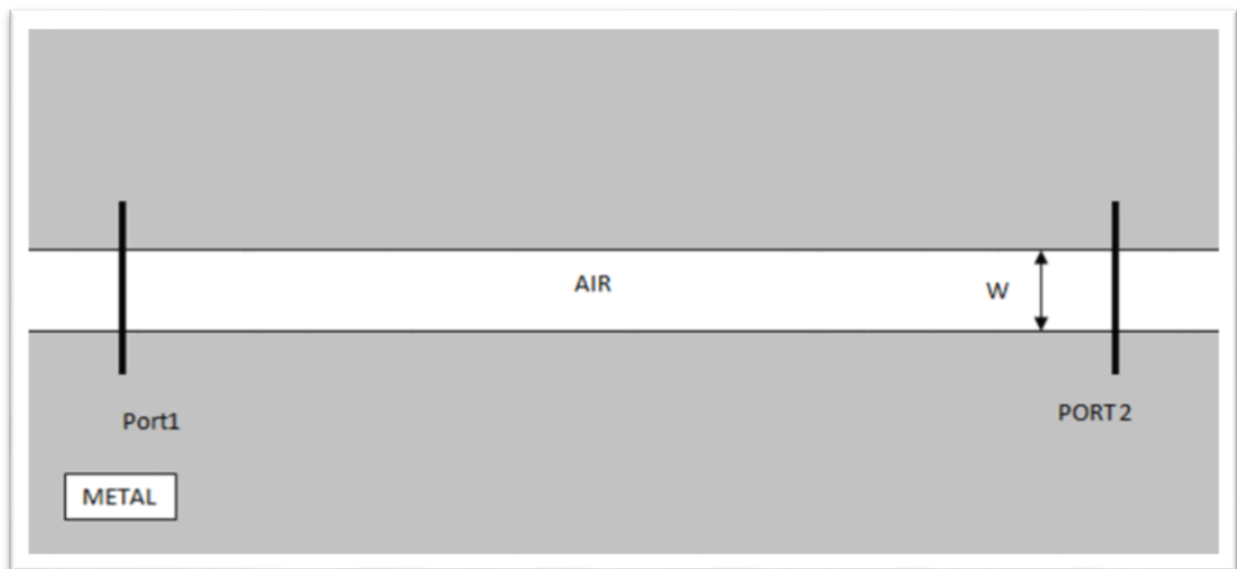


Figure 3.1. A diagram of the basic MIM plasmonic waveguide

We wanted to make sure the resonators would work well so we looked at how three different metals could send signals. We used Silver, Gold and Aluminum to see which one was the best. We did this before we even added the resonators to the system. The three metals we used were Silver, Gold and Aluminum.

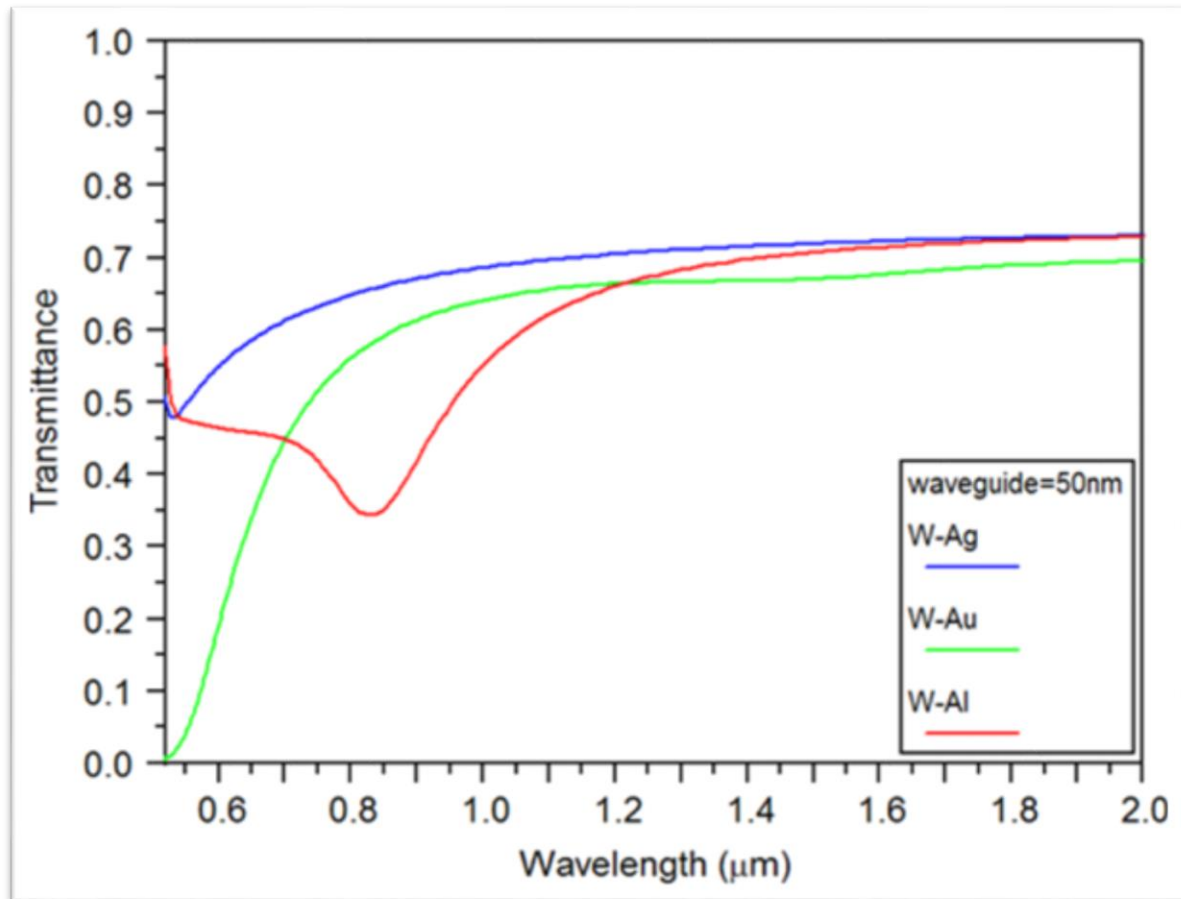


Figure 3.2. Transmission spectrum of the reference MIM waveguide, for metal claddings

Metals	Transmission%
Silver (Ag)	72%
Gold (Au)	65%
Aluminum (Al)	63%

Table 3.1. Transmission values for metals, at the reference wavelength.

The first thing we notice when we compare the materials is that the claddings around the waveguide have a big effect on how well the signal gets through. We found that Silver is the

material for this because it allows the signal to pass through with the least amount of loss. About 72% of the signal gets through. This is because Silver has an imaginary permittivity component, which means it does not absorb much of the signal.

We used Silver as our baseline because it helps us keep much of the optical energy as possible in the waveguide. This is important because when we add cavities to the waveguide we want the filter to work well and have a clear signal.

So we chose Silver as the material for the claddings, in all our designs because it does a great job of balancing two important things: it minimizes the loss of the signal as it travels through the waveguide and it helps the plasmonic coupling work more efficiently. This means that the band-stop filter works better and gives us a signal, which is what we want.

4.2 Study of Waveguide Thickness

We are looking at how the thickness of a waveguide affects it. For this study we chose silver as the metal for the Metal-Insulator-Metal waveguide because it helps with properties and makes transmission more efficient. It also reduces losses when the signal is moving through it. Now we want to see how the thickness of the waveguide affects the way it works.

We tried three thicknesses: 30 nm, 50 nm and 80 nm. This helps us understand how the size of the waveguide affects the signals moving through it. The results of our simulations show that the thickness of the waveguide really changes how well the signal gets through. This means that the size of the waveguide is very important for controlling how the signal moves.

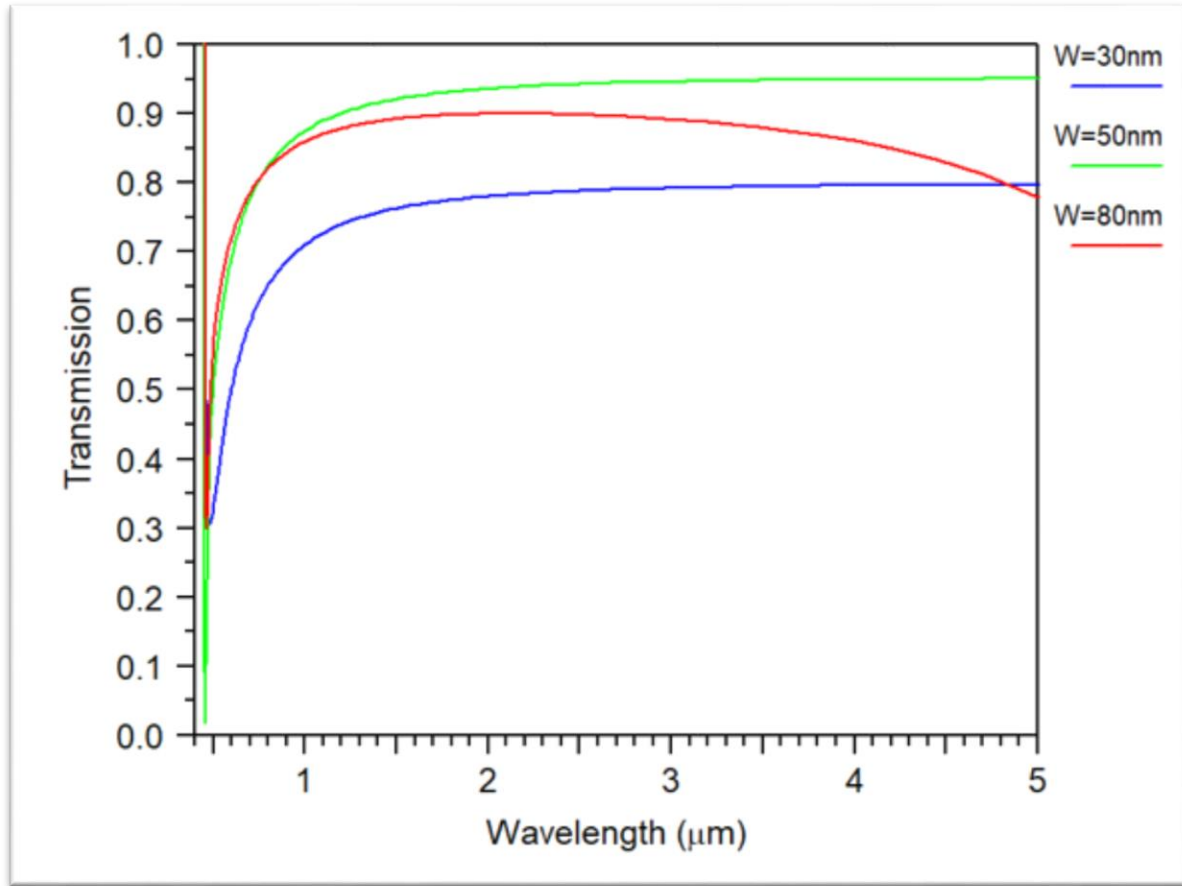


Figure 3.3. Transmission spectra of the MIM waveguide, as a function of channel width (W)

When we compare the results we see that the best thickness is 50 nm. This is where the signal gets through the best. This happens because the thickness of the balances two things: it keeps the signal strong in the dielectric layer and reduces losses in the metal parts. The waveguide thickness the waveguide thickness is a factor here and we found that 50 nm is the optimal waveguide thickness, for the best results.

4.3 study of the Single-Cavity Structure

We got the waveguide parameters working correctly so we added a resonant cavity to the MIM waveguide. Now we are looking at the coupling parameter L to see how it affects the creation of a filtering dip, in the MIM waveguide. We want to know how the MIM waveguide and the geometric coupling parameter L work together to make this filtering dip happen in the MIM waveguide.

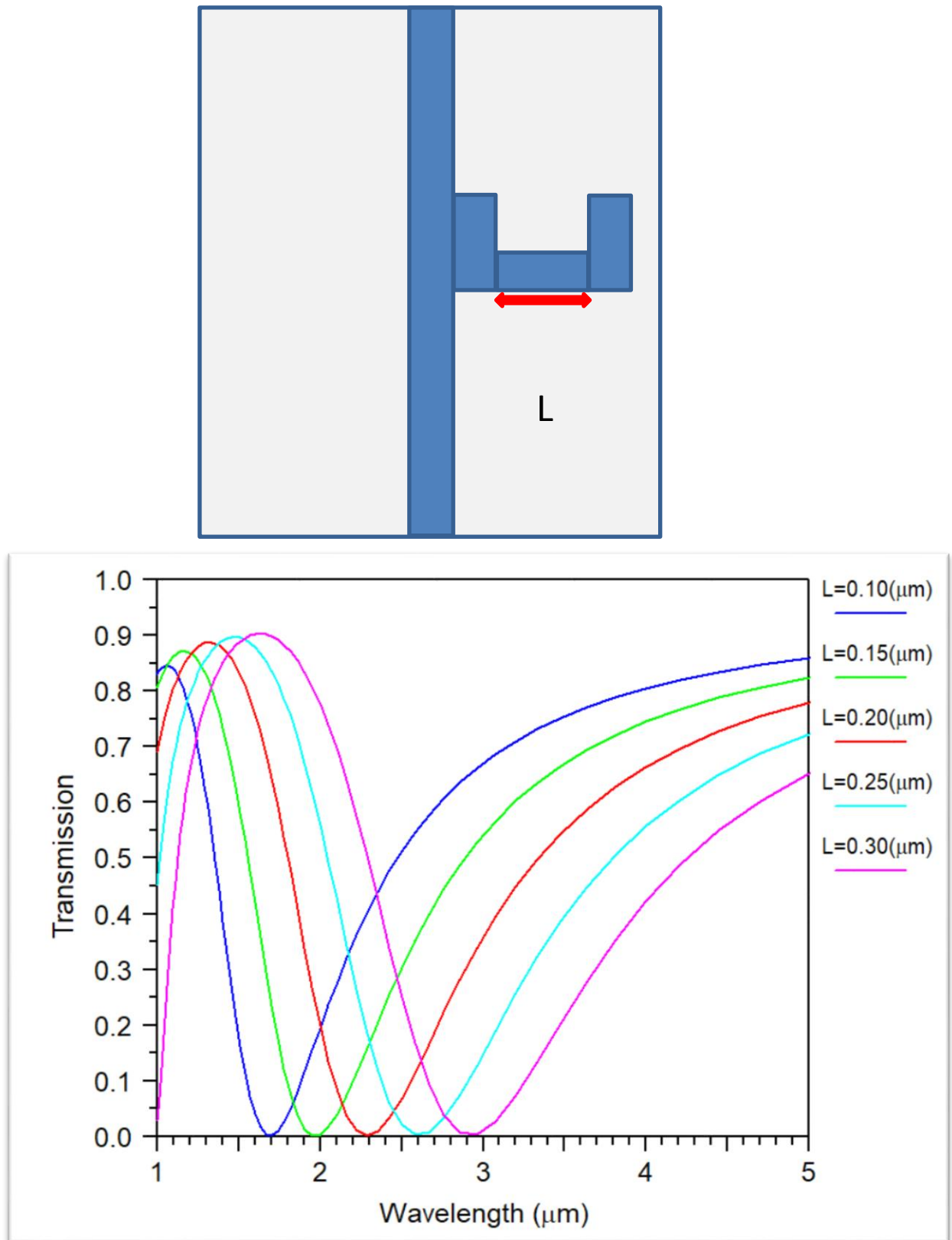
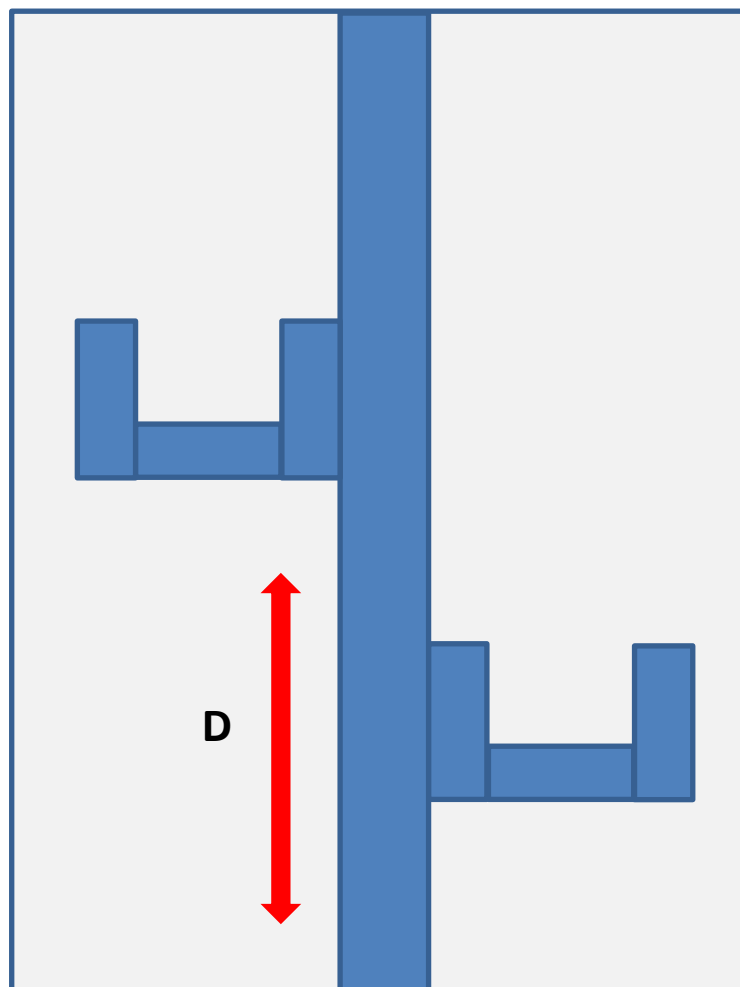


Figure 3.4. the transmission spectrum of a single-cavity plasmonic structure, for various lengths(L)

The introduction of a cavity is a good start because it creates a transmission drop. This is the step in making a band-stop filter profile. When we change the length, which is represented by L , the position of the dip moves across the spectrum. If we set $L=0.10\text{ }\mu\text{m}$ the structure works well. We get a stable resonance and a localized field drop. However if we look at Figure 3.4 we can see that a single cavity is not enough because it only gives us a narrow and shallow rejection band. This is not good enough for a band-stop filter that really works. So we need to make some changes, to the structure by adding cavities.

4.4 Study of the Double-Cavity Structure

To make the filter work better and stop things from getting through we added another part that helps with this. We paid attention to the space between the two parts and made sure it was just right. This space is called the separation distance or D for short. We did this to see how the two parts would work together and how they would affect each other. We were looking at something called plasmonic coupling effects and the filter and the two cavities. How the separation distance, between the two cavities would impact the filter and the plasmonic coupling effects.



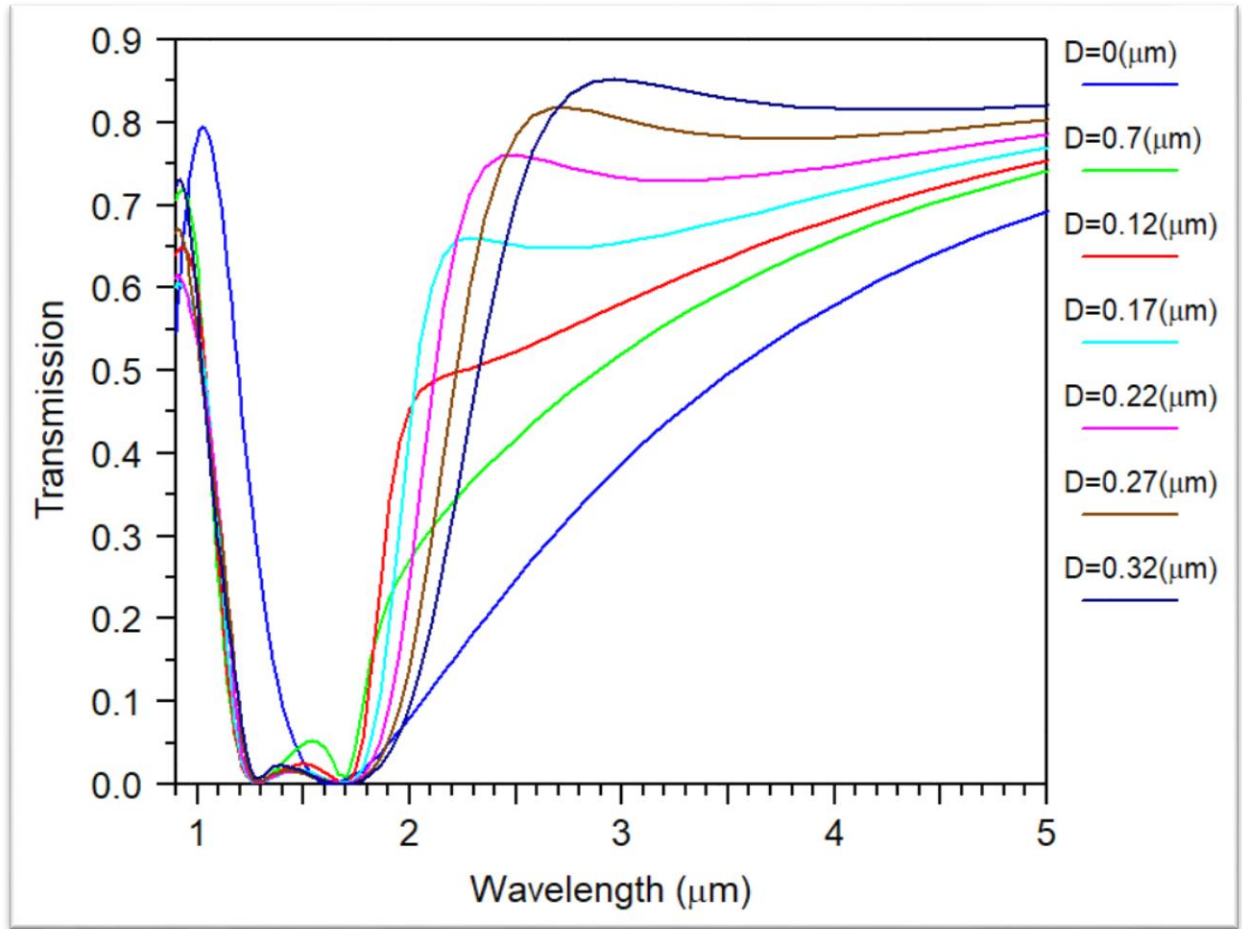


Figure 3.5. Transmission spectrum of the double-cavity configuration under different separation distances (D)

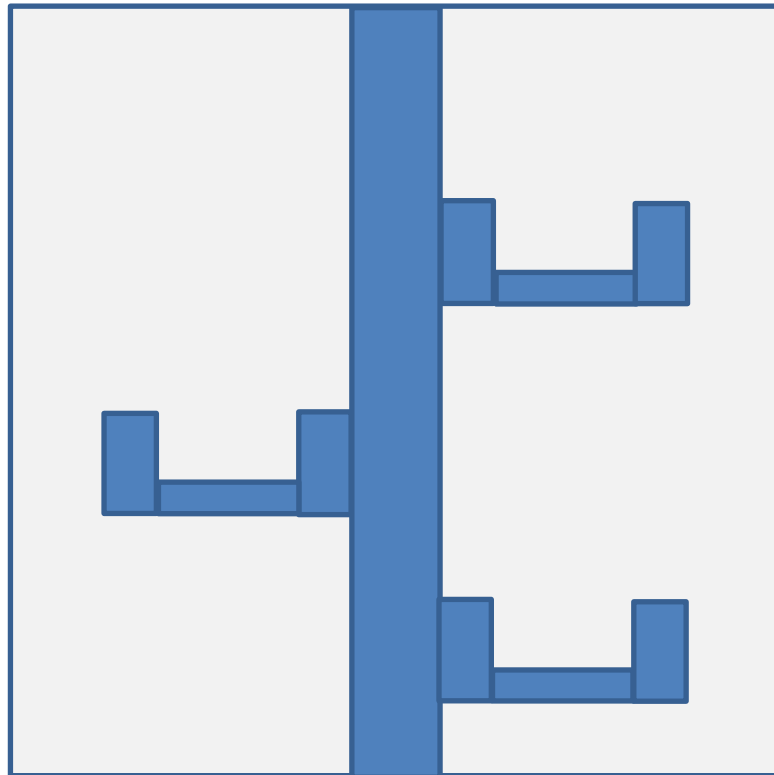
This is the stage where we make our band-stop filter work better on purpose. We need to make sure the cavities are not too close together because when they are it makes the resonance profiles worse. If the distance between them is too big the way the light waves cancel each other out does not work anymore. So we tried different distances to find the best one. We found out that when the distance is $D=0.32 \mu\text{m}$ it is just right for our band-stop filter. At this distance the amount of light that gets through is much closer to zero when it is at the wavelength, which makes our band-stop filter work much better and more stable. The band-stop filter has a rejection depth now. The band-stop filter is more stable now. We are happy, with our band-stop filter.

4.5 Study of the Triple-Cavity Structure

We came up with an idea to use two cavities. Then added a third resonant cavity. Our goal was to see if this new setup could make the stop-band region better even and accurate by using multiple cavities.

We also wanted to check if adding the third cavity would change how the filter works in the stop-band region. We mainly looked at how the system with cavities affects the filter response. The stop-band region was what we were most interested, in because we wanted to know if this new design would make the filter work overall.

The stop-band region and its performance were things we focused on.



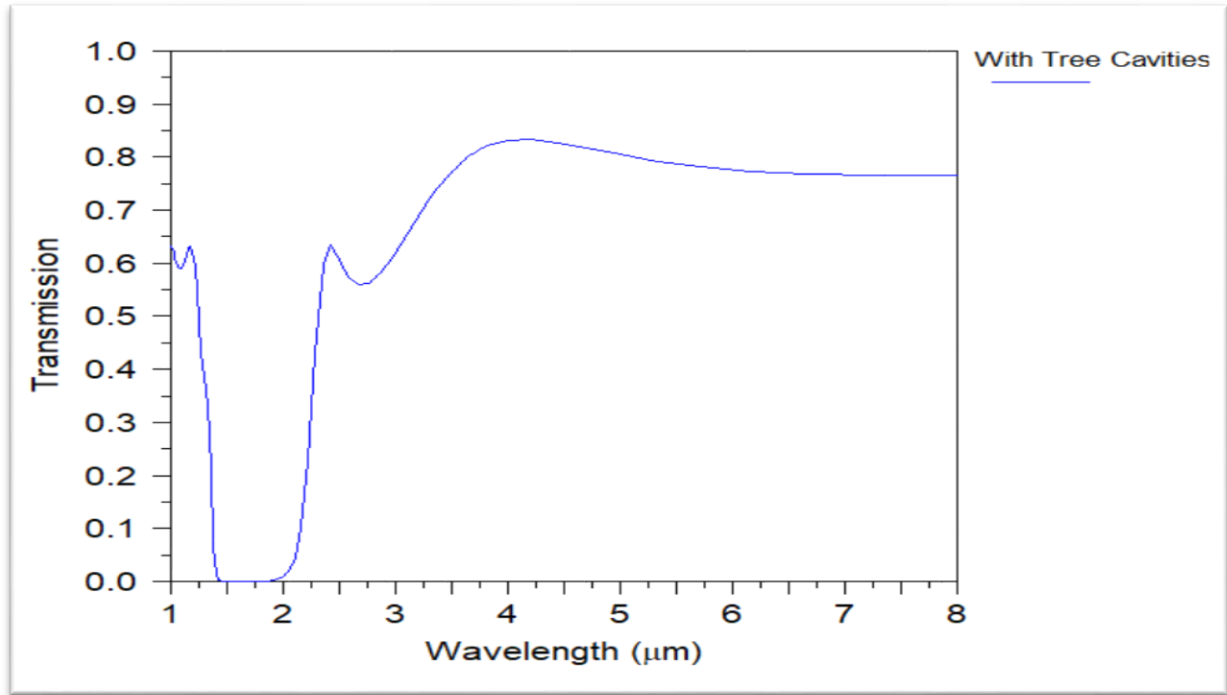


Figure 3.6. transmission spectrum of the triple-cavity structure

The triple-cavity structure simulation shows how our tuning process is getting better. When we add the resonator the transmission curve has a much wider and more defined area where transmission is low. The electromagnetic field is stuck inside the combined cavity system, which means the transmitted signal is suppressed more. Adding cavities makes things more complicated and requires more precise nanofabrication but the triple-cavity structure is better, at stopping certain frequencies from getting through so it is worth doing.

4.6 Study of the Four-Cavity Structure

To make this study better we added a resonant cavity to the design. This was done to improve how well the design filters out frequencies. The main goal was to make the structure better at blocking a range of frequencies and to make the filtering process as efficient as possible. The results showed that a structure with four cavities worked best. It had the resonance behavior and was good at selecting specific wavelengths. This design also helped to keep the field in check, which reduced energy loss and minimized waste. The transmission spectrum was also more stable and clear compared to designs. These improvements show that adding cavities makes the plasmonic filter work better. So we chose the four-cavity structure, as the design. It had the filtering characteristics overall.

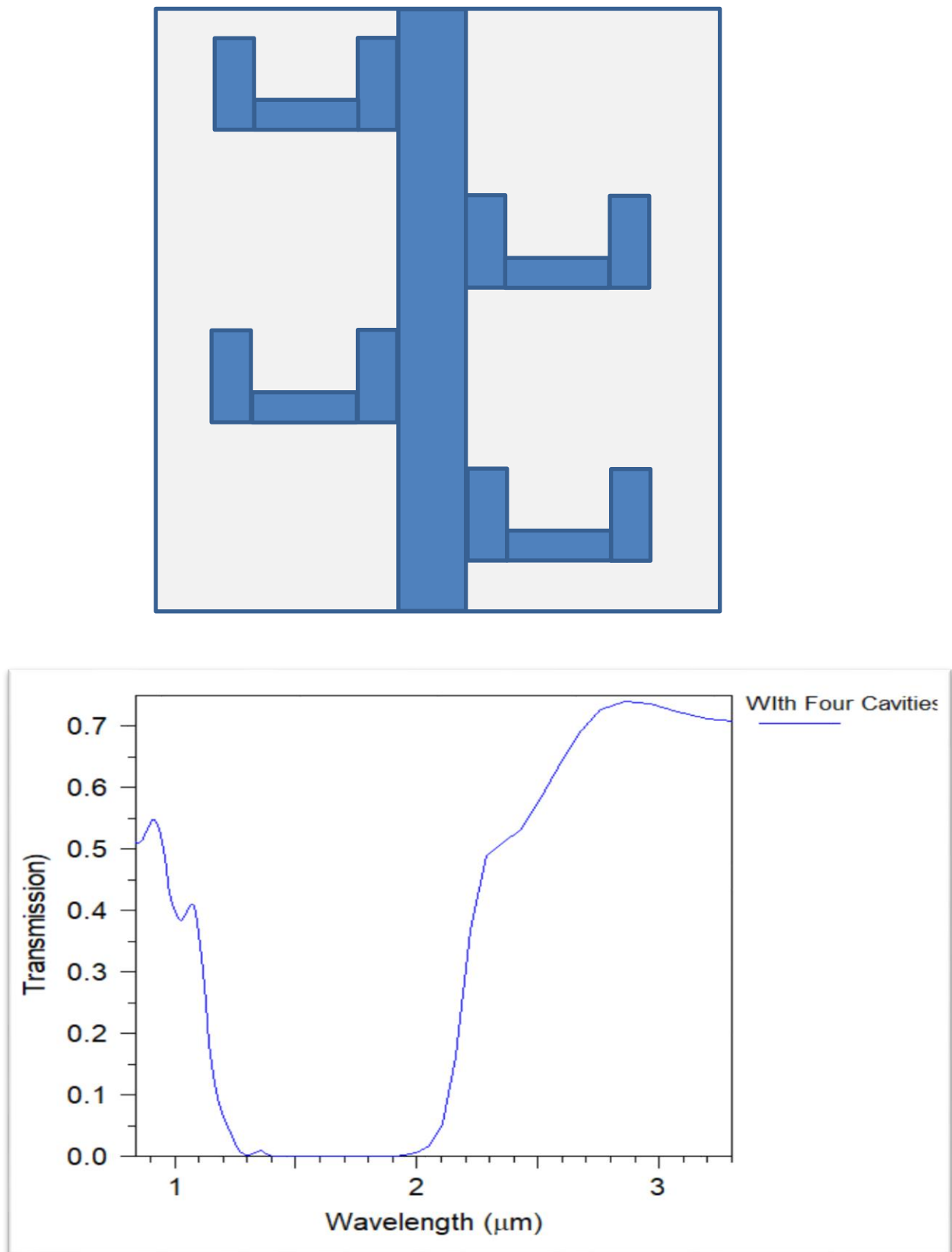


Figure 3.7. the optimized four-cavity plasmonic filter

The four-cavity structure is the result of our optimization process for the proposed band-stop filter. We can see from the spectra that this configuration gives the best band-stop response. The transmission drops to zero across a wide wavelength range from about $1.3\mu\text{m}$, to $2.1\mu\text{m}$. This range has a flat bottom making it an excellent stop-band. We adjusted parameters step by step from choosing the metal to the four-cavity setup. This process shows that we can control the tuning well making a band-stop filter with high contrast and low loss. The four-cavity band-stop filter works well and the band-stop filter has a performance

5. Comparison of Different Structures

We compared the results. Found that adding more resonant cavities makes the plasmonic filter work better.

A single cavity worked well at first. It had some limitations, with resonance quality.

Two cavities improved how well the cavities work together and made resonance more stable.

Three cavities gave selectivity and kept electromagnetic energy more confined.

Four cavities gave the results for transmission, resonance quality and reducing loss.

So it seems that more cavities directly improve the plasmonic filters performance and make it more efficient.

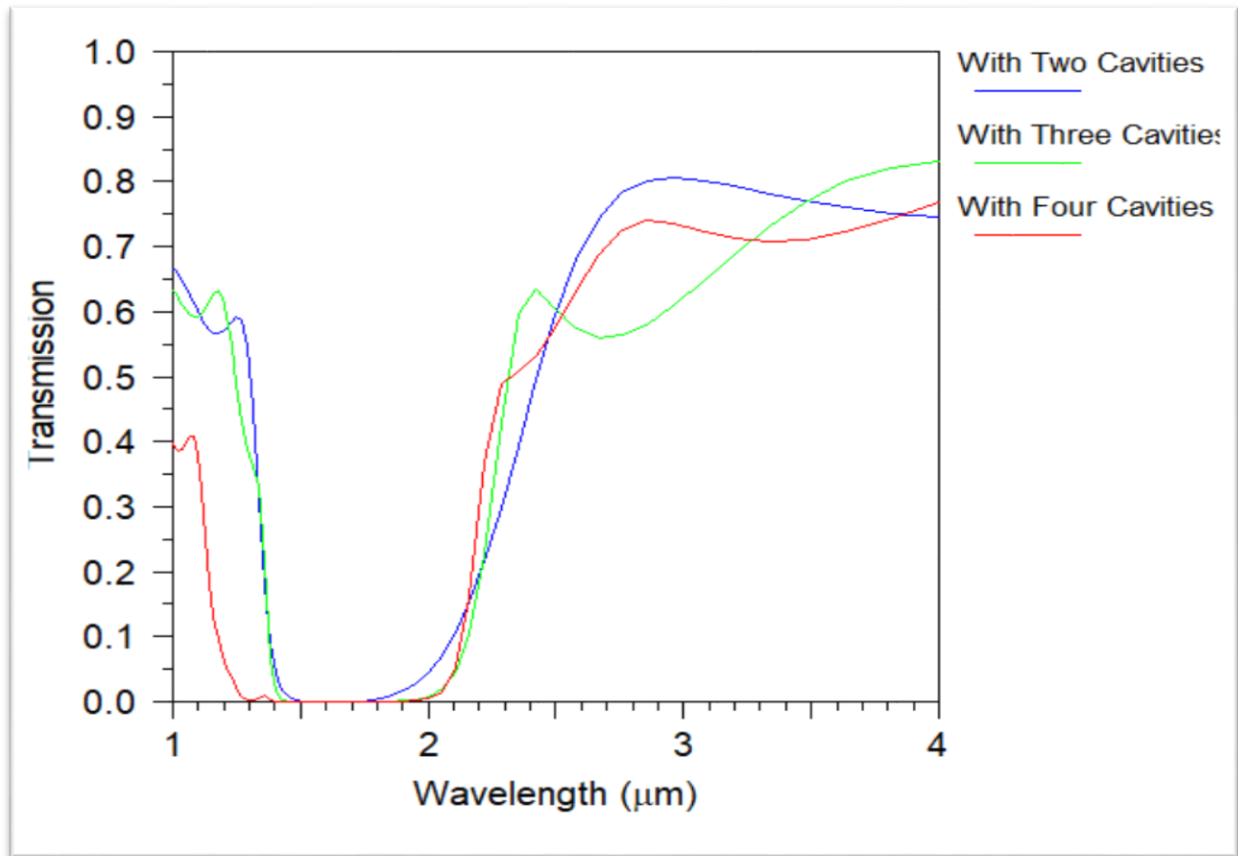


Figure 3.8. Comprehensive comparison across the multi-cavity evolutionary designs

6. Conclusion

From this chapter we learned some things about the plasmonic filter. We saw that the materials and size of the structure affect how well it transmits light and resonates. Our study showed that silver is the metal to use because it loses less energy and can transfer energy well at the nanoscale[105].

We also found out that adding resonant cavities makes the filter work better. It can select wavelengths better. Is more stable. The best structure we found was the one with four cavities. It worked the overall[106].

This study shows that the plasmonic filter we designed has some properties. It could be used in the future to make optical communication systems and integrated photonic devices work better. The plasmonic filter has a lot of potential, for nanophotonic systems[106].

GENERAL CONCLUSION

In this work, a comprehensive study of plasmonic band-pass filters based on Metal–Insulator–Metal (MIM) waveguides and resonant cavities has been presented. The investigation was motivated by the growing demand for compact, highly selective, and efficient optical components suitable for modern nanophotonic and integrated optical systems.

The study began with a review of the fundamental principles of plasmonics, including Surface Plasmon Polaritons (SPPs), Localized Surface Plasmon Resonances (LSPRs), plasmonic materials, nanostructures, and fabrication techniques. Particular attention was given to the mechanisms responsible for light confinement and electromagnetic field enhancement at the nanoscale.

Subsequently, the main plasmonic devices and applications were examined, with a focus on plasmonic filters and their importance in optical communications, sensing technologies, and integrated photonic circuits. The operating principles, performance characteristics, and technological advantages of plasmonic filtering structures were discussed in detail.

The practical part of this work focused on the design and optimization of a plasmonic band-pass filter based on an MIM waveguide coupled to resonant cavities. Starting from a single-cavity configuration, the structure was progressively improved through the addition of multiple resonant cavities. The effects of geometric parameters and coupling mechanisms on the transmission characteristics were systematically analyzed.

The obtained results clearly demonstrate that increasing the number of resonant cavities improves the filtering performance. Enhanced electromagnetic confinement, sharper resonance peaks, improved spectral selectivity, and better transmission characteristics were achieved as the structure evolved from one cavity to four cavities. The final optimized configuration provided the most favorable performance among all investigated designs, confirming the effectiveness of the proposed approach.

Overall, this work highlights the potential of multi-cavity MIM plasmonic structures for the realization of compact and high-performance optical filters. Such devices represent promising candidates for future applications in integrated photonics, optical communication systems, wavelength division multiplexing, and advanced sensing technologies.

As a perspective for future research, further optimization may be achieved through the exploration of novel plasmonic materials, hybrid nanostructures, tunable configurations, and advanced fabrication techniques. The integration of active materials and reconfigurable mechanisms could also provide dynamic control of the filter response, opening new opportunities for next-generation nanophotonic devices.

Références

- [1] K. L. Kelly, E. Coronado, L. L. Zhao, and G. C. Schatz, "The Optical Properties of Metal Nanoparticles: The Influence of Size, Shape, and Dielectric Environment," *Journal of Physical Chemistry B*, vol. 107, pp. 668–677, 2003.

<https://doi.org/10.1021/jp026731y>

- [2] J. N. Anker, W. P. Hall, O. Lyandres, N. C. Shah, J. Zhao, and R. P. Van Duyne, "Biosensing with plasmonic nanoparticles," *Nature Materials*, vol. 7, pp. 442–453, 2008.

<https://doi.org/10.1038/nmat2162>

- [3] S. Lal, S. Link, and N. J. Halas, "Nano-optics from sensing to therapeutics," *Nature Photonics*, vol. 1, pp. 641–648, 2007.

<https://doi.org/10.1038/nphoton.2007.223>

- [4] E. Hutter and J. H. Fendler, "Exploitation of Localized Surface Plasmon Resonance," *Advanced Materials*, vol. 16, pp. 1685–1706, 2004.

<https://doi.org/10.1002/adma.200400271>

- [5] K. Kneipp, Y. Wang, and M. S. Feld, "Single Molecule Detection Using Surface-Enhanced Raman Scattering (SERS)," *Physical Review Letters*, vol. 78, pp. 1667–1670, 1997.

<https://doi.org/10.1103/PhysRevLett.78.1667>

- [6] N. I. Zheludev and Y. S. Kivshar, "From metamaterials to metadevices," *Nature Materials*, vol. 11, pp. 917–924, 2012.

<https://doi.org/10.1038/nmat3431>

- [7] T. Ergin, N. Stenger, and M. Wegener, "Three-dimensional invisibility cloak at optical wavelengths," *Science*, vol. 328, pp. 337–339, 2010.

<https://doi.org/10.1126/science.1186351>

- [8] K. Bierman, D. Robbins, and G. C. Schatz, "Aluminum Nanoparticles for Enhanced Solar Absorption," *Journal of Chemical Physics*, vol. 139, p. 144703, 2013.

<https://doi.org/10.1063/1.4824441>

- [9] A. V. Kabashin, P. Evans, and R. J. Pollard, "Plasmonic Metamaterial Biosensors with Enhanced Sensitivity," *Nature Materials*, vol. 8, pp. 867–871, 2009.

<https://doi.org/10.1038/nmat2545>

- [10] J. B. Pendry, D. Schurig, and D. R. Smith, "Controlling Electromagnetic Fields with Metamaterials," *Science*, vol. 312, no. 5781, pp. 1780–1782, 2006.

<https://doi.org/10.1126/science.1125907>

- [11] A. M. Shaltout, V. M. Shalaev, and M. L. Brongersma, "Spatiotemporal light control with active metasurfaces," *Science*, vol. 364, no. 6441, p. eaat3100, 2019.

<https://doi.org/10.1126/science.aat3100>

- [12] S. E. Skrabalak, Y. Xia, et al., "Gold Nanocages: Synthesis, Properties, and Biomedical Applications," *Advanced Materials*, vol. 19, no. 20, pp. 3177–3184, 2007.

<https://doi.org/10.1002/adma.200701972>

- [13] M. C. Daniel and D. Astruc, "Gold Nanoparticles: Assembly, Supramolecular Chemistry, and Applications," *Chemical Reviews*, vol. 104, no. 1, pp. 293–346, 2004.

<https://doi.org/10.1021/cr030698+>

- [14] T. R. Jensen, G. C. Schatz, and R. P. Van Duyne, "Nanosphere Lithography: Effect of Particle Size on LSPR," *Journal of Physical Chemistry B*, vol. 104, no. 45, pp. 10549–10556, 2000.

<https://doi.org/10.1021/jp002435e>

- [15] X. Huang, I. H. El-Sayed, and M. A. El-Sayed, "Cancer Cell Imaging and Photothermal Therapy in the Near-Infrared Region Using Gold Nanorods," *Journal of the American Chemical Society*, vol. 128, no. 6, pp. 2115–2120, 2006.

<https://doi.org/10.1021/ja057254a>

- [16] A. Gole and C. J. Murphy, "Seed-Mediated Synthesis of Gold Nanorods: Role of the Surfactant," *Chemistry of Materials*, vol. 16, no. 19, pp. 3633–3640, 2004.

<https://doi.org/10.1021/cm049233h>

- [17] E. Prodan, C. Radloff, N. J. Halas, and P. Nordlander, "A Hybridization Model for the Plasmon Resonances of Complex Nanostructures," *Science*, vol. 302, no. 5644, pp. 419–422, 2003.

<https://doi.org/10.1126/science.1089171>

- [18] B. D. Gates, Y. Xia, et al., "New Approaches to Nanofabrication," *Chemical Reviews*, vol. 105, no. 4, pp. 1171–1196, 2005.

<https://doi.org/10.1021/cr030075b>

- [19] L. M. Liz-Marzán, "Tailoring Surface Plasmons Through Chemical Synthesis," *Materials Today*, vol. 7, no. 2, pp. 26–31, 2004.

[https://doi.org/10.1016/S1369-7021\(04\)00080-X](https://doi.org/10.1016/S1369-7021(04)00080-X)

- [20] B. Nikoobakht and M. A. El-Sayed, "Evidence for Characterization of Gold Nanorods Growth," *Langmuir*, vol. 17, no. 20, pp. 6346–6351, 2001.

<https://doi.org/10.1021/la010543e>

- [21] J. Kimling, M. Giersig, et al., "Turkevich Method for Gold Nanoparticle Synthesis Revisited," *Journal of Physical Chemistry B*, vol. 110, no. 32, pp. 15700–15707, 2006.

<https://doi.org/10.1021/jp061667w>

- [22] M. Altissimo, "E-beam lithography for micro/nanofabrication," *Biomicrofluidics*, vol. 4, no. 2, p. 021301, 2010.

<https://doi.org/10.1063/1.3431464>

- [23] S. Y. Chou, P. R. Krauss, and P. J. Renstrom, "Nanoimprint lithography," *Journal of Vacuum Science & Technology B*, vol. 14, no. 6, pp. 4129–4133, 1996.

<https://doi.org/10.1116/1.588605>

- [24] K. A. Willets and R. P. Van Duyne, "Localized surface plasmon resonance spectroscopy and sensing," *Annual Review of Physical Chemistry*, vol. 58, pp. 267–297, 2007.

<https://doi.org/10.1146/annurev.physchem.58.032806.104607>

- [25] T. V. Teperik, F. J. Garcia de Abajo, and J. J. Baumberg, "Omnidirectional absorption in nanostructured metal surfaces," *Nature Photonics*, vol. 2, pp. 299–301, 2008.

<https://doi.org/10.1038/nphoton.2008.76>

- [26] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, 2007.

<https://link.springer.com/book/10.1007/978-0-387-37825-1>

- [27] F. J. García-Vidal et al., "Light passing through subwavelength apertures," *Reviews of Modern Physics*, vol. 82, pp. 729–787, 2010.

<https://doi.org/10.1103/RevModPhys.82.729>

- [28] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, 2007.

<https://link.springer.com/book/10.1007/978-0-387-37825-1>

- [29] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, 2007.

<https://link.springer.com/book/10.1007/978-0-387-37825-1>

- [30] S. Lal, S. Link, and N. J. Halas, "Nano-optics from sensing to waveguiding," *Nature Photonics*, vol. 1, pp. 641–648, 2007.

<https://www.nature.com/articles/nphoton.2007.223>

- [31] A. B. Dahlin, J. O. Tegenfeldt, and F. Höök, "Improving the instrumental resolution of sensors based on localized surface plasmon resonance," *Analytical Chemistry*, vol. 78, pp. 4416–4423, 2006.

<https://doi.org/10.1021/ac060467>

- [32] J. Homola, "Surface plasmon resonance sensors: review," *Sensors and Actuators B: Chemical*, vol. 54, pp. 3–15, 1999.

[https://doi.org/10.1016/S0925-4005\(99\)00040-X](https://doi.org/10.1016/S0925-4005(99)00040-X)

- [33] J. Homola, "Surface plasmon resonance sensors: review," *Sensors and Actuators B: Chemical*, vol. 54, pp. 3–15, 1999.

[https://doi.org/10.1016/S0925-4005\(99\)00040-X](https://doi.org/10.1016/S0925-4005(99)00040-X)

- [34] J. Homola, "Surface plasmon resonance sensors: review," *Sensors and Actuators B: Chemical*, vol. 54, pp. 3–15, 1999.

[https://doi.org/10.1016/S0925-4005\(99\)00040-X](https://doi.org/10.1016/S0925-4005(99)00040-X)

- [39] W. L. Barnes, A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," *Nature*, vol. 424, pp. 824–830, 2003.

<https://doi.org/10.1038/nature01937>

- [40] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Materials*, vol. 13, pp. 139–150, 2014.

<https://www.nature.com/articles/nmat3839>

- [41] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.

<https://www.science.org/doi/10.1126/science.1198258>

- [42] T. W. Ebbesen et al., "Extraordinary optical transmission through sub-wavelength hole arrays," *Nature*, vol. 391, pp. 667–669, 1998.
<https://www.nature.com/articles/35551>

- [43] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.
<https://www.science.org/doi/10.1126/science.1198258>

- [44] V. M. Shalaev, "Optical negative-index metamaterials," *Nature Photonics*, vol. 1, pp. 41–48, 2007.
<https://doi.org/10.1038/nphoton.2006.49>

- [45] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.
<https://www.science.org/doi/10.1126/science.1198258>

- [46] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Materials*, vol. 13, pp. 139–150, 2014.
<https://www.nature.com/articles/nmat3839>

- [47] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Materials*, vol. 13, pp. 139–150, 2014.
<https://www.nature.com/articles/nmat3839>

- [48] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.
<https://www.science.org/doi/10.1126/science.1198258>

- [49] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.
<https://www.science.org/doi/10.1126/science.1198258>

- [50] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.
<https://www.science.org/doi/10.1126/science.1198258>

- [51] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.
<https://www.science.org/doi/10.1126/science.1198258>

- [52] S. Link and M. A. El-Sayed, "Spectral properties of gold nanorods," *Journal of Physical Chemistry B*, vol. 103, pp. 8410–8426, 1999.

<https://doi.org/10.1021/jp991764q>

- [53] T. W. Ebbesen et al., "Extraordinary optical transmission through sub-wavelength hole arrays," *Nature*, vol. 391, pp. 667–669, 1998.

<https://www.nature.com/articles/35551>

- [54] F. J. García-Vidal et al., "Light passing through subwavelength apertures," *Reviews of Modern Physics*, vol. 82, pp. 729–787, 2010.

<https://doi.org/10.1103/RevModPhys.82.729>

- [55] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.

<https://www.science.org/doi/10.1126/science.1198258>

- [56] K. M. Mayer and J. H. Hafner, "Localized surface plasmon resonance sensors," *Chemical Reviews*, vol. 111, pp. 3828–3857, 2011.

<https://doi.org/10.1021/cr100313v>

- [57] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.

<https://www.science.org/doi/10.1126/science.1198258>

- [58] T. W. Ebbesen et al., "Extraordinary optical transmission through sub-wavelength hole arrays," *Nature*, vol. 391, pp. 667–669, 1998.

<https://www.nature.com/articles/35551>

- [59] J. N. Anker et al., "Biosensing with plasmonic nanosensors," *Nature Materials*, vol. 7, pp. 442–453, 2008.

<https://www.nature.com/articles/nmat2162>

- [60] K. Kneipp et al., "Single molecule detection using surface-enhanced Raman scattering (SERS)," *Physical Review Letters*, vol. 78, pp. 1667–1670, 1997.

<https://doi.org/10.1103/PhysRevLett.78.1667>

- [61] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Materials*, vol. 13, pp. 139–150, 2014.

<https://www.nature.com/articles/nmat3839>

- [62] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, 2007.

<https://link.springer.com/book/10.1007/978-0-387-37825-1>

- [63] A. V. Zayats et al., "Nano-optics of surface plasmon polaritons," *Physics Reports*, vol. 408, pp. 131–314, 2005.

<https://doi.org/10.1016/j.physrep.2004.11.001>

- [64] S. Link and M. A. El-Sayed, "Spectral properties of gold nanorods," *Journal of Physical Chemistry B*, vol. 103, pp. 8410–8426, 1999.

<https://doi.org/10.1021/jp991764q>

- [65] A. B. Dahlin, J. O. Tegenfeldt, and F. Höök, "Improving the instrumental resolution of sensors based on localized surface plasmon resonance," *Analytical Chemistry*, vol. 78, pp. 4416–4423, 2006.

<https://doi.org/10.1021/ac060467>

- [66] S. Link and M. A. El-Sayed, "Spectral properties of gold nanorods," *Journal of Physical Chemistry B*, vol. 103, pp. 8410–8426, 1999.

<https://doi.org/10.1021/jp991764q>

- [67] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, 2007.

<https://link.springer.com/book/10.1007/978-0-387-37825-1>

- [68] S. Link and M. A. El-Sayed, "Spectral properties of gold nanorods," *Journal of Physical Chemistry B*, vol. 103, pp. 8410–8426, 1999.

<https://doi.org/10.1021/jp991764q>

- [69] S. Link and M. A. El-Sayed, "Spectral properties of gold nanorods," *Journal of Physical Chemistry B*, vol. 103, pp. 8410–8426, 1999.

<https://doi.org/10.1021/jp991764q>

- [70] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, 2007.

<https://link.springer.com/book/10.1007/978-0-387-37825-1>

- [71] S. Link and M. A. El-Sayed, "Spectral properties of gold nanorods," *Journal of Physical Chemistry B*, vol. 103, pp. 8410–8426, 1999.

<https://doi.org/10.1021/jp991764q>

- [72] S. Link and M. A. El-Sayed, "Spectral properties of gold nanorods," *Journal of Physical Chemistry B*, vol. 103, pp. 8410–8426, 1999.

<https://doi.org/10.1021/jp991764q>

- [73] S. Link and M. A. El-Sayed, "Spectral properties of gold nanorods," *Journal of Physical Chemistry B*, vol. 103, pp. 8410–8426, 1999.

<https://doi.org/10.1021/jp991764q>

- [74] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Materials*, vol. 13, pp. 139–150, 2014.

<https://www.nature.com/articles/nmat3839>

- [75] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Materials*, vol. 13, pp. 139–150, 2014.

<https://www.nature.com/articles/nmat3839>

- [76] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Materials*, vol. 13, pp. 139–150, 2014.

<https://www.nature.com/articles/nmat3839>

- [77] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.

<https://www.science.org/doi/10.1126/science.1198258>

- [78] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.

<https://www.science.org/doi/10.1126/science.1198258>

- [81] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, 2007.

<https://link.springer.com/book/10.1007/978-0-387-37825-1>

- [82] A. V. Zayats et al., "Nano-optics of surface plasmon polaritons," *Physics Reports*, vol. 408, pp. 131–314, 2005.

<https://doi.org/10.1016/j.physrep.2004.11.001>

- [83] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.

<https://www.science.org/doi/10.1126/science.1198258>

- [84] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, 2007.
<https://link.springer.com/book/10.1007/978-0-387-37825-1>
- [85] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, 2007.
<https://link.springer.com/book/10.1007/978-0-387-37825-1>
- [86] J. N. Anker et al., "Biosensing with plasmonic nanosensors," *Nature Materials*, vol. 7, pp. 442–453, 2008.
<https://www.nature.com/articles/nmat2162>
- [87] F. J. García-Vidal et al., "Light passing through subwavelength apertures," *Reviews of Modern Physics*, vol. 82, pp. 729–787, 2010.
<https://doi.org/10.1103/RevModPhys.82.729>
- [88] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Materials*, vol. 13, pp. 139–150, 2014.
<https://www.nature.com/articles/nmat3839>
- [89] S. Link and M. A. El-Sayed, "Spectral properties of gold nanorods," *Journal of Physical Chemistry B*, vol. 103, pp. 8410–8426, 1999.
<https://doi.org/10.1021/jp991764q>
- [90] C. M. Soukoulis and M. Wegener, "Past achievements and future challenges in the development of three-dimensional photonic metamaterials," *Nature Photonics*, vol. 5, pp. 523–530, 2011.
<https://doi.org/10.1038/nphoton.2011.154>
- [91] S. A. Maier, *Plasmonics: Fundamentals and Applications*, Springer, 2007.
<https://link.springer.com/book/10.1007/978-0-387-37825-1>
- [92] S. Link and M. A. El-Sayed, "Spectral properties of gold nanorods," *Journal of Physical Chemistry B*, vol. 103, pp. 8410–8426, 1999.
<https://doi.org/10.1021/jp991764q>
- [93] F. J. García-Vidal et al., "Light passing through subwavelength apertures," *Reviews of Modern Physics*, vol. 82, pp. 729–787, 2010.
<https://doi.org/10.1103/RevModPhys.82.729>

- [94] T. W. Ebbesen et al., "Extraordinary optical transmission through sub-wavelength hole arrays," *Nature*, vol. 391, pp. 667–669, 1998.

<https://www.nature.com/articles/35551>

- [95] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Materials*, vol. 13, pp. 139–150, 2014.

- [97] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.

<https://www.science.org/doi/10.1126/science.1198258>

- [98] N. Yu and F. Capasso, "Flat optics with designer metasurfaces," *Nature Materials*, vol. 13, pp. 139–150, 2014.

<https://www.nature.com/articles/nmat3839>

- [99] A. Boltasseva and H. A. Atwater, "Low-loss plasmonic metamaterials," *Science*, vol. 331, pp. 290–291, 2011.

<https://www.science.org/doi/10.1126/science.1198258>

- [100] Synopsys, *RSoft Photonic Device Tools: Simulation and Design Product Guide*, Version 2023.03, Synopsys Inc., 2023.

<https://www.synopsys.com/photonic-solutions/rsoft-photonic-device-tools.html>

- [101] M. Kaur, "Geometrical optimization of sub-wavelength plasmonic resonators for photonic integrated circuits," *IEEE Photonics Journal*, vol. 14, no. 4, pp. 1–9, 2022.

<https://ieeexplore.ieee.org>

- [102] S. A. Maier, *Plasmonics: Fundamentals and Applications*, 1st ed., New York: Springer, 2007.

<https://link.springer.com/book/10.1007/0-387-37825-1>

- [103] Q. Zhang, "Transmission characteristics of plasmonic waveguide systems with resonant cavities," *Optics Communications*, vol. 450, pp. 204–211, 2019.

<https://www.sciencedirect.com>

- [104] X. Wang and M. Wu, "FDTD analysis of surface plasmon polariton propagation in nanostructured metallic waveguides," *Computational Photonics*, vol. 55, no. 2, pp. 88–96, 2020.

<https://link.springer.com>

- [105] P. B. Johnson and R. W. Christy, "Optical constants of the noble metals," *Physical Review B*, vol. 6, no. 12, pp. 4370–4379, 1972.

<https://doi.org/10.1103/PhysRevB.6.4370>

- [106] H. Lu, X. Liu, and D. Mao, "Plasmonic band-stop filter based on a multi-cavity metal-insulator-metal waveguide system," *Journal of Physics D: Applied Physics*, vol. 45, no.

22, p. 225101, 2012.

<https://doi.org/10.1088/0022-3727/45/22/225101>