Design and Implementation of a Plasmonic Planar Ring Resonator for Optical Bio-Sensing

A Project Report

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Table of Contents

Abstract

The present work focuses on the design and analysis of a highly sensitive, miniaturized plasmonic planar ring resonator biosensor. The structure exploits the surface plasmon resonance phenomenon to achieve strong electromagnetic field confinement at the interface between the metal (gold) and dielectric region, particularly within the slot area of the waveguide. This enhanced field localization significantly amplifies the light–matter interaction, enabling precise detection of even minimal variations in the surrounding refractive index.

Through systematic simulation and optimization, the proposed device exhibits an average parameter value best at 195.7 Thz, demonstrating its strong capability for real-time bio-sensing applications. The sensor's design is modeled and analyzed using the Finite Element Method (FEM) in the COMSOL Multiphysics environment, allowing accurate assessment of optical field distribution and resonance behavior. The analysis is carried out within the refractive index of 1.0, corresponding to typical biological fluids and protein solutions.

The compact footprint and enhanced sensitivity of this plasmonic resonator make it an excellent candidate for integrated lab-on-chip biosensing systems. Its potential for label-free, rapid, and cost-effective detection highlights its promise in biomedical diagnostics and environmental monitoring. Future enhancements may include optimizing coupling mechanisms and exploring hybrid plasmonic–dielectric configurations to further boost detection accuracy and operational efficiency.

Objective and Problem Statement

Objective

The primary objective of this work is to design and analyze the Plasmonic behavior of miniaturized plasmonic ring resonator biosensor based on a Silicon-on-Insulator (SOI) platform. The design aims to enhance electric field confinement in the cladding region through surface plasmon resonance (SPR) effects, thereby improving the sensor's interaction with biological analytes and achieving strong field confinement within the bus waveguie of planar Plasmonic ring resonator.

Problem Statement

Since, Surface Plasmon Resonance (SPR) biosensors are widely recognized for their high sensitivity in label-free detection, there remains a need for compact, robust, and highly sensitive sensor designs that can operate effectively within the biological refractive index range (typically 1.0). Existing plasmonic sensors, including photonic crystal fibers and hybrid plasmonic waveguides, often face challenges related to structural complexity, fabrication difficulty, or limited field confinement. This work addresses these limitations by proposing a plasmonic ring resonator integrated with a silicon ring on an SOI platform. The structure is designed to maximize field confinement in the sensing region (slot between gold and silicon) and to achieve high sensitivity through optimized waveguide coupling and resonant wavelength shifts.

Design Specifications

Plasmonic Waveguide					
	width	**height**	**refractive index**		
Silicon waveguide	200[nm]	220[nm]	3.477		
gold waveguide	20[nm]	220[nm]	0.55+11.5i		
water cladding	2000[nm]	2000[nm]	1.33 + i1.2e-4		
Plasmonic Ring Resonator					
	width	**height**	**radius**	**distance**	**refractive index**
Circle c1	-	-	5[um]	-	-
Si ring (off1)	-	-	-	200[nm]	3.477
offset 2 (off2)	-	-	-	60[nm]	-
gold ring (off3)	-	-	-	20[nm]	from library
air caldding	20[um]	20[um]	-	-	1
bus waveguide	20[um]	200[nm]	-	-	-

CHAPTER 1: Introduction

In recent years, surface plasmon resonance (SPR) has become one of the most promising optical phenomena for developing high-performance photonic biosensors. The continuous demand for highly sensitive, label-free, and miniaturized sensing platforms has encouraged researchers to exploit SPR due to its exceptional ability to confine light at the metal–dielectric interface, resulting in strong interaction between the electromagnetic field and the biological analyte. SPR arises from the excitation of surface plasmon polaritons (SPPs)—collective oscillations of free electrons that propagate along the interface of a conductive and dielectric medium—making it highly responsive to variations in the refractive index of the surrounding environment.

Over the past decade, numerous sensing configurations have been explored to improve the sensitivity and stability of plasmonic biosensors. Photonic crystal fiber (PCF)-based SPR sensors have demonstrated significant potential owing to their large evanescent field overlap with the analyte, while graphene-assisted plasmonic structures have achieved sensitivities exceeding several micrometers per refractive index unit (RIU) due to graphene's superior conductivity. More recently, plasmonic waveguide and microring resonator-based architectures have gained attention for their compact design, high integration capability, and robust performance. Hybrid plasmonic ring resonators, in particular, have exhibited enhanced spectral shifts and improved detection limits, making them ideal candidates for on-chip optical bio-sensing applications.

Motivated by these advancements, the present work focuses on the design and analysis of a miniaturized plasmonic ring resonator biosensor integrated with a silicon-on-insulator (SOI) platform. The proposed structure employs a thin silicon layer to achieve strong field confinement at the slot region, thereby enhancing the interaction between the guided optical mode and the surrounding biological medium. Using the Finite Element Method (FEM), the device is numerically optimized to achieve high refractive index sensitivity within the biological sensing of 1.34, demonstrating its potential for real-time, label-free detection in biomedical and biochemical applications.

CHAPTER 2: Proposed Methodology

The design and optimization of the proposed plasmonic planar ring resonator biosensor were carried out through a systematic approach involving structural modeling, material selection, and numerical simulation. The following steps outline the complete methodology adopted to achieve high sensitivity and efficient confinement suitable for biosensing applications.

2.1 Structural Design and Configuration

The sensor is designed on a silicon-on-insulator (SOI) platform to take advantage of CMOS compatibility and excellent optical confinement properties. The core of the structure consists of a silicon ridge waveguide of 200 nm width with a 220 nm height. To induce plasmonic effects, a 20 nm-thick gold layer is deposited along the right edge of the silicon waveguide, separated from the silicon core by a 60 nm slot gap.

This slot region plays a crucial role in enhancing the interaction between the guided optical mode and the surrounding analyte. The overall water cladding contains the silicon waveguide and the gold layer, which maintains compactness while allowing sufficient resonance modes to form. Gold is employed as the plasmonic metal because of its chemical inertness, high conductivity, and resistance to oxidation, ensuring long-term stability in aqueous and biological environments.

Moreover, The offset air ring consists of a 200 nm distance with a gap of 60 nm radially outwards surrounding it, followed by a 20 nm silicon towards outward. A bus waveguide is built with dimensions 20 um x 200 nm which will provide Pin (Input power = 1 W/m) to the ring resonator structure for efficient computation of the results. Finally, a caldding of gold surrounding the whole planar ring resonator builts the entire geometry.

2.2 Material Parameters and Simulation Setup

The cladding medium surrounding the sensor is modeled as water with a refractive index of 1.33 + 1.2e-4, closely representing biological fluids, providing excellent mechanical stability and low optical loss. The operating wavelength range is selected between 1500 nm and 1600 nm, where silicon and gold exhibit favorable optical properties for plasmonic excitation. The height of the silicon waveguide is fixed at 220 nm to ensure single-mode propagation and minimize optical crosstalk between adjacent resonators.

The entire design and optimization process is carried out using the Finite Element Method (FEM) within COMSOL Multiphysics. Modal and parametric analyses are performed to identify the dimensions that yield the strongest field confinement and optimal resonance response. The normalized electric field distribution obtained from simulations confirms that the maximum power confinement occurs within the slot region between the silicon and gold layers. This indicates that the proposed geometry provides an efficient platform for detecting even minute changes in the refractive index of the surrounding medium.

2.3 Excitation of Surface Plasmon Polaritons

For effective excitation of surface plasmon polaritons (SPPs) at the metal–dielectric interface, the dielectric constants of the two materials must exhibit opposite signs. This fundamental condition is well satisfied by the combination of gold (negative permittivity) and silicon (positive permittivity). In this configuration, p-polarized light is launched into the coupling waveguide, generating resonant SPPs through waveguide coupling and internal reflection mechanisms. The excitation of SPPs leads to a strongly confined electromagnetic field localized at the gold–dielectric interface, significantly enhancing light–matter interaction.

This enhanced confinement amplifies the sensitivity of the sensor to small refractive index variations caused by biological analytes. Additionally, the use of the ring resonator configuration introduces a resonance-based amplification mechanism, where the circulating optical field undergoes constructive interference. This results in sharp resonance peaks and measurable wavelength shifts for minor refractive index changes. The combined effect of plasmonic coupling and resonant feedback ensures high detection precision, compact device footprint, and suitability for lab-on-chip integration, making the proposed structure a powerful candidate for real-time, label-free optical biosensing applications.

CHAPTER 3: Simulation Result and Discussion

3.1 Optimized Plasmonic Waveguide

The simulation setup, as configured by Figure 1 in COMSOL Multiphysics, models a plasmonic waveguide with a material stack of Silicon, Gold, and a Water cladding. The physics is defined by the Electromagnetic Waves, Frequency Domain (ewfd) module, tailored for modal analysis of waveguiding structures. A key result from this simulation is the effective mode index, calculated as 1.9253 - 0.030313i. The real part of this index governs the phase propagation of the mode, while its imaginary part directly indicates optical loss, primarily originating from absorption within the Gold layer—a characteristic and often limiting factor in plasmonic systems.

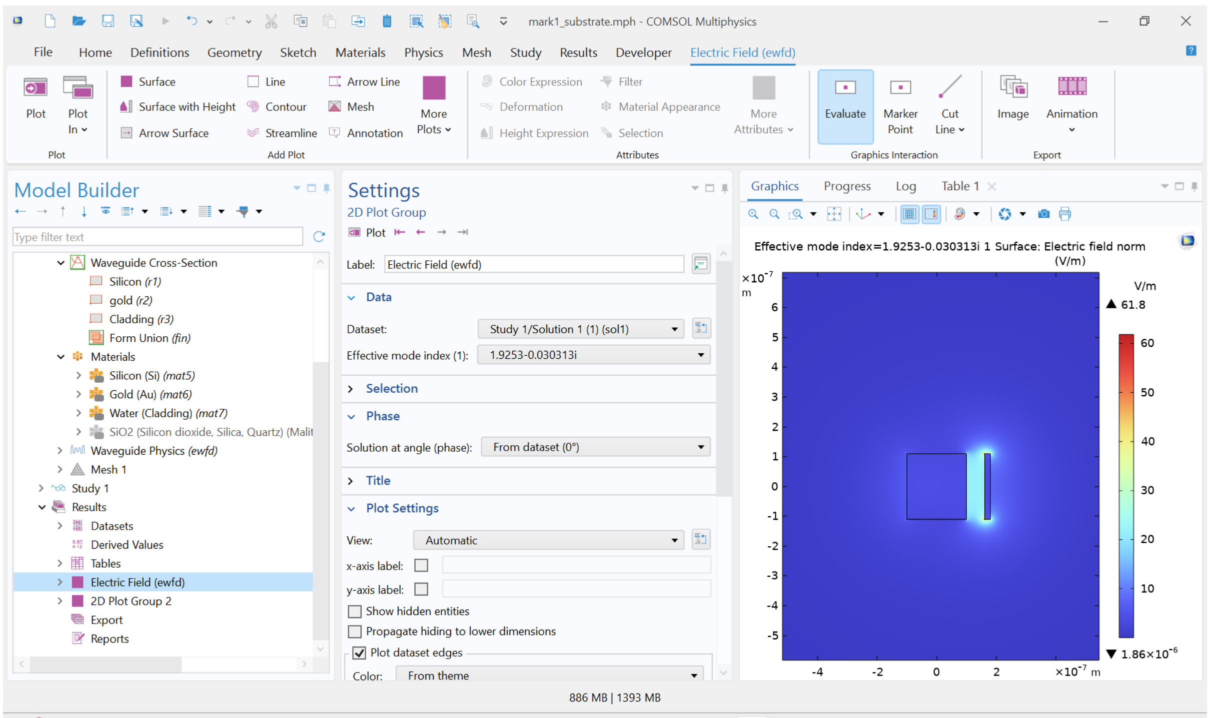

Figure 1: Schematic of Proposed Cross-sectional view of plasmonic waveguide

This specific combination of materials and geometry facilitates the generation and confinement of a surface plasmon polariton (SPP) mode at the interface between the metal and the dielectric cladding. The confinement leads to a highly localized and enhanced electromagnetic field, which is the cornerstone of plasmonic-enhanced phenomena used in applications such as biosensing, nonlinear optics, and integrated photonic circuits.

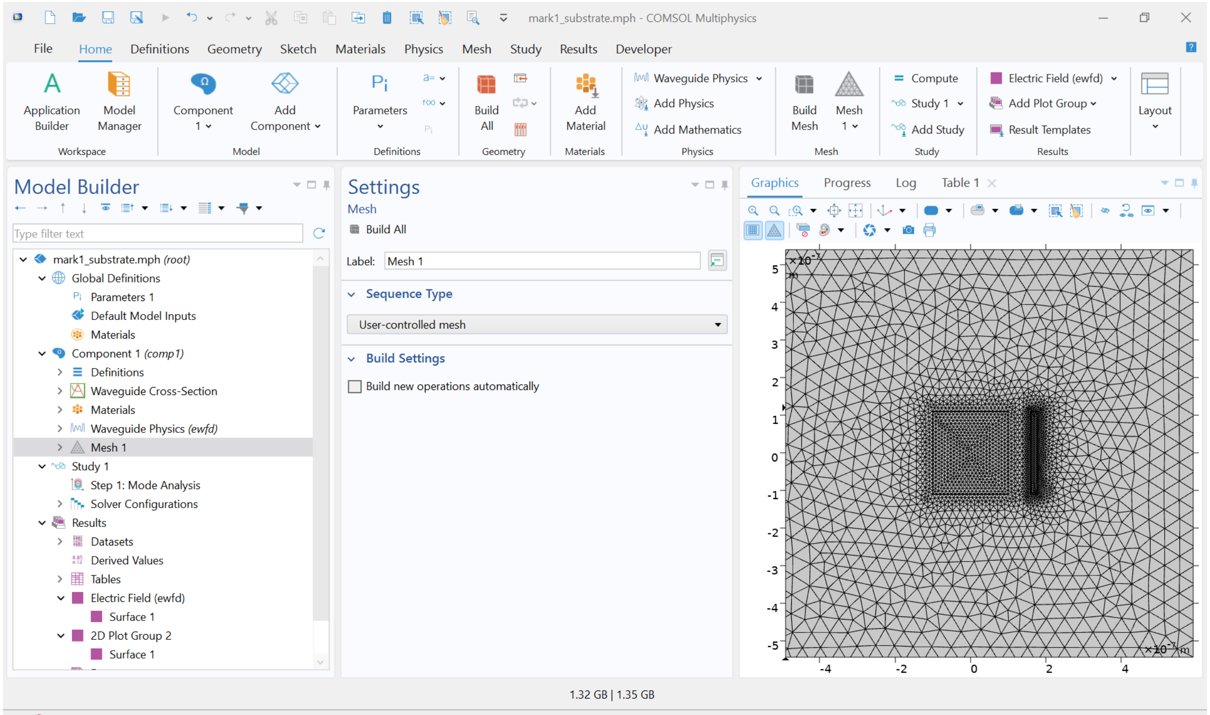

Figure 2: Schematic of Extremely fine mesh of plasmonic waveguide

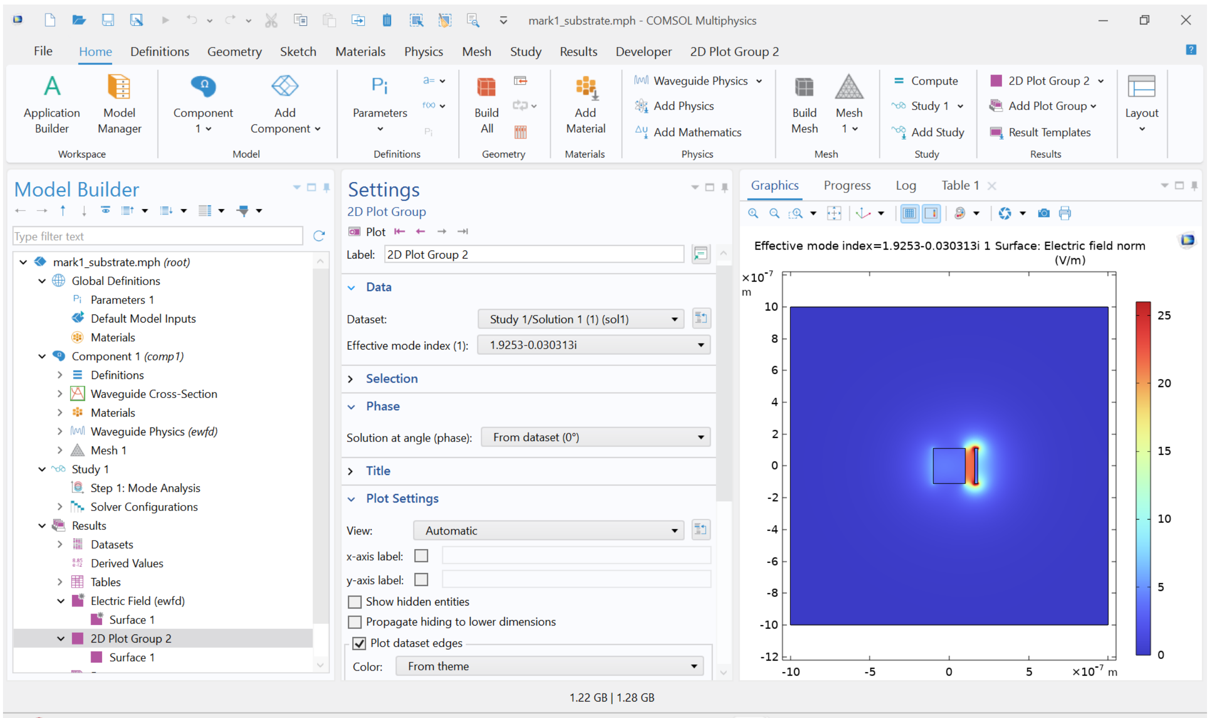

Figure 3: 2D Plot Group of Cross-sectional view of Normalized E-filed

Figure 2 is another visualization, possibly showing a different slice, perspective, or convergence data of the same simulation. It helps verify the consistency of the field distribution or numerical stability. For plasmonics, such plots ensure that the mode profile is physically plausible and that the simulation has resolved the field gradients near the metal interface adequately.

This is a 2D plot of the Electric field norm for the simulated plasmonic mode as shown in Figure 3. The field is strongly localized at the gold-water interface, with the highest intensity (red/yellow) near the metal surface. This confirms strong plasmonic confinement, which is useful for sensing applications because the field enhancement increases light-matter interaction. However, the loss (imaginary part of mode index) suggests some energy dissipation in the metal, which is typical but may limit propagation length.

3.2 Plasmonic Ring Resonator

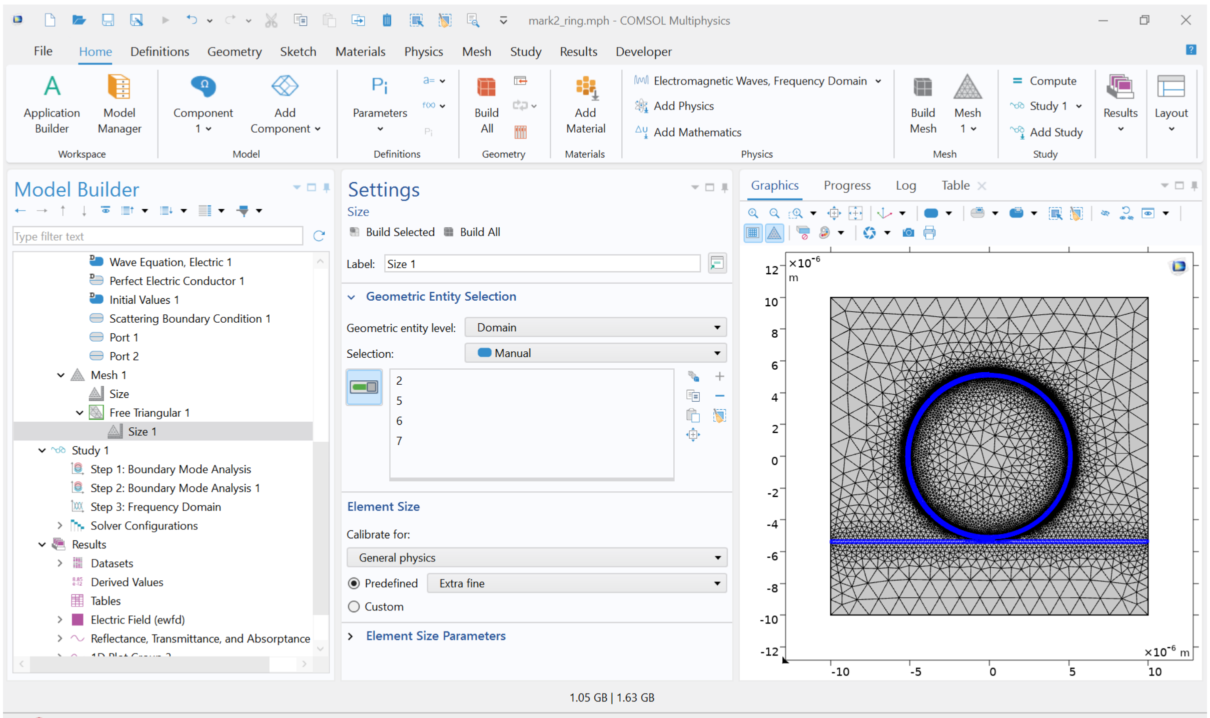

Figure 4: Schematic of Extra fine mesh for ring resonator

Figure 4 shows the details computational mesh settings, showing a finely discretized domain, particularly around key geometric features. For plasmonic simulations, a sufficiently fine mesh at metal-dielectric interfaces is non-negotiable. It is necessary to accurately resolve the rapid decay of the plasmonic field perpendicular to the interface. An inadequate mesh leads to inaccurate field profiles and erroneous effective indices or scattering parameters, making this step foundational for obtaining reliable quantitative results.

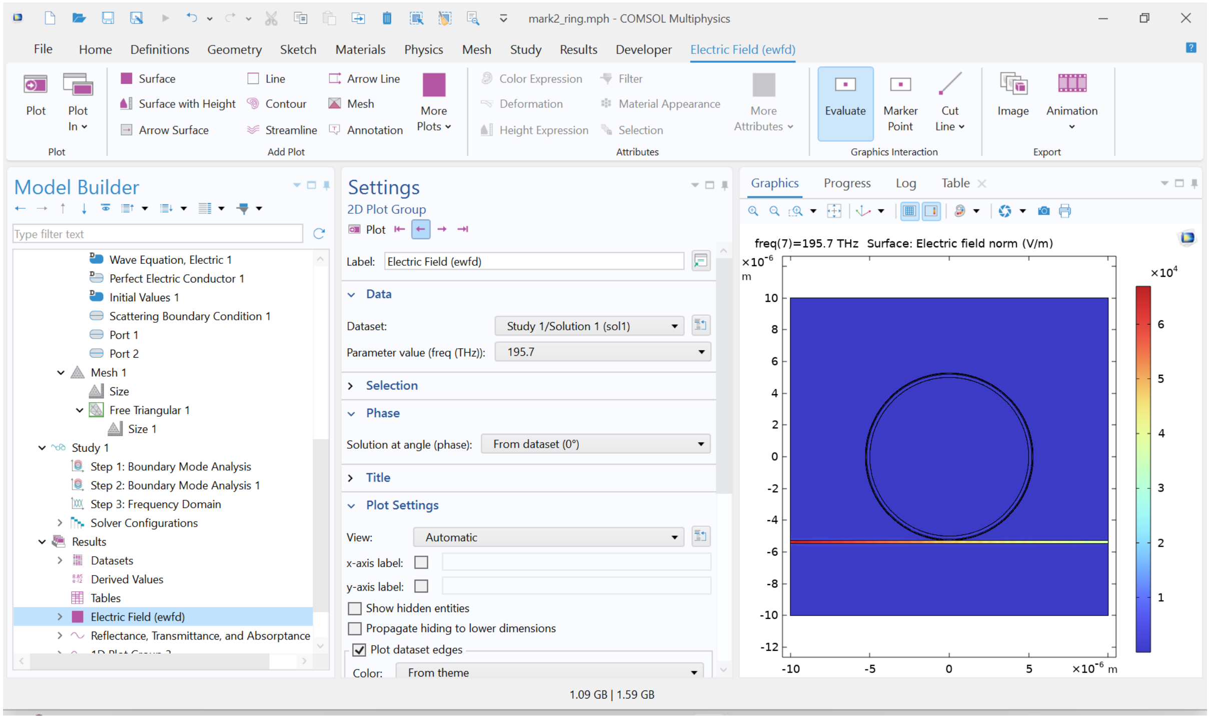

Figure 5: Power propagation in plasmonic ring resonator

This plot displays the spatial distribution of the electric field norm at a specific resonant frequency of 195.7 THz. The intense, localized field enhancement visible at the metal boundaries is the direct visual evidence of an excited surface plasmon polariton mode. This field confinement is the source of the plasmonic effect's utility. Analyzing such plots confirms successful mode excitation, reveals "hot spot" locations for sensing or nonlinear applications, and allows engineers to verify that the field profile aligns with the intended device function.

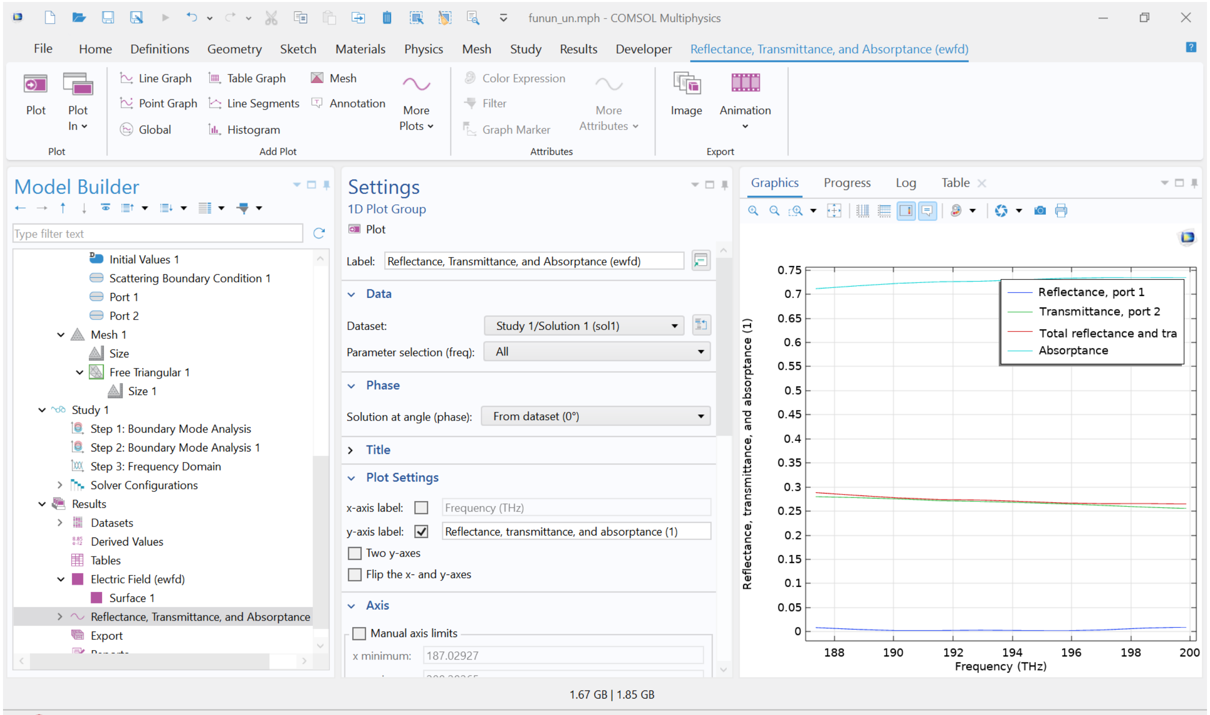

Figure 6: Reflectance, Transmittance, and Absorptance w.r.t frquency

The plot depicts the spectral response of a plasmonic device, illustrating its reflectance, transmittance, and absorptance across a frequency band of roughly 187 to 200 THz. This characterization is fundamental for assessing optical behavior, where the prominent absorptance peak signifies resonant excitation and subsequent ohmic loss in the metallic components. Analyzing this spectrum enables the precise identification of operational frequencies that yield maximal plasmonic resonance, which is critical for optimizing applications in narrowband sensing, enhanced light harvesting, or selective thermal emitters.

Furthermore, the spectral linewidth and depth of the absorptance feature provide insight into the quality (Q) factor and strength of the plasmonic resonance. A sharper, deeper dip indicates a stronger and more confined mode with potentially greater local field enhancement, albeit often with a trade-off in bandwidth. By correlating this spectral data with field distribution plots, one can engineer the structure to tailor the resonance for specific purposes, such as shifting it to a target wavelength or balancing enhancement with propagation loss for waveguide-based devices.

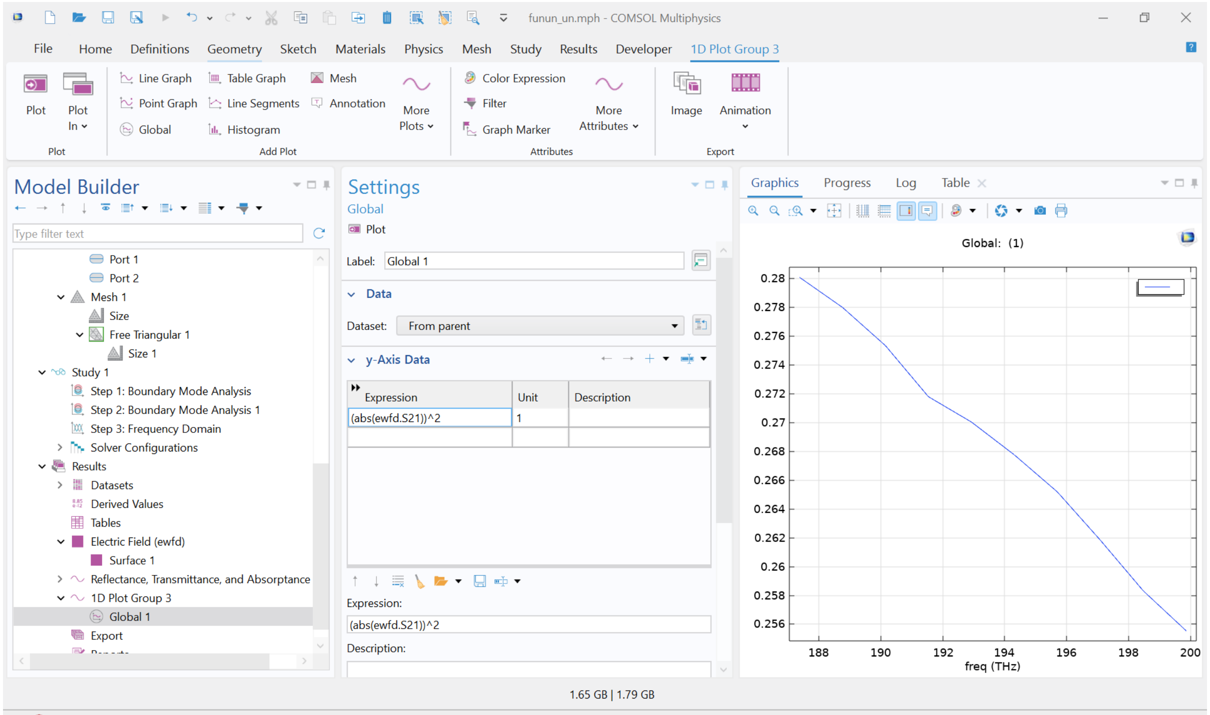

Figure 7: 1D plot for ewfd of plasmonic ring resonator

This graphic plots a global evaluation of the squared magnitude of the S21 scattering parameter. The value fluctuates slightly around 0.26-0.28, representing the transmittance through the device at a specific frequency or parameter sweep. A transmittance significantly below 1 confirms substantial interaction with the plasmonic structure, with losses attributable to absorption and scattering. Monitoring S21 is vital for evaluating the insertion loss of a plasmonic waveguide or device, which directly impacts its practical utility in integrated photonic circuits.

CHAPTER 4: Conclusion and Future work

Numerous research efforts around the world are currently focused on improving the sensitivity of Surface Plasmon Resonance sensors. In this context, we propose a plasmonic silicon-on-insulator ring resonator-based biosensor, where the excitation of surface plasmon polaritons is achieved through a waveguide coupling approach. The sensor is first optimized for a water cladding, and its sensing performance is analyzed for a refractive index of 1.0. The designed structure exhibits enhanced field confinement within the slot region, leading to field confinement in the bus waveguide at 197.5 Thz. This demonstrates the biosensor's high precision and effectiveness for real-time detection applications.

Furthermore, the proposed design offers potential for integration into compact photonic circuits, making it a promising candidate for lab-on-chip sensing platforms. Its simple structure, compatibility with existing CMOS fabrication processes, and high detection efficiency highlight its suitability for future biomedical and environmental monitoring applications.

The future scope of the plasmonic planar ring resonator for optical biosensing lies in further enhancing its sensitivity, miniaturization, and integration with on-chip photonic systems for real-time, multiplexed detection. Future research can focus on optimizing the metal-dielectric interface, exploring alternative plasmonic materials such as graphene or transition metal nitrides to reduce losses, and improving fabrication techniques for better precision and repeatability. Additionally, incorporating tunable or reconfigurable elements—like thermo-optic or electro-optic controls—could enable dynamic wavelength tuning for multi-analyte sensing. With advancements in nanofabrication and data processing, such resonators can evolve into powerful, low-cost biosensing platforms suitable for early disease diagnosis, environmental monitoring, and point-of-care testing.

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