

RIGOROUS DESIGNS OF NANO-OPTICAL COUPLERS AND ABSORBERS
WITH PHOTONIC CRYSTALS INVOLVING IRREGULAR ARRAYS AND
NONIDENTICAL ELEMENTS

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ARRAYS AND NONIDENTICAL ELEMENTS**

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ABSTRACT

RIGOROUS DESIGNS OF NANO-OPTICAL COUPLERS AND ABSORBERS WITH PHOTONIC CRYSTALS INVOLVING IRREGULAR ARRAYS AND NONIDENTICAL ELEMENTS

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This thesis presents design and analyses of compact and effective nano-optical couplers and absorbers based on photonic crystals. Single-input and double-input nano-optical couplers that provide electromagnetic wave transmission in desired directions are designed, and important parameters regarding their transmission efficiency are investigated. These designs are further cascaded by adding one after another to create nano-optical transmission systems, whose transmission characteristics are also examined. In addition, nano-optical logic-gate couplers that perform certain logic operations, as well as nano-optical isolators that transmit electromagnetic waves only in the forward direction are designed and analyzed. On the other track, nano-optical absorbers are designed by combining metal plates with anti-reflective coatings made of photonic crystals. Anti-reflective absorber designs, which both confine high power density within themselves and prevent back reflections that are potentially harmful to other objects and sources, are successfully obtained. For all these nano-optical structures, electromagnetic simulations are performed by using an efficient implementation of the multilevel fast multipole algorithm. In addition, all designs are achieved by performing heuristic optimization via genetic algorithms. The numerical results

show that it is possible to design and further improve efficient nano-optical couplers and absorbers with relatively simple geometries based on the principles of photonic crystals.

Keywords: photonic crystals, nano-optical couplers, nano-optical absorbers, nano-optical isolators, genetic algorithms, multilevel fast multipole algorithm



ÖZ

NANO-OPTİK BAĞLAŞTIRICILARIN VE SOĞURUCULARIN DÜZENSİZ DİZİLER VE ÖZDEŞ OLMAYAN ELEMENTLER İÇEREN FOTONİK KRİSTALLER İLE KAPSAMLI TASARIMLARI

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Bu tezde, fotonik kristallerin çalışma prensibine dayalı, kompakt ve etkin nano-optik bağlaştırmaların ve soğurucuların tasarımları ve analizleri sunulmuştur. İstenilen yönlerde elektromanyetik dalga iletimini sağlayan tek girdili ve çift girdili optik bağlaştırmalar tasarlanmış, önemli parametrelerin iletim verimine olan etkisi incelenmiştir. Bu tasarımların arka arkaya eklenmesiyle nano-optik iletim sistemleri elde edilmiş, bu sistemlerin de iletim özellikleri incelenmiştir. Bunların yanında, belirli mantık işlemlerini gerçekleştirebilen nano-optik mantık kapı bağlaştırmaları ile elektromanyetik dalgaları sadece ileri yönde ileten nano-optik izolatörler tasarlanmış ve analiz edilmiştir. Diğer taraftan, fotonik kristallerin yansıma engelleyici kaplamalar olarak kullanılıp metallerle birleştirildiği optik soğurucular tasarlanmıştır. Hem kendi içinde yüksek güç yoğunluğu hapseden hem de diğer cisimlere ve kaynaklara zararlı olabilecek geri yansımaları önleyen yansıma-karşıtı soğurucu tasarımları başarılı olarak elde edilmiştir. Bütün bu nano-optik yapıların elektromanyetik benzetimleri, çok seviyeli hızlı çokkutup algoritmasının verimli bir uygulamasıyla gerçekleştirilmiştir.

Ayrıca, tüm tasarımlar genetik algoritmaların kullanılmasıyla gerçekleştirilen keşifsel optimizasyonlarla elde edilmiştir. Sayısal sonuçlar, fotonik kristal prensiplerine bağlı olarak geliştirilen görece basit geometrilerle, verimli nano-optik bağlaştırmacı ve soğurucuların tasarlanabileceğinin mümkün olduğunu göstermektedir.

Anahtar Kelimeler: fotonik kristaller, nano-optik bağlaştırmacılar, nano-optik soğurucular, nano-optik izolatörler, genetik algoritmalar, çok seviyeli hızlı çokkutup algoritması





To my lovely family

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LIST OF ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
ARC	Anti-Reflective Coating
CSPB	Complex Source Point Beam
CTF	Combined Tangential Formulation
FMM	Fast Multipole Method
GA	Genetic Algorithm
JMCFIE	Electric and magnetic current combined-field integral equation
MCTF	Modified combined tangential formulation
MLFMA	Multilevel Fast Multipole Algorithm
MoM	Method of Moments
MVM	Matrix-vector multiplication
N-EFIE	Normal Electric-Field Integral Equation
N-MFIE	Normal Magnetic-Field Integral Equation
PMCHWT	Poggio-Miller-Chang-Harrington-Wu-Tsai
RWG	Rao-Wilton-Glisson
SIE	Surface Integral Equation
T-EFIE	Tangential Electric-Field Integral Equation
T-MFIE	Tangential Magnetic-Field Integral Equation

CHAPTER 1

INTRODUCTION

Manipulating and directing an electromagnetic wave in intended directions and with desired patterns are crucial for proper functioning of most electronic devices that we use today. Photonic crystals, which are periodic arrays of dielectric unit cells have been utilized in lots of applications in electromagnetics for over 25 years [1]. They can be used to control and direct electromagnetic waves as desired which make them attractive for especially coupling and switching applications [2–7]. Due to their typically non-complex geometries, photonic crystals are usually easy to design and manufacture. They are used at optical frequencies and their sizes are comparable with the wavelength [8]. Specifically, their dimensions change from 100 nanometers to several micrometers, which make them suitable for designing and constructing small and compact optical structures. Moreover, there is a quite wide range of available materials that can be used to build photonic crystals [9]. These merits of photonic crystals make them excellent candidates for designing small, compact, and easy-to-fabricate nano-optical structures.

In photonic crystals, it is not possible for electromagnetic waves to propagate in a frequency range called forbidden gap of photons [10]. If an incident wave is within this frequency range, it is not transmitted and reflected back. Preventing the transmission of an electromagnetic wave in this frequency range can be explained by Wulff–Bragg’s interference condition. When the wave incident onto a photonic crystal reaches the structure, the incoming wave is divided into different components as a result of diffraction and scattering, and when these components come together, if they interfere destructively, transmitted wave may vanish [11]. Therefore, the direction and phase of a wave within a photonic crystal structure are important parameters

that determine whether the wave continues to propagate through the structure. Consequently, by providing a control on electromagnetic waves photonic crystal structures operate almost like waveguides.

Photonic crystals made of dielectric elements are much preferable to be used at optical frequencies, in comparison to metallic waveguides that become lossy at high frequencies [11]. For this waveguiding behavior of photonic crystals to be observed, dielectric structures must be arranged periodically, and the periodicity must be comparable with half of the incoming wavelength, often depending on the dielectric constant of the structure. For example, in this study, the distance between the centers of nearby dielectric rods is kept at 300 nm ($\lambda/5$). If well adjusted, defects created in a photonic crystal structure can localize electromagnetic energy, leading to resonances. Consequently, design parameters, such as geometry, periodicity, and materials can be used to design various photonic crystals to control propagation of electromagnetic waves in desired directions and to increase electromagnetic fields and power at desired locations, while inhibiting propagation in undesired directions.

Optical couplers are used for coupling electromagnetic power from input(s) to desired output(s) in nano-optical systems. Transmitting input power to desired output ports with high efficiency is naturally one of the most important criteria that should be considered during the design of such couplers. Also, there is an increasing need for more compact optical couplers due to the continuous demand in decreasing sizes of electronic devices. Fortunately, it is possible to both improve transmission and coupling abilities of optical couplers and make them small with the help of computational analysis and optimization [12]. In the first part of this thesis, we present compact and highly efficient nano-optical coupler designs based on photonic crystals, each of which provides different coupling characteristics. Specifically, these nano-optical couplers are designed by numerical analyses and optimization of dielectric rods to construct efficient photonic crystals. Shapes, permittivities, and arrangements of dielectric rods are rigorously selected to efficiently transmit input electromagnetic fields to desired output ports. The coupling efficiency is maximized via on/off optimization, either directly or when combined with length optimization applied to dielectric rods.

As particular examples in this thesis, forward-transmitting couplers and 90-degree

rotating couplers with single input and single output are designed, while various parameters are investigated to improve their operation. In addition, cascaded structures are obtained by combining these structures one after another. Optical coupler designs with double inputs are also discussed. In addition to these designs, couplers that operate as optical logic gates are studied. Given alternative sets of input excitations, a logic-gate coupler is expected to behave in accordance with pre-determined rules. In all-optical systems, the design of such logic gates are particularly important as they can provide essential capabilities like switching, data transferring and processing with high speeds. In this study, small, compact, and efficient optical AND and OR logic-gate couplers are designed and presented.

In addition to electromagnetic coupling in one direction, optical isolation is a critical property in optical coupling devices. Particularly, optical isolators are used in cases where efficient transmission of electromagnetic waves is needed to be unidirectional or circular in one direction. In other words, due to their non-reciprocal nature, these structures allow the transmission of wave in one direction, while preventing propagation in the reverse direction. To date, various non-reciprocal optical isolator designs have been proposed, including non-linear optical structures and magneto-optical isolators [13–16]. However, for such isolators that provide high contrast between forward and reverse transmissions, the output power in the forward direction is decreased at the expense of the higher margin between forward and backward transmissions [13–15]. In addition, due to their sizes, they are not usually suitable to be used in nano-optical devices. Photonic crystals, on the other hand, with their small sizes are very suitable for the design of compact nano-optical isolators that can provide high-quality forward transmission and minimized backward transmission. In the second part of this study, we show several nano-optical isolator designs made of photonic crystals that meet the expected efficiency and size requirements for nano-optical devices.

Designing nano-optical couplers thoroughly requires a full-wave electromagnetic solver for accurate numerical analyses. We use the multilevel fast multipole algorithm (MLFMA), which is an efficient and accurate solution technique for numerical analyses of three-dimensional (3D) complex problems [17]. During the design processes, several critical parameters including shapes, dielectric properties, and arrangements

of dielectric rods, are considered. Hence, each design process involves a lot of candidate solutions that approximate the optimal nano-optical coupler for given requirements. Since analyzing all possible solutions is not practical considering computational costs, we design and employ an efficient optimization tool based on an integrated combination of genetic algorithms (GAs) and MLFMA [18]. The optimization tool is used to design efficient and effective couplers and isolators composed of different arrangements of dielectric elements to control and guide optical waves.

Optical anti-reflecting coatings (ARC) are structures that enable minimum reflection of electromagnetic waves from where they are used. In the most basic form, electromagnetic waves reflecting from an ARC must destructively interfere with each other to minimize total reflection. For this purpose, the effective refractive index, shape, and thickness of each layer of an ARC design are all important. In addition, the direction of the excitation and the observation angles to minimize reflection should be specified to design an effective coating. Optical ARC designs are used in many areas, especially in solar cells, anti-glare coatings, corrective lenses in eyeglasses, and coatings on camera lenses [19–22]. Both single-layer dielectric and multi-layer dielectric-metallic structures are used to design ARCs, while the designs to date suffer from various issues, such as narrow bandwidth, high fabrication costs, complex geometries, and lack of flexibility [21, 23, 24]. In this thesis, novel ARCs are designed based on the principles of photonic crystals, i.e., using carefully located air holes in dielectric slabs. The designed coatings are combined with metallic layers to design optical absorbers. Specifically, by combining ARCs with metallic layers to further prevent forward propagation, we design effective optical absorbers. The designed optical absorbers are intended to confine high power density distributions within themselves, while preventing scattering, particularly backward reflections toward the excitation that may overheat and damage the source and other nano-optical structures. In order to increase absorbance and decrease reflections, fundamental parameters, such as the shape, size, and periodicity of air holes, are investigated to reach optimal designs. The optimization tool aforementioned above, based on MLFMA and GAs, is used for this purpose, while the parameters of the tool itself are also examined for efficient optimization [18]. Consequently, in the second part of the thesis, we propose efficient and compact optical absorber designs with anti-reflective properties

operating in relatively wide frequency bands.

This thesis is divided into chapters according to the studies summarized above. First, in Chapter 2, the full-wave numeric solver used in electromagnetic analyses of nano-optical structures is described. The details of formulations based on surface integral equations (SIEs) and MLFMA are presented. Next, in Chapter 3, the simulation environment and three different optimization environments, including their essential parameters, are explained. In Chapter 4, various optical coupler designs with different features, as well as their characteristics depending on some parameters are examined. Then, in Chapter 5, optical ARC designs and optical absorbers are investigated. Finally, this thesis ends with concluding remarks in Chapter 6.





CHAPTER 2

NUMERICAL SOLUTIONS OF ELECTROMAGNETIC PROBLEMS INVOLVING PHOTONIC CRYSTALS

In this chapter, full-wave numerical solutions of nano-optical structures involving photonic crystals are explained starting from the basics.

2.1 Maxwell's Equations

Assuming the existence of magnetic sources, the differential form of Maxwell's equations in time domain can be written as

$$\nabla \times \mathbf{E}(\mathbf{r}, t) = -\frac{\partial \mathbf{B}(\mathbf{r}, t)}{\partial t} - \mathbf{M}(\mathbf{r}, t) \quad [\text{Faraday's Law}] \quad (2.1)$$

$$\nabla \times \mathbf{H}(\mathbf{r}, t) = \frac{\partial \mathbf{D}(\mathbf{r}, t)}{\partial t} + \mathbf{J}(\mathbf{r}, t) \quad [\text{Ampere's Law}] \quad (2.2)$$

$$\nabla \cdot \mathbf{D}(\mathbf{r}, t) = \rho_e(\mathbf{r}, t) \quad [\text{Gauss's Law for Electricity}] \quad (2.3)$$

$$\nabla \cdot \mathbf{B}(\mathbf{r}, t) = \rho_m(\mathbf{r}, t) \quad [\text{Gauss's Law for Magnetism}] \quad (2.4)$$

where $\mathbf{E}(\mathbf{r}, t)$ is the electric field intensity, $\mathbf{H}(\mathbf{r}, t)$ is the magnetic field intensity, $\mathbf{D}(\mathbf{r}, t)$ is the electric flux density, $\mathbf{B}(\mathbf{r}, t)$ is the magnetic flux density, $\mathbf{J}(\mathbf{r}, t)$ is the electric current density, $\mathbf{M}(\mathbf{r}, t)$ is the magnetic current density, $\rho_e(\mathbf{r}, t)$ is the electric charge density, and $\rho_m(\mathbf{r}, t)$ is the magnetic charge density. Even if, $\mathbf{M}(\mathbf{r}, t)$ and $\rho_m(\mathbf{r}, t)$ are not physical, they are used as equivalent sources in generalized models of electromagnetic problems.

For a simple (homogeneous, isotropic, and linear) medium, the relationship between

field intensities and flux densities can be written as

$$\mathbf{D}(\mathbf{r}, t) = \epsilon \mathbf{E}(\mathbf{r}, t) \quad (2.5)$$

$$\mathbf{B}(\mathbf{r}, t) = \mu \mathbf{H}(\mathbf{r}, t), \quad (2.6)$$

where ϵ is the permittivity and μ is the permeability of the medium.

An equation and its time derivative in time domain can be expressed in phasor domain as

$$f(\bar{r}, t) = \text{Re}\{f(\bar{r}) \exp(-i\omega t)\} \quad (2.7)$$

$$\frac{\partial f(\bar{r}, t)}{\partial t} = -i\omega \text{Re}\{f(\bar{r}) \exp(-i\omega t)\}, \quad (2.8)$$

where ω is the angular frequency. Using this convention, Maxwell's equation in phasor domain can be written as

$$\nabla \times \mathbf{E}(\mathbf{r}) = i\omega\mu \mathbf{H}(\mathbf{r}) - \mathbf{M}(\mathbf{r}) \quad (2.9)$$

$$\nabla \times \mathbf{H}(\mathbf{r}) = -i\omega\epsilon \mathbf{E}(\mathbf{r}) + \mathbf{J}(\mathbf{r}) \quad (2.10)$$

$$\nabla \cdot \mathbf{E}(\mathbf{r}) = \frac{1}{\epsilon} \rho_e(\mathbf{r}) \quad (2.11)$$

$$\nabla \cdot \mathbf{H}(\mathbf{r}) = \frac{1}{\mu} \rho_m(\mathbf{r}) \quad (2.12)$$

where

$$\nabla \cdot \mathbf{J}(\mathbf{r}) = i\omega\rho_e(\mathbf{r}) \quad [\text{continuity equation for } \mathbf{J}(\mathbf{r})] \quad (2.13)$$

$$\nabla \cdot \mathbf{M}(\mathbf{r}) = i\omega\rho_m(\mathbf{r}) \quad [\text{continuity equation for } \mathbf{M}(\mathbf{r})]. \quad (2.14)$$

2.2 Surface Integral Equations

Taking the curl of both sides of Equation 2.9, an equation for electric field intensity can be derived as

$$\nabla \times \nabla \times \mathbf{E}(\mathbf{r}) = i\omega\mu \nabla \times \mathbf{H}(\mathbf{r}) - \nabla \times \mathbf{M}(\mathbf{r}) \quad (2.15)$$

$$\nabla \nabla \cdot \mathbf{E}(\mathbf{r}) - \nabla^2 \mathbf{E}(\mathbf{r}) = i\omega\mu(-i\omega\epsilon \mathbf{E}(\mathbf{r}) + \mathbf{J}(\mathbf{r})) - \nabla \times \mathbf{M}(\mathbf{r}) \quad (2.16)$$

$$\frac{1}{\epsilon} \nabla \rho_e(\mathbf{r}) - \nabla^2 \mathbf{E}(\mathbf{r}) = \omega^2 \mu \epsilon \mathbf{E}(\mathbf{r}) + i\omega\mu \mathbf{J}(\mathbf{r}) - \nabla \times \mathbf{M}(\mathbf{r}) \quad (2.17)$$

$$\nabla^2 \mathbf{E}(\mathbf{r}) + k^2 \mathbf{E}(\mathbf{r}) = -i\omega\mu \mathbf{J}(\mathbf{r}) + \frac{1}{\epsilon} \nabla \rho_e(\mathbf{r}) + \nabla \times \mathbf{M}(\mathbf{r}). \quad (2.18)$$

Repeating similar steps by taking the curl of both sides of Equation 2.10, an equation for magnetic field intensity can be obtained as

$$\nabla^2 \mathbf{H}(\mathbf{r}) + k^2 \mathbf{H}(\mathbf{r}) = -i\omega\mu \mathbf{M}(\mathbf{r}) + \frac{1}{\mu} \nabla \rho_m(\mathbf{r}) - \nabla \times \mathbf{J}(\mathbf{r}). \quad (2.19)$$

In the above, $k = \omega\sqrt{\mu\epsilon}$ is the wavenumber.

Using vector and scalar potential functions, electric and magnetic field intensities can be written as

$$\mathbf{E}(\mathbf{r}) = i\omega \mathbf{A}_m(\mathbf{r}) - \nabla \phi_e(\mathbf{r}) - \frac{1}{\epsilon} \nabla \times \mathbf{A}_e(\mathbf{r}) \quad (2.20)$$

$$\mathbf{H}(\mathbf{r}) = i\omega \mathbf{A}_e(\mathbf{r}) - \nabla \phi_m(\mathbf{r}) + \frac{1}{\mu} \nabla \times \mathbf{A}_m(\mathbf{r}), \quad (2.21)$$

where $\mathbf{A}_e(\mathbf{r})$ is the electric vector potential, $\mathbf{A}_m(\mathbf{r})$ is the magnetic vector potential, $\phi_e(\mathbf{r})$ is the electric scalar potential, and $\phi_m(\mathbf{r})$ is the magnetic scalar potential.

Then, Helmholtz equations for potentials can be obtained as

$$\nabla^2 \mathbf{A}_e(\mathbf{r}) + k^2 \mathbf{A}_e(\mathbf{r}) = -\epsilon \mathbf{M}(\mathbf{r}) \quad (2.22)$$

$$\nabla^2 \mathbf{A}_m(\mathbf{r}) + k^2 \mathbf{A}_m(\mathbf{r}) = -\mu \mathbf{J}(\mathbf{r}) \quad (2.23)$$

$$\nabla^2 \phi_e(\mathbf{r}) + k^2 \phi_e(\mathbf{r}) = -\frac{1}{\epsilon} \rho_e(\mathbf{r}) \quad (2.24)$$

$$\nabla^2 \phi_m(\mathbf{r}) + k^2 \phi_m(\mathbf{r}) = -\frac{1}{\mu} \rho_m(\mathbf{r}), \quad (2.25)$$

where the Lorentz gauge

$$\nabla \cdot \mathbf{A}_e(\mathbf{r}) = i\omega\epsilon\mu\phi_m(\mathbf{r}) \quad (2.26)$$

$$\nabla \cdot \mathbf{A}_m(\mathbf{r}) = i\omega\epsilon\mu\phi_e(\mathbf{r}) \quad (2.27)$$

is applied.

The solution of Helmholtz equations for a point source gives the homogeneous-space Green's function, which can be written as

$$g(\mathbf{r}, \mathbf{r}') = \frac{\exp(ik|\mathbf{r} - \mathbf{r}'|)}{4\pi|\mathbf{r} - \mathbf{r}'|} \quad (2.28)$$

where $\mathbf{r}$ is the source point and $\mathbf{r}'$ is the observation point.

Then, using Green's function, vector and scalar electric and magnetic potentials can

be expressed as

$$\mathbf{A}_e(\mathbf{r}) = \epsilon \int d\mathbf{r}' g(\mathbf{r}, \mathbf{r}') \mathbf{M}(\mathbf{r}') \quad (2.29)$$

$$\mathbf{A}_m(\mathbf{r}) = \mu \int d\mathbf{r}' g(\mathbf{r}, \mathbf{r}') \mathbf{J}(\mathbf{r}') \quad (2.30)$$

$$\phi_e(\mathbf{r}) = \frac{1}{\epsilon} \int d\mathbf{r}' g(\mathbf{r}, \mathbf{r}') \rho_e(\mathbf{r}') \quad (2.31)$$

$$\phi_m(\mathbf{r}) = \frac{1}{\mu} \int d\mathbf{r}' g(\mathbf{r}, \mathbf{r}') \rho_m(\mathbf{r}') . \quad (2.32)$$

Based on these expressions, field intensities can be written in terms of current sources $\mathbf{J}(\mathbf{r})$ and $\mathbf{M}(\mathbf{r})$ as

$$\mathbf{E}(\mathbf{r}) = ik\eta \int d\mathbf{r}' \left[\mathbf{J}(\mathbf{r}') + \frac{1}{k^2} \nabla' \cdot \mathbf{J}(\mathbf{r}') \nabla \right] g(\mathbf{r}, \mathbf{r}') \quad (2.33)$$

$$- \int d\mathbf{r}' \nabla g(\mathbf{r}, \mathbf{r}') \times \mathbf{M}(\mathbf{r}') \quad (2.34)$$

$$\mathbf{H}(\mathbf{r}) = ik\eta^{-1} \int d\mathbf{r}' \left[\mathbf{M}(\mathbf{r}') + \frac{1}{k^2} \nabla' \cdot \mathbf{M}(\mathbf{r}') \nabla \right] g(\mathbf{r}, \mathbf{r}') \quad (2.35)$$

$$+ \int d\mathbf{r}' \nabla g(\mathbf{r}, \mathbf{r}') \times \mathbf{J}(\mathbf{r}') \quad (2.36)$$

where η is the intrinsic impedance and equal to $\sqrt{\mu}/\sqrt{\epsilon}$. In more compact forms, $\mathbf{E}(\mathbf{r})$ and $\mathbf{H}(\mathbf{r})$ can be written in terms of integro-differential operators as

$$\mathbf{E}(\mathbf{r}) = \eta \mathcal{T}\{\mathbf{J}\}(\mathbf{r}) - \mathcal{K}\{\mathbf{M}\}(\mathbf{r}) \quad (2.37)$$

$$\mathbf{H}(\mathbf{r}) = \eta^{-1} \mathcal{T}\{\mathbf{M}\}(\mathbf{r}) + \mathcal{K}\{\mathbf{J}\}(\mathbf{r}) \quad (2.38)$$

where these operators are defined as

$$\mathcal{T}\{\mathbf{X}\}(\mathbf{r}) = ik \int d\mathbf{r}' \left[\mathbf{X}(\mathbf{r}') + \frac{1}{k^2} \nabla' \cdot \mathbf{X}(\mathbf{r}') \nabla \right] g(\mathbf{r}, \mathbf{r}') \quad (2.39)$$

$$\mathcal{K}\{\mathbf{X}\}(\mathbf{r}) = \int d\mathbf{r}' \mathbf{X}(\mathbf{r}') \times \nabla' g(\mathbf{r}, \mathbf{r}') \quad (2.40)$$

According to the equivalence principle, equivalence currents, $\mathbf{J}$ and $\mathbf{M}$, are defined on surfaces of dielectric and metallic parts such that a given electromagnetic problem is divided into equivalent sub-problems. Even if these surfaces can be defined anywhere, they usually correspond to actual physical boundaries.

For a surface boundary S_{uv} shown in Figure 2.1, D_u and D_v are homogeneous penetrable regions bounded by S_u and S_v , while $\hat{\mathbf{n}}_u$ and $\hat{\mathbf{n}}_v$ are inward unit normal vectors for S_u and S_v , respectively. Then, field intensities in these regions can be written as

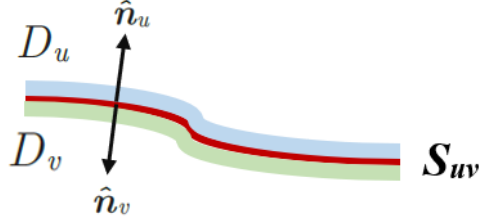


Figure 2.1: Boundary between two regions

combinations of incident fields $\mathbf{E}_u^{\text{inc}}$ and $\mathbf{H}_u^{\text{inc}}$ due to external sources and secondary fields $\mathbf{E}_u^{\text{sec}}$ and $\mathbf{H}_u^{\text{sec}}$ created by equivalent sources, i.e.,

$$\begin{aligned}\mathbf{E}_u(\mathbf{r}) &= \mathbf{E}_u^{\text{inc}}(\mathbf{r}) + \mathbf{E}_u^{\text{sec}}(\mathbf{r}) \\ \mathbf{H}_u(\mathbf{r}) &= \mathbf{H}_u^{\text{inc}}(\mathbf{r}) + \mathbf{H}_u^{\text{sec}}(\mathbf{r}).\end{aligned}\tag{2.41}$$

For each region, the integro-differential operators $\mathcal{T}_u$ and $\mathcal{K}_u$ can be defined as in Equations 2.39 and 2.40. When the limit of $\mathcal{K}_u$ operator is extracted, its principal value is obtained. Hence, $\mathcal{K}_u$ can be decomposed as

$$\mathcal{K}_u\{\mathbf{X}\}(\mathbf{r}) = \mathcal{K}_u^{\text{PV}}\{\mathbf{X}\}(\mathbf{r}) - \frac{4\pi - \Omega_u}{4\pi} \hat{\mathbf{n}}_u \times \mathbf{X}(\mathbf{r}),\tag{2.42}$$

where Ω_u is the solid angle. Taking the continuity of tangential fields into account to satisfy the boundary conditions at the interface between D_u and D_v , and applying equivalence principle, equivalent surface currents can be defined as

$$\begin{aligned}-\mathbf{M}_u(\mathbf{r}) &= \hat{\mathbf{n}}_u \times \mathbf{E}_u(\mathbf{r}) = -\hat{\mathbf{n}}_v \times \mathbf{E}_v(\mathbf{r}) = \mathbf{M}_v(\mathbf{r}) \\ \mathbf{J}_u(\mathbf{r}) &= \hat{\mathbf{n}}_u \times \mathbf{H}_u(\mathbf{r}) = -\hat{\mathbf{n}}_v \times \mathbf{H}_v(\mathbf{r}) = -\mathbf{J}_v(\mathbf{r}).\end{aligned}\tag{2.43}$$

Then, equivalence surface currents $\mathbf{J}_u(\mathbf{r})$ and $\mathbf{M}_u(\mathbf{r})$ can be written in terms of integro-differential equations as

$$\begin{aligned}-\mathbf{M}_u(\mathbf{r}) &= \hat{\mathbf{n}}_u \times \mathbf{E}_u^{\text{inc}}(\mathbf{r}) + \eta_u \hat{\mathbf{n}}_u \times \mathcal{T}_u\{\mathbf{J}_u\}(\mathbf{r}) \\ &\quad - \hat{\mathbf{n}}_u \times \mathcal{K}_u^{\text{PV}}\{\mathbf{M}_u\}(\mathbf{r}) - \mathbf{M}_u(\mathbf{r}) + \frac{\Omega_u}{4\pi} \mathbf{M}_u(\mathbf{r})\end{aligned}\tag{2.44}$$

$$\begin{aligned}\mathbf{J}_u(\mathbf{r}) &= \hat{\mathbf{n}}_u \times \mathbf{H}_u^{\text{inc}}(\mathbf{r}) + \eta_u^{-1} \hat{\mathbf{n}}_u \times \mathcal{T}_u\{\mathbf{M}_u\}(\mathbf{r}) \\ &\quad + \hat{\mathbf{n}}_u \times \mathcal{K}_u^{\text{PV}}\{\mathbf{J}_u\}(\mathbf{r}) + \mathbf{J}_u(\mathbf{r}) - \frac{\Omega_u}{4\pi} \mathbf{J}_u(\mathbf{r}).\end{aligned}\tag{2.45}$$

Rearranging Equations 2.44 and 2.45, normal electric-field integral equation (N-EFIE)

and normal magnetic-field integral equation (N-MFIE) can be obtained as

$$\begin{aligned} \eta_u \hat{\mathbf{n}}_u \times \mathcal{T}_u \{ \mathbf{J}_u \}(\mathbf{r}) - \hat{\mathbf{n}}_u \times \mathcal{K}_u^{PV} \{ \mathbf{M}_u \}(\mathbf{r}) + \frac{\Omega_u}{4\pi} \mathbf{M}_u(\mathbf{r}) \\ = -\hat{\mathbf{n}}_u \times \mathbf{E}_u^{\text{inc}}(\mathbf{r}) \end{aligned} \quad (2.46)$$

$$\begin{aligned} \eta_u^{-1} \hat{\mathbf{n}}_u \times \mathcal{T}_u \{ \mathbf{M}_u \}(\mathbf{r}) + \hat{\mathbf{n}}_u \times \mathcal{K}_u^{PV} \{ \mathbf{J}_u \}(\mathbf{r}) - \frac{\Omega_u}{4\pi} \mathbf{J}_u(\mathbf{r}) \\ = -\hat{\mathbf{n}}_u \times \mathbf{H}_u^{\text{inc}}(\mathbf{r}) \end{aligned} \quad (2.47)$$

If the left-hand and right-hand sides of Equations 2.46 and 2.47 are multiplied with $-\hat{\mathbf{n}}_u$, tangential electric-field integral equation (T-EFIE) and tangential magnetic-field integral equation (T-MFIE) can be obtained as

$$\begin{aligned} -\eta_u \hat{\mathbf{n}}_u \times \hat{\mathbf{n}}_u \times \mathcal{T}_u \{ \mathbf{J}_u \}(\mathbf{r}) + \hat{\mathbf{n}}_u \times \hat{\mathbf{n}}_u \times \mathcal{K}_u^{PV} \{ \mathbf{M}_u \}(\mathbf{r}) \\ - \frac{\Omega_u}{4\pi} \hat{\mathbf{n}}_u \times \mathbf{M}_u(\mathbf{r}) = \hat{\mathbf{n}}_u \times \hat{\mathbf{n}}_u \times \mathbf{E}_u^{\text{inc}}(\mathbf{r}) \end{aligned} \quad (2.48)$$

$$\begin{aligned} -\eta_u^{-1} \hat{\mathbf{n}}_u \times \hat{\mathbf{n}}_u \times \mathcal{T}_u \{ \mathbf{M}_u \}(\mathbf{r}) - \hat{\mathbf{n}}_u \times \hat{\mathbf{n}}_u \times \mathcal{K}_u^{PV} \{ \mathbf{J}_u \}(\mathbf{r}) \\ + \frac{\Omega_u}{4\pi} \hat{\mathbf{n}}_u \times \mathbf{J}_u(\mathbf{r}) = \hat{\mathbf{n}}_u \times \hat{\mathbf{n}}_u \times \mathbf{H}_u^{\text{inc}}(\mathbf{r}) \end{aligned} \quad (2.49)$$

2.3 Surface Formulations

For a homogeneous penetrable region inside a homogeneous medium, the electromagnetic problem can be divided into two sub-problems: inner problem and outer problem. SIEs are applied to both of these sub-problems. If the excitation is only in the outer region, when N-EFIE, N-MFIE, T-EFIE, and T-MFIE for the inner problem are considered, the right-hand side of Equations 2.46, 2.47, 2.48, and 2.49 are set to zero. On the other hand, considering N-EFIE, N-MFIE, T-EFIE and T-MFIE for the outer problem, the right-hand sides involve tested incident fields as indicated in the same set of equations. For example, N-EFIE can be decomposed into N-EFIE-in and N-EFIE-out, which can be written as

$$\eta_{in} \hat{\mathbf{n}} \times \mathcal{T}_{in} \{ \mathbf{J} \}(\mathbf{r}) - \hat{\mathbf{n}} \times \mathcal{K}_{in}^{PV} \{ \mathbf{M} \}(\mathbf{r}) + \frac{\Omega_{in}}{4\pi} \mathbf{M}(\mathbf{r}) = 0 \quad (2.50)$$

$$\eta_{out} \hat{\mathbf{n}} \times \mathcal{T}_{out} \{ \mathbf{J} \}(\mathbf{r}) - \hat{\mathbf{n}} \times \mathcal{K}_{out}^{PV} \{ \mathbf{M} \}(\mathbf{r}) + \frac{\Omega_{out}}{4\pi} \mathbf{M}(\mathbf{r}) = -\hat{\mathbf{n}} \times \mathbf{E}^{\text{inc}}(\mathbf{r}), \quad (2.51)$$

respectively, where Ω_{in} is the inner solid angle and $\Omega_{out} = 4 \times \pi - \Omega_{in}$ is the outer solid angle. Similar expressions can be written for the other integral equations.

Different combinations of N-EFIE, N-MFIE, T-EFIE, and T-MFIE for inner and outer problems result in various surface formulations. Such combinations can be divided into three groups. Tangential formulations include only tangential SIEs, normal formulations include only normal SIEs, and finally, mixed formulations include at least one tangential and one normal SIEs.

Any combination of SIEs can be written in general as

$$\begin{bmatrix} a\text{T-EFIE-out} + b\text{T-EFIE-in} + e\text{N-MFIE-out} - f\text{N-MFIE-in} \\ c\text{T-MFIE-out} + d\text{T-MFIE-in} - g\text{N-EFIE-out} + h\text{N-EFIE-in} \end{bmatrix} \quad (2.52)$$

Different values of the constants $\{a, b, c, d, e, f, g, h\}$ lead to different surface formulations, such as Poggio-Miller-Chang-Harrington-Wu-Tsai (PMCHWT) formulation, combined T formulation (CTF), modified combined T formulation (MCTF), and electric-magnetic current combined-field integral equation (JMCFIE).

In this thesis, two different formulations are used, considering different materials of the structures. Nano-optical couplers and isolators consist of photonic crystal structures that are made of silicon nitride (Si_3N_4). On the other hand, nano-optical absorbers are formed of metal tungsten (W) plates and silicon-based photonic crystals. In the numerical solutions of nano-optical couplers and isolators, JMCFIE formulation is used, while MCTF is preferred for analyses of optical absorbers. The reasoning behind this choice will be clarified in Section 2.7.

The values of $\{a, b, c, d, e, f, g, h\}$ for JMCFIE and MCTF are given as

$$a = \eta_{out}^{-1}, b = \eta_{in}^{-1}, c = \eta_{out}, d = \eta_{in}, e = 1, f = 1, g = 1, h = 1 \quad (2.53)$$

$$a = 1, b = 1, c = \eta_{out}\eta_{in}, d = \eta_{out}\eta_{in}, e = 0, f = 0, g = 0, h = 0, \quad (2.54)$$

respectively. In any case, surface formulations can be written in a compact form as

$$\begin{bmatrix} \mathcal{Z}_{11} & \mathcal{Z}_{12} \\ \mathcal{Z}_{21} & \mathcal{Z}_{22} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{J}(\mathbf{r}) \\ \mathbf{M}(\mathbf{r}) \end{bmatrix}(\mathbf{r}) = \begin{bmatrix} \mathbf{w}_1(\mathbf{r}) \\ \mathbf{w}_2(\mathbf{r}), \end{bmatrix} \quad (2.55)$$

where the right-hand side can be expressed in terms of incident fields as

$$\begin{bmatrix} \mathbf{w}_1(\mathbf{r}) \\ \mathbf{w}_2(\mathbf{r}) \end{bmatrix} = \begin{bmatrix} a\hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathbf{E}^{\text{inc}}(\mathbf{r}) - e\hat{\mathbf{n}} \times \mathbf{H}^{\text{inc}}(\mathbf{r}) \\ c\hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathbf{H}^{\text{inc}}(\mathbf{r}) + g\hat{\mathbf{n}} \times \mathbf{E}^{\text{inc}}(\mathbf{r}). \end{bmatrix} \quad (2.56)$$

The elements of $\mathcal{Z}$ matrix can be written using the constants in 2.52 as

$$\begin{aligned} \mathcal{Z}_{11} = & -a\eta_{\text{out}}\hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathcal{T}_{\text{out}} - b\eta_{\text{in}}\hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathcal{T}_{\text{in}} \\ & + e\hat{\mathbf{n}} \times \mathcal{K}_{\text{out}}^{PV} - f\hat{\mathbf{n}} \times \mathcal{K}_{\text{in}}^{PV} - (e + f)\mathcal{I}/2 \end{aligned} \quad (2.57)$$

$$\begin{aligned} \mathcal{Z}_{12} = & a\hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathcal{K}_{\text{out}}^{PV} + b\hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathcal{K}_{\text{in}}^{PV} \\ & - (a - b)\hat{\mathbf{n}} \times \mathcal{I}/2 + e\eta_{\text{out}}^{-1}\hat{\mathbf{n}} \times \mathcal{T}_{\text{out}} - f\eta_{\text{in}}^{-1}\hat{\mathbf{n}} \times \mathcal{T}_{\text{in}} \end{aligned} \quad (2.58)$$

$$\begin{aligned} \mathcal{Z}_{21} = & -c\hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathcal{K}_{\text{out}}^{PV} - d\hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathcal{K}_{\text{in}}^{PV} \\ & + (c - d)\hat{\mathbf{n}} \times \mathcal{I}/2 - g\eta_{\text{out}}\hat{\mathbf{n}} \times \mathcal{T}_{\text{out}} + h\eta_{\text{in}}\hat{\mathbf{n}} \times \mathcal{T}_{\text{in}} \end{aligned} \quad (2.59)$$

$$\begin{aligned} \mathcal{Z}_{22} = & -c\eta_{\text{out}}^{-1}\hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathcal{T}_{\text{out}} - d\eta_{\text{in}}^{-1}\hat{\mathbf{n}} \times \hat{\mathbf{n}} \times \mathcal{T}_{\text{in}} \\ & + g\hat{\mathbf{n}} \times \mathcal{K}_{\text{out}}^{PV} - h\hat{\mathbf{n}} \times \mathcal{K}_{\text{in}}^{PV} - (g + h)\mathcal{I}/2. \end{aligned} \quad (2.60)$$

Here, $\mathcal{I}$ is the identity operator defined as

$$\mathcal{I}\{\mathbf{X}\}(\mathbf{r}) = \mathbf{X}(\mathbf{r}). \quad (2.61)$$

2.4 Method of Moments

Method of moments (MoM), a well-known solution technique, can be used to convert integral equations into linear matrix equations that can be solved numerically. In MoM, the unknown function is expanded into basis functions with unknown coefficients. Then, by using testing functions, matrix equations are constructed and solved to obtain the unknown coefficients. To demonstrate how MoM works, a linear operator $\mathcal{L}$, an unknown vector function $\mathbf{f}(\mathbf{r})$, and a known vector function $\mathbf{g}(\mathbf{r})$ can be considered as

$$\mathcal{L}\{\mathbf{f}\}(\mathbf{r}) = \mathbf{g}(\mathbf{r}). \quad (2.62)$$

SIEs are related to Equation 2.62 as $\mathcal{L}$, $\mathbf{f}(\mathbf{r})$, and $\mathbf{g}(\mathbf{r})$ correspond to integral operators, unknown electric and magnetic currents and incident electric and magnetic fields, respectively.

After defining basis functions $\mathbf{b}_n(\mathbf{r})$, the unknown function $\mathbf{f}(\mathbf{r})$ can be expanded in terms of them via unknown coefficients $\mathbf{a}[n]$ as

$$\mathbf{f}(\mathbf{r}) \approx \sum_{n=1}^N \mathbf{a}[n] \mathbf{b}_n(\mathbf{r}), \quad (2.63)$$

where N is the number of unknowns. To obtain unknown coefficients, N equations are needed, which can be obtained by testing both sides of 2.62 with testing functions $\mathbf{t}_m(\mathbf{r})$ as

$$\int d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \sum_{n=1}^N \mathbf{a}[n] \mathcal{L}\{\mathbf{b}_n\}(\mathbf{r}) = \int d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \mathbf{g}(\mathbf{r}). \quad (2.64)$$

By changing the order of summation and integration, Equation 2.64 can be modified as

$$\sum_{n=1}^N \mathbf{a}[n] \int d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \mathcal{L}\{\mathbf{b}_n\} = \int d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \mathbf{g}(\mathbf{r}). \quad (2.65)$$

Equation 2.65 can be written in a matrix equation form as

$$\sum_{n=1}^N \mathbf{a}[n] \bar{\mathbf{Z}}[m, n] = \mathbf{w}[m] \quad (2.66)$$

where

$$\bar{\mathbf{Z}}[m, n] = \int d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \mathcal{L}\{\mathbf{b}_n\}(\mathbf{r}) \quad (2.67)$$

$$\mathbf{w}[m] = \int d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \mathbf{g}(\mathbf{r}). \quad (2.68)$$

Considering an electromagnetic problem, $\bar{\mathbf{Z}}$, $\mathbf{w}$, and $\mathbf{a}$ in Equation 2.66 represent impedance matrix, excitation vector, and coefficient vector, respectively.

2.5 Discretization of Surface Formulations

For numerical solutions of electromagnetic problems, there may be different choices of basis and testing functions. In this thesis, Galerkin Method is applied by using the same set of functions as basis and for testing. Among alternative choices, Rao-Wilton-Glisson (RWG) functions on triangular domains are used by using small triangles with respect to the wavelength [25]. Two examples of discretized objects are given in Figure 2.2.

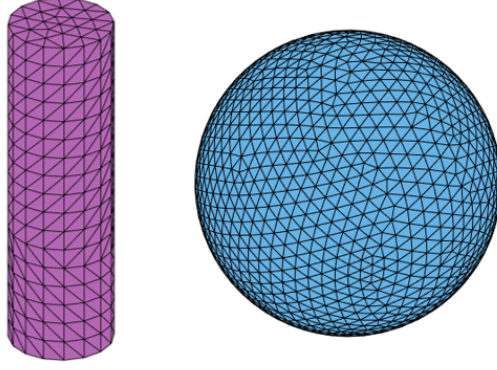


Figure 2.2: Discretization of a 3D cylinder and a sphere with triangles

For each pair of triangles sharing an edge, one RWG function is defined. For the triangle pair in Figure 2.3, the RWG function and its divergence can be written as

$$\mathbf{b}_n^{\text{RWG}}(\mathbf{r}) = \begin{cases} \frac{l_n}{2A_{n1}} (\mathbf{r} - \mathbf{r}_{n1}), & \mathbf{r} \in S_{n1} \\ \frac{l_n}{2A_{n2}} (\mathbf{r}_{n2} - \mathbf{r}), & \mathbf{r} \in S_{n2} \\ 0, & \mathbf{r} \notin S_n, \end{cases} \quad (2.69)$$

$$\nabla \cdot \mathbf{b}_n^{\text{RWG}}(\mathbf{r}) = \begin{cases} \frac{l_n}{A_{n1}}, & \mathbf{r} \in S_{n1} \\ -\frac{l_n}{A_{n2}}, & \mathbf{r} \in S_{n2} \\ 0, & \mathbf{r} \notin S_n \end{cases} \quad (2.70)$$

where l_n , A_{n1} , and A_{n2} represent the length of the common edge, area of S_{n1} triangle, and area of S_{n2} triangle, respectively. It can be verified by Equation 2.70 that the divergence of $\mathbf{b}_n^{\text{RWG}}(\mathbf{r})$ is finite and the total charges on the triangles have the same magnitude but in opposite signs. Hence, the total charge is zero for an RWG function.

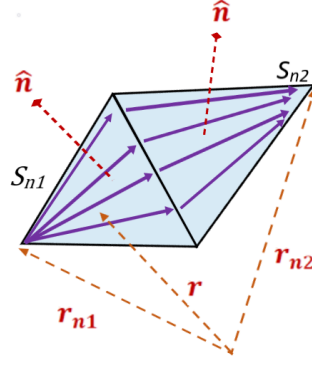


Figure 2.3: Demonstration of an RWG function

By using the RWG functions, integro-differential identity operators can be discretized. Discrete forms of the tangentially-tested integro-differential operators can be expressed as

$$\begin{aligned}\bar{\mathbf{T}}_u^T[m, n] &= \int d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \mathcal{T}_u \{ \mathbf{b}_n \} (\mathbf{r}) \\ &= ik_u \int_{S_m} d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \int_{S_n} d\mathbf{r}' g_u(\mathbf{r}, \mathbf{r}') \mathbf{b}_n(\mathbf{r}') \\ &\quad + \frac{i}{k_u} \int_{S_m} d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \int_{S_n} d\mathbf{r}' \nabla g_u(\mathbf{r}, \mathbf{r}') \nabla' \cdot \mathbf{b}_n(\mathbf{r}')\end{aligned}\quad (2.71)$$

$$\begin{aligned}\bar{\mathbf{K}}_{PV,u}^T[m, n] &= \int d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \mathcal{K}_u^{PV} \{ \mathbf{b}_n \} (\mathbf{r}) \\ &= \int_{S_m} d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \int_{PV, S_n} d\mathbf{r}' \mathbf{b}_n(\mathbf{r}') \times \nabla' g_u(\mathbf{r}, \mathbf{r}')\end{aligned}\quad (2.72)$$

$$\bar{\mathbf{I}}^T[m, n] = \int_{S_m} d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \mathbf{b}_n(\mathbf{r}). \quad (2.73)$$

Normally-tested integro-differential operators can be written as

$$\begin{aligned}\bar{\mathbf{T}}_u^N[m, n] &= \int d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \hat{\mathbf{n}} \times \mathcal{T} \{ \mathbf{b}_n \} (\mathbf{r}) \\ &= ik_u \int_{S_m} d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \hat{\mathbf{n}} \times \int_{S_n} d\mathbf{r}' g_u(\mathbf{r}, \mathbf{r}') \mathbf{b}_n(\mathbf{r}') \\ &\quad + \frac{i}{k_u} \int_{S_m} d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \hat{\mathbf{n}} \times \int_{S_n} d\mathbf{r}' \nabla g_u(\mathbf{r}, \mathbf{r}') \nabla' \cdot \mathbf{b}_n(\mathbf{r}')\end{aligned}\quad (2.74)$$

$$\begin{aligned}\bar{\mathbf{K}}_{PV,u}^N[m, n] &= \int d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \hat{\mathbf{n}} \times \mathcal{K}_u^{PV} \{ \mathbf{b}_n \} (\mathbf{r}) \\ &= \int_{S_m} d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \hat{\mathbf{n}} \times \int_{PV, S_n} d\mathbf{r}' \mathbf{b}_n(\mathbf{r}') \times \nabla' g_u(\mathbf{r}, \mathbf{r}')\end{aligned}\quad (2.75)$$

$$\bar{\mathbf{I}}^N[m, n] = \int_{S_m} d\mathbf{r} \mathbf{t}_m(\mathbf{r}) \cdot \hat{\mathbf{n}} \times \mathbf{b}_n(\mathbf{r}). \quad (2.76)$$

Discretization of integro-differential and identity operators with the interactions of two half RWG functions (as commonly used implementations) can be written for the a th triangle of the m th edge, and the b th triangle of the n th edge as

$$\begin{aligned}\bar{\mathbf{T}}_u^T[m, n, a, b] &= ik_u \mathcal{A}_{ma, nb} \int_{S_{ma}} d\mathbf{r} (\mathbf{r} - \mathbf{r}_{ma}) \cdot \int_{S_{nb}} d\mathbf{r}' (\mathbf{r}' - \mathbf{r}_{nb}) g_u(\mathbf{r}, \mathbf{r}') \\ &\quad - \frac{4i}{k_u} \mathcal{A}_{ma, nb} \int_{S_{ma}} d\mathbf{r} \int_{S_{nb}} d\mathbf{r}' g_u(\mathbf{r}, \mathbf{r}')\end{aligned}\quad (2.77)$$

$$\begin{aligned}\bar{\mathbf{T}}_u^N[m, n, a, b] &= ik_u \mathcal{A}_{ma, nb} \int_{S_{ma}} d\mathbf{r} [(\mathbf{r} - \mathbf{r}_{ma}) \times \hat{\mathbf{n}}] \cdot \int_{S_{nb}} d\mathbf{r}' (\mathbf{r}' - \mathbf{r}_{nb}) g_u(\mathbf{r}, \mathbf{r}') \\ &\quad - \frac{2i}{k_u} \mathcal{A}_{ma, nb} \int_{S_{ma}} d\mathbf{r} [(\mathbf{r} - \mathbf{r}_{ma}) \times \hat{\mathbf{n}}] \cdot \int_{S_{nb}} d\mathbf{r}' \nabla' g_u(\mathbf{r}, \mathbf{r}')\end{aligned}\quad (2.78)$$

$$\begin{aligned}\bar{\mathbf{K}}_{PV, u}^T[m, n, a, b] &= \mathcal{A}_{ma, nb} \int_{S_{ma}} d\mathbf{r} (\mathbf{r} - \mathbf{r}_{ma}) \\ &\quad \cdot \left((\mathbf{r} - \mathbf{r}_{nb}) \times \int_{PV, S_{nb}} d\mathbf{r}' \nabla' g_u(\mathbf{r}, \mathbf{r}') \right)\end{aligned}\quad (2.79)$$

$$\begin{aligned}\bar{\mathbf{K}}_{PV, u}^N[m, n, a, b] &= \mathcal{A}_{ma, nb} \int_{S_{ma}} d\mathbf{r} [(\mathbf{r} - \mathbf{r}_{ma}) \times \hat{\mathbf{n}}] \\ &\quad \cdot [\mathbf{r} - \mathbf{r}_{nb}) \times \int_{PV, S_{nb}} d\mathbf{r}' \nabla' g_u(\mathbf{r}, \mathbf{r}')\end{aligned}\quad (2.80)$$

$$\bar{\mathbf{I}}^T[m, n, a, b] = \mathcal{A}_{ma, nb} \delta_{ma, nb} \int_{S_{ma}} d\mathbf{r} (\mathbf{r} - \mathbf{r}_{ma}) \cdot (\mathbf{r} - \mathbf{r}_{nb}) \quad (2.81)$$

$$\bar{\mathbf{I}}^N[m, n, a, b] = \mathcal{A}_{ma, nb} \delta_{ma, nb} \int_{S_{ma}} d\mathbf{r} (\mathbf{r} - \mathbf{r}_{ma}) \cdot \hat{\mathbf{n}} \times (\mathbf{r} - \mathbf{r}_{nb}) \quad (2.82)$$

where $\delta_{ma, nb}$ is Kronecker delta and $\mathcal{A}_{ma, nb}$ is defined as

$$\mathcal{A}_{ma, nb} = \frac{l_m l_n}{4A_{ma} A_{nb}} \gamma_{ma} \gamma_{nb}. \quad (2.83)$$

2.6 Multilevel Fast Multipole Algorithm

MoM is an ideal numerical solution method for relatively simple electromagnetic problems; however, it is not effective alone considering the required computational loads in general. To reduce the load, matrix equations constructed by MoM can

be solved iteratively. This way, a solution of an electromagnetic problem involving N unknowns has $O(N^2)$ complexity per matrix-vector multiplication (MVM). This means excessive solution times and memory usage for problems with large numbers of unknowns. Various methods have been put forward to reduce solution time and memory load, one of which is the fast multipole method (FMM). Specifically, applying FMM, the complexity per MVM can be reduced to $O(N^{3/2})$. MLFMA, which puts forward the idea of using FMM recursively, further reduces the complexity of the problem. Specifically, using the factorization of the Green's function by employing the Gegenbauer's addition theorem, as well as diagonalization via plane waves at multiple levels, the complexity per MVM is reduced to $O(N \log N)$. Thus, using MLFMA, complex problems with many unknowns can be solved efficiently with remarkably less computational load in comparison to MoM and FMM.

In MLFMA, electromagnetic interactions are performed in a group-by-group manner. A computational box, which encloses the object under interest, is divided into sub-boxes subsequently at different levels to create a tree structure. The number of boxes to divide the object, consequently the number of levels, typically increase as the number of unknowns increases. Of these boxes, only those that contain a part of the object (discretization elements) are considered, while the others are automatically eliminated. The interactions are categorized as near-field, far-field, and very far-field applying a one-box buffer scheme. Accordingly, a MVM for an impedance matrix $\bar{\mathbf{Z}}$ can be decomposed into terms involving $\bar{\mathbf{Z}}^{\text{NF}}$ and $\bar{\mathbf{Z}}^{\text{FF}}$ as

$$\sum_{n=1}^N \bar{\mathbf{Z}}[m, n] \mathbf{a}[n] = \sum_{n=1}^N \bar{\mathbf{Z}}^{\text{NF}}[m, n] \mathbf{a}[n] + \sum_{n=1}^N \bar{\mathbf{Z}}^{\text{FF}}[m, n] \mathbf{a}[n] \quad (2.84)$$

$$(m = 1, 2, \dots, N).$$

Near-field interactions are calculated directly and kept in memory. Far-field interactions are computed on the fly at each iteration and are not kept in memory. In the computation of such far-field interactions, aggregation, translation, and disaggregation steps are followed. In the aggregation step, radiated fields are calculated from the lowest level to the highest level of the tree structure. At the lowest level, radiation patterns of the basis functions are shifted to the centers of the boxes. At the higher levels, radiated fields are shifted between box centers based on child-parent relationships. Then, in the translation step, radiated fields are converted into incoming fields

between far-zone boxes at the same level. Finally, in the disaggregation step, incoming fields are calculated from the highest level to the lowest level. At the lowest level, incoming fields are finally received by the testing functions to complete the MVM.

2.7 Comparison of Different Surface Formulations

Each surface formulation has advantages and disadvantages, mainly depending on the constitutive parameters of the analyzed object and the frequency of the electromagnetic problem at hand. For example, PMCHWT, which is a tangential formulation, provides accurate and reliable results using a conventional Galerkin discretization with low-order (such as, RWG) functions [26]. CTF, which is another tangential formulation, usually provides accurate solutions of ordinary dielectric objects with moderate permittivity and permeability values [27]. However, both PMCHWT and CTF are not efficient in terms of iterative convergence [28]. Moreover, their accuracy can be unstable as the frequency and the characteristics of the medium change. JMCFIE is a well-conditioned mixed formulation for ordinary dielectric objects and it often leads to fewer numbers of iterations, making it a good choice particularly for low-contrast media with positive permittivity and permeability values [29, 30]. In the design of nano-optical couplers, the photonic crystals are made of Si_3N_4 that has a relative permittivity of approximately 4 [31]. This is the reason why we prefer JMCFIE for numerical analyses of photonic crystals made of Si_3N_4 .

Modeling metals at optical frequencies requires the use of harmonic oscillator models. Drude model, which is the most common harmonic oscillator model, can be used to represent frequency-dependent permittivity of most metals. An extension of Drude model is Lorentz-Drude, which may better represent frequency-dependent permittivity, considering refraction and reflection properties of metals. Using Lorentz-Drude model, the relative permittivity of a metal can be expressed as

$$\varepsilon_{\text{LD}}(\omega) = \varepsilon_{\text{D}}(\omega) - \sum_j \frac{A_j}{\omega^2 - \omega_j^2 + j\omega\gamma_j}, \quad (2.85)$$

where j is the number of the resonant mode, while A_j , ω_j , γ_j are amplitude, resonant frequency, and damping coefficient of the j th mode, respectively. Here, ε_{D} is the

relative permittivity value found by Drude model, which can be further expressed as

$$\varepsilon_D(\omega) = 1 - \frac{\omega_p^2 \tau}{\omega^2 \tau + j\omega}, \quad (2.86)$$

where τ is the mean collision rate of electrons.

In this study, to model tungsten at optical frequencies, Lorentz-Drude model is used. According to this model, the complex permittivity of tungsten between 500 THz and 600 THz is plotted in Figure 2.4.

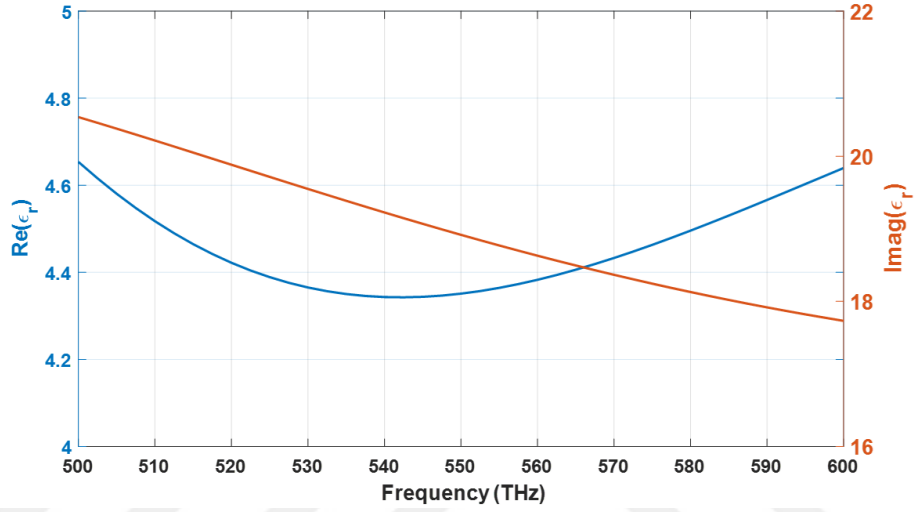


Figure 2.4: Relative complex permittivity of tungsten according to Lorentz-Drude model

Considering the characteristics in Figure 2.4, using either JMCIE or CTF is not a good choice, as these formulations may suffer accuracy and efficiency issues for large imaginary permittivity values [28, 32]. For this kind of problems, MCTF can provide accurate and reliable solutions for a wide range of frequency and permittivity values with reasonable numbers of iterations. The value of the real part of the permittivity does not significantly affect the accuracy of MCTF. Therefore, to solve composite nano-optical absorbers including both W and Si, MCTF formulation is preferred.

To demonstrate the accuracies of JMCIE for dielectric objects with moderate electrical parameters and MCTF for composite metallic-dielectric objects at optical frequencies, respectively, we can consider spherical problems whose analytical Mie-series solutions are available. First, an electromagnetic problem involving a sphere

of Si_3N_4 is studied. The sphere is discretized with a mesh size of $\lambda/20$ and it is illuminated by a plane-wave with 1 V/m electric field intensity at 200 THz. The relative permittivity of Si_3N_4 is defined as 4. The problem is solved by using JMCIE with a residual error of 10^{-4} to compare with the reference Mie-series solution. A comparison of the bistatic far-zone electric field intensity values is given in Figure 2.5. According to this result, JMCIE solution involves only 1.1% maximum relative error, which indicates a quite accurate numerical solution. The computation of the relative error can be written as

$$\text{Relative Error} = \frac{\|E_{\text{Numeric}}^{\text{far}} - E_{\text{Mie}}^{\text{far}}\|_2}{\|E_{\text{Mie}}^{\text{far}}\|_2} \quad (2.87)$$

where $\|\cdot\|_2$, $E_{\text{Numeric}}^{\text{far}}$, and $E_{\text{Mie}}^{\text{far}}$ represent l^2 norm, far-zone electric field intensity computed by using a SIE formulation and far-field electric field intensity obtained via Mie-series solutions, respectively.

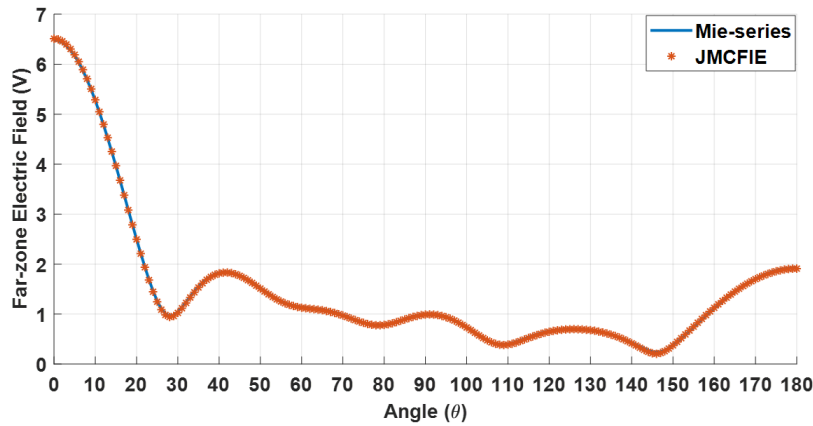


Figure 2.5: Far-zone electric field intensity scattered from a sphere of Si_3N_4

Similarly, a sphere of tungsten, having a radius of 600 nm is considered. Discretization with a mesh size of 27 nm is illuminated with a plane wave with 1 V/m electric field intensity, propagating in the z direction and polarized in the x direction. By using MCTF with a residual error of 10^{-4} as well as Mie series, the backscattered far-zone electric field of the sphere is obtained from 500 THz to 600 THz. The comparison is given in Figure 2.6, which shows accurate solutions by MCTF that provides maximum 0.453% relative error in the entire range.

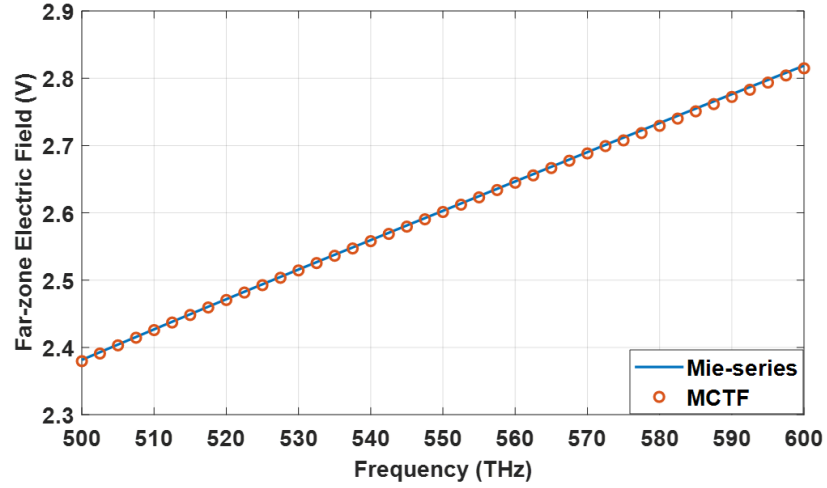


Figure 2.6: Far-zone electric field intensity scattered from a sphere of tungsten with 600 nm diameter in the backscattering direction

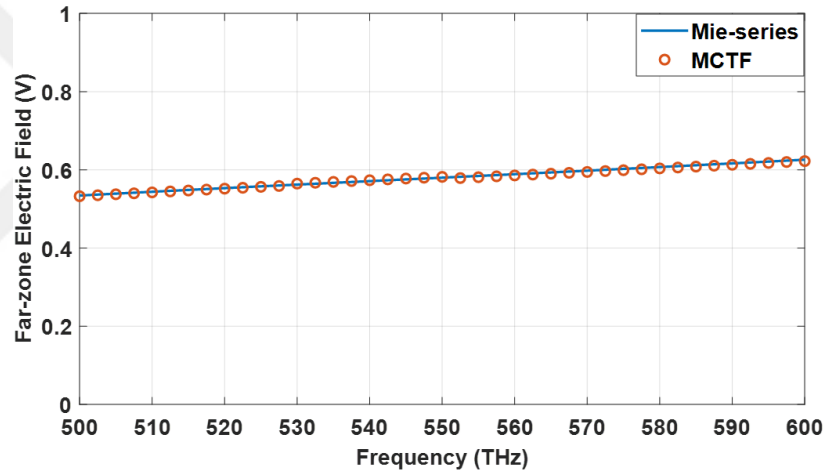


Figure 2.7: Far-zone electric field intensity scattered from a composite structure with Si core and tungsten layer

The accuracy of MCTF for the solution of composite problems can also be exemplified. For this purpose, a sphere of radius 270 nm (core) is placed into another sphere of radius 540 nm (shell). The core is made of Si and the relative permittivity of Si is assumed to be constant and equal to 12, while the shell is made of tungsten and its frequency-dependent relative permittivity is obtained by Lorentz-Drude model. The structure is illuminated by a plane wave with 1 V/m electric field intensity. The backscattered electric field intensity is calculated both with Mie series and MCTF.

The comparison is presented in Figure 2.7, where the accuracy of MCTF is clearly demonstrated, as well as verified by maximum 1.03% error in the entire range.

2.8 Concluding Remarks

This chapter presented important details about the full-wave electromagnetic solver used for numerical solutions and analyses of optical structures based on photonic crystals. Starting from SIEs, application of MoM with the RWG functions is detailed. Since a fast and effective solution method is required for large and complex problems, MLFMA is presented as the major solution tool. While JMCIE is preferred in the design and analysis of optical couplers, MCTF is proposed to analyze optical absorbers. Suitability of these formulations for related electromagnetic problems are demonstrated with examples before their application to more challenging problems in the next chapters.

CHAPTER 3

SIMULATION AND OPTIMIZATION ENVIRONMENT OF NANO-OPTICAL STRUCTURES

In this study, nano-optical coupler, isolator, and absorber designs are obtained by using photonic crystals and their optimization via GAs. The following sections provide details about geometric features, electromagnetic excitation, optimization environment, and field and power calculations of these design procedures.

3.1 Electromagnetic Excitation

The incident fields in Equation 2.41 are created by external sources. Different types of excitations can be simulated to create these incident fields, such as a plane wave, Hertzian dipole, and complex-source-point beam (CSPB). In this study, CSPB excitations are mainly used in the simulations of nano-optical couplers and isolators, as these excitations provide excellent represents of lasers in nano-optical systems. Depending on parameters, CSPB can be a highly focused source, and our aim in coupler designs is to maintain this high density electromagnetic power in the output ports. Thus, when we cascade these couplers by adding an optimized structure at the end of another optimized one, we reach an effectively operating system. CSPB is obtained by locating a Hertzian dipole at a location with complex coordinates. For a CSPB source with a dipole moment $\bar{I}_D$ located at $\bar{r}_D = \bar{r}_{D,R} + i\bar{r}_{D,I}$, we can express the created incident fields as

$$\bar{H}^{\text{inc}}(\bar{r}) = \bar{I}_D \times \hat{R} \frac{\exp(ikR)}{4\pi R} \left(\frac{1}{R} - ik \right), \quad (3.1)$$

$$\begin{aligned}\bar{E}^{\text{inc}}(\bar{r}) = i\omega\mu\frac{\exp(ikR)}{4\pi R} \left\{ \bar{I}_D \left(1 + \frac{i}{kR} - \frac{1}{k^2R^2} \right) \right. \\ \left. - \bar{I}_D \cdot \hat{R}\hat{R} \left(1 + \frac{3i}{kR} - \frac{3}{k^2R^2} \right) \right\}\end{aligned}\quad (3.2)$$

where $\bar{R} = \bar{r} - \bar{r}_D = \hat{R}R$.

In the simulations of nano-optical absorbers, plane wave excitations are preferred, while both far-zone scattered fields and near-zone power densities are examined in this study. Incident fields for a plane wave excitation can be written as

$$\bar{E}^{\text{inc}}(\bar{r}) = \hat{e}E_a \exp(ik\hat{k} \cdot \bar{r}) \quad (3.3)$$

$$\bar{H}^{\text{inc}}(\bar{r}) = \frac{1}{\eta}\hat{k} \times \bar{E}^{\text{inc}}(\bar{r}) = \hat{k} \times \hat{e}\frac{E_a}{\eta} \exp(ik\hat{k} \cdot \bar{r}), \quad (3.4)$$

where $\hat{e}$ and $\hat{k}$ are the direction of polarization, and the direction of propagation, respectively, which are perpendicular to each other.

3.2 Optimization Procedure

In the design of efficient nano-optical structures, multiple parameters exist, whose effects on the design must be examined carefully. Hence, a typical design procedure requires large numbers of electromagnetic simulations. Therefore, a fast and efficient method is needed to speed up and facilitate solutions. In this study, the optimization module and the full-wave electromagnetic solver are integrated for the design of nano-optical structures. GAs are used as suitable heuristic algorithms for optimization, while MLFMA is preferred as the full-wave solver due to its accuracy and efficiency in terms of computational load. The reason for which GA optimization is preferred is that GAs enable adjustable fitness functions, and can lead to successful results even for large optimization spaces [33, 34].

In Figure 3.1, a diagram of the developed GA optimization tool is given. In a GA optimization, a fitness function is defined a priori such that the goal of the optimization is to minimize/maximize the value of this function. From this perspective, the

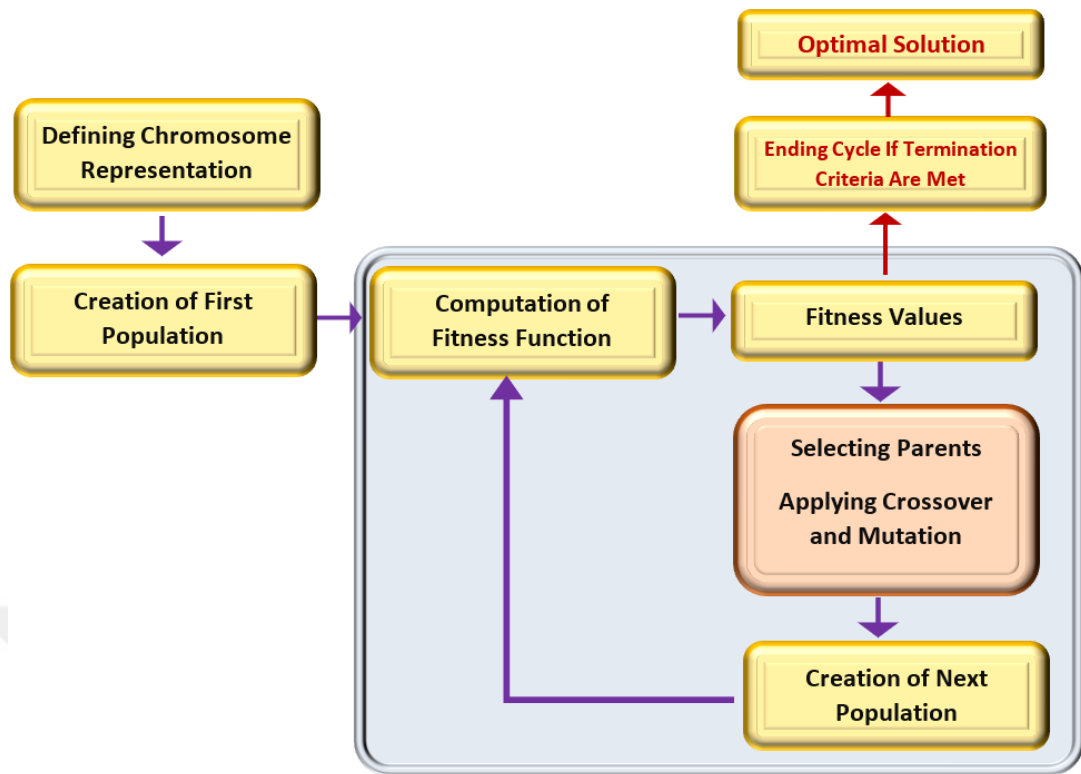


Figure 3.1: Flowchart of GA

definition of the fitness function is very important as it greatly affects the outcome of the optimization. When necessary, it can be determined by experimenting with different parameters before actual optimization trials. In order to complete an optimization, the total number of generations can also be defined at the beginning, or a certain threshold for the value of fitness function can be determined such that the optimization can be stopped once the threshold is reached. In the optimization trials of this study, the maximum number of generations is fixed as the termination criterion. For example, in an optimization with maximum 50 generations, the optimization ends at the 50th generation, and the best individual of the final population is considered as the optimization result. In the first generation of an optimization, a random pool of 40 individuals, each of which has a chromosome that represents a possible solution, is created. Parameters of the optimization are encoded in terms of bits into chromosomes. For example, in a typical on/off optimization, using binary encoding, 1 (on) can be used for the presence of a rod, while 0 (off) represents the absence of the associated rod. The design corresponding to each individual at any generation is eval-

uated by the electromagnetic solver (MLFMA). Once all evaluations are completed for a generation, all individuals are sorted according to their fitness values, and the two best individuals are transferred to the next generation via elitism. Thus, during an optimization, the maximum value of the fitness function never deteriorates, remaining the same in two subsequent generations in the worst case. Following the elitism of two individuals, the remaining 38 individuals of the next generation are determined by applying GA operations, such as mutation and crossover on parent chromosomes (tournament selection is used). According to the mutation rates determined at the beginning, the bits of the chromosomes are randomly inverted. Thus, it is aimed to increase the variety of the population and obtain chromosomes that potentially change the value of the fitness function in the desired direction. In crossover operations, new individuals are obtained from their parents by crossing over their chromosomes. This cycle continues until the last generation, and the best chromosome, i.e., the most successful individual, that provides the best fitness value is considered as the output of the optimization, i.e., the optimal design.

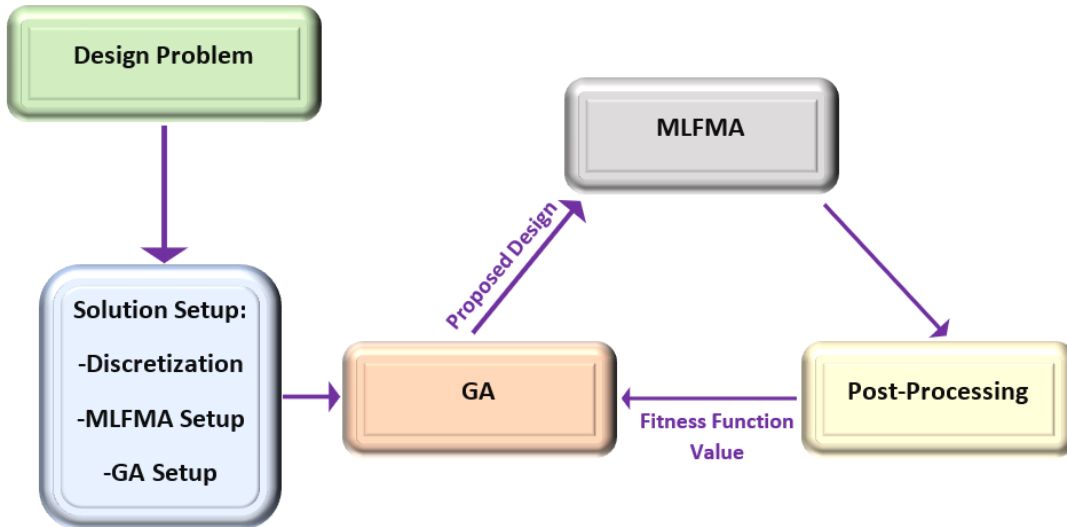


Figure 3.2: Flowchart of the optimization mechanism involving the GA module and MLFMA

For each calculation of the fitness function for an individual, a full-wave electromagnetic solution is performed by MLFMA. Figure 3.2 shows the overall optimization mechanism based on the integration of GAs with MLFMA. As shown in the diagram,

after an electromagnetic solution is completed with MLFMA, the value of the fitness function is computed via post-processing considering far-zone and/or near-zone characteristics. Then, according to fitness values of individuals, new individuals are formed by the GA module (as described above), and the process continues with new MLFMA simulations, until the last generation is reached and the optimal design is finally achieved.

In this study, different kinds of optimizations are designed and are performed: on/off optimization, length optimization, and depth optimization. In all these, the principle of operation is the same, but the variables are different. In nano-optical coupler designs, on/off optimization and length optimization are preferred and used. On the other hand, optical absorbers are mostly designed via depth optimization.

In an on/off optimization, dielectric rods are used as basic unit cells, and by making these rods present (on) or absent (off), we aim to reach optimal designs. For the designs considered in this thesis, a 10×10 array of dielectric rods is initially built, as shown in Figure 3.3.

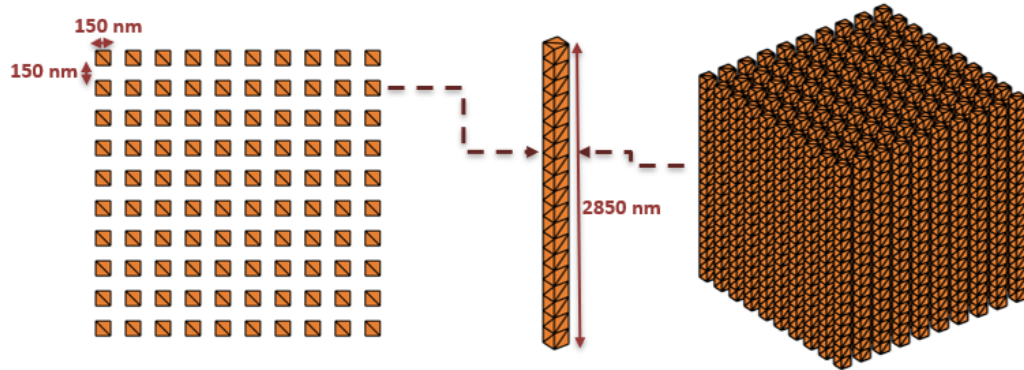


Figure 3.3: 10×10 array of dielectric rods discretized with triangles: top view (left) and trimetric view (right)

A 10×10 matrix is created for each 10×10 rod array in a way that each matrix element (either 0 or 1, which further corresponds to a bit in the associated chromosome) represents one rod in the array. Specifically, in such a matrix, which corresponds to an individual, the presence/absence of each rod in the array is represented by 1/0. Figure 3.4 shows a sample rod configuration and the matrix that represents it. An op-

timization continues by applying GA operations of selection, mutation, and crossover onto the matrices, as described above, so that new matrices of the next generation, i.e. individuals, are obtained.

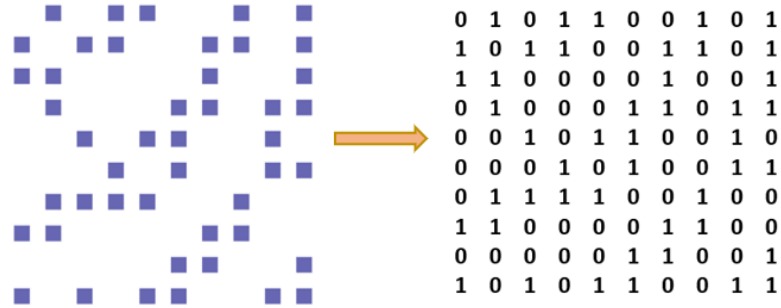


Figure 3.4: A sample array of dielectric rods: top view and the corresponding binary matrix to be used in on/off optimization

In a length optimization, rods of 4 different lengths shown in Figure 3.5 are used. Here, as in on/off optimization, each rod is still represented by a number, but the rods of length 1500 nm, 2000 nm, 2500 nm, and 3000 nm correspond to 1, 2, 3, and 4, respectively, while 0 means that there is no rod. This way, each 10×10 matrix that consists of numbers 0, 1, 2, 3, and 4 represents an individual, as exemplified in Figure 3.6. By following the conventional steps of GA optimization, the most optimal design is obtained as a structure involving rods of different lengths.



Figure 3.5: Dielectric rods used in optimization of rod lengths

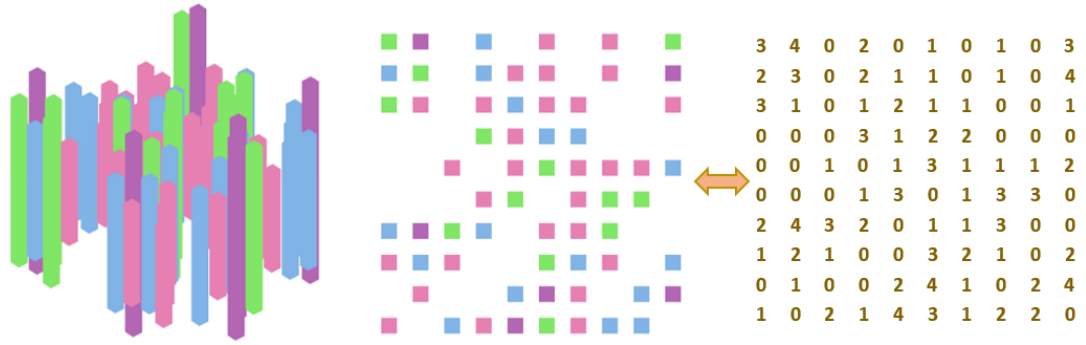


Figure 3.6: A sample array of dielectric rods: trimetric view (left), top view (middle), and the corresponding matrix representation to be used in length optimization

Finally, in a depth optimization, we particularly consider 10×10 air holes with varying depths drilled into dielectric slab, as shown in Figure 3.7. To obtain a nano-optical absorber, a metal plate is placed below the dielectric slab. Periodic air holes on a dielectric slab results in photonic crystal characteristics, and the combination of the slab with a metal plate leads to an efficient nano-optical absorber design.

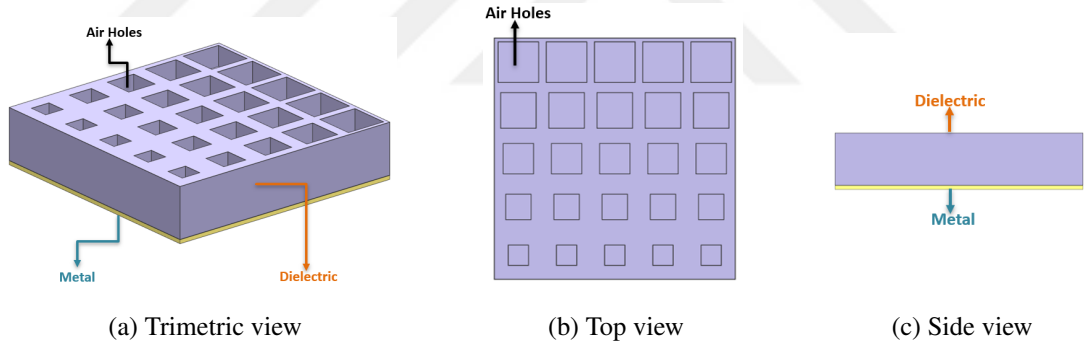


Figure 3.7: Dielectric slab + metal plate to construct a nano-optical absorber, where holes are opened into the dielectric slab to achieve absorbing characteristics

In a typical depth optimization for a nano-optical absorber, the depth of each hole is expressed as a number. Specifically, holes with 60 nm, 80 nm, 100 nm, 120 nm, and 140 nm depths correspond to 0, 1, 2, 3, and 4, respectively. Thereby, a 10×10 matrix involving a combination of numbers 0, 1, 2, 3, and 4 represents an individual (candidate design), as exemplified in Figure 3.8. Similar to the on/off or length op-

timization, GA operations lead to the most optimal design with air holes of different depths into the dielectric slab.

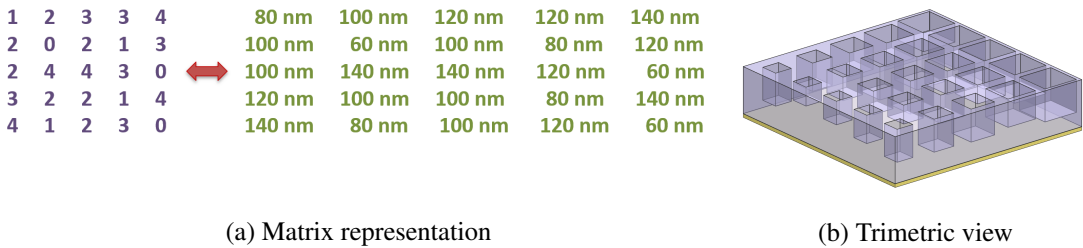


Figure 3.8: A nano-optical absorber involving holes with different depths opened into a dielectric slab backed by a metal plate, together with the corresponding matrix representation of the design

3.3 Concluding Remarks

In this chapter, simulation and optimization parameters used for electromagnetic design of nano-optical structures based on photonic crystals were presented. Plane-wave excitations used for optical absorbers and CSPB excitations used for optical couplers were explained. Important steps of GA optimization, such as mutation, crossover, and elitism have been emphasized. Integration of the GA module with MLFMA was visualized with flowcharts. Three different optimization types to design various nano-optical structures were introduced: on/off optimization, length optimization, and depth optimization. These optimizations were explained, and the main principles were illustrated via examples.

CHAPTER 4

DESIGN AND OPTIMIZATION OF NANO-OPTICAL COUPLERS

This chapter focuses on efficient designs of different nano-optical couplers that are obtained by optimizing a photonic crystal structure made of an array of dielectric rods. Coupler designs with both single and double input ports are considered. The function of such a design is to transmit an incoming electromagnetic wave efficiently to the desired output port, while minimizing transmission to other output regions. Specifically, by examining the effects of various variables, it is intended to obtain maximum electric field intensity at the desired output port, while achieving as low electric field intensity value as possible at undesired output regions. The effects of parameters and variables, such as the fitness function used in the optimization, the material of which photonic crystals are made, the cross section and length of each element in the photonic crystal array, as well as the distance between the elements of the array, are investigated in detail. Among alternatives, forward-transmitting nano-optical couplers, 90-degree nano-optical couplers, and their cascaded designs are considered in this thesis. Also double-input nano-optical couplers, isolating couplers (also known as nano-optical isolators), and logic-gate couplers are designed, and their transmission characteristics are investigated. On/off optimization and length optimization described in Section 3.2 are used in the design of these structures. We note that a length optimization includes an on/off optimization by allowing zero-length rods in order to improve the efficiency of the designs.

4.1 Determination of Fitness Function

In any GA optimization, a fitness function should carefully be defined, as previously mentioned in Section 3.2. Since the aim in a nano-optical coupler design is to maximize the electric field intensity value at the desired output port and minimize it at the other output regions, it is critical to define the fitness function in a way that enforces this condition. Therefore, this study is started by experimenting to find a fitness function that can provide the best results in the design of nano-optical couplers. As mentioned before, a photonic crystal structure is created by placing dielectric rods with square cross sections in a 10×10 array with 300 nm center-to-center distance between them, as shown in Figure 4.1. The array is centered at the origin and it extends from $x = -1.425 \mu\text{m}$ and $y = -1.425 \mu\text{m}$ to $x = 1.425 \mu\text{m}$ and $y = 1.425 \mu\text{m}$. Output Port-1 is located at the right edge of the array from $y = -0.125 \mu\text{m}$ to $y = 0.125 \mu\text{m}$ at $x = 1.400 \mu\text{m}$. Undesired transmission regions include the top edge, bottom edge, as well as those boundaries around the output port on the right edge.

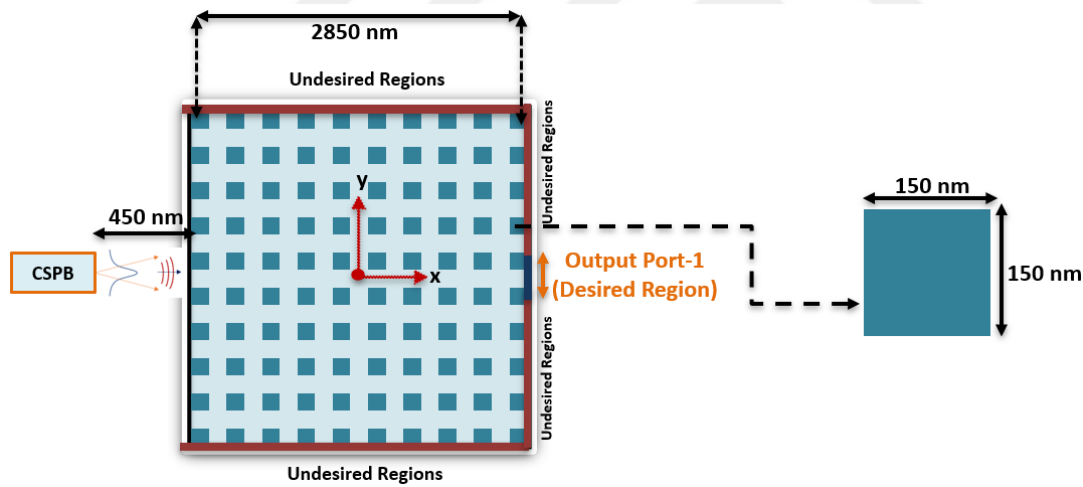


Figure 4.1: Desired and undesired transmission regions for a forward-transmitting coupler

In an optimization of a forward-transmitting coupler, the aim is to make the electric field intensity value maximum at Output Port-1, which is the desired output port defined on the structure, while minimizing the electric field intensity values at other output regions (undesired regions). In the following design results, the operating fre-

quency is selected as 200 THz. CSPB, previously detailed in 3.1, is used to excite the structure and placed 450 nm away from the structure at $x = (-1.875 - 5i) \mu\text{m}$, $y = 0 \mu\text{m}$, $z = 0 \mu\text{m}$ in complex coordinates, while the incident wave from this source is polarized in the z direction. MLFMA and JMCIE are used for numerical analyses during optimization trials, as well as for post processing.

Table 4.1: Simulation parameters and their specifications

Parameters	Specifications
Material of Dielectric Rods	Si_3N_4 ($\epsilon_r = 4$ and $\mu_r = 1$)
Dimensions of Dielectric Rods	150 nm $\times$ 150 nm $\times$ 2850 nm (Square Prism)
Spacing Between Dielectric Rods	150 nm
Frequency	200 THz
Excitation Source	CSPB (450 nm away from the rod array)
Numerical Solver	MLFMA
Formulation	JMCIE
Mesh Size	$\lambda/10$
Iterative Solver	GMRES
Residual Error	0.001
Optimization Type	On/Off optimization
Nano-Optical Coupler Type	Forward-transmitting coupler
Number of Generations	50

A total of three different fitness functions, namely Fitness Function₁ (FF₁), Fitness Function₂ (FF₂), and Fitness Function₃ (FF₃), are defined as

$$\text{FF}_1 = \text{Max}(\text{Desired Fields}) / \text{Max}(\text{Undesired Fields}) \quad (4.1)$$

$$\text{FF}_2 = \text{Max}(\text{Desired Fields}) - \text{Max}(\text{Undesired Fields}) \quad (4.2)$$

$$\text{FF}_3 = \text{Max}(\text{Desired Fields}) - \text{Mean}(\text{Undesired Fields}) \quad (4.3)$$

and using these functions, the optimization trials are carried out with the simulation and optimization details given in Table 4.1. Here, "Desired Fields" is the electric field intensity values (dBV/m) at the desired output region (Output Port-1) and "Undesired Fields" is the electric field intensity values (dBV/m) at the undesired output regions.

For all three fitness functions, mean electric field intensity values at Output Port-1 and at undesired output regions at the end of the optimization trials for a forward-transmitting coupler are given in Table 4.2. According to these results, FF_3 in Equation 4.3 provides the highest mean electric field intensity at the desired output port (34.4 dBV/m) while leading to the lowest mean electric field intensity at undesired regions (20.0 dBV/m). Moreover, the margin between the mean electric field intensity at the desired port and undesired regions is 14.4 dB, which is much higher than those obtained via the other two fitness functions. Therefore, for the following on/off optimization trials, FF_3 , is preferred.

Table 4.2: Mean electric field intensity values obtained via optimization trials using different fitness functions

Fitness Function	Mean E-Field Intensity at Output Port-1 (dBV/m)	Mean E-Field Intensity at Undesired Regions (dBV/m)
FF_1	28.9	21.1
FF_2	32.9	21.2
FF_3	34.4	20.0

4.2 Design of Forward-Transmitting Nano-Optical Coupler

The need and importance of well-designed nano-optical couplers can be understood better if they are compared against full arrays of dielectric rods, for which no design process is needed. In the following results, CSPB is generated by placing a Hertzian dipole at $x = (-1.875 - 5i) \mu\text{m}$, $y = 0 \mu\text{m}$, $z = 0 \mu\text{m}$ in complex coordinates, while the electric field intensity is polarized in the z direction. The near-zone electric field intensity, magnetic field intensity, and power density distributions are numerically calculated in the x - y plane ($z = 0$) from $x = -2.2 \mu\text{m}$ and $y = -2.2 \mu\text{m}$ to $x = 2.2 \mu\text{m}$ and $y = 2.2 \mu\text{m}$. For the generated two-dimensional (2D) near-zone plots, the same rectangular area is selected, if not stated otherwise. The near-zone power

density is calculated as

$$\text{Power density}(\mathbf{r}) = |\mathbf{E}(\mathbf{r}) \times [\mathbf{H}(\mathbf{r})]^*|, \quad (4.4)$$

where $\mathbf{E}(\mathbf{r})$ and $\mathbf{H}(\mathbf{r})$ are the electric field intensity and magnetic field intensity values at the observation point $\mathbf{r}$.

Near-zone electric field intensity, magnetic field intensity, and power density distributions obtained when there is no nano-optical coupler or any other structure, i.e., CSPB alone, are given in Figure 4.2.

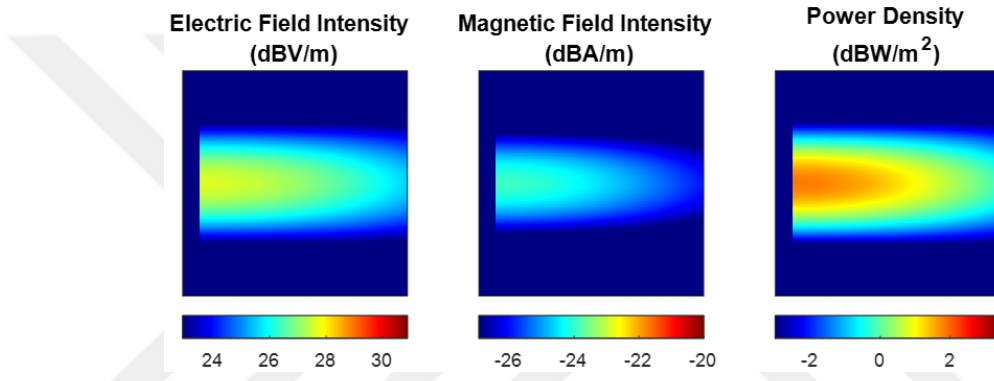


Figure 4.2: Near-zone electric field intensity, magnetic field intensity, and power density distributions for a CSPB

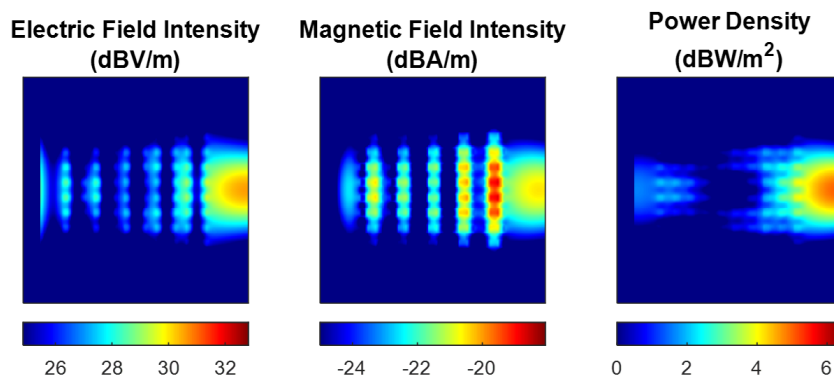


Figure 4.3: Near-zone electric field intensity, magnetic field intensity, and power density distributions when the full array of dielectric rods is excited by the CSPB in Figure 4.2

In Figure 4.3, the near-zone electric field intensity, magnetic field intensity, and power density distributions are given when the full 10×10 rod array is excited by the CSPB in Figure 4.2.

A design of forward-transmitting coupler is achieved via on/off optimization using FF_3 . The value of the fitness function with respect to generations and the resulting rod array configuration are given in Figure 4.4. When investigating the variation of the fitness function as the generations continue, it can be noticed that, at some point, the value of the fitness function is saturated, and there is not much change for many generations. Based on this and similar results, it is decided to perform subsequent optimization trials with maximum 50 generations, particularly considering computational costs.

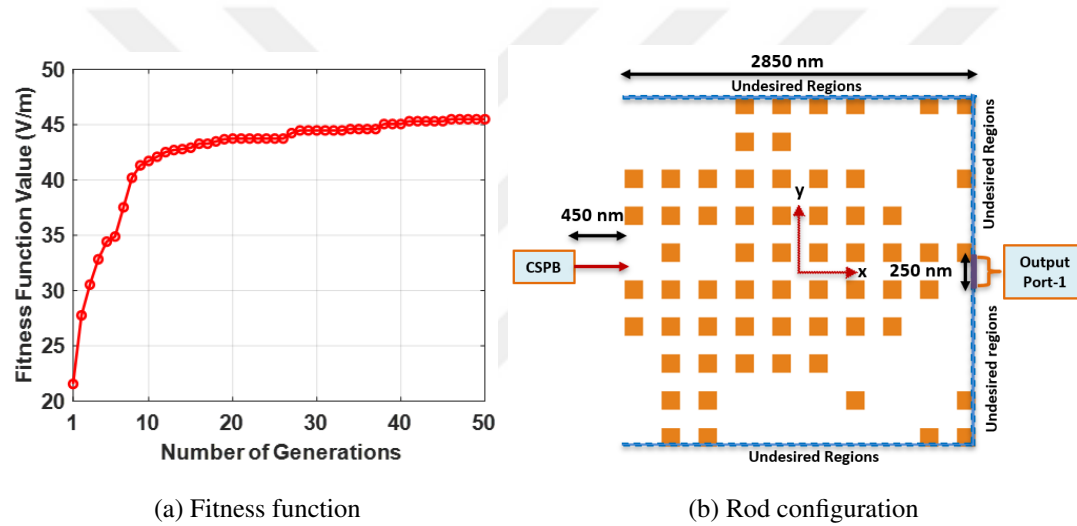


Figure 4.4: Fitness function and the resulting (optimized) rod configuration for a forward-transmitting coupler

The 2D near-zone electric field intensity, magnetic field intensity, and power density distributions which are obtained for the forward transmitting nano-optical coupler are given in Figure 4.5. Here, we note that while during optimizations, the geometries are discretized with a mesh size of $\lambda/10$ for lower computational load, the final near-zone distributions presented throughout this chapter are obtained when the same geometries are discretized with a mesh size of $\lambda/20$, for better accuracy. Looking at Figure 4.5, we observe that the coupler successfully transmits electromagnetic waves in the

forward direction, i.e., towards Output Port-1.

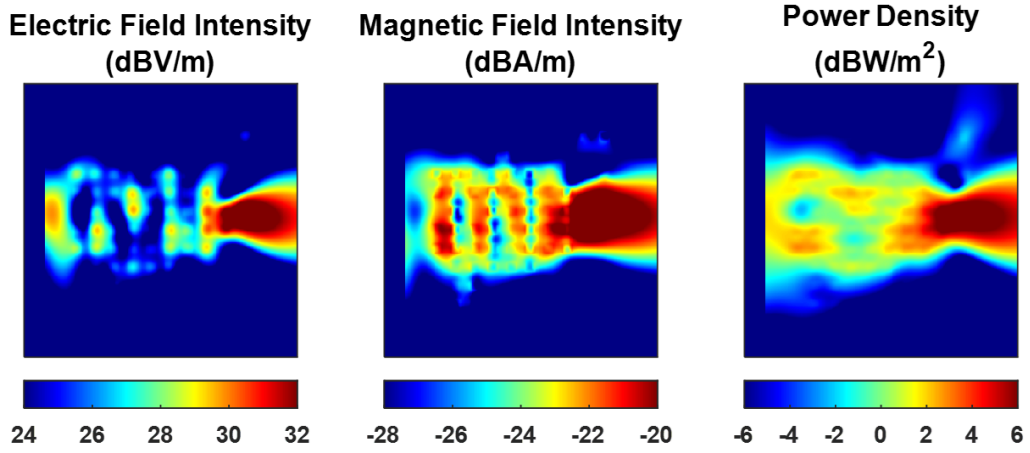


Figure 4.5: Near-zone results for the forward-transmitting coupler

Table 4.3: Electric field intensity values when forward-transmitting coupler is used, in comparison to no-coupler and full-array cases

Case	Mean E-Field Intensity at Output Port-1 (dBV/m)	Mean E-Field Intensity at Undesired Regions (dBV/m)
Forward-Transmitting Optical Coupler	34.4	20.0
No Coupler	26.1	22.3
Full Array of Rods	28.9	22.0

Table 4.3 compares the performance of the designed nano-optical coupler with the cases when there is no any structure (coupler) and when the full array of dielectric rods is used. The electric field intensity values are computed at the top, bottom, and right edges of the array. We recall that Output Port-1 (desired output port) is located at the right edge of the array from $y = -0.125 \mu\text{m}$ to $y = 0.125 \mu\text{m}$. The mean electric field intensity at the desired output port when the nano-optical coupler exists is 34.4 dBV/m which corresponds to 5.25 times of the mean electric field intensity value at the undesired output regions (20.0 dBV/m). Moreover, when the nano-optical coupler exists, the mean electric field intensity at Output Port-1 is 2.6 times of the mean electric field intensity (at the same location) when there is no coupler and almost 1.9

times of the mean electric field intensity (at the same location) when the full array is used. The mean electric field intensity value at the undesired output regions is also lower when the optimized nano-optical coupler is used. All these results indicate that the nano-optical coupler optimized with FF_3 works effectively.

4.3 Design of 90-Degree Nano-Optical Coupler

Electromagnetic wave transmission through sharp bends and corners requires the use of efficient nano-optical couplers [7,35]. In this study, a 90-degree coupler is designed by performing on/off optimization using FF_3 . The value of the fitness function with respect to the number of generations, and the resulting rod array configuration are given in Figure 4.6. The designed coupler is expected to transmit the incoming wave (in the form of CSPB) to Output Port-2 while minimizing the electric field intensity at the undesired regions shown in Figure 4.6b. Output Port-2 is located at the top edge of the array from $x = -0.125 \mu\text{m}$ to $x = 0.125 \mu\text{m}$ at $y = 1.400 \mu\text{m}$.

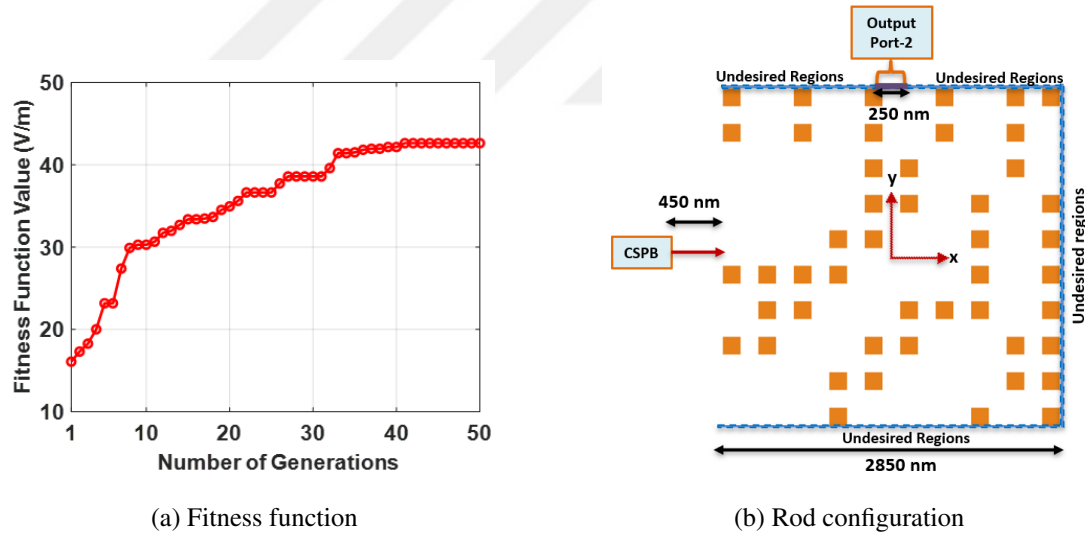


Figure 4.6: Fitness function and optimized rod configuration for 90-degree nano-optical coupler

The near-zone electric field intensity, magnetic field intensity, and power density distributions obtained for the 90-degree coupler are given in Figure 4.7.

It can be observed in Figure 4.7 that, while the intensity and density values at Output Port-2 are maximized, transmissions towards other regions are minimized, as much as possible. The mean electric field intensity value at Output Port-2 is 33.8 dBV/m, while the mean electric field intensity value at the other output regions is 22.2 dBV/m, corresponding to 11.6 dB difference between them. We conclude that the optimized 90-degree coupler can successfully couple incoming waves to Output Port-2, despite of the challenging nature of the operation.

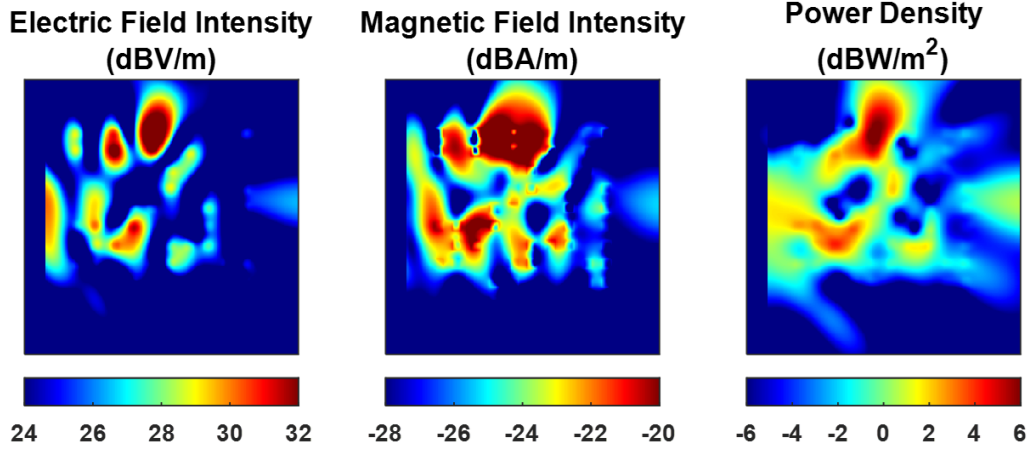


Figure 4.7: Near-zone results for 90-degree nano-optical coupler

4.4 Effect of Material

It is known that the material used in a nano-optical coupler design can significantly affect the transmission efficiency. Specifically, as the effective refractive index determines reflection, refraction, and diffraction characteristics of a structure, the dielectric constant of the rods becomes an important parameter to decide in rod arrays. It is desirable to maximize the field intensity at the desired port via constructive interference of waves propagating in different directions. However, propagation towards undesired regions should involve destructive interference so that intensity and density values in those regions can be minimized. In this context, nano-optical coupler designs are initially obtained when the relative permittivity of the rods is 4; and then, two separate scenarios are examined, in which the relative permittivity is reduced to 2 and increased to 8 for both forward-transmitting coupler and 90-degree coupler designs.

In the new optimization scenarios, the relative permittivity is the only variable that is changed compared to the previous nano-optical coupler scenarios, i.e., other simulation-related variables are kept the same. The obtained near-zone electric field intensity distributions for these cases are given in Figure 4.8. These new designs are further compared with the coupler designs using rods with relative permittivity equal to 4, as tabulated in Table 4.4.

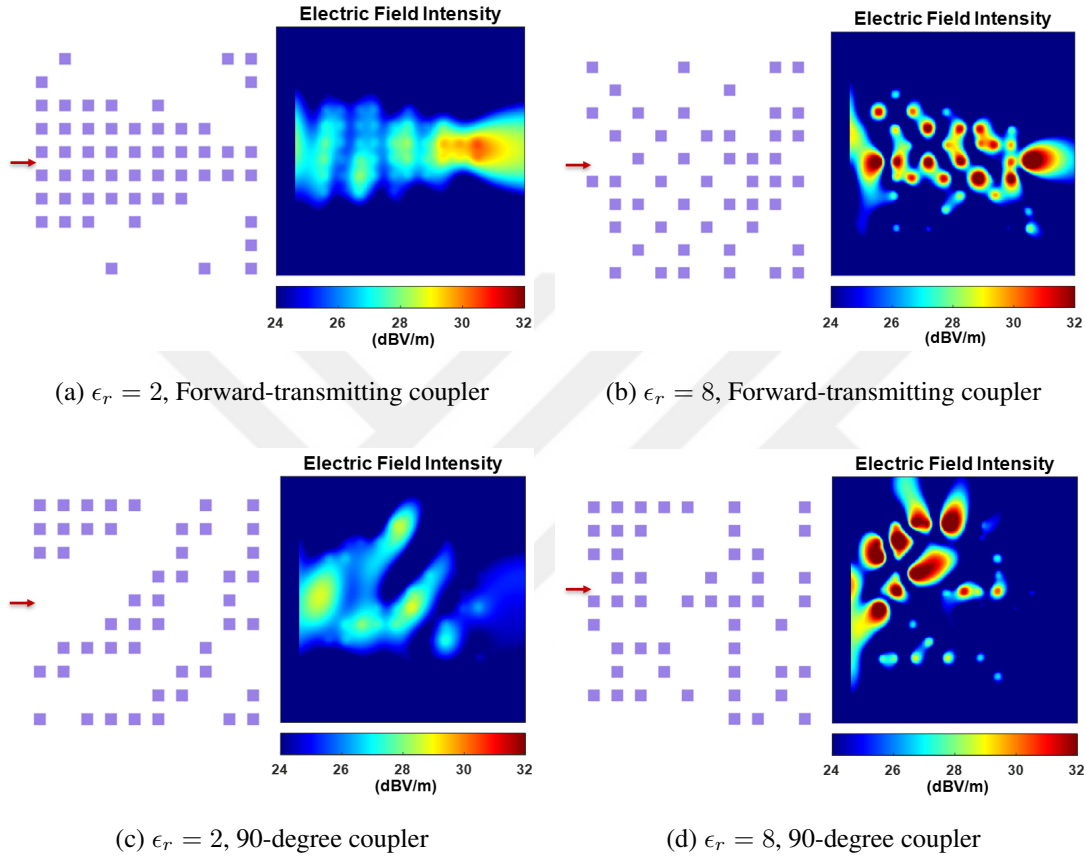


Figure 4.8: Rod configurations and near-zone electric field intensities for forward-transmitting (top) and 90-degree (bottom) nano-optical couplers made of dielectric rods with $\epsilon_r = 2$ (left) and $\epsilon_r = 8$ (right)

According to the results in Table 4.4, for forward-transmitting coupler, the best results seem to be obtained when the relative permittivity is 4. Particularly, for this relative permittivity value (4), the mean electric field intensity at the desired output port becomes higher, while difference between the desired and undesired output regions is also larger. Similarly, for 90-degree optical coupler, the best result is obtained when

the relative permittivity is 4, considering higher mean electric field intensity at the desired output port. These results show that the selection of material is crucial in the design of nano-optical couplers. Moreover, taking fabrication process into account, the selected material should not only provide the desired transmission characteristics, but also be feasible for use in the fabrication of couplers. If, as in our study, in the design of different couplers, a single material is used, the one that ensures desired transmission characteristics for all designs should be preferred. According to Table 4.4, both forward-transmitting and 90-degree couplers operate successfully when the relative permittivity is 4. One of common materials with this relative permittivity of 4 at our operating frequency of 200 THz is Si_3N_4 . In fact, Si_3N_4 is an excellent choice for efficient nano-optical structures due to its fairly light weight, as well as its flexibility owing to its good flexural strength (850 mPa) that makes it favorable in fabrication processes [36].

Table 4.4: The mean electric field intensity distributions obtained for two types of nano-optical coupler designs using different dielectric constants for the rods

Case	Mean E-Field Intensity at Desired Regions (dBV/m)	Mean E-Field Intensity at Undesired Regions (dBV/m)
Forward Coupler $\epsilon = 2$	30.2	20.8
Forward Coupler $\epsilon = 4$	34.4	20.0
Forward Coupler $\epsilon = 8$	32.3	19.5
90-degree Coupler $\epsilon = 2$	27.9	22.2
90-degree Coupler $\epsilon = 4$	33.8	22.2
90-degree Coupler $\epsilon = 8$	33.4	21.1

4.5 Effect of Cross Section

Next, we investigate the effect of cross section of the characteristics of the nano-optical structures. Specifically, new forward-transmitting couplers are designed by using rods with triangular and hexagonal cross sections, instead of square ones. The length and material properties of the dielectric rods used in these designs and the other

parameters of simulations are the same as those used for dielectric rods with square cross sections, as listed in Table 4.1. Again, FF_3 is used, and each optimization is carried out for 50 generations. In Figure 4.9, triangular and hexagonal prisms (rods) are given with their dimensions.

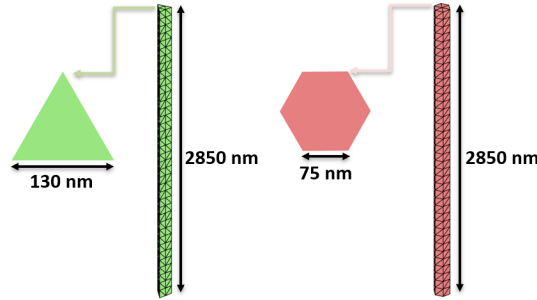


Figure 4.9: Prisms (rods) with triangular (equilateral) and hexagonal cross sections

Figure 4.10 shows the final rod configurations for forward-transmitting couplers obtained at the end of the optimization trials involving 10×10 grids of rods and the resulting near-zone electric field intensity distributions for these designs. As these results confirm, the geometric properties of the dielectric rods (specifically their cross sections) used can be critical to obtain efficient operation (in this case, forward transmission). In Table 4.5, the performances of these designs are quantitatively compared with the performance of the corresponding coupler involving dielectric rods of square cross sections.

Table 4.5: The mean electric field intensity distributions obtained for different forward-transmitting couplers using rods of different cross sections

Cross Section	Mean E-Field Intensity at Output Port-1 (dBV/m)	Mean E-Field Intensity at Undesired Regions (dBV/m)
Square	34.4	20.0
Triangular	30.4	20.8
Hexagonal	32.5	19.6

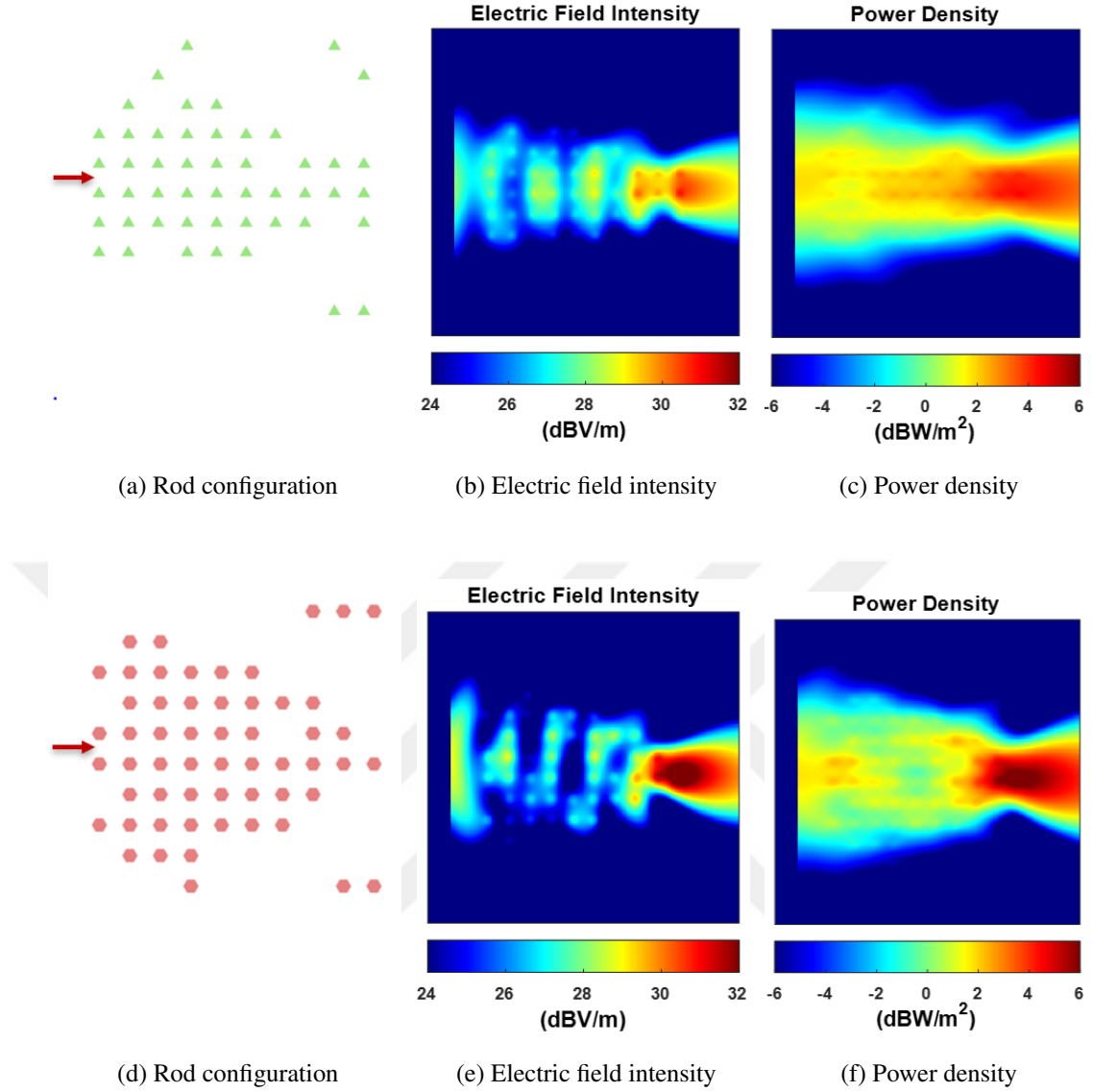


Figure 4.10: Optimization results when the rods have triangular (top) and hexagonal (bottom) cross sections

According to these optimization results, all three coupler designs provide good results, indicating that efficient designs can be obtained via GA optimization when rods of different cross sections are used. However, the original square prisms lead to the best result among the three types of dielectric rods. Specifically, using square prisms provides higher electric field intensity at Output Port-1 and higher difference between Output Port-1 and other output regions.

4.6 Effect of Spacing Between Dielectric Rods

In addition to the parameters described above, the effect of the distance between dielectric rods on the performance of the nano-optical couplers is examined. For example, using the rod configuration of the original design of the forward-transmitting coupler, where the distance between the rods is 150 nm, the distance between the rods is reduced to 100 nm or increased to 200 nm in two separate trials. Thus, an operational design is tested by changing its one of major parameters to observe how its performance is affected.

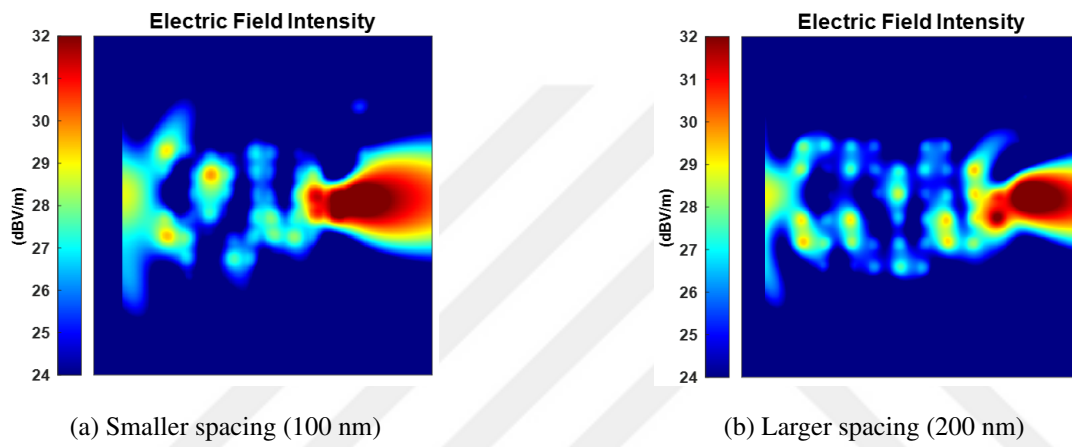


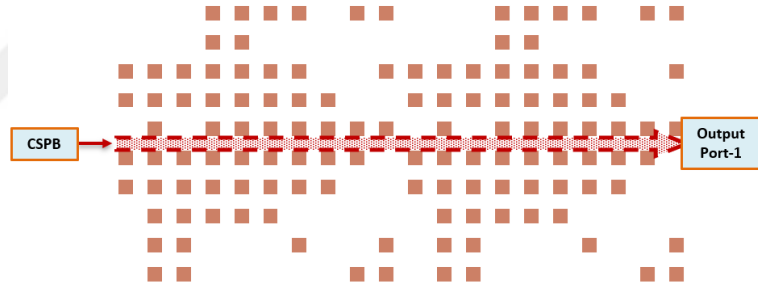
Figure 4.11: Near-zone electric field intensity distributions for forward-transmitting couplers using different spacings between the rods

Electric field intensity distributions for the cases where the distance between the elements is made 100 nm and 200 nm can be found in Figure 4.11. According to these results, when the distance between the rods is reduced to 100 nm, the mean electric field intensity at the desired output port becomes 33.5 dBV/m, while the mean electric field intensity at the undesired output regions is 19.7 dBV/m. On the other hand, when the distance between the rods is increased to 200 nm, the mean electric field intensity at the desired output port becomes 32.9 dBV/m, while the mean electric field intensity at the undesired output regions is 18.6 dBV/m. Hence, both the mean electric field intensity at the desired output port (34.4 dBV/m) and the difference between the desired and undesired regions (14.4 dB) are higher for the original value of spac-

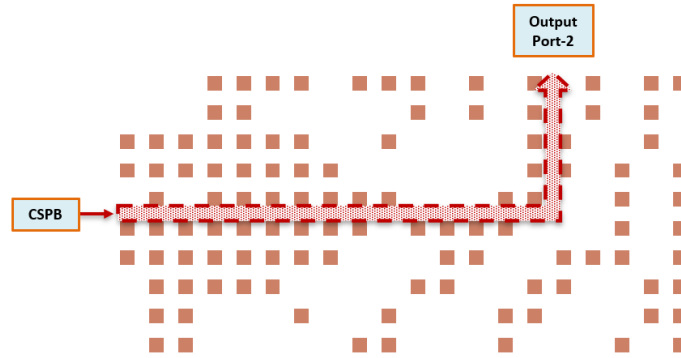
ing. These results support the fact that geometric parameters, such as rod shapes and distances between them, should be fixed before an optimization, and certain changes on the optimized geometries may deteriorate the performances of the structures (or re-optimization is required).

4.7 Cascaded Nano-Optical Couplers

We now discuss cascaded nano-optical couplers, where it is aimed to construct transmission systems by combining the designed nano-optical couplers one after another. In particular, to demonstrate working principles, we consider combinations involving two couplers. The first coupler is excited with CSPB, while the subsequent coupler uses the output of the first coupler as input to operate as it is designed. Two specific configurations obtained by adding two forward-transmitting couplers and adding a 90-degree coupler at the end of a forward-transmitting coupler are given Figure 4.12.

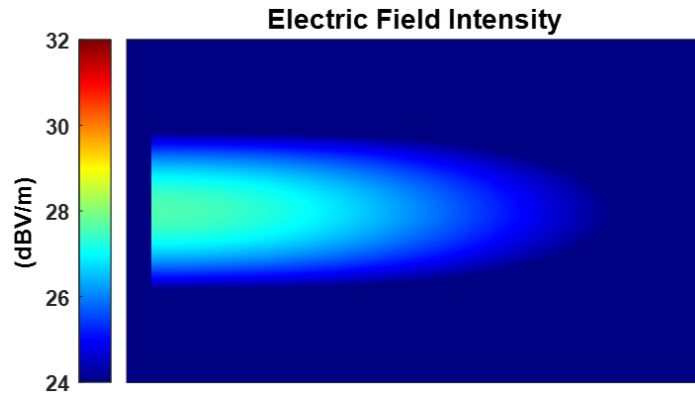


(a) Cascaded forward-transmitting couplers

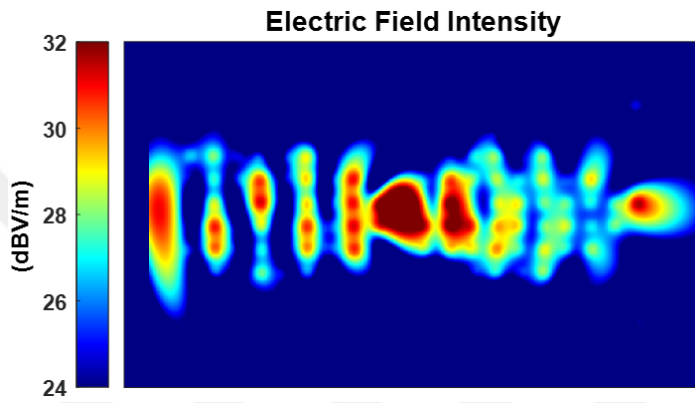


(b) Cascaded forward-transmitting and 90-degree couplers

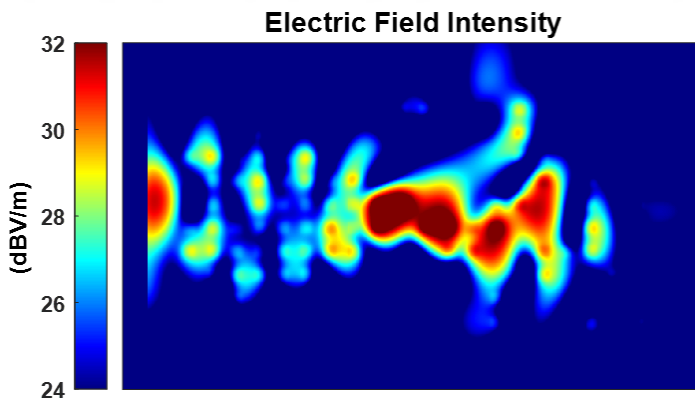
Figure 4.12: Rod configurations for cascaded couplers



(a) No coupler



(b) Cascaded forward-transmitting couplers



(c) Cascaded forward-transmitting and 90-degree couplers

Figure 4.13: Near-zone electric field intensity distributions without and with cascaded couplers shown in Figure 4.12

The near-zone electric field intensities are numerically calculated in the x - y plane

($z = 0$) from $x = -3.7 \mu\text{m}$ and $y = -2.2 \mu\text{m}$ to $x = 3.7 \mu\text{m}$ and $y = 2.2 \mu\text{m}$ and their plots for CSPB alone (without any couplers) and for the cascaded couplers are given in Figure 4.13.

Without nano-optical couplers, that is, only with CSPB, the mean electric field intensity value obtained at the locations of Output Port-1 is 23.7 dBV/m, while the mean electric field intensity value when using the cascaded system in Figure 4.12a is increased to 30.1 dBV/m. Similarly, when only CSPB exists, the mean electric field intensity value obtained at the locations of Output Port-2 is 21.2 dBV/m, which is increased to 26.5 dBV/m when the cascaded system in Figure 4.12b is used. According to these results, we conclude that the designed nano-optical couplers can successfully be cascaded to transmit electromagnetic power to desired directions in a controlled manner. It is remarkable that the couplers designed for CSPB excitations operate well when they are excited via another coupler, which makes the cascade operation possible. Nevertheless, we also note that the overall operation of a transmission system depends on its primary source, and a single source may not provide sufficient power to be transmitted to any desired location.

4.8 Double-Input Nano-Optical Couplers

In addition to nano-optical couplers that are excited with single inputs, double-input couplers are also designed and examined in this study. This type of couplers are particularly useful at a junction of a nano-optical system, where it is critical to direct incoming waves from multiple input sources to the desired output port, while inhibiting power from propagating towards the undesirable output regions.

The dielectric rods used in the following designs, as well as simulation and optimization parameters are the same as those in the design of single-input couplers. The only difference is the use of a second CSPB source. For the first design, one CSPB is placed in $x = (-1.875 - 5i) \mu\text{m}$, $y = 0 \mu\text{m}$, $z = 0 \mu\text{m}$ in the complex coordinates, while the other one is placed at $x = 0 \mu\text{m}$, $y = (-1.875 - 5i) \mu\text{m}$, $z = 0 \mu\text{m}$. In both cases, the incident wave is polarized in the z direction. Output Port-1 is located at the right edge of the array from $y = -0.125 \mu\text{m}$ to $y = 0.125 \mu\text{m}$ at $x = 1.400 \mu\text{m}$.

Figure 4.14a shows the positioning of CSPB sources and the rod configuration obtained as a result of the on/off optimization. In the optimization, the electric field intensity at Output Port-1 is maximized while it is minimized at other output regions. In Figure 4.14b and 4.14c, near-zone electric field intensity and power density distributions are shown. The mean electric field intensity at Output Port-1 is 36.8 dBV/m, while the mean electric field intensity at undesired output regions is 24.0 dBV/m, with a difference of 12.8 dB. Hence, with this design, electromagnetic transmission is successfully established towards Output Port-1.

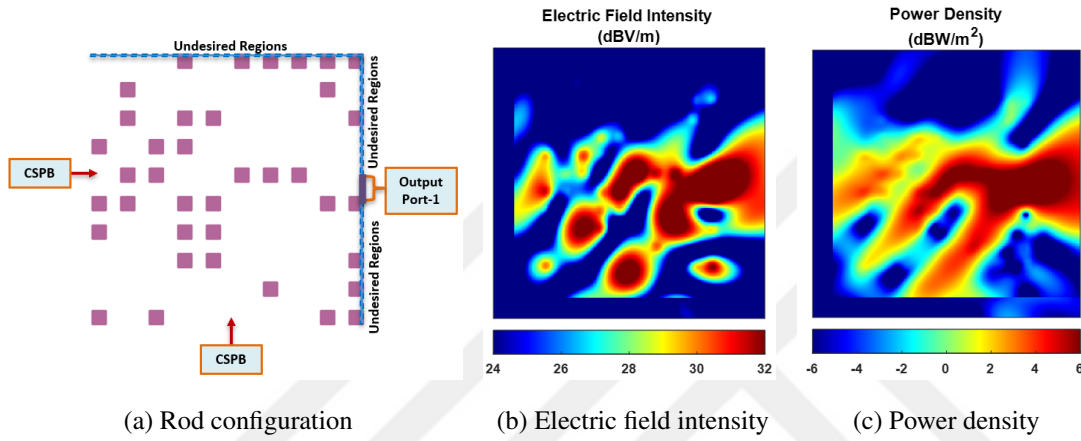
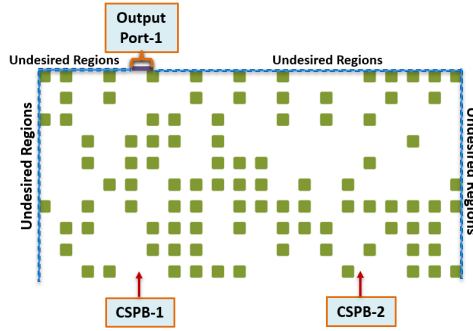


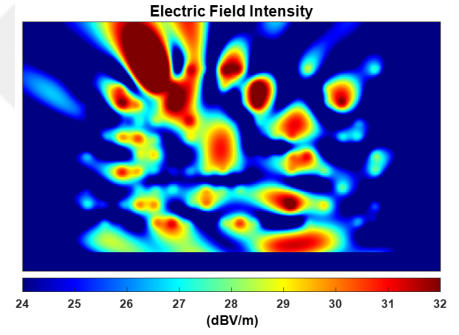
Figure 4.14: Optimization results for the first design of double-input nano-optical coupler

In the second and third designs, 10×20 dielectric rod arrays are used, unlike the first double-input nano-optical coupler using the standard 10×10 grid. The positions of the CSPB sources in the second and third designs are shown in Figure 4.15a and Figure 4.15c, respectively. The nano-optical couplers are centered at the origin and they cover a rectangular area extending from $x = -2.925 \mu\text{m}$, $y = -2.925 \mu\text{m}$ to $x = 2.925 \mu\text{m}$, $y = 2.925 \mu\text{m}$ in the x - y plane. In the second design, one CSPB source is positioned at $x = -1.425 \mu\text{m}$, $y = -1.875 - 5i \mu\text{m}$, $z = 0 \mu\text{m}$, while the other CSPB is positioned at $x = 1.425 \mu\text{m}$, $y = -1.875 - 5i \mu\text{m}$, $z = 0 \mu\text{m}$. Both excitations generate z -polarized waves, which are intended to be combined and transmitted to Output Port-1 in Figure 4.15a. This port is positioned at the top edge of the rod array from $x = -1.625 \mu\text{m}$ to $x = -1.375 \mu\text{m}$ at $y = 1.400 \mu\text{m}$. In the

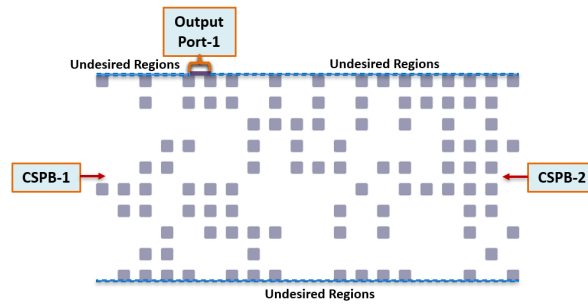
third design, one CSPB source is positioned at $x = -3.375 - 5i \mu\text{m}$, $y = 0 \mu\text{m}$, $z = 0 \mu\text{m}$, while the other one is positioned at $x = 3.375 + 5i \mu\text{m}$, $y = 0 \mu\text{m}$, $z = 0 \mu\text{m}$. Similar to the previous case, z -polarized waves emerging from these sources are to be collected at Output Port-1 in Figure 4.15c, which is positioned as in the previous case. The resulting rod configurations and near-zone electric field intensity plots are given in Figure 4.15. The difference between the mean electric field intensity at Output Port-1 (38.0 dBV/m) and mean electric field intensity at undesired output regions (24.0 dBV/m) for the second design is 14 dB. For the third design, the difference between mean electric field intensity at Output Port-1 is 35.7 dBV/m, while the mean electric field intensity at undesired output regions is 25.6 dBV/m, leading to a difference of 10.1 dB. Consequently, we conclude that all three designs provide successful results in terms of optimization aims and they are functional by providing the desired results for given input and output locations.



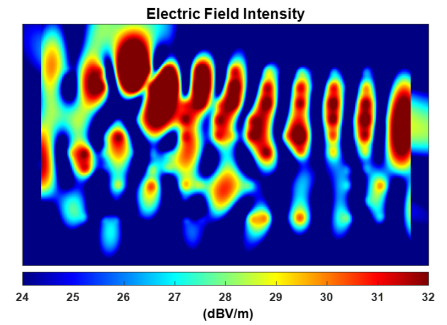
(a) Rod configuration



(b) Electric field intensity



(c) Rod configuration



(d) Electric field intensity

Figure 4.15: Optimization results for the second (a,b) and third (c,d) designs of double-input nano-optical couplers

4.9 Nano-Optical Isolators

Nano-optical isolators are non-reciprocal coupling structures that allow electromagnetic waves to propagate in one direction and prevent them from propagating in the opposite direction. This study aims to design a structure that both focuses the electric field intensity from the source to the output port and attenuates reflected waves that return back to the source. This way, high forward transmission is achieved, while the source is protected from reflected waves.

Figure 4.16 shows the particular scenario to be analyzed, where the location of the source and output ports' positions for forward and backward transmission cases are illustrated. What is desired in the forward transmission is that the nano-optical isolator, which is excited with CSPB-1, transmits the electromagnetic wave forward, maximizing the electric field intensity at Output Port-1. In the case of the reverse transmission, the same isolator, which is this time excited with CSPB-2, reduces the electric field intensity at Output Port-2 by attenuating the electromagnetic wave generated by CSPB-2. We require the forward transmission to become at least 7 times of backward transmission, which means about 17 dB difference between forward and backward transmissions. Then, a suitable fitness function is required to design an efficient structure that can behave as desired in both cases by satisfying the best conditions for electric field intensity values.

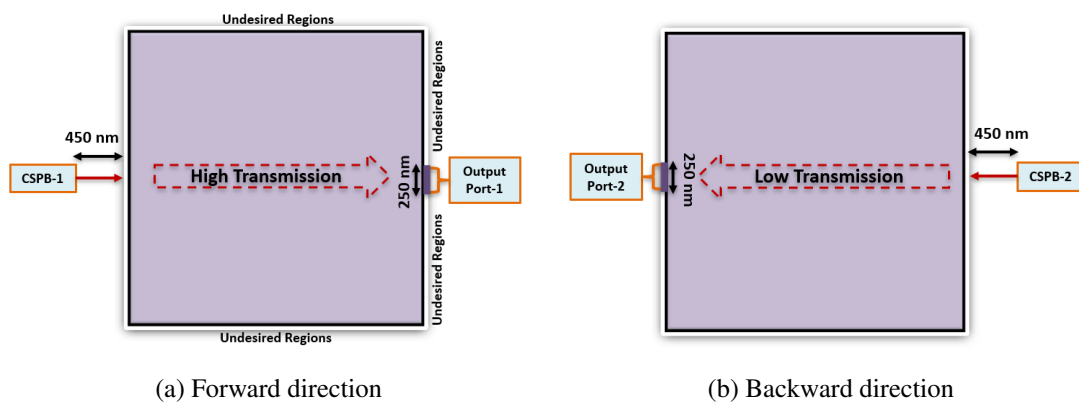


Figure 4.16: Excitation and output of a nano-optical isolator in forward and backward directions

CSPB-1 is placed at $x = (-1.875 - 5i) \mu\text{m}$, $y = 0 \mu\text{m}$, $z = 0 \mu\text{m}$ in the complex coordinates and the incident wave from this source is polarized in the z direction. CSPB-2 is placed at $x = (1.875 + 5i) \mu\text{m}$, $y = 0 \mu\text{m}$, $z = 0 \mu\text{m}$ in the complex coordinates, while the incident wave from this source is also z -polarized. Output Port-1 is placed at the right edge of the array from $y = -0.125 \mu\text{m}$ to $y = 0.125 \mu\text{m}$ at $x = 1.400 \mu\text{m}$. Output Port-2 is placed on the opposite side (at $x = -1.400 \mu\text{m}$) from $y = -0.125 \mu\text{m}$ to $y = 0.125 \mu\text{m}$.

Four different fitness functions, namely Fitness Function-1 (FF-1), Fitness Function-2 (FF-2), Fitness Function-3 (FF-3), and Fitness Function-4 (FF-4), are defined as

$$\text{FF-1} = \text{Max}(\text{DF}_1) - \text{Mean}(\text{UF}_1) - \text{Mean}(\text{UF}_2) \quad (4.5)$$

$$\text{FF-2} = \text{Max}(\text{DF}_1) - \text{Max}(\text{UF}_1) - \text{Mean}(\text{UF}_2) \quad (4.6)$$

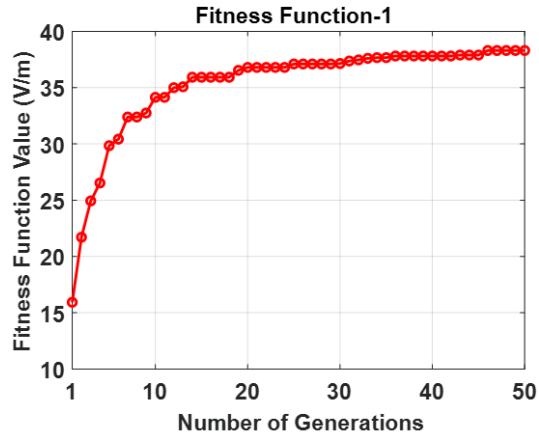
$$\text{FF-3} = \text{Max}(\text{DF}_1) / \text{Max}(\text{UF}_2) \quad (4.7)$$

$$\text{FF-4} = \text{Max}(\text{DF}_1) - \text{Max}(\text{UF}_2) \quad (4.8)$$

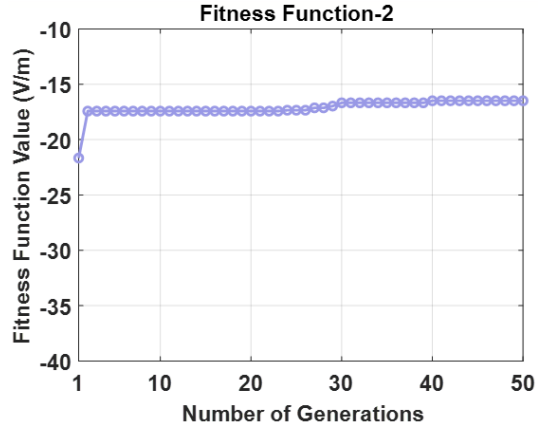
for the optimization of the optical isolator. Here, DF_1 is the electric field intensity value (V/m) at Output Port-1, while UF_1 is the electric field intensity values (V/m) at the undesired output regions when the isolator is excited with CSPB-1. In addition, UF_2 is the near-zone electric intensity value (V/m) at Output Port-2 when the isolator is excited with CSPB-2.

Using the fitness functions defined above, a 10×10 dielectric rod array is designed with on/off optimization. The dielectric rods in the previous nano-optical coupler designs, i.e., rods made of Si_3N_4 in the shape of prism with $150 \text{ nm} \times 150 \text{ nm} \times 2850 \text{ nm}$ dimensions are used. The rod array is again centered at the origin. Simulation and optimization parameters other than the positions of CSPB sources and output ports are kept the same as those listed in Table 4.1.

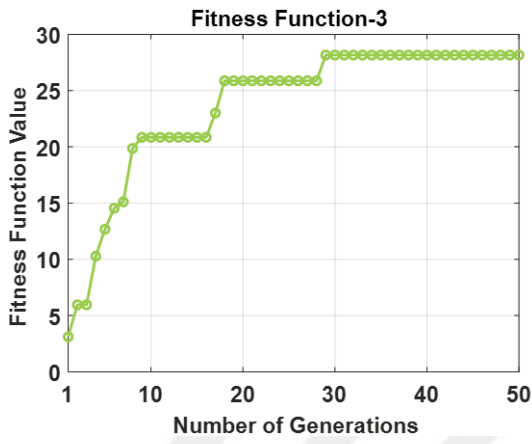
In Figure 4.17, the values of fitness functions are plotted with respect to generations for the design of the nano-optical isolator, when the maximum number of generations is fixed as 50.



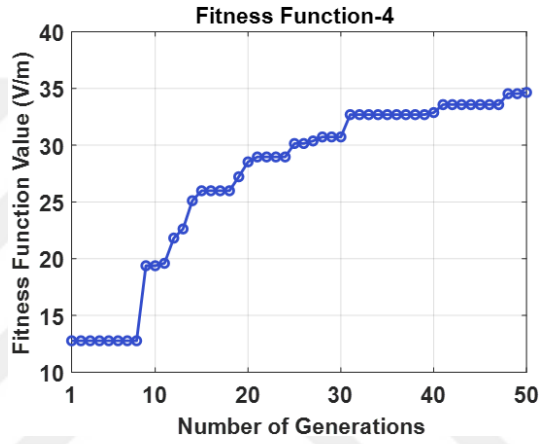
(a) Fitness Function-1



(b) Fitness Function-2



(c) Fitness Function-3



(d) Fitness Function-4

Figure 4.17: Fitness value versus generation in different optimization trials for the nano-optical isolator

According to Figure 4.17, there is no progress after some point in the optimization with FF-2, which may indicate that this fitness function is not effective. On the other hand, when FF-1, FF-3, or FF-4 is used, it is observed that the value of the fitness function is consistently improved as the generations continue, especially, in the last two cases.

In order to better compare FF-1, FF-3, and FF-4, the mean electric field intensity values obtained at Output Port-1 and Output Port-2 as optimization results are listed in Table 4.6. As shown in this table, the difference between Output Port-1 and Out-

put Port-2 of the isolator optimized with FF-1 is less than the differences obtained with the other two fitness functions. Therefore, taking the port-to-port difference into consideration, FF-1 can be assumed less successful, even though this fitness function leads to much higher intensity values at Output Port-1.

Table 4.6: The comparison of different fitness functions for nano-optical isolator optimizations

Case	Mean E-Field Intensity at Output Port-1 (dBV/m)	Mean E-Field Intensity at Output Port-2 (dBV/m)	Difference (dB)
FF-1	34.9	30.3	4.6
FF-3	26.4	3.8	22.6
FF-4	31.4	9.9	21.5

Figure 4.18 and Figure 4.19 present the near-zone electric field intensity distributions in forward and backward transmission modes of the successful isolator designs obtained with FF-3 and FF-4. These plots can be evaluated together with the values in Table 4.6.

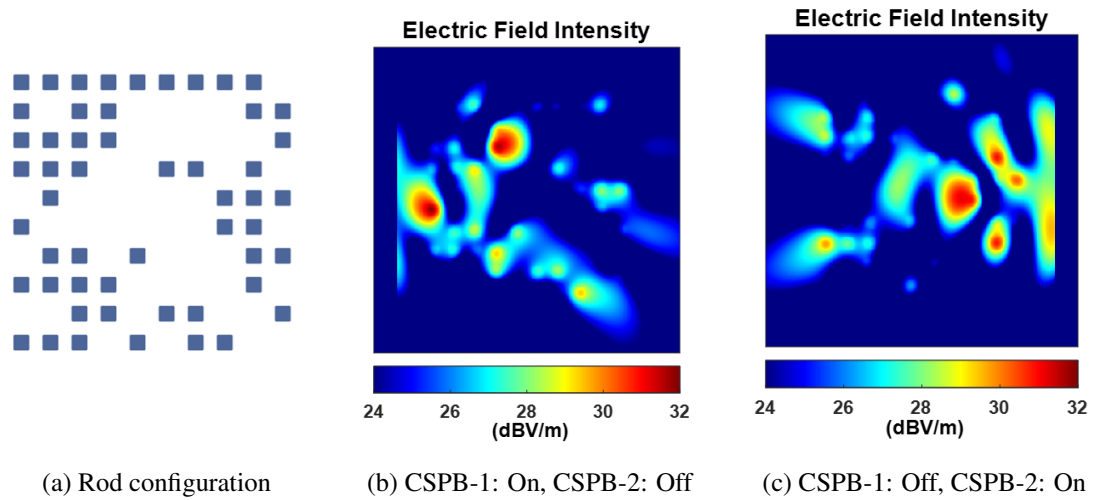


Figure 4.18: Rod configuration and near-zone electric field intensities for the nano-optical isolator optimized with FF-3

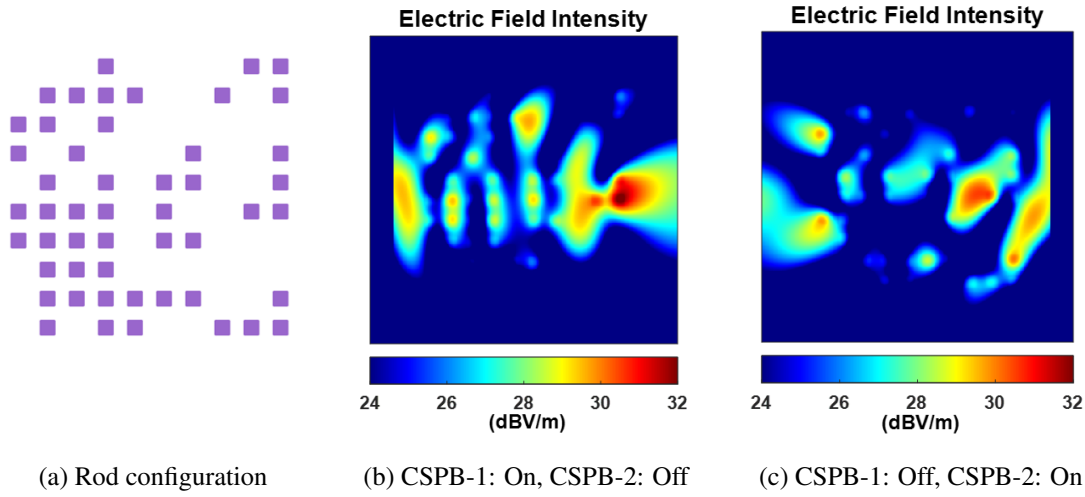


Figure 4.19: Rod configuration and near-zone electric field intensities for the nano-optical isolator optimized with FF-4

For the isolator designed with FF-3, the electric field is successfully directed to Output Port-1, while being minimized at other output regions in the forward-transmission mode. It is also the best nano-optical isolator in terms of the difference between the values of the electric field intensity at the ports in forward and backward transmissions. FF-3 also results in the lowest backward transmission; but FF-4 provides the highest electric field intensity at Output Port-1 in the forward-transmission case, while the forward-backward margin created by this isolator is only 1.1 dB less than that created by FF-3. Therefore, for nano-optical transmission applications requiring high forward transmission, the isolator designed with FF-4 is more preferable, while FF-3 can be more useful for applications that require lower backward transmission.

4.10 Design and Improvement of Nano-Optical Coupler Designs with Length Optimization

Up to this part of the thesis, rod arrays consisting of identical dielectric rods are used within on/off optimization to achieve nano-optical coupler structures that provide the best performances in terms of desired electromagnetic characteristics. The effects of some parameters, such as material, spacing between rods, and cross sectional geome-

try, on the performances of these successfully designed structures are examined. One of the most important parameters affecting the transmission efficiency of nano-optical couplers is the length of the dielectric rods used. Since a physical beam, such as represented by a CSP, has a 3D radiation, dramatic effects of rod heights to the response of a structure is plausible and predictable.

Table 4.7: Parameters and their specifications in length optimization

Optimization Parameters	Specifications
Optimization Type	Length Optimization
Number of Generations	100
Material of Dielectric Rods	Si_3N_4 ($\epsilon_r = 4$ and $\mu_r = 1$)
Dimensions of Rod-1	150 nm $\times$ 150 nm $\times$ 1500 nm (Square Prism)
Dimensions of Rod-2	150 nm $\times$ 150 nm $\times$ 2000 nm (Square Prism)
Dimensions of Rod-3	150 nm $\times$ 150 nm $\times$ 2500 nm (Square Prism)
Dimensions of Rod-4	150 nm $\times$ 150 nm $\times$ 3000 nm (Square Prism)
Spacing Between Dielectric Rods	150 nm
Numerical Solver	MLFMA
Formulation	JMCFIE
Mesh Size	$\lambda/10$
Iterative Solver	GMRES
Residual Error	0.001

In this part of the study, we make the length of the rods an optimization parameter to further improve the performances of the designs towards compact nano-optical couplers. Specifically, in length optimization trials, we aim to design nano-optical logic-gate couplers, as well as to improve the couplers designed previously via on/off optimization alone. The major parameters in these length optimization trials are summarized in Table 4.7.

Details of length optimization and descriptions on how it works are given in Chapter 3. To summarize briefly here, we again consider the 10×10 dielectric rod array used previously in on/off optimization, while the length of each rod of this array is now

an optimization parameter. To do this, four different rod lengths are determined, i.e., 1500 nm (Rod-1), 2000 nm (Rod-2), 2500 nm (Rod-3), and 3000 nm (Rod-4). In other words, discrete rod lengths are used, corresponding to minimum 1λ and maximum 2λ . Each rod length is represented by an integer, i.e., 1500 nm, 2000 nm, 2500 nm, and 3000 nm correspond to 1, 2, 3, and 4, respectively, while 0 corresponds to the absence of any rods. Thus, a 10×10 matrix that consists of various elements with values 0, 1, 2, 3, and 4 represents a possible design involving rods with different lengths. As usual, in a length optimization, the design with the highest fitness function value, i.e., the most successful one, is selected among such alternative designs.

4.10.1 Nano-Optical Logic-Gate Couplers

Logic gates are structures that possess various transmission properties for logic operations on different excitations. Designing efficient logic-gate couplers is essential in many nano-optical systems especially for all-optical systems, since all components in such systems should successfully operate with high speeds. A designed nano-optical logic-gate coupler must meet the transmission condition for each excitation case in order to be a successful design. In this study, nanometer-sized, compact, and effective optical logic-gate couplers are aimed to be designed and constructed by using only dielectric rods.

For the design of both AND and OR logic-gate couplers, the dielectric rod array is centered at the origin and CSPB-1 is placed at $x = (-1.875 - 5i) \mu\text{m}$, $y = 0 \mu\text{m}$, $z = 0 \mu\text{m}$ in the complex coordinates with a polarization in the z direction, while CSPB-2 is placed at $x = 0 \mu\text{m}$, $y = (-1.875 - 5i) \mu\text{m}$, $z = 0 \mu\text{m}$ in the complex coordinates with the same polarization. Output Port-1 is located at the right edge of the array from $y = -0.125 \mu\text{m}$ to $y = 0.125 \mu\text{m}$ at $x = 1.400 \mu\text{m}$.

4.10.1.1 Nano-Optical AND Logic-Gate Coupler

The desired transmission conditions for an AND logic-gate coupler are summarized in Table 4.8. When an AND logic-gate coupler is excited by two input sources, CSPB-1 and CSPB-2, the electric field intensity value must be high at the output (Output

Port-1), while it must be low when only one of input sources exists or when there is no input source at all.

In Table 4.8, the definitions of "high" and "low" are decided by investigating the difference between the values for different excitation scenarios.

Table 4.8: AND logic-gate coupling conditions

CSPB-1	CSPB-2	Electric Field Intensity at Output Port-1
On	Off	Low
Off	On	Low
On	On	High
Off	Off	None

In this study, to be considered "high" when both of the sources exist, we expect that the electric field intensity at Output Port-1 to be at least 3 dB greater than the same value at the same location when only one of the sources exists. To enforce this condition, the fitness function is defined as

$$\text{Fitness Function} = (\min(\text{Output}_1) - \max(\text{Output}_2 + \text{Output}_3)). \quad (4.9)$$

Here, we have the following definitions.

Output₁: Electric field intensity along Output Port-1 when both CSPB-1 and CSPB-2 exist

Output₂: Electric field intensity along Output Port-1 when only CSPB-1 exists

Output₃: Electric field intensity along Output Port-1 when only CSPB-2 exists

At the end of 100 generations, the AND logic-gate coupler with the highest fitness value is obtained. Figure 4.20 shows the matrix representation and the rod configuration of the optimized array.

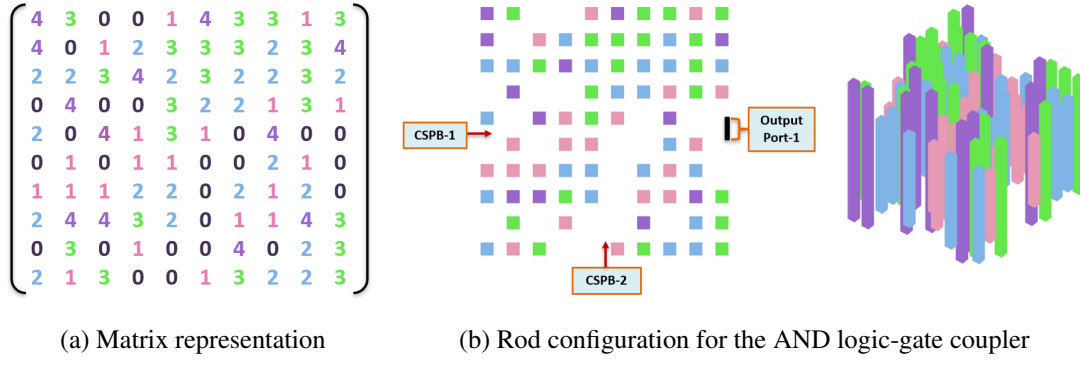


Figure 4.20: Optimized nano-optical AND logic-gate coupler

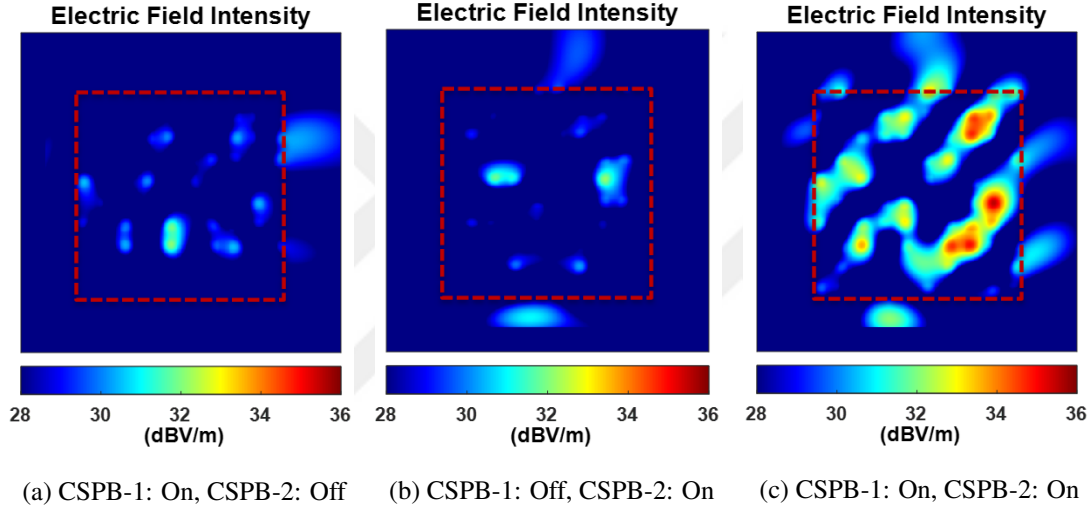


Figure 4.21: Near-zone electric field intensity distributions for the designed nano-optical AND logic-gate coupler

The near-zone electric field intensity distributions for the designed coupler in response to single and double inputs are plotted in Figure 4.21. According to these results, the mean electric field intensity value at Output Port-1 is 26.5 dBV/m when there is only CSPB-1 and 18.7 dBV/m when there is only CSPB-2. On the other hand, the value of the intensity at the output becomes 29.7 dBV/m when both CSPB-1 and CSPB-2 exist. Accordingly, the field intensity value when both input sources are present is even higher than the direct sum of the intensity values obtained with single inputs, indicating that the AND logic-gate coupler meets the operation requirements.

4.10.1.2 Nano-Optical OR Logic-Gate Coupler

The expected transmission conditions for an OR logic-gate coupler are summarized in Table 4.9. When an OR logic-gate coupler is excited by at least one of the two input sources, CSPB-1 and CSPB-2, the electric field intensity value must be high at the output (Output Port-1).

Table 4.9: OR logic gate coupling conditions

CSPB-1	CSPB-2	Electric field intensity at Output Port-1
On	Off	High
Off	On	High
On	On	High
Off	Off	None

Here, "high" electric field intensity is defined as the intensity greater than that at the output port when there is no nano-optical coupler. In this study, we expect that there should be at least 5 dB difference between the cases when the nano-optical OR logic-gate coupler exists or not.

The fitness function used in the optimization of nano-optical OR logic-gate coupler is defined as

$$\text{Fitness Function} = \min(\text{Output}_1, \text{Output}_2, \text{Output}_3). \quad (4.10)$$

Here, we define the parameters as follows.

Output₁: Maximum electric field intensity along Output Port-1 when both CSPB-1 and CSPB-2 exist

Output₂: Maximum electric field intensity along Output Port-1 when only CSPB-1 exists

Output₃: Maximum electric field intensity along Output Port-1 when only CSPB-2 exists

At the end of 100 generations, the nano-optical OR logic-gate coupler with the highest fitness value is obtained. Figure 4.22 shows the rod configuration of the optimized

array, while near-zone electric field intensity distributions for single and double inputs are plotted in Figure 4.23.

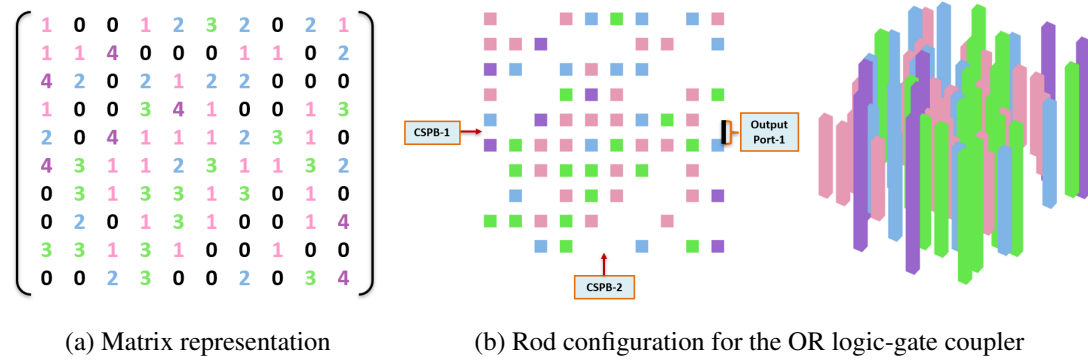


Figure 4.22: Optimized nano-optical OR logic-gate coupler

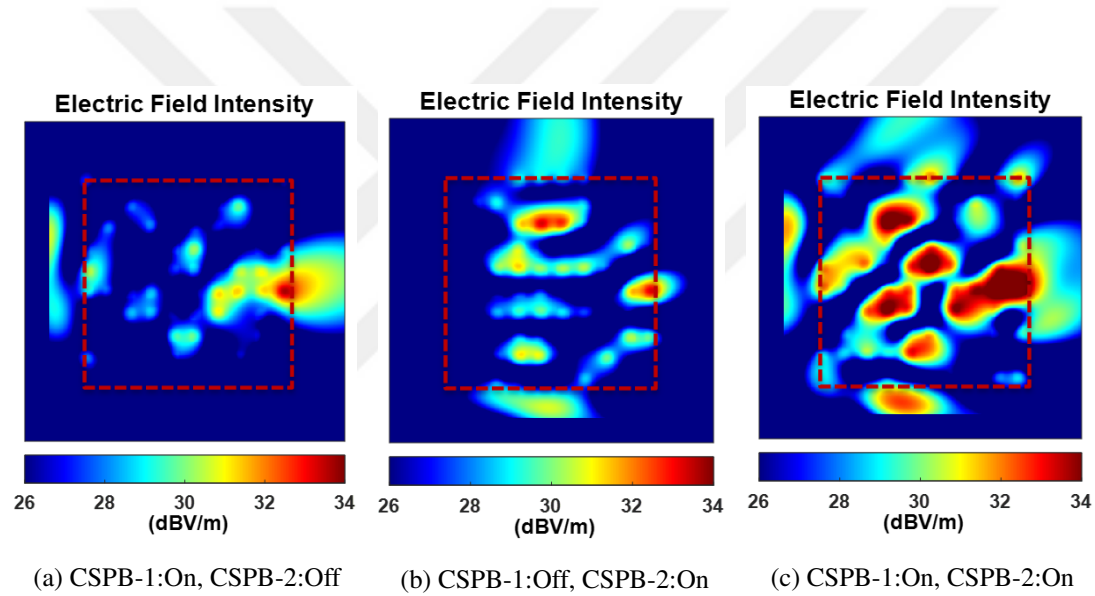


Figure 4.23: Near-zone electric field intensities for nano-optical OR logic-gate coupler

Table 4.10 summarizes the mean nearfield electric field intensity values obtained by the designed OR logic-gate coupler, where the values obtained with the coupler are compared to those without the coupler. According to these results, the mean electric field intensity value at Output Port-1 is 32.3 dBV/m when there is only CSPB-1, 30.7 dBV/m when there is only CSPB-2, and 34.8 dBV/m when both CSPB-1 and CSPB-2 exist. While all these values are much larger than the corresponding values without

the coupler, it is also remarkable that any of two single-source cases with the coupler leads to a higher intensity value than the double-source case without the coupler.

Table 4.10: The mean electric field intensity at Output Port-1 for the OR coupler

Cases	With Coupler (dBV/m)	Without Coupler (dBV/m)
CSPB-1	32.3	26.1
CSPB-2	30.7	20.9
CSPB-1 and CSPB-2	34.8	29.0

4.10.2 Forward-Transmitting Nano-Optical Coupler

Using length optimization, the designs of forward-transmitting nano-optical couplers considered earlier are aimed to be improved. Simulation and optimization parameters are the same as those listed in Table 4.7. The goal of the length optimization is to create an array of 10×10 dielectric rods with different lengths in order to direct the electromagnetic wave from a CSPB source to Output Port-1 shown in Figure 4.16a.

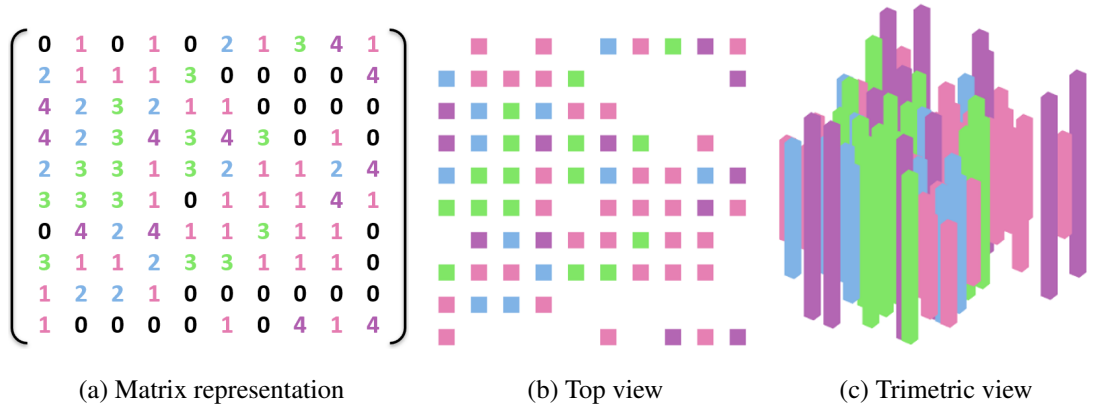


Figure 4.24: Matrix representation and the resulting forward-transmitting coupler design obtained via length optimization

Using FF_3 in Equation 4.3, the best rod configuration is obtained after 100 generations, as described in Figure 4.24.

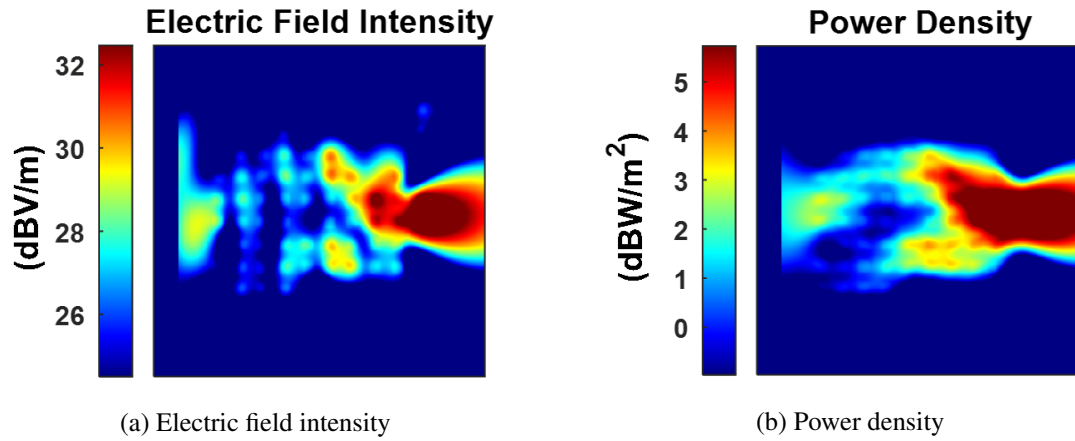


Figure 4.25: Near-zone results for the forward-transmitting coupler obtained with length optimization

Near-zone electric field intensity and power density distributions for the forward-transmitting coupler obtained by length optimization are given in Figure 4.25.

Comparing the new forward-transmitting coupler design with the previously designed one obtained via on/off optimization, it can be said that the length optimization provides a better design. Numerical comparisons of the electric field intensity values are listed in Table 4.11. According to these results, changing the rod lengths clearly improves the design as the mean electric field intensity at the output is increased to 35.7 dBV/m and the difference between the mean electric field intensity values at Output Port-1 and undesired output regions is increased to 15.1 dBV/m.

Table 4.11: Comparison of on/off optimization and length optimization to design forward-transmitting couplers

Case	Mean E-Field Intensity at Output Port-1 (dBV/m)	Mean E-Field Intensity at Output Port-2 (dBV/m)
On/off Optimization	34.4	20.0
Length Optimization	35.7	20.6

4.10.3 90-Degree Nano-Optical Coupler

Length optimization is also used to improve the design of 90-degree nano-optical coupler obtained previously by on/off optimization. The CSPB source and output port (Output Port-2) is positioned as in the previous case illustrated in Figure 4.6b. It is aimed to create an array of 10×10 dielectric rods with different lengths such that the structure directs the electromagnetic wave from the CSPB source to Output Port-2, i.e., maximizes port, using the optimization parameters given in Table 4.7 For this purpose, FF_3 in Equation 4.3 is used, and the matrix representation and the corresponding rod configuration for the optimal design are achieved after 100 generations which are given Figure 4.26.

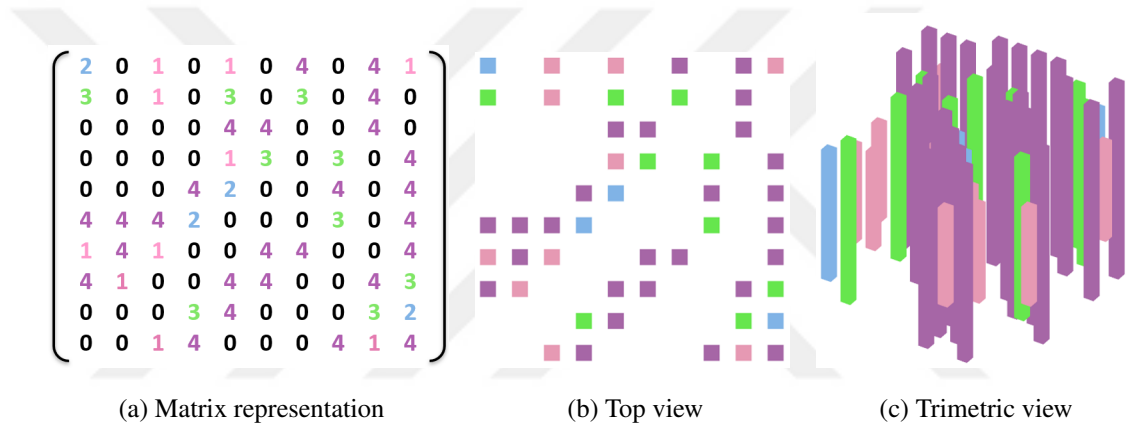


Figure 4.26: Matrix representation and the resulting 90-degree coupler design obtained via length optimization

Near-zone electric field intensity distributions for length optimization are given in Figure 4.27. As can be seen from this plot, the design of 90-degree nano-optical coupler obtained with length optimization guides the electromagnetic wave better. Numerical comparison of the designs obtained with the on/off and length optimization are summarized in Table 4.12. Applying length optimization, the mean electric field intensity at Output Port-2 is increased to 34.4 dBV/m, while the mean electric field intensity in the undesired output regions is 22.7 dBV/m resulting in a difference of 11.7 dB. Accordingly, allowing change in rod lengths contributes to the improvement of the design.

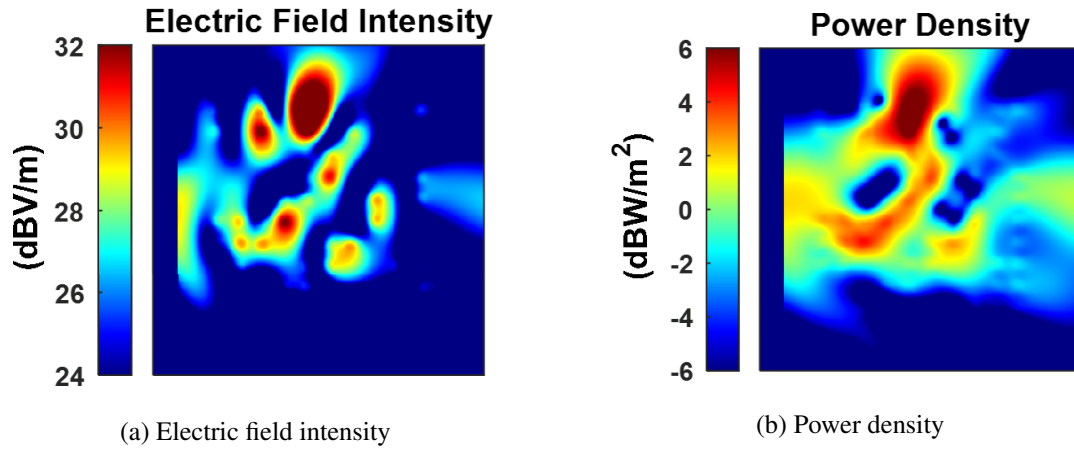


Figure 4.27: Near-zone results for the 90-degree coupler obtained with length optimization

Table 4.12: The comparison of on/off and length optimization trials to design 90-degree nano-optical couplers

Case	Mean E-Field Intensity at Output Port-2 (dBV/m)	Mean E-Field Intensity at Output Port-2 (dBV/m)
On/off Optimization with FF ₃	33.8	22.2
Length Optimization with FF ₃	34.4	22.7

4.10.4 Nano-Optical Isolator

Applying length optimization, it is further aimed to design a nano-optical isolator, which may perform better than the isolators previously designed with on/off optimization. What is expected from the length optimization is to achieve higher electric field intensity at the output port in forward direction, while the transmission is desired to be low in the backward direction. At the end of 100 generations, the optimized rod configuration along with the relevant matrix representation obtained by length optimization are shown in Figure 4.28.

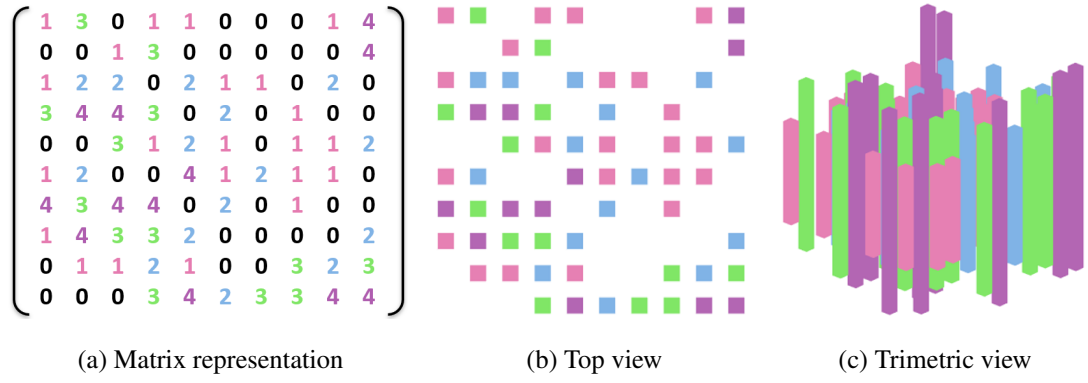


Figure 4.28: Optimized matrix representation and the resulting nano-optical isolator design

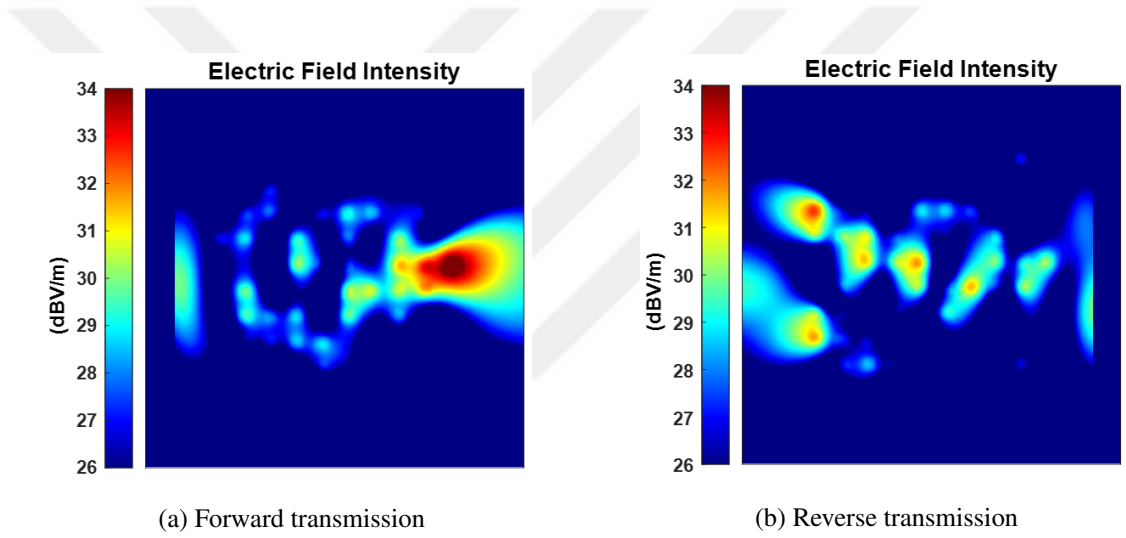


Figure 4.29: Near-zone electric field intensity distributions for the nano-optical isolator obtained via length optimization

In Figure 4.29, the near-zone electric field intensity distributions for the designed nano-optical isolator in forward and backward directions are given. For the optimal isolator designed by the length optimization, the mean electric field intensity at Output Port-1 in the forward transmission is 33.8 dBV/m. The mean electric field intensity at Output Port-2 in the backward direction is 16.4 dBV/m. Numerical comparisons with the previously designed nano-optical isolators via on/off optimization verify that the length optimization provides a higher forward transmission, increas-

ing the mean electric field intensity by 32%. The difference between forward and backward transmissions become 17.4 dB, which means that the forward transmission is about 7.4 times the backward transmission, still satisfying our condition for difference between forward and backward transmissions.

4.10.5 Double-Input Nano-Optical Coupler

Finally, length optimization is used to design a double-input nano-optical coupler, which again operates more efficiently than the corresponding structure designed with on/off optimization. Two CSPB sources are located as shown in 4.14a. The aim is to maximize the electric field intensity at Output Port-1 shown in the same figure.

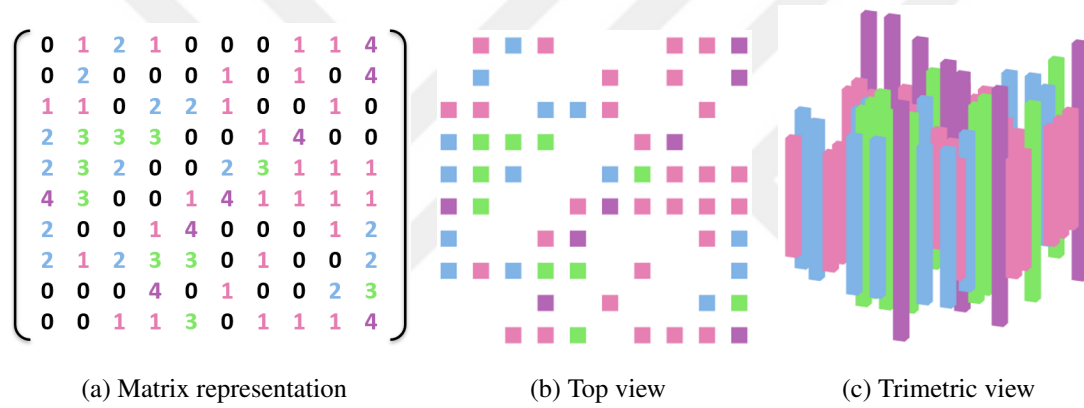


Figure 4.30: Optimized matrix representation and the resulting double-input nano-optical coupler

At the end of 100 generations, the optimized rod configuration and the corresponding matrix representation obtained by length optimization are shown in Figure 4.30.

The near-zone electric field intensity distributions for the double-input nano-optical coupler designed by length optimization are given in Figure 4.31. The mean electric field intensity at Output Port-1 is 38.4 dBV/m, while the mean electric field intensity in undesired output regions is 25.5 dBV/m. Comparing numerical results with those obtained by the previously designed double-input coupler via on/off optimization, we confirm that the length optimization provides higher transmission to Output Port-1.

Moreover, the difference between the mean electric field intensity at Output Port-1 and the mean electric field intensity in undesired output regions is higher when length optimization is performed.

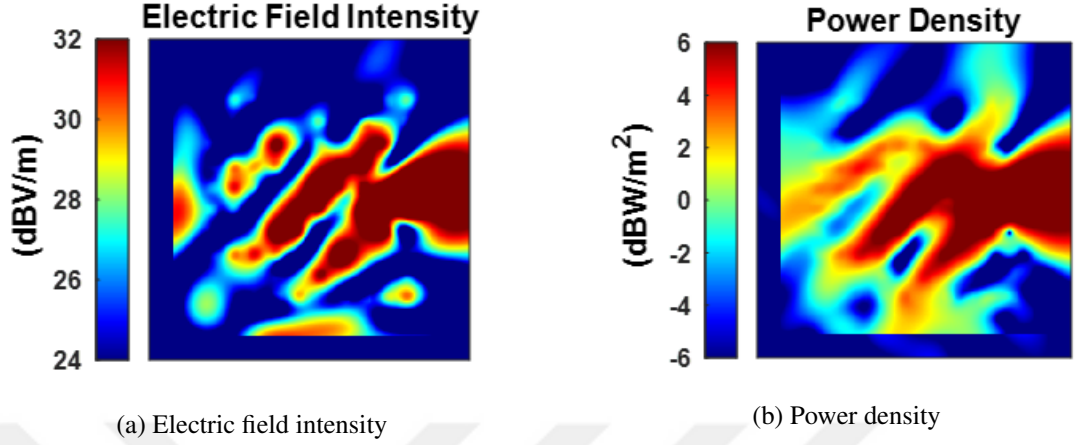


Figure 4.31: Near-zone results for the double-input nano-optical coupler obtained with length optimization

4.11 Concluding Remarks

This chapter was dedicated to design and analysis of nano-optical couplers based on photonic crystals consisting of dielectric rods arranged in array forms. As remarkable results of on/off optimization of a 10×10 dielectric rod array, nano-optical couplers that support transmission of electromagnetic waves in a desired direction and suppress waves in undesired regions can be designed. We showed that success of optimization trials depends on initial experiments involving proper selections of fitness functions and other parameters. As the first set of designs, a forward-transmitting coupler and a 90-degree coupler were designed and investigated. The effects of parameters, such as material, spacing between rods as well as the shape of the rods, on the efficiency of nano-optical couplers were examined. It was also shown that electromagnetic transmission systems can be created by cascading these designs. In addition to single-input nano-optical couplers, double-input couplers were also designed to be used at junction locations in nano-optical systems. Furthermore, nano-optical AND and OR logic-gate coupler designs were shown to be possible to obtain with the pro-

posed design approach. Nano-optical isolators that transmit electromagnetic waves in the forward direction but do not transmit them in the backward direction were also designed. Finally, length optimization was introduced to improve the designs by making the lengths of the rods parameters of optimization trials. As demonstrated via numerous results, length optimization leads to more efficient and effective designs in all types of applications.



CHAPTER 5

DESIGN AND OPTIMIZATION OF NANO-OPTICAL ABSORBERS

In this part of the thesis, nano-optical absorbers are designed using photonic crystals, and the effects of some parameters on the efficiency of these designs are examined. The designed absorbers are expected to confine the incoming power within themselves, while providing low backscattering values. The electromagnetic power trapped by the absorber can be harvested for various purposes. At the same time, minimized backward reflections are crucial in a plethora of applications, including nano-optical systems, where such reflections must be minimized to avoid interference of signals, minimize overheating of sources, and improve the efficiency of components. The range of operating frequencies for nano-optical absorbers in this study is selected from 500 THz to 600 THz. The reason for this selection is that we aim to design nano-optical absorbers not only to absorb incoming waves from lasers in nano-optical systems, but also to be used in solar cells. When the solar radiation spectrum is examined, it can be observed that the solar energy peaks at around 500 nm, which corresponds to 600 THz in frequency [37]. In addition, lower side of this peak requires novel technologies to improve the absorption rate and benefit from the solar radiation as much as possible.

To date, different nano-optical absorber designs containing metallic and dielectric structures have been realized [38–41]. Nano-optical absorber designs with metal-dielectric-metal layers form Fabry-Perot-type cavities, which are among the most commonly used structures; but, these structures are usually difficult to fabricate as they require the use of several different materials as intermediate layers, leading to rather complex designs [42–44]. In this study, our aim is to realize designs with only two types of layers and two materials but that can effectively absorb power and op-

erate in a frequency band up to 100 THz. Such an absorber that we propose consists of an optimized ARC based on photonic crystals and a metal plate at the bottom. By combining ARC with the metal plate, both an anti-reflective, while absorbing structure is obtained and the effects of some parameters are further observed by a detailed analysis on the structure.

To design photonic-crystal-based ARCs, air holes are drilled on silicon dielectric slabs. Silicon is selected as the substrate because it is the most widely used dielectric material in nano-optical systems, widely available, low-cost, and also suitable to build structures with different geometries [45]. For metal plates under the designed ARCs, tungsten is selected as the material due to its high melting temperature and low thermal expansion. Resistance to high temperatures is particularly essential considering nano-optical absorbers.

First, given the dimensions and positioning in Figure 5.1a, a tungsten plate is examined alone. The plate covers an area from $x = -0.475 \mu\text{m}$ and $y = -0.475 \mu\text{m}$ to $x = 0.475 \mu\text{m}$ and $y = 0.475 \mu\text{m}$ in x - y plane, while having a height of 20 nm in the z direction. Then, the combination of the tungsten plate with a silicon slab is examined. The slab also extends from $x = -0.475 \mu\text{m}$ and $y = -0.475 \mu\text{m}$ to $x = 0.475 \mu\text{m}$ and $y = 0.475 \mu\text{m}$ in x - y plane, while having a height of 200 nm in the z direction. The tungsten plate is positioned at the bottom of the silicon slab in Figure 5.1b. The Lorentz-Drude model is used to determine the relative permittivity of tungsten in the frequency range of operations. Specifically, tungsten has a complex refractive index in the interested frequency range; while the real part has a significant impact on the reflection and refraction characteristics, the imaginary part, called extinction coefficient, determines absorption properties as it defines how much attenuation occurs in the material. The real and imaginary parts of the permittivity of the tungsten with respect to frequency were previously given in Figure 2.4. For silicon, although there are slight changes in its relative permittivity in the interested frequency range, it is generally assumed to be 12.0 at all frequencies. Both the isolated tungsten plate and the combination of the tungsten plate with the silicon slab are excited by a plane wave (from 500 THz to 600 THz) with an amplitude of 1 V/m. All important details about the simulations are provided in Table 5.1.

Table 5.1: Simulation parameters and their specifications

Simulation Parameters	Specifications
Material of Dielectric Slab	Silicon ($\varepsilon_r = 12$ and $\mu_r = 1$)
Material of Metal Plate	Tungsten
Dimensions of Dielectric Slab	950 nm $\times$ 950 nm $\times$ 200 nm
Dimensions of Metal Plate	950 nm $\times$ 950 nm $\times$ 20 nm
Frequency	500-600 THz
Excitation Source	Plane Wave (1 V/m)
Numerical Solver	MLFMA
Formulation	MCTF
Mesh Size	27 nm
Iterative Solver	GMRES
Residual Error	0.0001

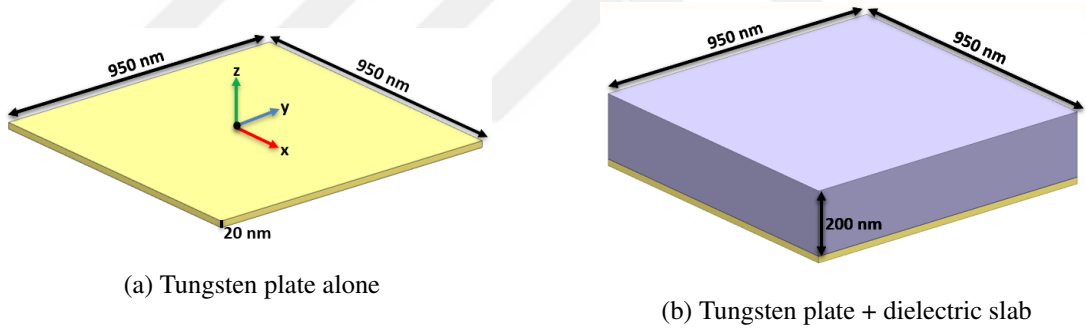
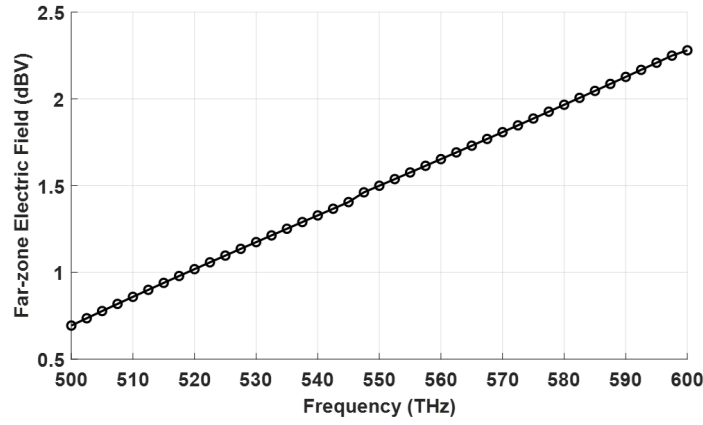


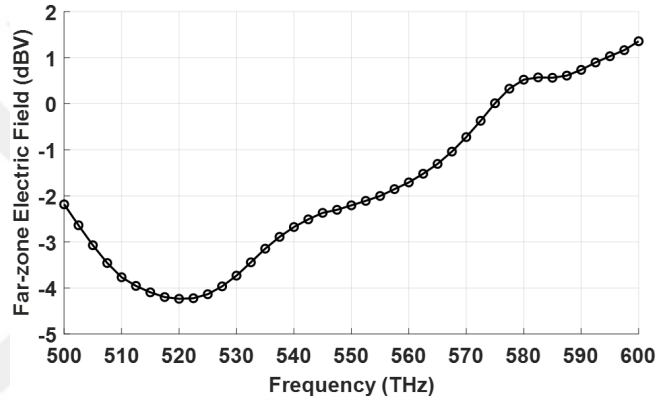
Figure 5.1: Tungsten plate (left) and the combination of the plate with a dielectric slab

Figure 5.2 presents far-zone backscattering results for both models when they are illuminated by plane waves polarized in the x direction and propagating in the $-z$ direction. According to these results, the silicon slab placed on top of the tungsten plate reduces the backward reflection at some frequencies; but, this reduction is not sufficient as it is for a limited frequency range. Hence, simply placing a dielectric slab has very limited effects on the absorption characteristics, and well-designed structures

are needed, as detailed in the next sections.



(a) Tungsten plate alone



(b) Tungsten plate + dielectric slab

Figure 5.2: Backscattered electric field in the far zone for a tungsten plate and for its combination with a dielectric slab

5.1 Initial Nano-Optical Absorber Design

To be used instead of a flat silicon slab, photonic-crystal-based ARCs are designed by drilling air holes into the slab to reach an effective nano-optical absorber design that can both reduce backscattering and increase internal power density enhancement. Air holes in the shape of square prisms with 80 nm edge lengths and 100 nm depths are created in the initial design, as shown in Figure 5.3. These air holes are positioned periodically at 190 nm intervals. Excitation is the same as the previous case, which

is a plane wave propagating in the $-z$ direction and polarized in the x direction. The same excitation is used also for all designs.

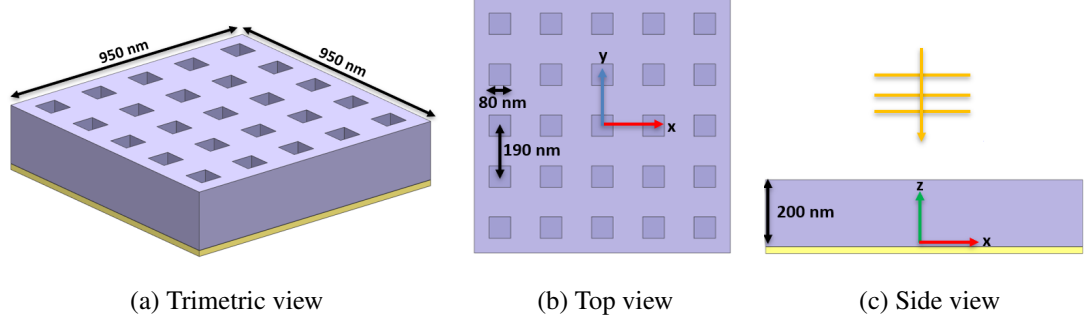


Figure 5.3: Tungsten plate + ARC geometry

The far-zone backscattered electric field intensity with respect to frequency for the initial nano-optical absorber is plotted in Figure 5.4a. When these results are compared with those obtained for the tungsten plate and silicon slab in Figure 5.2, we observe that the structure with ARC is more effective, as it leads to lower backscattering values at all frequencies. As we also expect the nano-optical absorber to maximize the internal power density, the maximum power density enhancement for the initial design is given in Figure 5.4b. At each frequency, the power density enhancement is calculated as

$$\text{Power Density Enhancement}(\mathbf{r}) = \frac{|\mathbf{E}(\mathbf{r}) \times [\mathbf{H}(\mathbf{r})]^*|}{|\mathbf{E}^{\text{inc}}(\mathbf{r}) \times [\mathbf{H}^{\text{inc}}(\mathbf{r})]^*|}, \quad (5.1)$$

where $\mathbf{E}^{\text{inc}}$ and $\mathbf{H}^{\text{inc}}$ are incident electric field intensity and magnetic field intensity, respectively while $\mathbf{E}(\mathbf{r})$ and $\mathbf{H}(\mathbf{r})$ are the total electric field intensity and magnetic field intensity values at the observation point $\mathbf{r}$. Equation 5.1 is calculated everywhere inside the ARC and the maximum of it is plotted in Figure 5.4b.

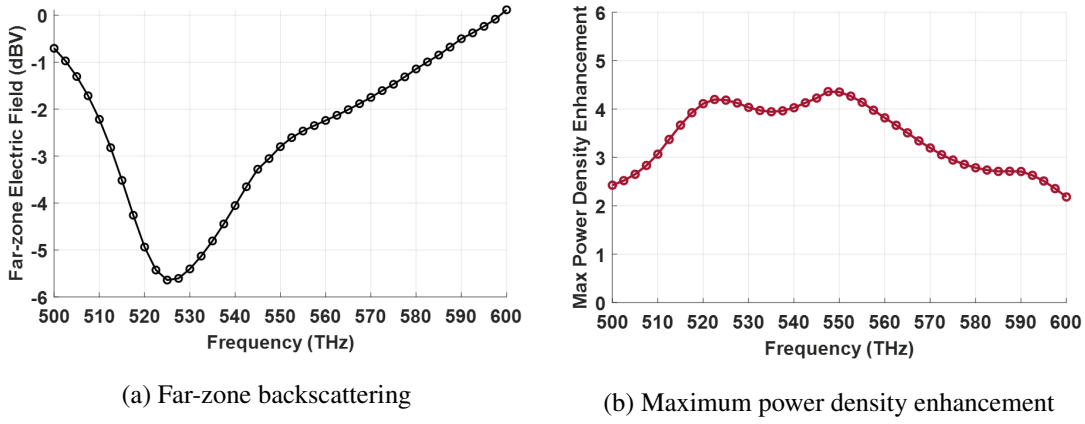


Figure 5.4: Backscattered electric field intensity in the far zone and the maximum power density enhancement for the initial nano-optical absorber design

To better understand how the designed nano-optical absorber works, where the power density is larger, and where it is smaller, 2D near-zone power density enhancement plots at five different frequencies are visualized in Figure 5.5. As the frequency samples, 510 THz, 530 THz, 550 THz, 570 THz, and 590 THz are selected to reach a general idea in the entire frequency range. Near-zone field intensity calculations are performed in a rectangular area extending from $x = -1500$ nm and, $y = -1500$ nm to $x = 1500$ nm and $y = 1500$ nm. Investigating the results in Figure 5.5, we observe that the frequencies at which the nano-optical absorber operates best are 530 THz and 550 THz, since the power density enhancement is required to be high inside the absorber while it should be low as much as possible outside. These results are consistent with Figure 5.4b, where the maximum power density enhancement is obtained at around 547.5 THz. At the same time, Figure 5.4a shows that the backscattered electric field intensity remains below -3 dBV in the frequency range from 522.5 THz to 570 THz. Hence, in this particular frequency range, both the power density in the nano-optical absorber is high, the power density outside is low, and the backward reflection is low. However, this initial nano-optical absorber design needs to be improved so that it can operate in a wider range of frequency, while absorbing electromagnetic waves more effectively. For this purpose, various parameters are considered in the next design stages, and it is aimed to achieve the best design with the available materials.

In general, we want incoming waves to be efficiently transmitted into the nano-optical absorber with minimum reflection in a way that the waves propagating into the ARC may constructively interfere with each other, while the reflected waves destructively interfere. Hence, the modifications onto the photonic crystal structure should be in a way to support these requirements.

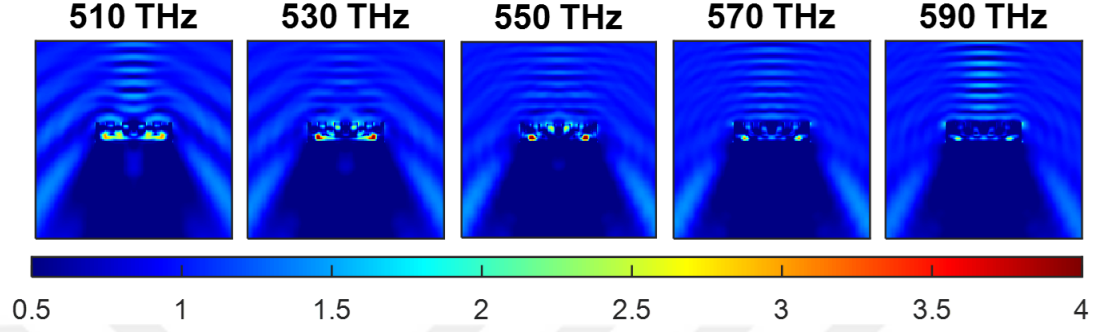


Figure 5.5: Power density enhancement for the initial nano-optical absorber design

5.1.1 Effect of Air Holes' Width

The width of square prism air holes in photonic-crystal ARC is changed from 80 nm to 120 nm and 160 nm to examine the effect of the hole width on the reflection and absorbance characteristics of the structure. The resulting geometries with modified hole widths are presented in Figure 5.6. The depth of holes are kept at 100 nm, while the same tungsten plate is placed below these ARCs.

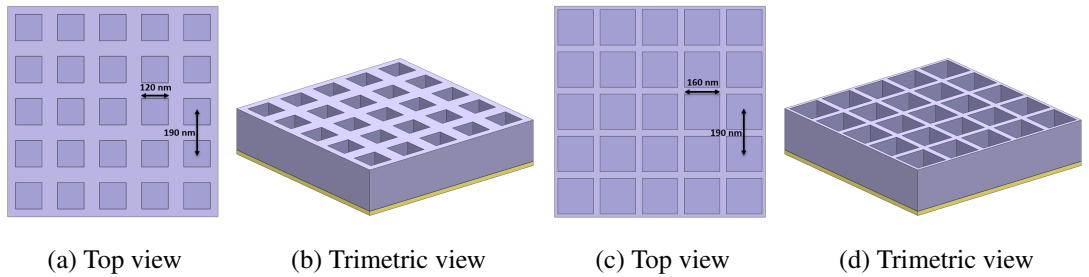


Figure 5.6: Nano-optical absorbers involving holes with 120 nm (left) and 160 nm (right) edges

In Figure 5.7, backscattered electric field intensity values of the nano-optical ab-

sorbers with different hole widths are compared.

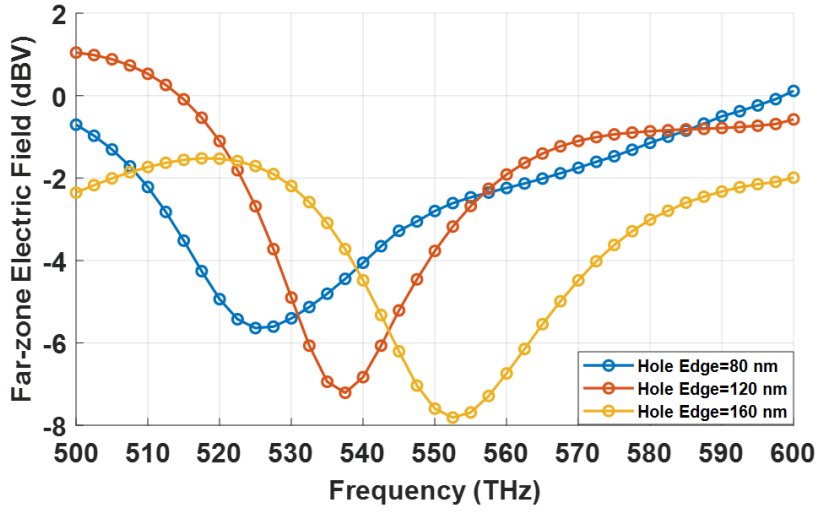


Figure 5.7: Backscattered electric field intensity in the far zone for the nano-optical absorbers with different hole widths

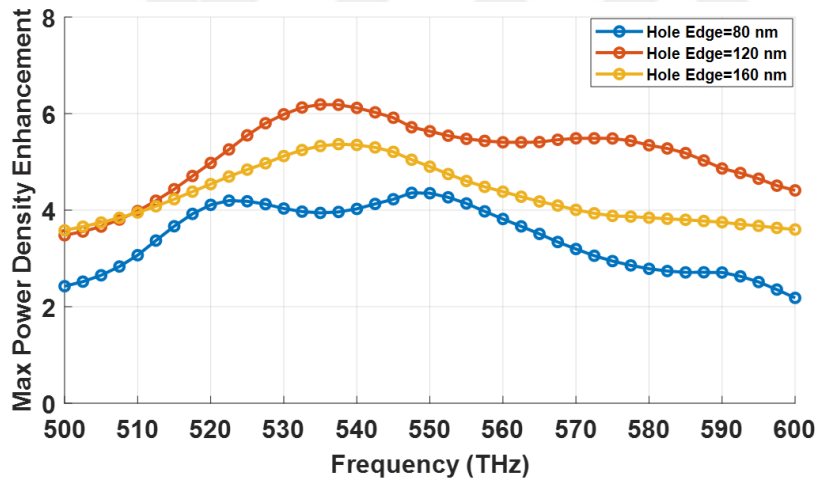


Figure 5.8: Maximum power density enhancement for the nano-optical absorbers with different hole widths

According to the plot in Figure 5.7, when the width of the air holes is 120 nm the backscattered field intensity is relatively high at the lower frequencies, while it has quite small values from 530 THz to 555 THz (e.g., in comparison to the structure with 80 nm hole width). On the other hand, when the width is 160 nm, the backscattered field intensity becomes relatively low from 540 THz to 600 THz. These conclusions

imply that the hole width significantly affects the anti-reflectivity of the nano-optical absorber, making it effective at different frequencies. The design with 120 nm holes decreases the backward reflection to -7.21 dBV at 537.5 THz, while the one with 160 nm holes achieves -7.81 dBV reflection at 552.5 THz.

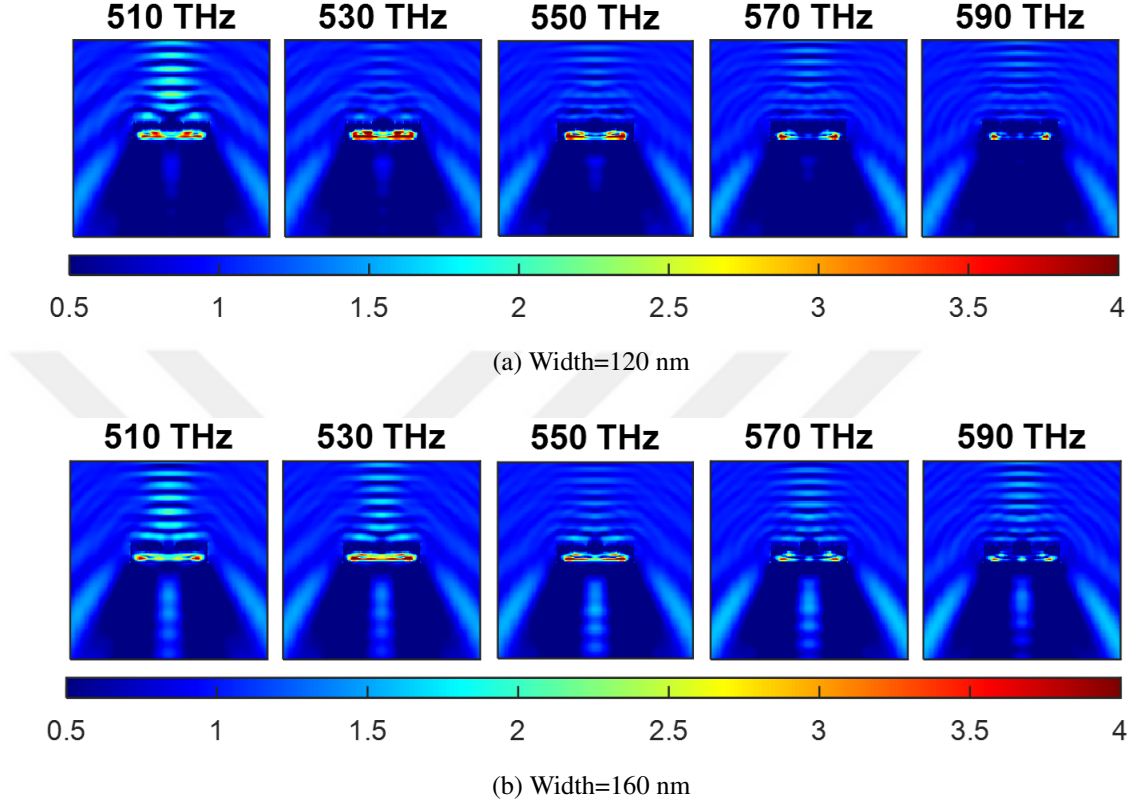


Figure 5.9: 2D near-zone power density enhancement for different widths of air holes

For the nano-optical absorbers with modified hole widths, the maximum power density enhancement values with respect to frequency are also compared in Figure 5.8. In addition, 2D near-zone power density enhancement plots are visually given Figure 5.9 at five different frequencies. As shown in Figure 5.8, the highest power density enhancement values are obtained when width is 120 nm, followed by the nano-optical absorber with 160 nm width. When both far-zone backscattering and near-zone power density enhancement values are taken into account, the design with 120 nm air holes seems to outperform the other two designs, except at the lower frequencies of the investigated range.

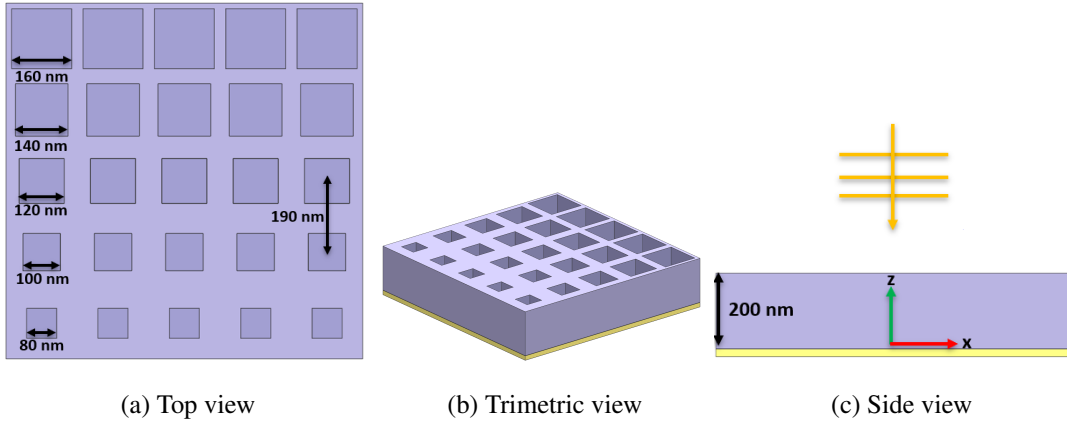


Figure 5.10: Nano-optical absorber with air holes of varying widths

After observing that changing the width of air holes has a remarkable effect on both backscattering and power density enhancement, a nano-optical absorber design with air holes of varying widths instead of fixed-width air holes is examined. Square prism air holes with widths decreasing from 160 nm to 80 nm in 20 nm steps from one side to the opposite side of the structure are opened, as shown in Figure 5.10. Other parameters are kept the same as those in the previous cases.

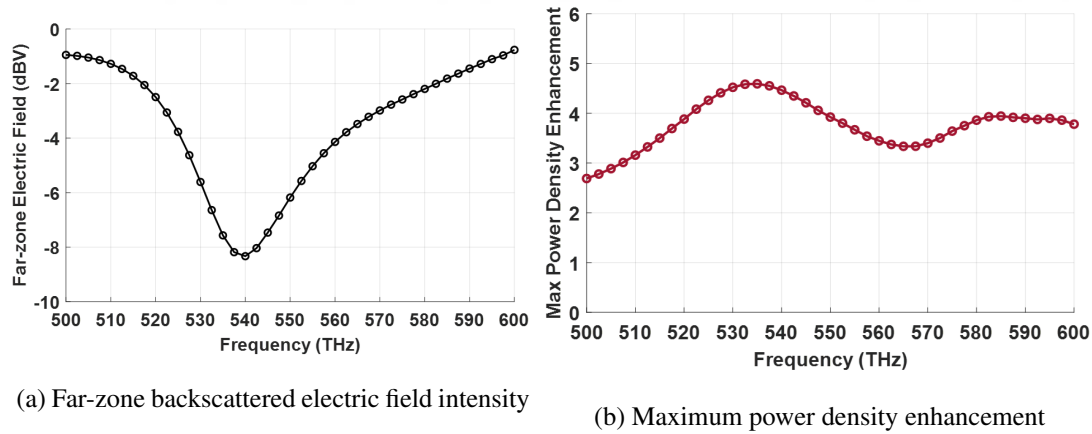


Figure 5.11: Numerical results for the nano-optical absorber with air holes of varying widths

Far-zone backscattered electric field intensity values and near-zone maximum power density enhancement values in the frequency range from 500 THz to 600 THz are

given in Figure 5.11. Using air holes of varying widths rather than fixed-width air holes leads to improvements in the backscattering values. Specifically, the backscattered electric field intensity decreases to -8.33 dBV at 540 THz. On the other hand, there is a little improvement in the maximum power density inside the nano-optical absorber compared to the previous design.

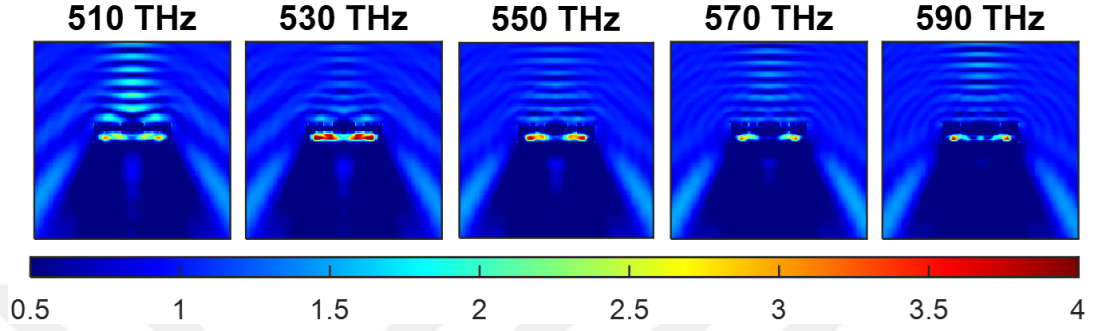
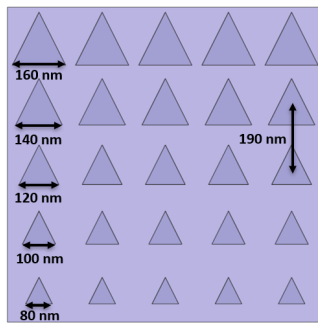


Figure 5.12: 2D near-zone power density enhancement for the optical absorber with air holes of varying widths

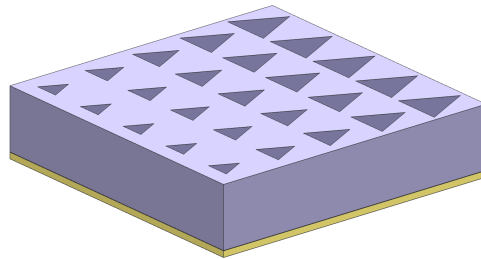
2D near-zone maximum power density enhancement plots in Figure 5.12 support the near-zone maximum power density enhancement plot. At around 540 THz, i.e., when the backscattering is low, the power density enhancement is high (reaching the maximum value of 4.59 at 535 THz), while the power density is low outside the absorber. In the following sections, further modifications are implemented on the design to improve its performance in terms of low backscattering and high power density enhancement.

5.2 Effect of Cross Section

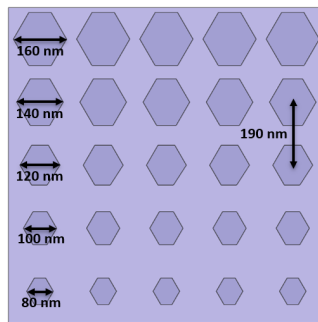
For the nano-optical absorber designs considered so far, photonic-crystal ARCs are designed by drilling square prism air holes into silicon slabs. In this part, triangular prism and hexagonal prism air holes are considered, as described in Figure 5.13.



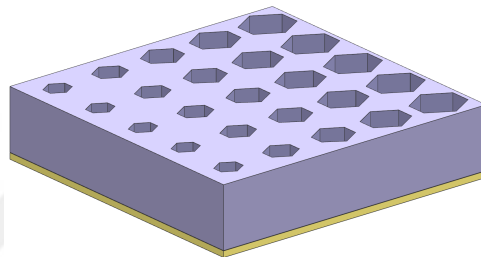
(a) Top view



(b) Trimetric view



(c) Top view



(d) Trimetric view

Figure 5.13: Nano-optical absorbers involving air holes with different cross-sectional shapes

Similar to the square air holes, the dimensions of the triangular and hexagonal air holes are reduced from top to bottom. The new designs are illuminated by plane waves and the obtained results are compared with those obtained for the design involving square air holes. This way, the effect of the cross sections of the air holes on backward reflection and power density enhancement is examined.

Figure 5.14 shows the far-zone backscattered electric field intensity, while Figure 5.15 features the near-zone maximum power density enhancement. Furthermore, in Figure 5.16, 2D near-zone power density enhancement plots are provided for both cases. We observe that the maximum power density enhancements obtained with air holes having different cross sections are close to each other. At frequencies higher than 550 THz, the enhancement inside the nano-optical absorber becomes slightly higher with hexagonal air holes. However, investigating the backscattering results,

the nano-optical absorber with square air holes is distinctively better because of its considerably lower back reflection. In the following designs, holes with square cross sections are considered and further investigated.

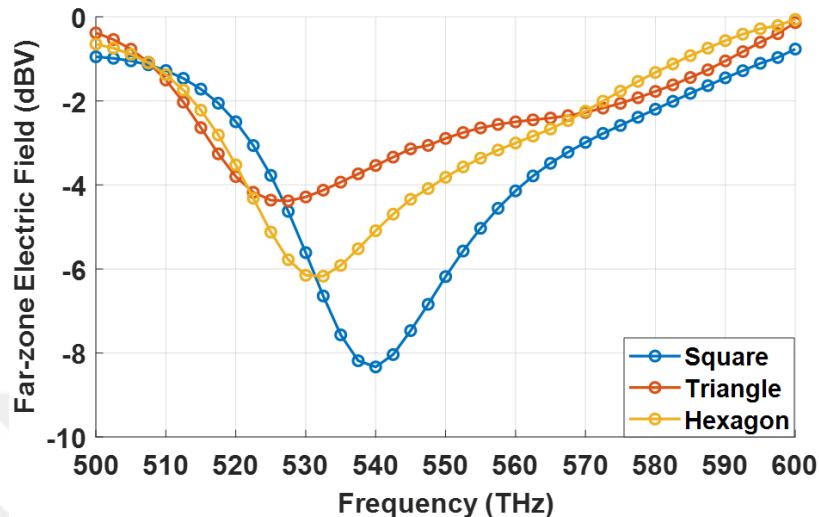


Figure 5.14: Far-zone backscattered electric field intensity obtained for designs involving air holes with different cross sections

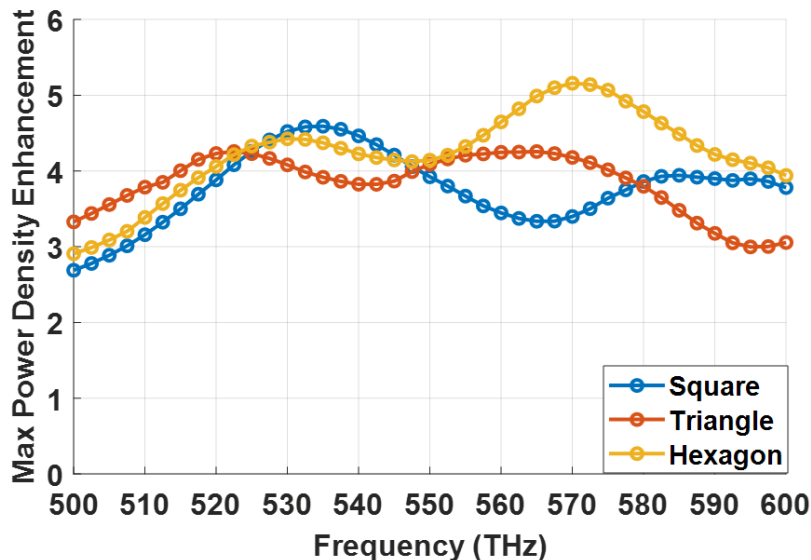
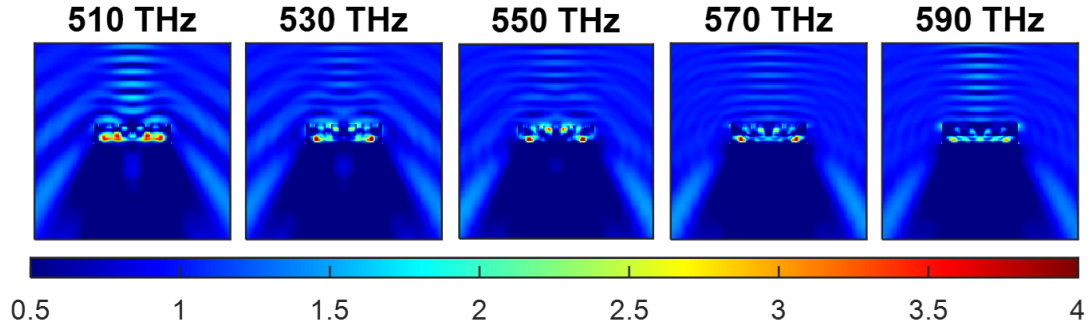
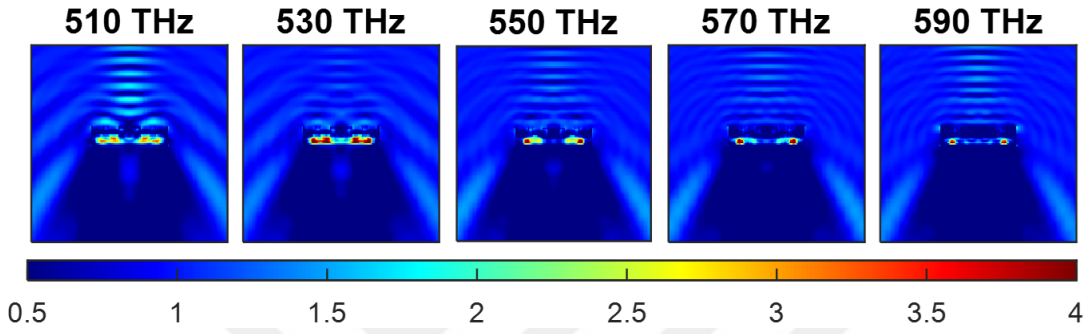


Figure 5.15: Maximum power density enhancement in the near zone obtained for designs involving air holes with different cross sections



(a) Triangular prism air holes



(b) Hexagonal prism air holes

Figure 5.16: 2D near-zone power density enhancements obtained for designs involving holes with for different cross sections

5.3 Effect of Hole Depth

Initial ARC designs described above are obtained with air holes of 100 nm depth, while in this part, the effect of the hole depth is examined. In fact, the considerable difference between the cases when there are holes (with 100 nm depth) and not suggests that changing the depth of the air holes may significantly affect both the backward reflection and the maximum power density enhancement inside the absorber.

In the following parts, first, the depth of air holes is increased, and then, it is decreased, to see the effect of deeper and shallower air holes on anti-reflectivity and power density enhancement in nano-optical absorbers.

5.3.1 Increasing the Depth of Air Holes

In the following, a nano-optical absorber involving air holes with varying widths is considered, while the only difference in comparison to the previous design is the increased depth of the air holes. Particularly, the depth of the air holes in the photonic crystal is changed from 100 nm to 120 nm and 140 nm, as shown in Figure 5.17.



Figure 5.17: Nano-optical absorbers involving holes with higher depths

Figure 5.18 and Figure 5.19 show frequency-dependent far-zone backscattering and near-zone maximum power density enhancement plots. According to these plots, increasing the depth of the holes causes increased backscattering, and it also results in lower values for the maximum power density enhancement. Especially, when the depth of the holes is 140 nm, that is, in the deepest case, the maximum power density enhancement value is very close to unity (corresponding to no absorbency) in the entire frequency range.

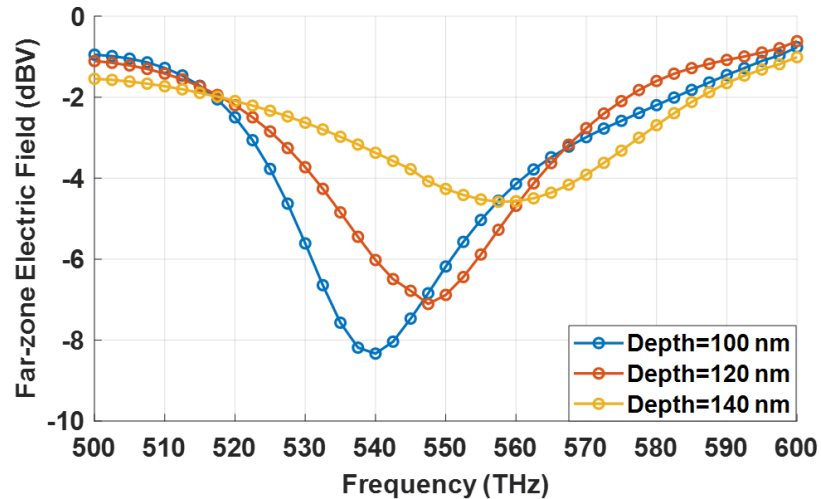


Figure 5.18: Far-zone backscattered electric field intensity obtained for designs involving air holes with different depths

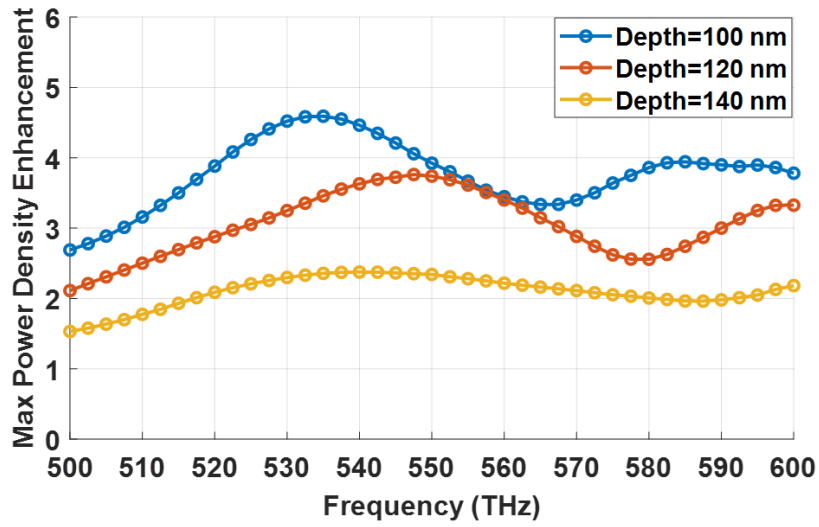
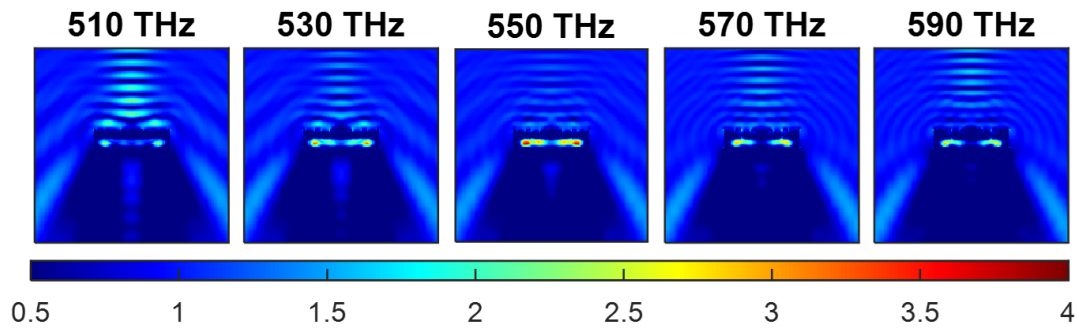
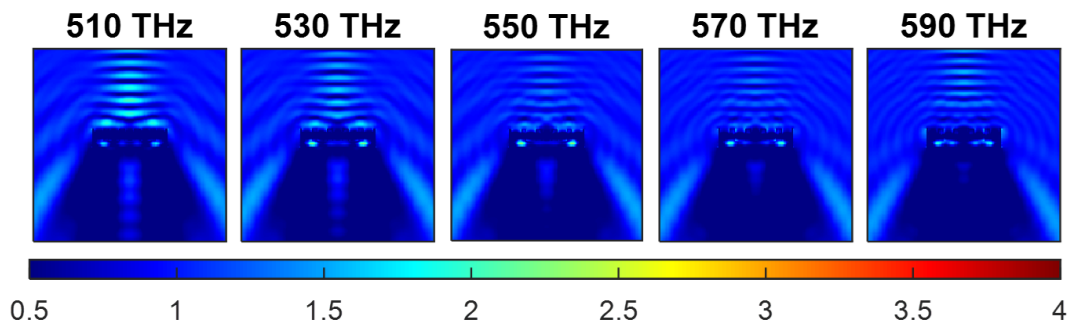


Figure 5.19: Maximum power density enhancement in the near zone obtained for designs involving air holes with different depths



(a) Depth of air holes = 120 nm



(b) Depth of air holes = 140 nm

Figure 5.20: 2D near-zone power density enhancements obtained for designs involving holes with different depths

For the two different depths of the air holes, 2D near-zone power density enhancement plots are given in Figure 5.20a and Figure 5.20b. As seen in these plots, in both cases, the maximum power density enhancement inside the structure is not high enough, while relatively large power density values are obtained outside the structure. Therefore, we conclude that increasing the depth of the air holes deteriorates the performance of the structure in terms of both anti-reflection and power density enhancement characteristics.

5.3.2 Decreasing the Depth of Air Holes

The depth of the air holes in the previously designed photonic crystal is also reduced from 100 nm to 60 nm and 80 nm, as shown in Figure 5.21, to find out if decreasing the depth of the air holes improves the absorbance capabilities of the nano-optical absorber.



Figure 5.21: Nano-optical absorbers involving holes with lower depths

Figure 5.22 and Figure 5.23 present far-zone backscattering and near-zone maximum power density enhancement values with respect to frequency. When these plots are examined, it can be deduced that the case of 80 nm depth yields to results close to the original case when the depth is 100 nm. On the other hand, reducing the depth of the holes to 60 nm results in lower backscattering and higher near-zone power density enhancement values. The backscattered electric field intensity reaches down to -9.51 dBV at 555 THz, while the maximum power density enhancement inside the nano-optical absorber increases to 5.26 at 592.5 THz.

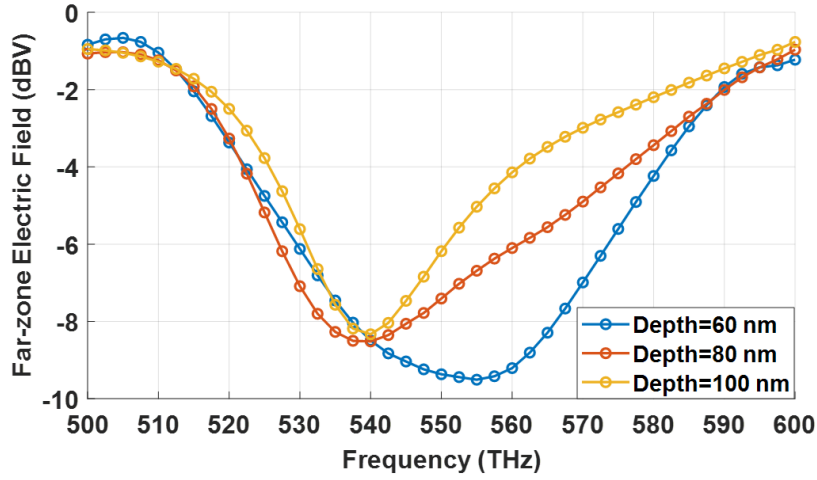


Figure 5.22: Far-zone backscattered electric field intensity obtained for designs involving air holes with different depths

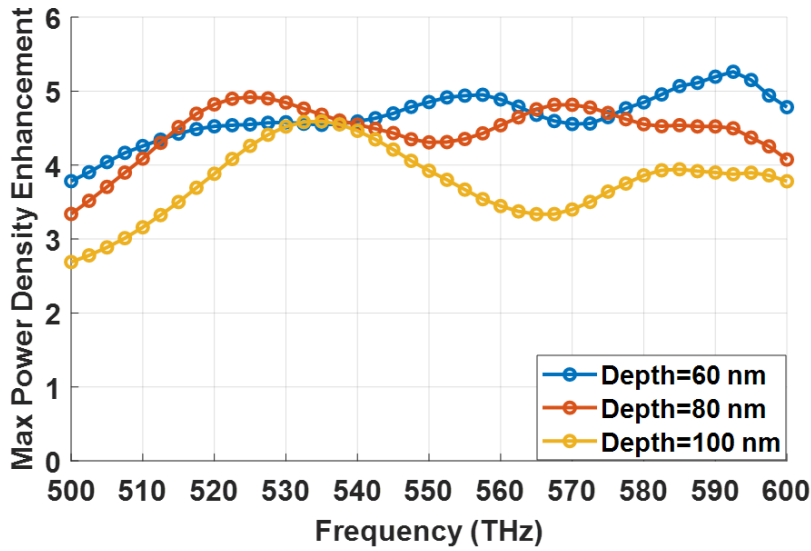


Figure 5.23: Maximum power density enhancement in the near zone obtained for designs involving air holes with different depths

For the structures involving holes with reduced depths, 2D near-zone power density enhancement plots are given in Figure 5.24a and in Figure 5.24b. According to these plots, when the depth is 60 nm, the difference between the power density enhancement values in the absorber and outside the absorber becomes higher. This suggests that reducing the depth to 60 nm effectively improves the performance of the nano-

optical absorber.

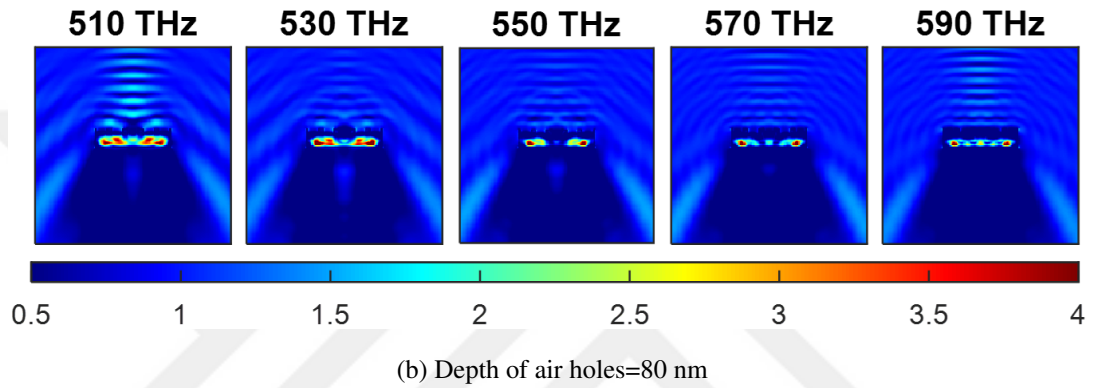
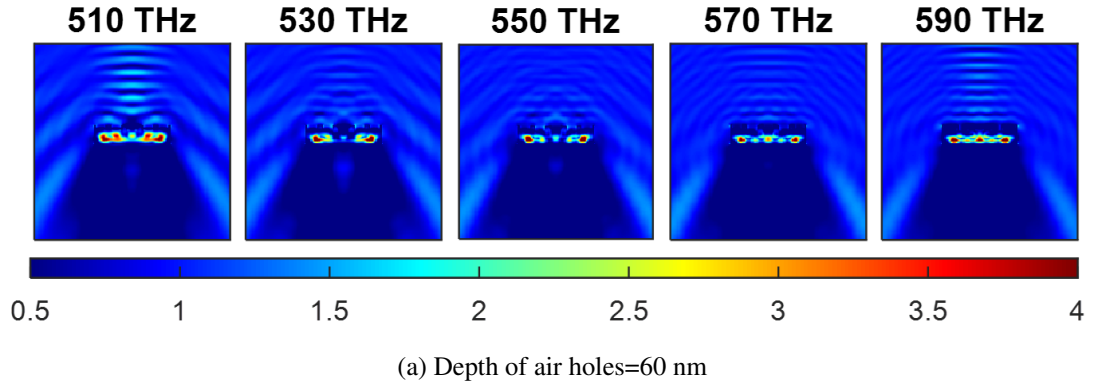


Figure 5.24: 2D near-zone power density enhancements obtained for designs involving holes with different depths

5.3.3 Depth Optimization with GAs

Since it has been observed that the depth of air holes in a photonic-crystal-based ARC has significant effects on the performance of the nano-optical absorber, depth optimization is performed with GAs to see if better depth values can be found instead of defining a fixed value. The details of such depth optimization trials are explained in Chapter 3. Among alternative selections, five different depth values are selected: 60 nm, 80 nm, 100 nm, 120 nm, and 140 nm. These depth values are represented by numbers 0, 1, 2, 3, and 4, respectively, leading to 5×5 matrices to represent arrays of air holes with a total of 25 elements. Thus, each element of the matrix refers to the depth of the relevant hole. An example of this was given also in Chapter 3.

The nano-optical absorber structure involving square air holes with decreasing widths from 160 nm to 80 nm from one side to the opposite side, placed on a tungsten plate of 20 nm thickness is selected as the main structure to be optimized. This structure is known to have relatively low backward reflection and high power density enhancement values at around 540 THz, according to the results given in Figure 5.11a and 5.11b. This time, the depth of each hole is changed by selecting one of five different depth options, and GA optimization is performed to obtain the lowest possible backward reflection with the available options. To achieve this, a fitness function is defined as

$$\text{Fitness Function} = -(\text{Backscattered Electric Field Intensity}). \quad (5.2)$$

Considering the size of the optimization space, it is expected that an optimization with 30 generations can be sufficient. The calculation load of full-wave solutions of each individual problem in the optimization becomes higher for small mesh size used for discretization of the geometries. To reduce the calculation load, for depth optimization, the mesh size is increased to 48 nm, while the presented far-zone and near-zone results of optimal absorbers in this study are obtained with a mesh size of 27 nm for better accuracy.

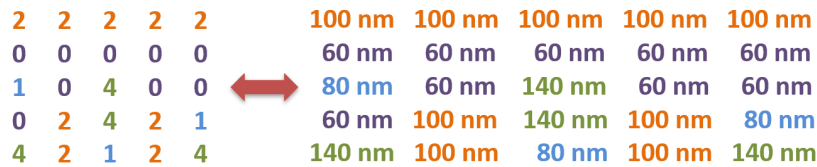


Figure 5.25: Optimal matrix representation and the corresponding depth values for lower backward reflection at 535 THz

In the first trial, the optimization frequency is selected as 535 THz, which is one of the frequencies at which the non-optimal nano-optical absorber operates best. The optimal matrix obtained at the end of 30 generations and the corresponding hole depths are given in Figure 5.25. The geometry of the nano-optical absorber optimized at 535 THz is described Figure 5.26.

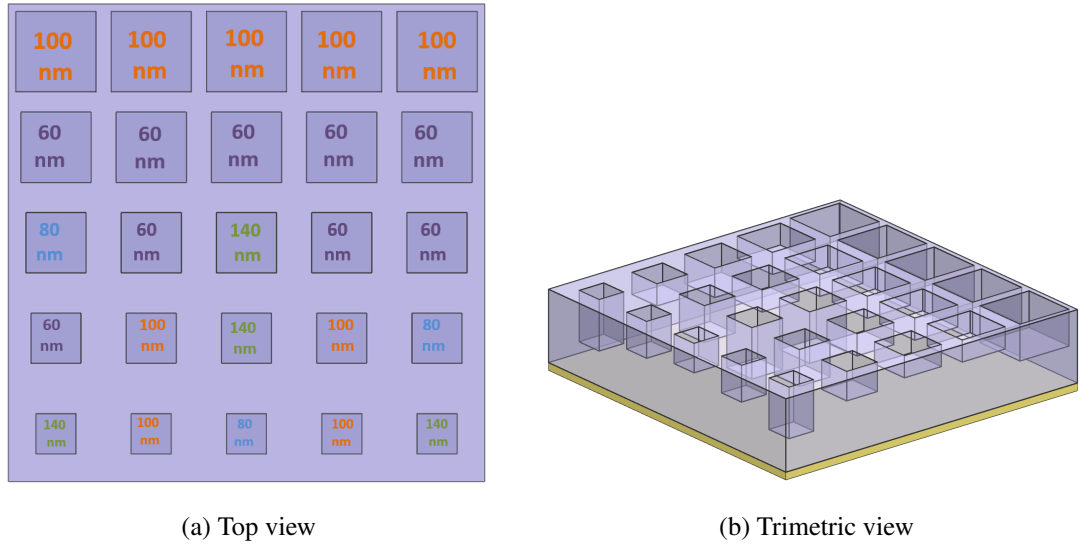


Figure 5.26: Optimized nano-optical absorber designed to have a lower backward reflection at 535 THz

Far-zone backscattered electric field intensity and near-zone power density enhancement values obtained for the optimized structure are given in Figure 5.27 and Figure 5.28.

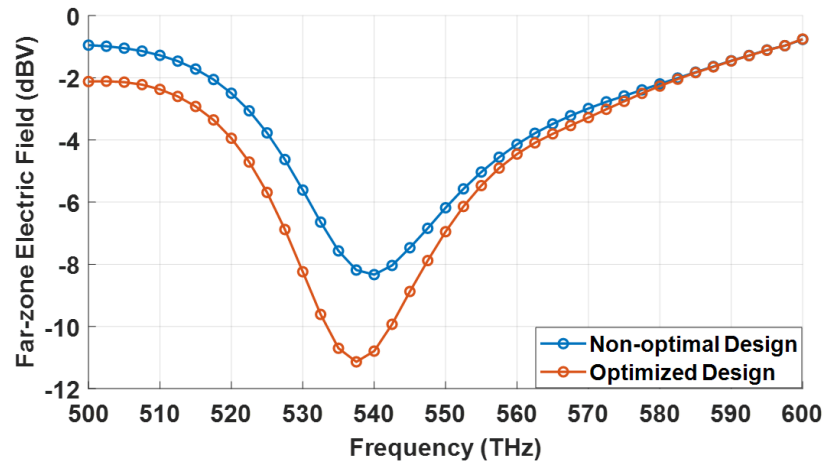


Figure 5.27: Far-zone backscattered electric field intensity obtained for the nano-optical absorber optimized at 535 THz, in comparison to the values obtained for the non-optimal design

According to backscattering field intensity and power density enhancement results,

depth optimization improves by making nano-optical absorber more anti-reflective and enhancing power density to higher values within the structure. The backscattered electric field intensity decreases to -11.14 dBV at 537.5 THz which is 2.8 dB lower than the backscattered electric field intensity of non-optimal nano-optical absorber. The maximum power density enhancement is higher for the optimal nano-optical absorber for the whole frequency range increasing to 5.90 at 570 THz.

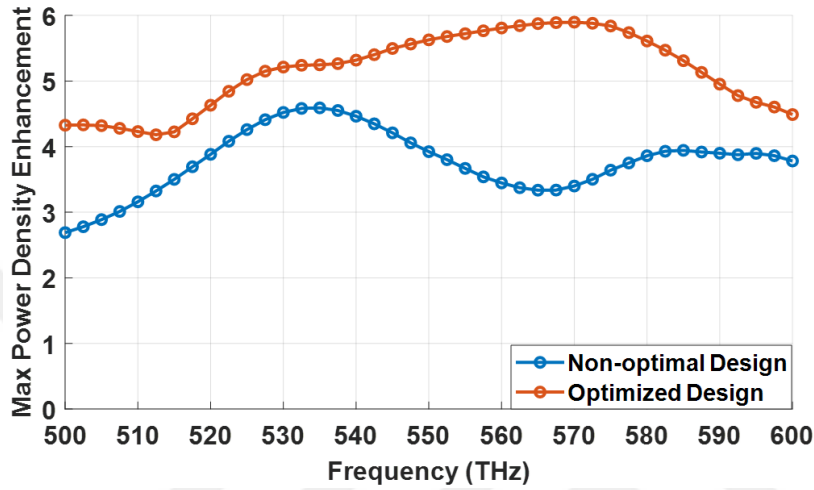


Figure 5.28: Maximum power density enhancement obtained for the nano-optical absorber optimized at 535 THz, in comparison to the values obtained for the non-optimal design

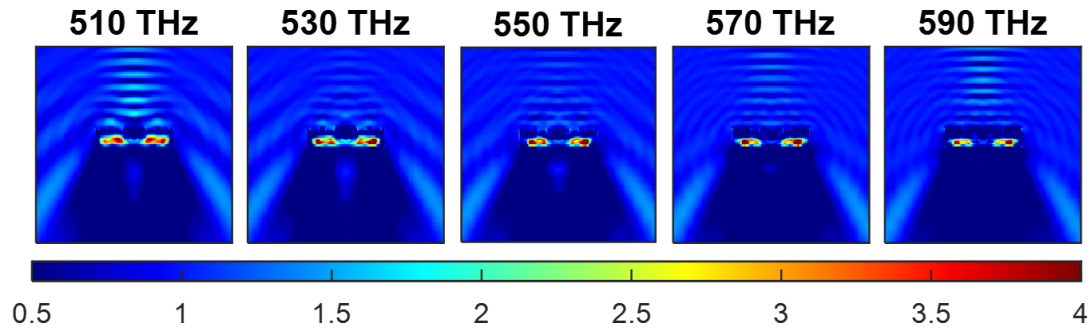


Figure 5.29: 2D near-zone power density enhancement for nano-optical absorber optimized at 535 THz for lower back reflection

2D near-zone power density enhancement plots in Figure 5.29 indicate that the power density enhancement significantly increases within the nano-optical absorber, while

it is close to unity (corresponding to negligible secondary fields) outside the absorber. In fact, the maximum power density enhancement inside the optimal nano-optical absorber is higher than the maximum power density enhancement inside the non-optimal nano-optical absorber, as already verified in Figure 5.29. These results suggest that optimization with GAs to find optimal depth values provides successful results.

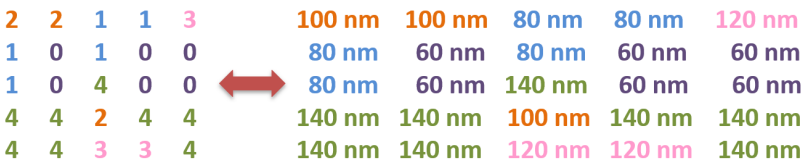


Figure 5.30: Optimal matrix representation and the corresponding depth values for lower backward reflection at 520 THz

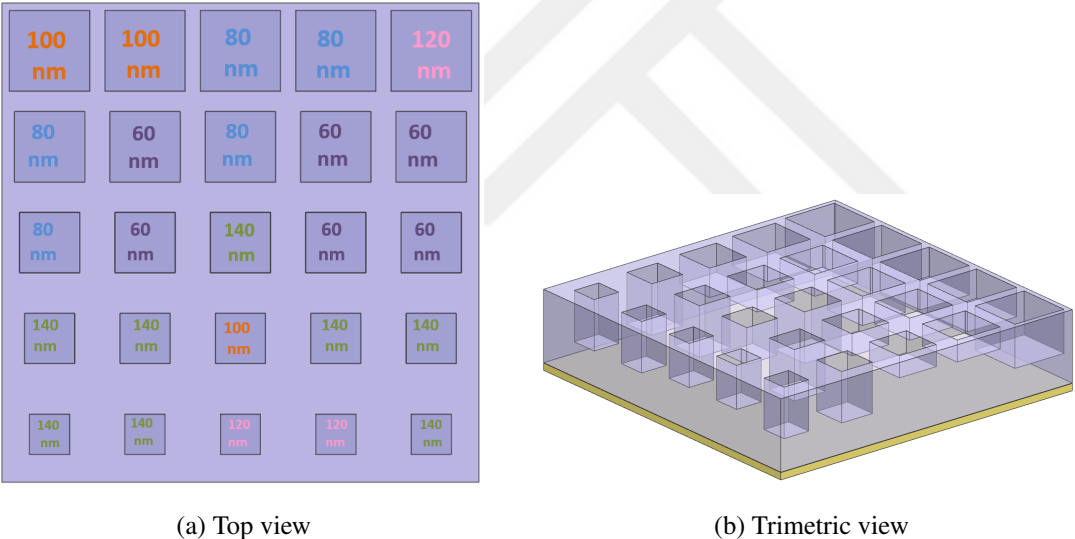


Figure 5.31: Optimized nano-optical absorber designed to have a lower backward reflection at 520 THz

For the second depth optimization, the same non-optimal nano-optical absorber is considered, while the frequency is selected as 520 THz, at which the absorber does not operate efficiently and it needs to be improved. Hence, at a frequency where the structure does not work well, we seek the answer to the question of whether

the nano-optical absorber can be improved as a result of depth optimization. Matrix representation and the corresponding depths of air holes obtained at the end of 30 generations are given in Figure 5.30. The geometry of the nano-optical absorber optimized at 520 THz is given Figure 5.31.

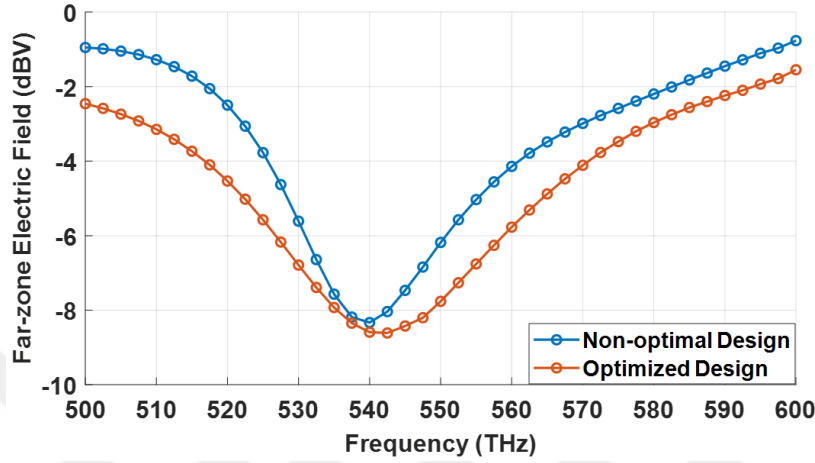


Figure 5.32: Far-zone backscattered electric field intensity obtained for the nano-optical absorber optimized at 520 THz, in comparison to the values obtained for the non-optimal design

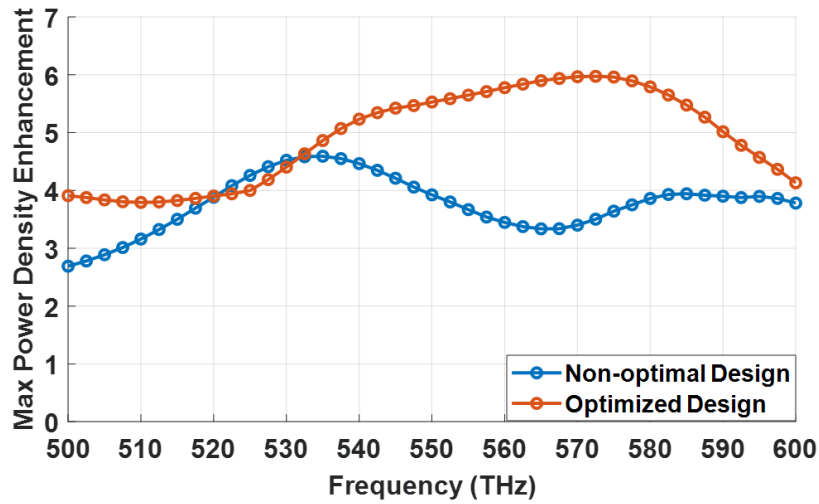


Figure 5.33: Maximum power density enhancement obtained for the nano-optical absorber optimized at 520 THz, in comparison to the values obtained for the non-optimal design

The far-zone backscattering and near-zone power density enhancement values obtained with this geometry are given in Figure 5.32 and Figure 5.33.

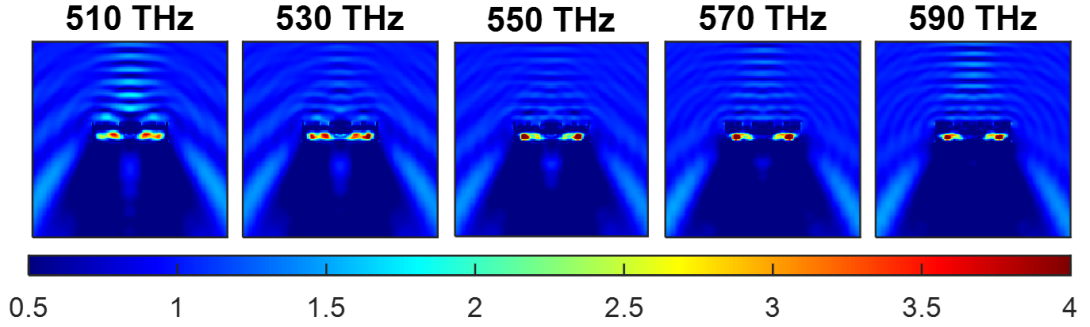


Figure 5.34: 2D near-zone power density enhancement distributions for the nano-optical absorber optimized at 520 THz to achieve low backward reflection

2D near-zone power density enhancement plots are also given at five different frequencies in Figure 5.34. Considering the plots for this optimized nano-optical absorber, we observe that depth optimization allows nano-optical absorber to work better even at a frequency where it does not work well before. The backscattered fields are reduced thanks to the optimization. Considering numerical values at the optimization frequency, the backscattered electric field intensity is -2.50 dBV for the non-optimal nano-optical absorber, while it is effectively reduced to -4.53 dBV with the optimal design. Thus, it is shown that nano-optical absorbers that possess better anti-reflection performance can be designed with depth optimization by using GAs.

Depth optimization is also applied to directly increase the maximum power density enhancement inside the nano-optical absorber. As an example we select 535 THz, where the non-optimal nano-optical absorber operates well, while the maximum power density enhancement may still be maximized at this frequency. A fitness function is directly defined for this purpose as

$$\text{Fitness Function} = \text{Maximum Power Density Enhancement.} \quad (5.3)$$

Performing an optimization using the fitness function in Equation 5.3, the optimal matrix obtained at the end of 30 generations and the corresponding hole depths are given in Figure 5.35.



Figure 5.35: Optimal matrix representation and the corresponding depth values for higher maximum power density enhancement at 535 THz

The geometry of the nano-optical absorber optimized for maximum power density enhancement at 535 THz is given Figure 5.36.

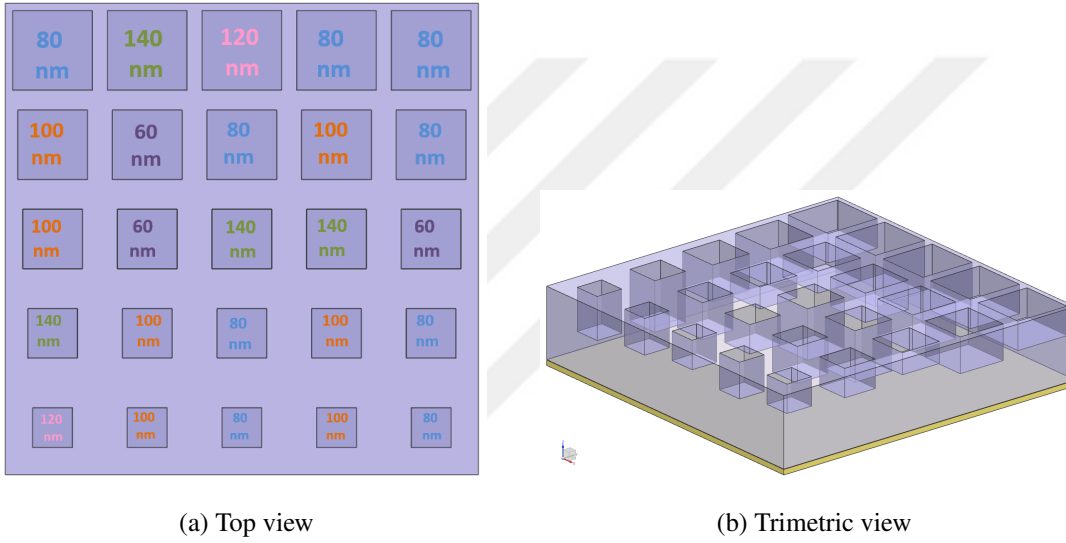


Figure 5.36: Nano-optical absorber obtained via optimization at 535 THz for higher maximum power density enhancement

Far-zone backscattered electric field intensity and near-zone power density enhancement values of the optimized structure are given in Figure 5.37 and Figure 5.38. According to these results, depth optimization significantly improves the nano-optical absorber by increasing the power density values within the absorber to higher values in almost the entire frequency range. The enhancement value reaches 7.31 at 535 THz, increasing by 59.3%. The backscattered electric field intensity also decreases to -6.98 dBV at 537.5 THz. However, as shown in Figure 5.37, when the depth optimization is applied to only increase the near-zone power density enhancement

within the absorber, it does not improve anti-reflectivity significantly. Unless more complicated fitness functions are used, the decision of either decreasing the backward reflection or increasing the power density enhancement should be made before starting a depth optimization, depending on the application where the nano-optical absorber will be used.

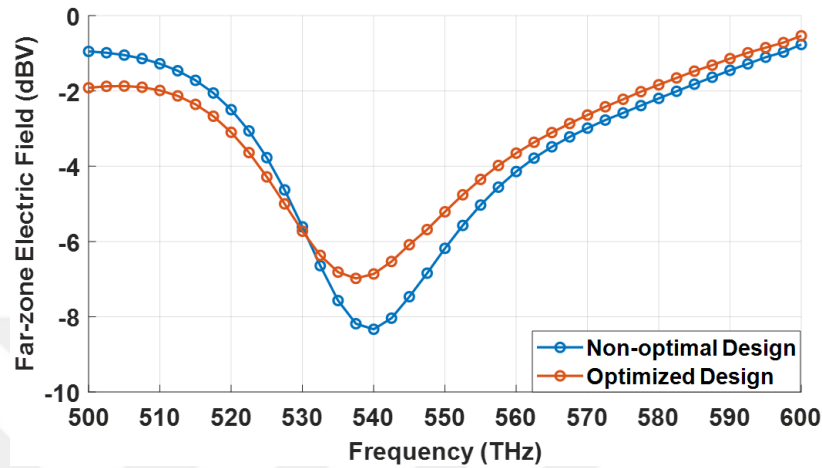


Figure 5.37: Far-zone backscattered electric field intensity obtained for the nano-optical absorber optimized at 535 THz for higher maximum power density enhancement, in comparison to the values obtained for the non-optimal design

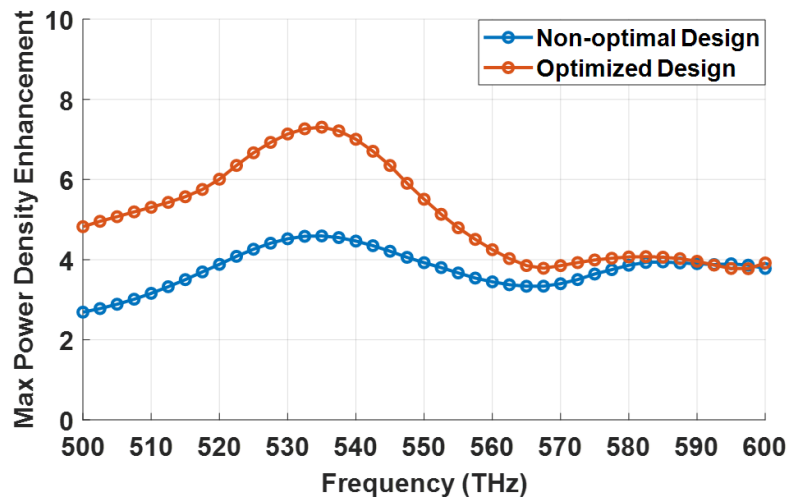


Figure 5.38: Maximum power density enhancement obtained for the nano-optical absorber optimized at 535 THz for higher maximum power density enhancement, in comparison to the values obtained for the non-optimal design

2D near-zone power density enhancement plots in Figure 5.39 indicate that near-zone power density enhancement within the optimized nano-optical absorber becomes higher, in comparison to the non-optimal absorber, especially for the first three frequencies. At 530 THz, which is close to the frequency at which the depth optimization is applied, the power density enhancement outside the nano-optical absorber becomes very close to unity. The results suggest that the depth optimization with GAs leads to successful results and more effective nano-optical absorber designs with higher power density enhancement capabilities.

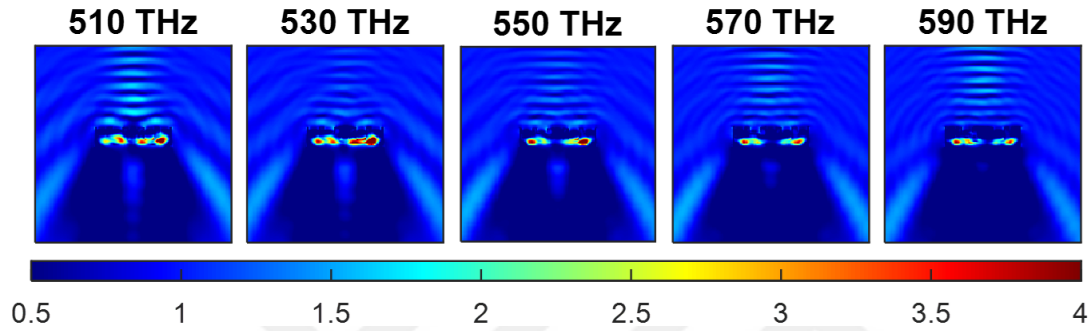


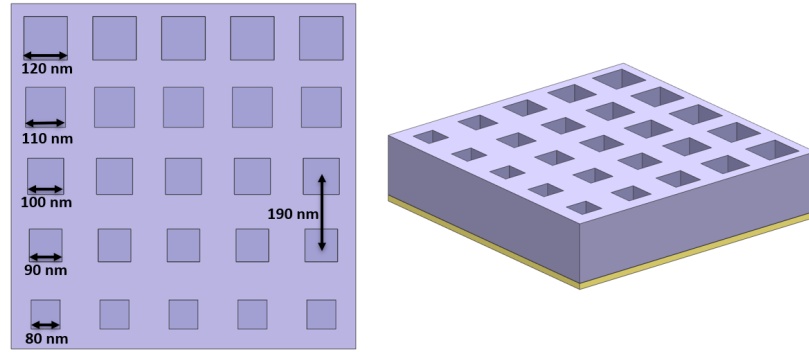
Figure 5.39: 2D near-zone power density enhancement distributions for the nano-optical absorber optimized at 535 THz to achieve high maximum power density enhancement

5.4 Further Investigations on the Width of Air Holes

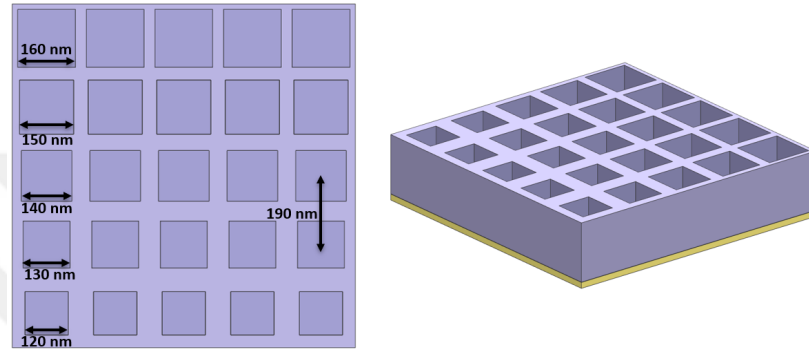
Finally, we investigate the effects of *change rate* and *direction of change* on the characteristics of nano-optical absorbers involving air holes with varying widths.

Firstly, nano-optical absorber designs that involve air holes with varying widths, decreasing from 160 nm to 120 nm and from 120 nm to 80 nm in 10 nm steps are examined. The geometries of these designs are shown in Figure 5.40.

The far-zone backscattering and near-zone power density enhancement results obtained when these nano-optical absorbers are excited with a plane wave are presented in Figure 5.41 and Figure 5.42, in comparison to the original design in which the hole width is reduced from 160 nm to 80 nm.



(a) Width = [120 110 100 90 80] nm



(b) Width = [160 120 110 100 90] nm

Figure 5.40: Nano-optical absorbers involving holes with different widths

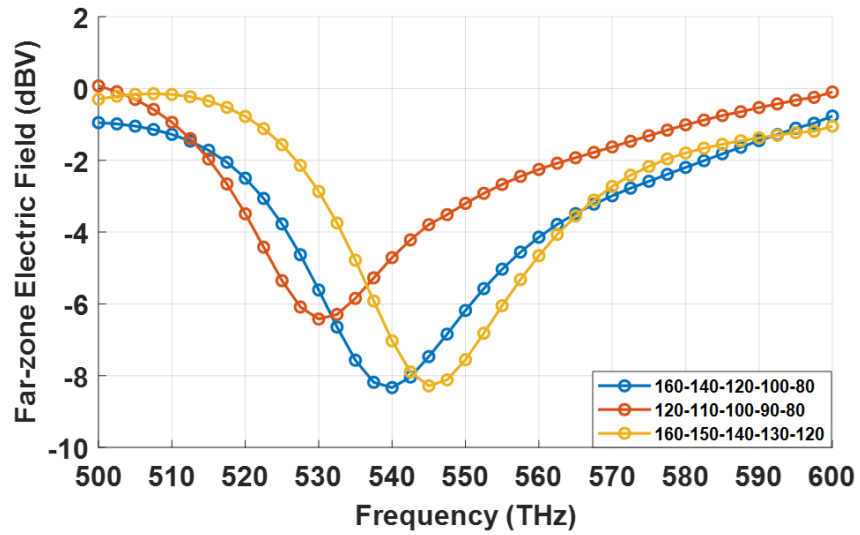


Figure 5.41: Far-zone backscattered electric field intensity for nano-optical absorbers with different width configurations for the air holes

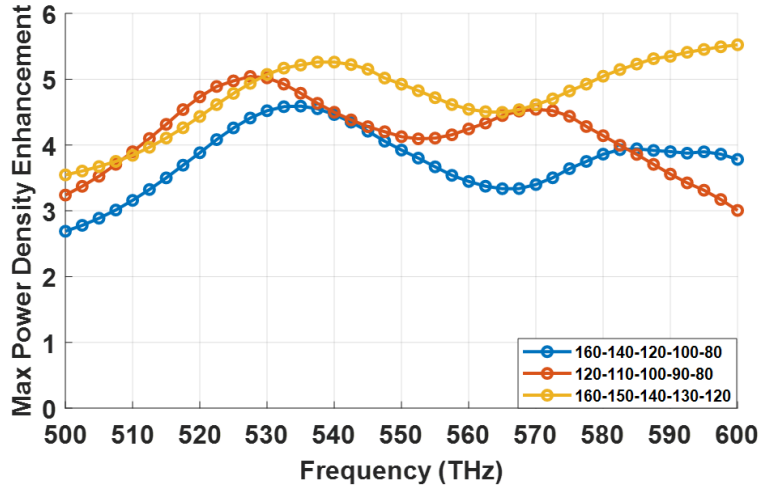


Figure 5.42: Maximum power density enhancement for nano-optical absorbers with different width configurations for the air holes

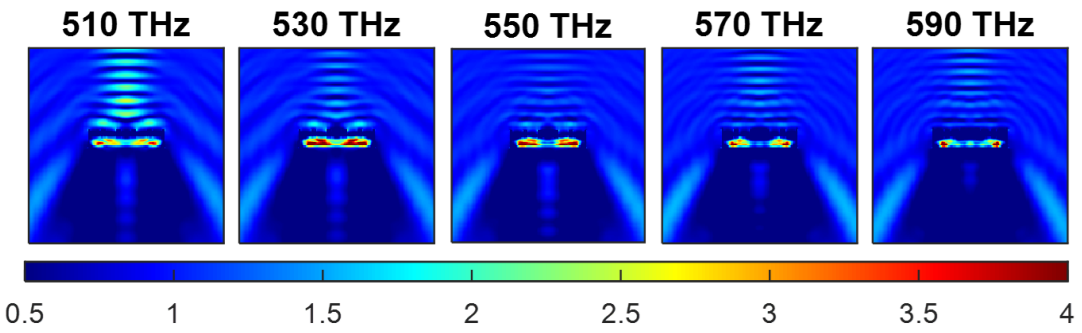
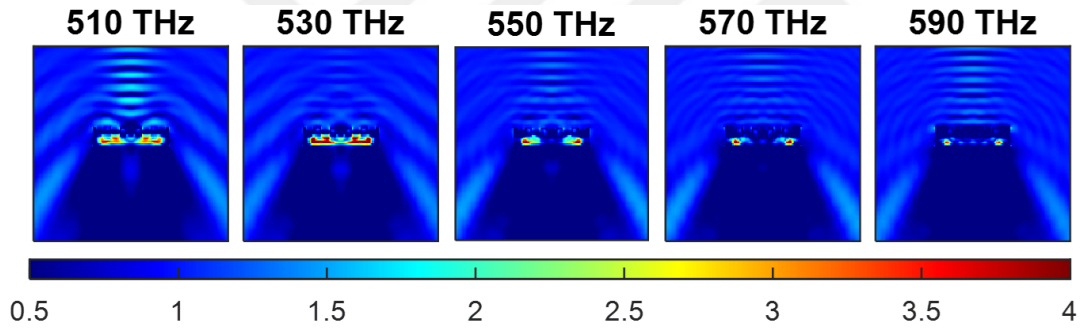


Figure 5.43: 2D near-zone power density enhancement for nano-optical absorbers involving holes with different widths

For these designs with different width configurations, 2D power density enhancement plots are provided in Figure 5.43 at five different frequencies. The nano-optical absorber design, for which the hole width decreases from 160 nm to 120 nm in 10 nm steps, has higher internal power density enhancement values than the other two designs; but, no significant improvement is observed for the backward reflection.

Next, alternative nano-optical absorbers, for which the width of the air holes changes from one side to the opposite side as 80-120-160-120-80 nm and 160-120-80-120-160 nm are examined. As shown in Figure 5.44, one of these designs has the largest holes in the middle, and the other has them at the edges. We note that, in both cases, the rate of change is 40 nm.

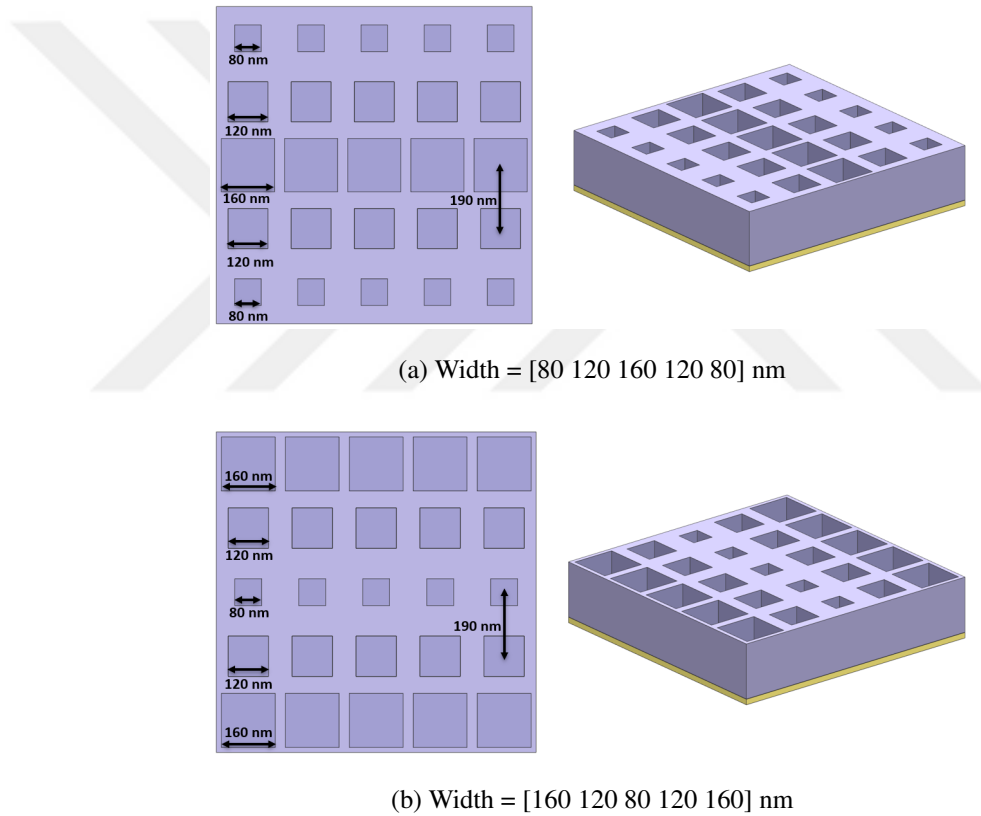


Figure 5.44: Nano-optical absorbers with different hole configurations (directions of changes)

In Figure 5.45 and Figure 5.46, far-zone backscattering and near-zone power density enhancement results obtained for the two nano-optical absorbers in Figure 5.44

are compared to those values obtained for the original design (air holes with widths reduced from 160 nm to 80 nm).

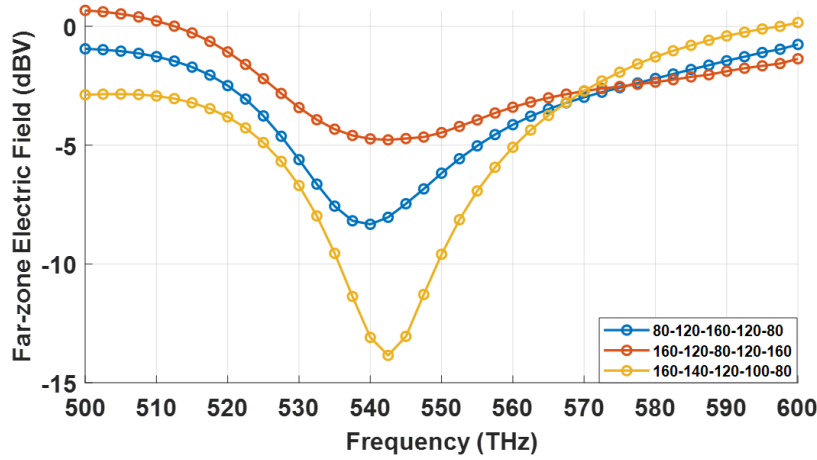


Figure 5.45: Far-zone backscattered electric field intensity for the nano-optical absorbers in Figure 5.44, in comparison to the original design in Figure 5.10

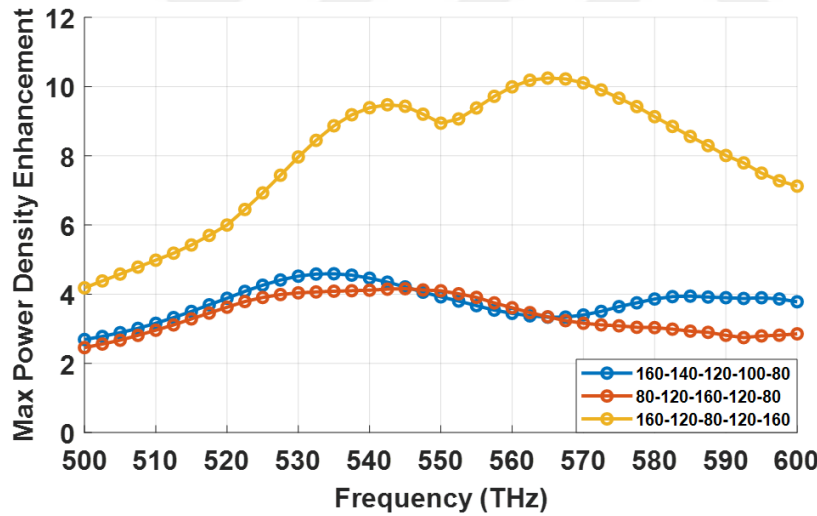


Figure 5.46: Maximum power density enhancement for the nano-optical absorbers in Figure 5.44, in comparison to the original design in Figure 5.10

For the two new designs, 2D near-zone power density enhancement plots are given in Figure 5.47. Considering the results in Figure 5.45, Figure 5.46, and Figure 5.47, we observe that the design, in which the hole width varies as 160-120-80-120-160 nm, leads to a very successful nano-optical absorber since it causes very low backward

reflection and provides very high power density enhancement. At some frequencies, the power density inside this nano-optical absorber is more than 10 times the power density outside the structure. In addition, the backscattered field decreases to -13.85 dBV at 542.5 THz. In 2D plots, we observe that the power density enhancement is either unity or below unity outside the structure, while it increases to more than 10 in internal regions. To sum up, by both changing the direction and the rate of change of the widths, we reach a simple and effective nano-optical absorber design that possesses high-quality anti-reflection and power density enhancement capabilities.

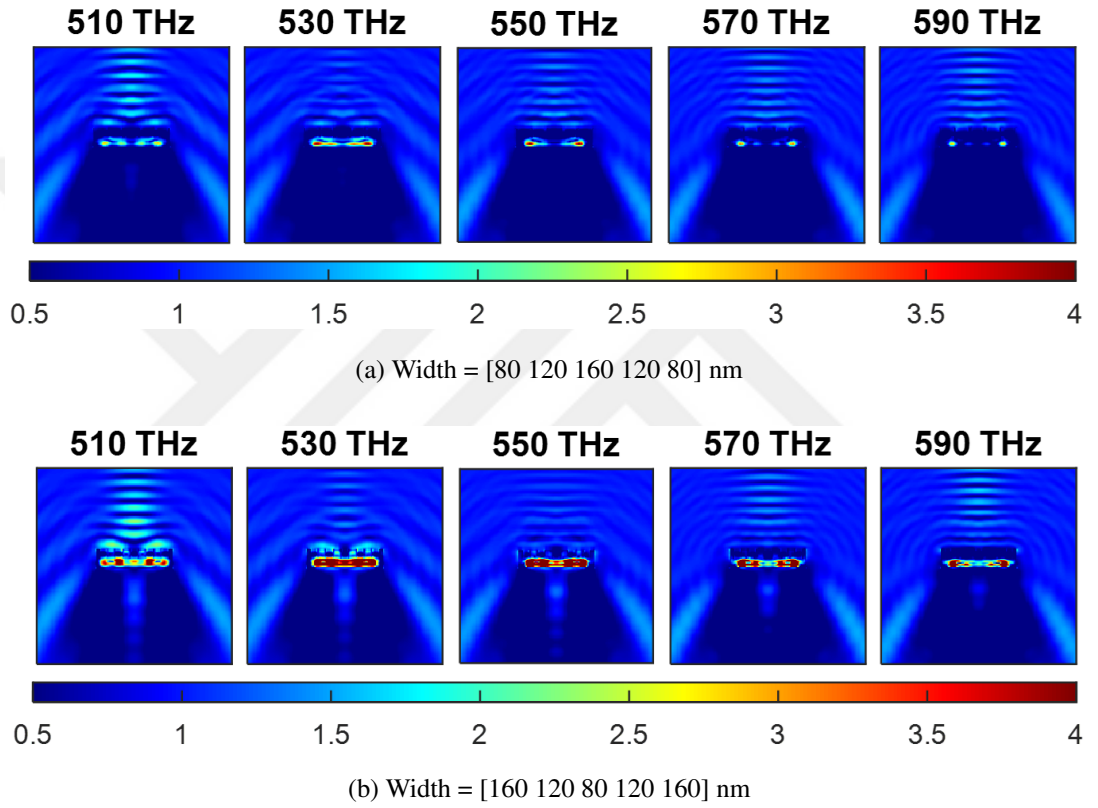


Figure 5.47: 2D near-zone power density enhancement for nano-optical absorbers in Figure 5.44

5.5 Concluding Remarks

Composite nano-optical absorbers obtained by combining ARCs based on photonic crystals with metallic plates were presented in this chapter. It was shown that pho-

tonic crystal structures consisting of periodic arrangements of air holes on dielectric slabs show anti-reflection properties, while this feature can be controlled by changing various parameters, such as the width, arrangement, and shape of the holes. As a result of the combination of these photonic-crystal ARCs with metallic plates, efficient nano-optical absorbers that provide high internal power density enhancement and show anti-reflective properties were designed. Such a nano-optical absorber with minimized backward reflections can be used to minimize interference in nano-optical systems. Depth optimization based on GAs was performed to further improve nano-optical absorber designs in terms of reflection and power density enhancement. In conclusion, the results showed the feasibility of efficient and effective nano-optical absorbers involving only two layers and two types of materials.



CHAPTER 6

CONCLUSION

In this thesis, different nano-optical structures based on the principles of photonic crystals were designed and analyzed. Nano-optical couplers that transmit electromagnetic wave in desired directions under different conditions, as well as nano-optical absorbers that trap electromagnetic power and also reduce backward reflection were considered in detail. The effects of various variables on the efficiency of these designs were examined, from parametric analyses to rigorous optimization via GAs.

In the first part of the thesis, forward-transmitting and 90-degree nano-optical couplers were designed based on on/off optimization of dielectric nano-rod arrangements. The effectiveness of the coupler designs that can be used both as repeaters (forward-transmitting) and in bent transmission lines was shown in detail. We observed how critical parameters, such as the material and shape of the rods, as well as the distance between them, affect coupling efficiency. The designs were also examined when one of them is added after another to create larger transmission systems. In addition to these single-input nano-optical couplers, double-input nano-optical couplers were designed to be used in electromagnetic wave transmission at junction locations. The numerical results proved that these designs effectively transmit waves in the desired directions. In addition, nano-optical AND and OR logic gate coupler designs were obtained for all-optical systems. Such designs that can operate according to certain logic principles were also shown to be possible with GA optimization of photonic crystals. In addition to these designs, nano-optical isolators, which provide high transmission in the forward direction but prevent backward transmission, were also developed. These isolators can be particularly used to minimize interference between the components of a nano-optical system, including the sources. In order to

improve the designs, not only on/off optimization trials but also length optimization trials were designated and performed. It is shown that an effective integration of GAs and MLFMA enable efficient design of compact nano-optical couplers that can be used in a plethora of applications.

In the second part of the thesis, composite, nanometer-sized optical absorbers were designed by combining photonic crystals obtained with periodic air holes drilled into dielectric slabs with metallic plates. These designed optical absorbers were intended to provide high power enhancement within themselves, while, at the same time, show anti-reflective properties by preventing problematic backward reflections (e.g., that may have destructive effects for the nano-optical source or other structures). Different parameters, such as the width, shape, and sequence of air holes were investigated, and their effects on the reflectivity and power enhancement abilities were examined. More effective designs, in which the air holes have different depth values, were realized via a novel GA-based depth optimization technique. The developed designs showed that, with the optimization of photonic crystals, efficient nano-optical absorber designs that possess both anti-reflective and power-enhancing characteristics can be obtained.

Compact and efficient structures presented in this thesis make contributions to the rapidly developing technology, where nano-optical systems with smaller components are required to build more functional systems. Since the designed structures have relatively simple geometries and are based on only one or two materials, they are favorable compared to many other structures in the literature.

Although this study has reached its aims by demonstrating the feasibility of various compact nano-optical components that possess novel characteristics, such as variable lengths (for rods) and depths (for holes), it can be considered as a starting point for the design of more complicated nano-optical systems involving these components. Adding such parameters is the central novelty of this work; but realization of these structures, as well as their integration into large systems for more complex operations can be addressed in future works.

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