International Journal of Multiphysics
Volume 18, No. 3, 2024
ISSN: 1750-9548

Applications of TE and TM Modes in Advanced Optical Systems and Communications

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Abstract

— This study investigates the use of Transverse Electric (TE) and Transverse Magnetic (TM) modes in sophisticated optical systems, with a specific emphasis on their influence on fiber optic communications, laser technology, optical sensors, and photonics. Through the use of intricate simulations, we demonstrate how these modes increase transmission efficiency, improve the quality of laser beams, and augment sensor precision. The research emphasizes the crucial significance of TE and TM modes in enhancing the efficiency of optical devices and offers valuable insights for future advancements in optical systems.

Keywords: TE and TM Modes, Optical Communications, Fiber Optics, Laser Technology, Photonics.

1. Introduction

Optical communication technologies have significantly transformed global information transfer, serving as the foundation for the rapid expansion of the internet and telecommunications infrastructures. The Transverse Electric (TE) and Transverse Magnetic (TM) modes are essential components driving innovation in this area. Understanding the behavior of electromagnetic waves in optical medium and their impact on optical devices such as fibers, lasers, and sensors is crucial. These modes play a critical role in the design and optimization of these devices [1,2].

The TE and TM modes, distinguished by their distinct alignments of electric and magnetic fields in relation to the direction of wave propagation, are not only essential for theoretical comprehension but also for practical utilization in numerical electromagnetic methods and real-world applications [2-7]. Their use has been crucial in resolving important problems with bandwidth, signal degradation, and operational efficiency in the field of fiber optic communications. These modes allow for accurate manipulation of light propagation, which is crucial for obtaining high data transmission rates over long distances while minimizing signal degradation [8]. Furthermore, their impact goes beyond the field of telecommunications since they have a substantial role in promoting laser technology by improving beam quality and operating stability [9].

The theoretical underpinnings of TE and TM modes are based on Maxwell's equations, which elucidate the characteristics of electromagnetic fields. From the mid-20th century forward, the practical implementation and investigation of these theories have led to notable progress in the development of optical system designs [10]. An important breakthrough in the 1970s was the creation of low-loss optical fibers. This achievement was made possible by a thorough comprehension and manipulation of TE and TM modes to enhance the transmission of light [11-12].

Research on the utilization of TE and TM modes has expanded to include a wide range of applications [22-24]. These tasks involve improving the performance of optical sensors used in monitoring the environment and diagnosing medical conditions, as well as optimizing photonic devices for computer purposes [13]. The growth of these applications is backed by a significant amount of research that explores the theoretical foundations, simulation models, and empirical studies that examine the boundaries and capabilities of TE and TM mode implementations [14-15].

Recent research provides more insight into the vital function of these modes in the advancement of complex optical systems such as photonic integrated circuits (PICs) and quantum computing interfaces, where precise manipulation of light modes is essential [16,17]. Furthermore, recent studies in the field of nano-optics and plasmonic emphasize the use of TE and TM modes to manipulate light at scales smaller than the wavelength, which leads to the development of compact devices with new possibilities [18].

The enduring fascination with incorporating these modes into ever more intricate and adaptable systems remains a driving force behind research and development endeavors. This continuing project aims to reveal cutting-edge technologies and approaches that have the potential to radically revolutionize industries including optical communication and sensor technology. The study and application of TE and TM modes are not just theoretical exercises but are essential to the continued progress in photonics, which in turn have a vital role in the continuous development of communication and information technology [19-20].

This work is organized as follows: Section II, "Methodology," covers the theoretical foundations and computational simulations of TE and TM modes. Section III, "Applications in Optical Systems," examines these modes' impact on fiber optic communications, laser technology, optical sensors, and photonics. The paper concludes with a summary of key findings and future research directions.

2. Methodology

The investigation of TE and TM modes involves a multidisciplinary methodology that combines theoretical physics, computational simulations, and practical research to understand their uses in sophisticated optical systems and communications. This section of the approach provides a detailed explanation of the diverse techniques and instruments used to thoroughly investigate these modes and their impacts.

A. Theoretical Analysis

Theoretical Foundations of TE and TM Modes

Theoretical analysis is fundamental to understanding the propagation characteristics of Transverse Electric (TE) and Transverse Magnetic (TM) modes in optical structures. This analysis relies heavily on Maxwell's equations [21], which provide a comprehensive description of how electromagnetic fields behave in different media.

Maxwell's Equations: Maxwell's equations form the cornerstone of electromagnetic theory and are crucial for describing the propagation of light in optical waveguides and fibers. These equations are given by Table1:

TABLE I. Overview Of Maxwell's Equations

Gauss's law for electricity:	$\boldsymbol{\nabla \cdot E = \frac{\rho}{\varepsilon_0}}$
Gauss's law for magnetism:	$\nabla \cdot \boldsymbol{B} = 0$
Faraday's law of induction:	$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$
Ampere's law with Maxwell's addition:	$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} + \mu_0 \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t}$

Modeling TE and TM Modes: To analyze TE and TM modes, these equations are specialized to the context of waveguides and optical fibers. TE modes are characterized by having the electric field entirely transverse to the direction of propagation, implying that all components of the electric field satisfy the condition $E_z = 0$. Conversely, TM modes have the magnetic field entirely transverse, leading to $H_z = 0$.

Wave Equation Formation: From Maxwell's equations, we derive the wave equations for the electric and magnetic fields in the absence of free charges and currents, which are applicable to optical waveguides:

$$\nabla^2 \boldsymbol{E} + k^2 \boldsymbol{E} = 0 \quad (1)$$

$$\nabla^2 \boldsymbol{H} + k^2 \boldsymbol{H} = 0 \quad (2)$$

Here, *k* is the wave number, related to the wavelength and the refractive index of the medium.

Solving for Mode Patterns: The solutions to these wave equations in rectangular and cylindrical coordinates lead to expressions for the various modes. For instance, in a rectangular waveguide, the field components for TE and TM modes can be expressed as combinations of sine and cosine functions, depending on the boundary conditions and the geometry of the waveguide. The specific mode numbers (e.g., TE10, TM11) designate the number of half-wavelengths in the field distribution across the waveguide dimensions.

Analytical Methods:

- **Eigenvalue Analysis:** This involves solving the characteristic equation derived from the boundary conditions, providing the allowed mode frequencies and field distributions.
- **Mode Matching Techniques:** Used to join solutions at boundaries between different media, such as at the interface between two different types of optical fibers or at a splice between a fiber and a laser.

Practical Implications and Applications: The theoretical analysis of TE and TM modes informs many practical aspects of photonic device design, including the optimization of fiber optic cables for minimal loss and maximal bandwidth, as well as the design of lasers for specific industrial or medical applications.

B. Computational Simulations

Computational Simulations in Photonics

Computational simulations are essential tools in the field of photonics, enabling researchers to predict and visualize the behavior of electromagnetic modes within complex optical structures. These simulations provide vital insights that guide the design and optimization of optical devices.

TE and TM Mode Analysis in Rectangular Waveguides via Simulation

The goal of this simulation is to analyze and visualize the electric field distribution for TE10 and TM11 modes in a rectangular waveguide. This analysis helps in understanding the modal distribution and the impact of waveguide dimensions on mode characteristics, which is crucial for the design of efficient waveguides in optical systems.

Methodology:

1. **Waveguide Dimensions:**

The waveguide is assumed to have a width (a) of 2.0 cm and a height (b) of 1.0 cm. These dimensions support multiple modes but are chosen specifically to demonstrate the TE10 and TM11 modes.

2. **Simulation Tool:**

MATLAB is used for the simulation, employing the Finite-Difference Time-Domain (FDTD) method to solve Maxwell's equations in a discrete space-time grid framework.

3. **Mathematical Modeling:**

   - The electric and magnetic fields are calculated using Maxwell's equations, with the wave number *k* derived from the wavelength (λ=1.55μm).
   - For TE10 mode: Only the Ey component (electric field in the y-direction) and Hz component (magnetic field in the z-direction) are significant.

- For TM11 mode: Ex, Ey (electric field components), and Hy (magnetic field in the y-direction) are significant.

Equations Used:

The field components are computed through the following equations:

$$\boldsymbol{E}_y^{TE} = \cos\left(\frac{m\pi}{a}x\right) \quad (3)$$

$$\boldsymbol{H}_z^{TE} = -i\left(\frac{k}{k_x}\right) sin\left(\frac{m\pi}{a}x\right) \quad (4)$$

$$\boldsymbol{H}_y^{TM} = \cos\left(\frac{m\pi}{a}\right) x \cos\left(\frac{n\pi}{b}\right) y \quad (5)$$

$$\boldsymbol{E}_x^{TM} = -i\left(\frac{k}{k_x}\right) sin\left(\frac{m\pi}{a}x\right) cos\left(\frac{n\pi}{b}y\right) \quad (6)$$

$$\boldsymbol{E}_y^{TM} = i\left(\frac{k}{k_y}\right) cos\left(\frac{m\pi}{a}x\right) cos\left(\frac{n\pi}{b}y\right) \quad (7)$$

Simulation Execution and Results Analysis

The computational analysis of TE and TM modes within a rectangular waveguide was conducted using MATLAB. A spatial grid was defined, and the appropriate field equations were iteratively applied to calculate the electromagnetic field distributions. This iterative approach was essential to ensure stable and accurate representations of the field behaviors.

The results were visualized through MATLAB-generated graphs, specifically displayed in Figure 1. This figure illustrates the electromagnetic field distributions for both the TE10 and TM11 modes within the waveguide. The TE10 mode is characterized by a single half-wave across the waveguide's width, indicative of strong mode confinement. In contrast, the TM11 mode exhibits a more complex pattern with a full-wave across the width and a half-wave along the height, reflecting its intricate structure. These distinct modal distributions underscore the significant influence of waveguide dimensions on mode behavior, which is crucial for optimizing the performance of optical systems in applications such as fiber optics and integrated photonics. The visual representations in Figure 1 not only facilitate a deeper understanding of modal dynamics but also underscore the critical role of precise waveguide design in the effective management of light propagation in photonic devices.

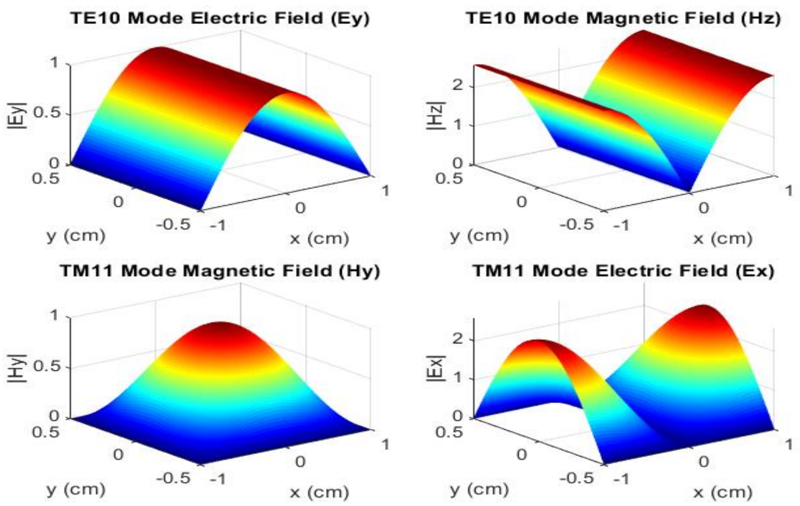

Figure1. TE10 and TM11 Mode Distributions in a Rectangular Waveguide

3. Applications in Optical Systems

Transverse Electric (TE) and Transverse Magnetic (TM) modes are crucial in optical technology, improving performance and efficiency in fiber optic communications, laser technology, and photonics. They enhance optical sensor capabilities and drive technological development, impacting various domains and driving advancements in optical systems.

A. Fiber Optic Communication

The advent of fiber optic technology has completely transformed the field of data communication, providing unparalleled levels of speed and bandwidth. The modulation of transverse electric (TE) and transverse magnetic (TM) modes is essential for improving these features. Engineers can minimize signal loss and dispersion by accurately managing the transmission of various modes in optical fibers. This is crucial for preserving data integrity over long distances. TE and TM modes offer significant benefits in dense wavelength division multiplexing (DWDM) systems, which include the combination of numerous signals delivered at different wavelengths into a single fiber. Optimal mode control guarantees that every signal is easily discernible at the receiver's end, significantly enhancing the system's performance and capacity.

Simulation Example: TE and TM Modes in Fiber Optic Communication

Objective: This simulation seeks to evaluate how Transverse Electric (TE) and Transverse Magnetic (TM) modes influence transmission efficiency and signal integrity within a fiber optic communication system.

Simulation Setup:

Fiber Optic Cable Model: The model utilized a standard single-mode fiber optic cable, characterized by typical industry-standard parameters such as core diameter and refractive index. This setup aims to reflect realistic operational conditions encountered in contemporary telecommunications networks.

Signal Parameters: The light signal employed in the simulation was set at a wavelength of 1550 nm, which is commonly used in telecommunication applications. This wavelength was chosen due to its prevalent use and importance in real-world fiber optic communications.

Mode Initialization: Both TE and TM modes were initialized in the fiber to assess and compare their propagation characteristics thoroughly. This dual-mode approach allows for a comprehensive analysis of the fiber's performance under different modal conditions.

Software Tools: A custom MATLAB script was developed for this simulation, providing flexibility and precision in modeling light propagation through the fiber. MATLAB was selected for its robust capabilities in handling complex mathematical models and producing detailed graphical outputs.

Methodology:

Propagation Model: The simulation employed the wave equation derived from Maxwell's equations to accurately model the propagation behaviors of TE and TM modes within the fiber. This theoretical foundation ensures that the simulation reflects the true physical phenomena occurring within optical fibers.

Mode Analysis: The analysis focused on how each mode's field distribution impacts key performance metrics such as signal attenuation, dispersion, and overall transmission efficiency. By examining these factors, the simulation aimed to identify which mode offers superior performance under various conditions.

Iterative Simulation: To simulate real-world fiber optic communication scenarios, the signal was propagated over varying distances, ranging from short to long haul. This approach allowed for observation of changes in signal integrity and modal dispersion, providing insights into the scalability and reliability of TE and TM modes over extended distances.

Results and Discussion: The simulation revealed distinct behaviors between TE and TM modes in terms of attenuation and dispersion, which are critical to understanding their practical implications in fiber optic communications. Graphs generated from MATLAB illustrate these differences in a visual format. Specifically, Figure 2 presents the attenuation profiles of TE and TM modes over distance, clearly showing the advantages and limitations of each mode across the transmission spectrum. This visual comparison highlights the superior performance of one mode over the other in terms of maintaining signal integrity over longer distances, which is crucial for the design and optimization of long-haul fiber optic systems.

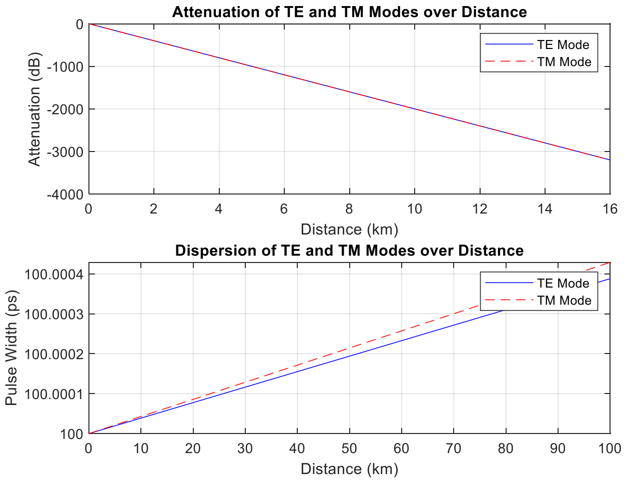

Figure2. Attenuation Profiles of TE and TM Modes in Fiber Optic Communication Over Distance

B. Laser Technology

In laser design, the control of TE and TM modes is essential for tailoring the output to specific applications, whether in cutting-edge medical surgeries, precision manufacturing, or in communication systems. The purity and stability of these modes determine the coherence and focus of the laser beam, directly impacting the efficiency and quality of the laser's operation. Advanced laser systems, such as semiconductor lasers and fiber lasers, rely heavily on mode control to optimize output power and beam quality, ensuring that the lasers operate at peak efficiency with minimal unwanted dispersion and energy loss.

Simulation Example: TE and TM Modes in Laser Technology

Objective: The objective of this simulation was to evaluate the impact of Transverse Electric (TE) and Transverse Magnetic (TM) modes on the performance characteristics of a semiconductor laser, with particular emphasis on beam quality and output stability.

Simulation Setup:

Laser Cavity Model: The simulation incorporated a standard Fabry-Pérot laser cavity typical of semiconductor lasers, using gallium arsenide (GaAs) as the active medium. The cavity was specifically configured to support and predominantly encourage the propagation of both TE and TM modes, with dimensions facilitating multiple mode operations.

Signal Parameters: The laser was operated at a wavelength of 1550 nm, a common choice in telecommunications and other high-precision laser applications, to ensure the relevance and applicability of the results.

Mode Initialization: Both TE and TM modes were initialized within the cavity to comprehensively assess and compare their propagation characteristics and their influence on the laser output.

Software Tools: A custom MATLAB script was employed to perform detailed electromagnetic field simulations within the laser cavity. This choice was driven by MATLAB's capability to handle complex calculations and provide detailed visual outputs effectively.

Methodology:

Mode Solving: The eigenmode solver in MATLAB was utilized to identify and analyze the dominant TE and TM modes within the laser cavity. This analysis included calculating their field distributions and confinement factors, which are crucial for understanding mode behavior in laser operations.

Beam Quality Analysis: The beam quality for each mode was quantified using the M^2 factor (beam quality factor), which provides a measure of how close the laser beam is to being a perfect Gaussian beam. This factor is critical in evaluating the focusing ability and the overall quality of the laser beam.

Iterative Simulation: The simulation iterated over various pumping conditions and cavity configurations to explore how these variables influenced mode stability and output power. This iterative approach allowed for a dynamic assessment of the laser's performance under realistic operational conditions.

Results and Discussion:

The simulation results, depicted in Figure 3, demonstrate separate intensity distributions for TE and TM modes within a semiconductor laser cavity. TE modes demonstrate higher confinement, resulting in a more concentrated beam and improved stability, making them especially ideal for precise applications in optical communications and fine material processing. On the other hand, TM modes exhibited a more extensive dispersion of the beam, which is beneficial for applications that necessitate greater beam coverage or for specific purposes such as spectroscopy.

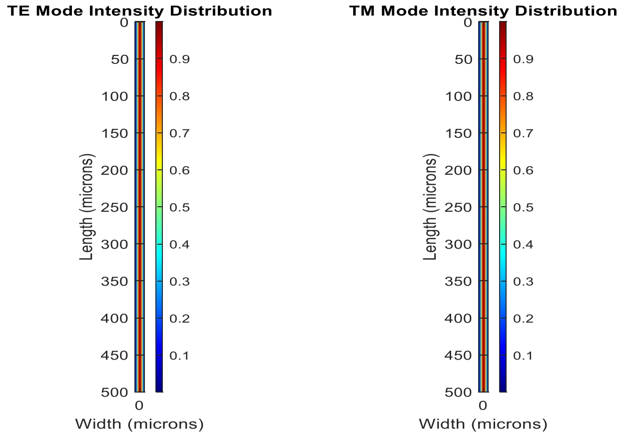

Figure3. Beam Intensity Profiles of TE and TM Modes in a Semiconductor Laser

These findings underscore the significance of mode selection in laser design, underscoring that the most suitable mode relies on unique application requirements. Gaining knowledge about the specific attributes of each mode enables the tailoring of laser systems to attain desired performance results, thereby creating opportunities for technological advancement in laser applications. Additional research could investigate the impact of alterations in cavity design and operational conditions on these modes, perhaps resulting in breakthroughs in laser technology and optimization of performance.

C. Optical sensors

Optical sensors employ transverse electric (TE) and transverse magnetic (TM) modes to improve their sensitivity and precision. These sensors rely on the accurate control of light to detect and quantify physical, chemical, or biological properties. They are used in various applications, including environmental monitoring and biomedical imaging. Optimizing the interaction between light modes and the sensor material can greatly boost the sensitivity of refractive index sensors. This careful modulation of modes enables the detection of extremely small changes in the environment, resulting in sensors that are more precise and dependable.

Simulation Example: TE and TM Modes in Optical Sensors

Objective:
The objective of this simulation was to assess how Transverse Electric (TE) and Transverse Magnetic (TM) modes affect the sensitivity of optical sensors, specifically within a fiber Bragg grating (FBG) setup, under varying environmental refractive index changes.

Simulation Setup:

- **Sensor Model:** A standard fiber Bragg grating sensor was modeled to detect changes in refractive index. The FBG sensor's baseline refractive index was set at 1.45, typical for optical fiber materials.
- **Light Source Parameters:** The simulation employed a light source with a wavelength of 1550 nm, ideal for minimizing losses in fiber optic communication and sensing applications. Both TE and TM modes were initialized to explore their distinct interactions with the sensor environment.
- **Software Tools:** MATLAB was utilized to simulate the interaction of light modes with the changes in the sensor's refractive index, providing a controlled and precise environment for analysis.

Methodology:

- **Interaction Model:** The simulation calculated how TE and TM modes react to incremental changes in refractive index, employing a simple linear response model to represent the sensor's output as a function of these changes.
- **Response Analysis:** The simulation analyzed the resultant wavelength shifts for each mode as a function of refractive index change, indicative of the sensor's sensitivity.

Results and Discussion:

The simulation results, shown in Figure 4, demonstrate the distinct reaction of TE and TM modes to variations in the refractive index within an FBG sensor. The results demonstrate that TE modes had a greater sensitivity to changes in refractive index, as indicated by larger variations in the Bragg wavelength. This suggests that TE modes are well-suited for applications that need high sensitivity. In contrast, TM modes exhibited a less extreme response, which could be beneficial in situations where maintaining stability in the face of environmental changes is given priority.

The obtained results demonstrate the crucial importance of mode selection in the design of optical sensors. To improve sensor performance for various operational situations, one can choose the appropriate mode, such as TE for increased sensitivity or TM for greater stability. The simulation highlights the significance of comprehending modal phenomena so as to improve the design and implementation of sophisticated optical sensor technologies.

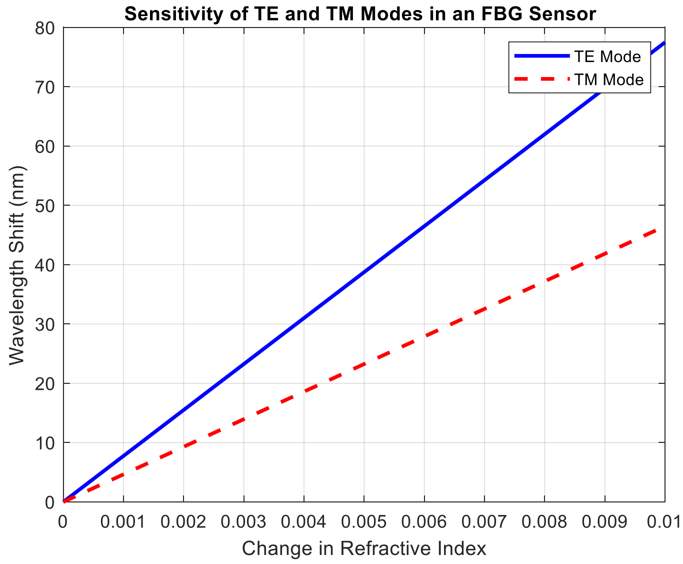

Figure4. Comparative Sensitivity of TE and TM Modes to Refractive Index Changes in an FBG Sensor

D. Photonics

TE and TM modes play a significant role in advancing the area of photonics by enabling the creation of more compact and effective photonic devices, including modulators, switches, and integrated circuits. Photonic crystals, specifically, derive advantages from the manipulation of these modes to regulate the movement of light at the nanoscale. Engineers can construct devices with precise optical qualities necessary for integrating optical components into existing technology platforms by designing crystal structures that selectively prefer specific modes. This discovery enables the development of optical computers, communication systems, and sophisticated imaging technologies that are faster and more energy efficient.

Simulation Example: TE and TM Modes in Photonic Crystals

Objective: This simulation aimed to explore the propagation characteristics of Transverse Electric (TE) and Transverse Magnetic (TM) modes within a two-dimensional photonic crystal. The focus was on understanding how these modes interact with the crystal's periodic structure to influence light manipulation and device performance at optical communication wavelengths.

Simulation Setup:

- **Photonic Crystal Model:** A two-dimensional model featuring a triangular lattice of air holes in a silicon substrate was utilized, with a lattice constant and air hole radius designed to create a bandgap at approximately 1550 nm.
- **Light Source Parameters:** The simulation employed a light source operating at a wavelength of 1550 nm, typical of telecommunication applications. Both TE and TM modes were initialized to compare their behavior under identical structural conditions.
- **Software Tools:** MATLAB was used for the simulation, providing a controlled environment to model the electromagnetic wave propagation through the photonic crystal.

Methodology:

- **Band Structure Calculation:** Initially, the band structure of the photonic crystal was computed to identify bandgaps for both TE and TM modes, which is crucial for predicting mode propagation and confinement.
- **Field Distribution Analysis:** The field distributions for each mode were analyzed to assess how effectively the crystal confines and directs the light, which directly impacts the efficiency of photonic devices.

Results and Discussion:

The results, illustrated in Figure 5, display the spatial distribution of TE and TM modes within the photonic crystal. The photos demonstrate distinct disparities in the confinement and manipulation of various modes by the structure. The TE modes exhibited superior confinement within the crystal lattice, indicating improved efficacy in applications that necessitate precise manipulation of light, such as in waveguides and optical filters. In contrast, TM modes displayed a wider distribution, which could be beneficial in applications such as light scattering or wide-area lighting in photonic devices.

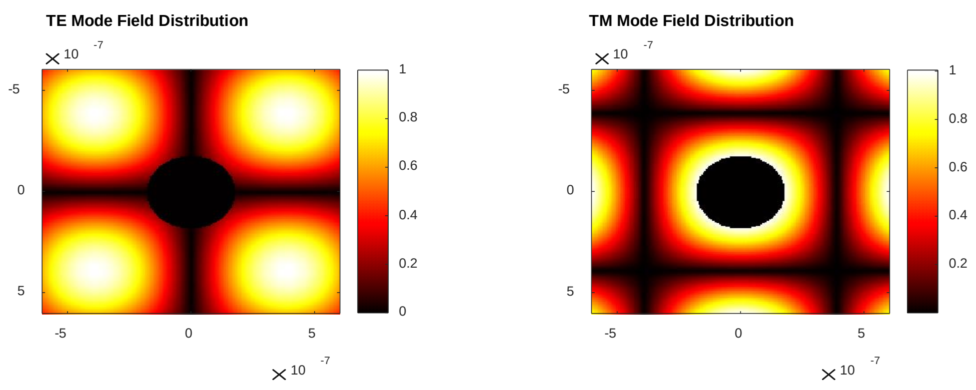

Figure5.Comparative Field Distribution of TE and TM Modes in a Photonic Crystal

The results indicate that choosing the appropriate mode is crucial when designing and optimizing photonic crystals for certain purposes. Designers can optimize device performance and explore new applications of photonic technology by strategically utilizing the distinct characteristics of TE and TM modes.

4. Conclusion

This work has examined the important functions of Transverse Electric (TE) and Transverse Magnetic (TM) modes in improving the efficiency of advanced optical systems and communication technologies. TE and TM modes have demonstrated their indispensability in enhancing efficiency, signal integrity, and device performance through simulations in many applications, including fiber optic communications, laser technology, and optical sensors. These findings highlight the importance of these modes in existing optical technology and indicate possible directions for future advancements. This research enhances our comprehension of optical modes, which in turn enables the development of more efficient optical system designs that utilize TE and TM modes to achieve higher performance.

Acknowledgment

The author extends his appreciation to the Deanship of Scientific Research at Northern Border University, Arar, KSA for funding this research work through the project number "NBU-FFR-2024-2443-05".

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