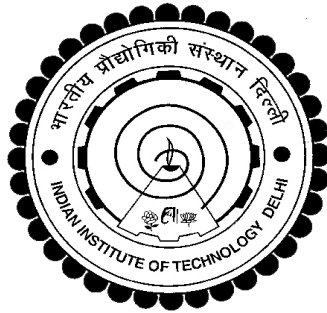


**VECTOR WAVE PROPAGATION METHODS FOR
GUIDED-WAVE PHOTONIC STRUCTURES**

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**VECTOR WAVE PROPAGATION METHODS FOR
GUIDED-WAVE PHOTONIC STRUCTURES**

by

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Department of Physics

Submitted

in fulfilment of the requirements of the degree of

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Dedicated to My Family

CERTIFICATE

This thesis, "**VECTOR WAVE PROPAGATION METHODS FOR GUIDED-WAVE PHOTONIC STRUCTURES**," that Pratiksha Choudhary submitted to the Indian Institute of Technology, Delhi, is an account of her research. To the best of our knowledge, she completed the requirements while working under my supervision, satisfying the requirements for the submission of this thesis. No other institution or organization has received the results discussed in this thesis, either in full or in part, for the purpose of awarding a degree or diploma.



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ABSTRACT

Optical waveguides are critical components in photonic technologies, designed to guide electromagnetic waves along specific paths with minimal loss over long distances. These structures exploit the principle of total internal reflection, confining light within a high-refractive-index core while surrounded by lower-index materials. The core of the waveguide enables efficient light transmission, with various forms such as planar, strip, and fiber waveguides serving different applications. For instance, strip waveguides are integral to integrated photonic circuits, directing light in two-dimensional geometries, while fiber waveguides are pivotal in telecommunications for long-distance data transmission with minimal attenuation. The refractive index profiles of waveguides can be categorized into step-index profiles, characterized by abrupt transitions between core and cladding, and graded-index profiles, which feature gradual index transitions. The choice of materials for waveguides ranging from silica and lithium niobate to silicon and polymers depends on the application's specific requirements, including operating wavelength and optical transmission characteristics. The propagation characteristics of waveguides are derived from Maxwell's equations, with appropriate boundary conditions defined by the structure. In uniform waveguides, propagation can be analysed in terms of modes field configurations that maintain their intensity profile as they propagate. For practical applications, mode solutions are often obtained numerically, and in non-uniform guiding structures, direct numerical solutions of the wave equation are employed. Numerical methods, particularly the beam propagation method (BPM) based on the fast Fourier transform (FFT), have been the foundation for simulating photonic systems. Traditional BPM methods rely on paraxial approximations, valid only for weakly guiding waveguides. However, with advancements in high-contrast waveguides like silicon waveguides, non-paraxial vector wave propagation methods have emerged as essential tools. This thesis presents the development and application of such non-paraxial vector wave

propagation methods tailored for modern photonic devices. The finite difference split-step non-paraxial (FDSSNP) method is the key numerical approach explored in this work. It integrates the finite difference method with the split-step technique to solve the full wave equation without relying on paraxial approximations. In this method, the wave propagation operator is split into components that account for uniform structures and the variations present in the guiding structures. While previously applied primarily to scalar wave propagation problems, this thesis extends the FDSSNP method to vector wave propagation. A novel operator splitting technique is introduced, enhancing computational efficiency and significantly reducing memory requirements while ensuring accurate propagation of modes through various waveguide structures. Moreover, the thesis investigates the propagation of vector waves in complex structures, including waveguide, tapers and s-junctions. A critical challenge in numerical simulations arises from the necessity to truncate the transverse domain, which can lead to spurious reflections and consequent inaccuracies. To minimize these issues, various boundary conditions have been employed, including absorbing boundary conditions (ABC) and perfectly matched layer (PML) conditions. We have introduced a new boundary condition, the field domain boundary condition (FDBC), which modifies the field directly and have demonstrated performance accuracy being comparable to existing methods, but being very simple to use. For uniform waveguides, mode analysis and characterization are essential, with several numerical methods developed for obtaining scalar and vector modes. This thesis contributes a formulation for wave propagation that is directly convertible into a mode computation framework, utilizing enhanced finite-difference approximations for derivatives. This capability allows for application across various waveguide geometries, including rectangular, circular, triangular, trapezoidal, and ring core fibers. Convergence studies have been conducted to minimize numerical errors and ensure consistent results, with comparative analysis against analytical methods and existing numerical works further validating the

approach. In summary, the thesis has contributed to the development of numerical simulation domain with new methods for full vector non-paraxial propagation and modal computation for arbitrary shaped waveguides.

सारांश (Abstract)

ऑप्टिकल वेवगाइड (Optical Waveguides) फोटोनिक प्रौद्योगिकियों के महत्वपूर्ण घटक हैं, जिन्हें विद्युतचुंबकीय तरंगों को विशिष्ट मार्गों पर न्यूनतम हानि के साथ लंबी दूरी तक प्रसारित करने के लिए डिज़ाइन किया जाता है। ये संरचनाएँ पूर्ण आंतरिक परावर्तन (Total Internal Reflection) के सिद्धांत का उपयोग करती हैं, जिससे प्रकाश उच्च अपवर्तनांक (high refractive index) वाले कोर में सीमित रहता है और इसे निम्न अपवर्तनांक वाले पदार्थों से घेर लिया जाता है।

वेवगाइड का कोर प्रभावी रूप से प्रकाश संचरण को सक्षम बनाता है और इसे विभिन्न रूपों में निर्मित किया जा सकता है, जैसे समतल (planar), स्ट्रिप (strip), तथा फाइबर वेवगाइड (fiber waveguides), जो विभिन्न अनुप्रयोगों में उपयोगी हैं। उदाहरणस्वरूप, स्ट्रिप वेवगाइड्स एकीकृत फोटोनिक परिपथों (Integrated Photonic Circuits) में महत्वपूर्ण भूमिका निभाते हैं, जो द्वि-आयामी ज्यामिति में प्रकाश का निर्देशन करते हैं, जबकि फाइबर वेवगाइड्स लंबी दूरी की डेटा संचार प्रणालियों में न्यूनतम क्षीणन (attenuation) के साथ सूचना प्रसारित करने में सहायक होते हैं।

वेवगाइड्स के अपवर्तनांक प्रोफ़ाइल को दो श्रेणियों में विभाजित किया जा सकता है—**स्टेप-इंडेक्स प्रोफ़ाइल (step-index)**, जिसमें कोर और क्लैडिंग के बीच तीव्र परिवर्तन होता है, तथा **ग्रेडेड-इंडेक्स प्रोफ़ाइल (graded-index)**, जिसमें अपवर्तनांक का परिवर्तन क्रमिक होता है। सिलिका, लिथियम नियोबेट, सिलिकॉन तथा पॉलिमर जैसे विभिन्न पदार्थों का चयन उनके अनुप्रयोग की आवश्यकताओं—जैसे कार्यरत तरंगदैर्घ्य और प्रकाशीय संचरण विशेषताओं—के अनुसार किया जाता है।

वेवगाइड्स की प्रसार विशेषताएँ (propagation characteristics) मैक्सवेल समीकरणों (Maxwell's Equations) से व्युत्पन्न होती हैं, जिनके लिए उपयुक्त सीमा स्थितियाँ (boundary conditions) संरचना द्वारा परिभाषित की जाती हैं। समान (uniform) वेवगाइड्स में प्रसार को ऐसे मोड्स (modes) के रूप में विश्लेषित किया जा सकता है जो अपने तीव्रता प्रोफ़ाइल को प्रसार के दौरान बनाए रखते हैं। व्यावहारिक अनुप्रयोगों में मोड समाधानों (mode solutions) को प्रायः संख्यात्मक रूप से प्राप्त किया जाता है, विशेषकर असमान संरचनाओं में जहाँ तरंग समीकरण का प्रत्यक्ष संख्यात्मक हल आवश्यक होता है।

संख्यात्मक विधियों में **बीम प्रोपेगेशन मेथड (BPM)**, विशेष रूप से **फास्ट फूरियर ट्रांसफॉर्म (FFT)** पर आधारित BPM, फोटोनिक प्रणालियों के सिमुलेशन की आधारशिला रहा है। पारंपरिक BPM पद्धतियाँ पराक्सियल (paraxial) समीकरणों पर निर्भर होती हैं, जो केवल कमजोर गाइडिंग संरचनाओं के लिए मान्य होती हैं। किंतु उच्च-विपरीत (high-contrast) वेवगाइड्स, जैसे सिलिकॉन वेवगाइड्स, में इस पराक्सियल अनुमान की सीमाएँ स्पष्ट हो जाती हैं। इसलिए, आधुनिक फोटोनिक उपकरणों के लिए **नॉन-पैराक्सियल वेक्टर वेव प्रोपेगेशन विधियाँ** आवश्यक हो गई हैं।

इस शोध में ऐसी ही एक उन्नत विधि, **फाइनाइट डिफरेंस स्प्लिट-स्टेप नॉन-पैराक्सियल (FDSSNP)** पद्धति का विकास और अनुप्रयोग प्रस्तुत किया गया है। यह विधि पराक्सियल अनुमानों पर निर्भर हुए बिना पूर्ण तरंग समीकरण को हल करने हेतु **फाइनाइट डिफरेंस मेथड** और **स्प्लिट-स्टेप तकनीक** का संयोजन करती है।

इसमें तरंग प्रसार ऑपरेटर को इस प्रकार विभाजित किया जाता है कि यह समान संरचनाओं और गाइडिंग संरचनाओं में उपस्थित विविधताओं दोनों को ध्यान में रखता है।

पहले जहाँ यह विधि केवल स्केलर तरंग प्रसार समस्याओं तक सीमित थी, वहीं यह शोध FDSSNP पद्धति को **वेक्टर वेव प्रोपेगेशन** तक विस्तारित करता है। इसमें एक नवीन ऑपरेटर स्प्लिटिंग तकनीक प्रस्तुत की गई है, जो गणनात्मक दक्षता को बढ़ाती है, मेमोरी आवश्यकताओं को घटाती है, तथा विभिन्न वेवगाइड संरचनाओं में मोड्स के सटीक प्रसार को सुनिश्चित करती है।

इसके अतिरिक्त, यह शोध वेवगाइड्स, टेपर्स, और एस-जंक्शनों जैसी जटिल संरचनाओं में वेक्टर तरंगों के प्रसार का अध्ययन करता है। संख्यात्मक सिमुलेशनों में मुख्य चुनौती ट्रांसवर्स डोमेन की सीमाओं के कारण उत्पन्न **स्प्यूरियस रिफ्लेक्शन्स (spurious reflections)** से निपटना है। इस समस्या के समाधान हेतु विभिन्न सीमा स्थितियाँ—जैसे **Absorbing Boundary Condition (ABC)** और **Perfectly Matched Layer (PML)**—का उपयोग किया गया है।

इस शोध में एक नई सीमा स्थिति, **फील्ड डोमेन बाउंडरी कंडीशन (FDBC)**, प्रस्तावित की गई है, जो सीधे क्षेत्र (field) को संशोधित करती है और अपनी सरलता के बावजूद सटीकता में मौजूदा विधियों के तुल्य प्रदर्शन करती है।

समान वेवगाइड्स के लिए मोड विश्लेषण और लक्षणान्कन (characterization) अत्यंत आवश्यक हैं। यह शोध तरंग प्रसार के लिए ऐसी रूपरेखा प्रस्तुत करता है जो सीधे **मोड कंप्यूटेशन फ्रेमवर्क** में परिवर्तनीय है, और जिसमें सीमित अंतर (finite-difference) आधारित डेरिवेटिव्स का उपयोग किया गया है। यह रूपरेखा विभिन्न वेवगाइड ज्यामितियों—जैसे आयताकार, वृत्ताकार, त्रिकोणीय, ट्रेपेज़ॉयडल और रिंग कोर वेवगाइड्स—पर भी लागू की जा सकती है।

संख्यात्मक त्रुटियों को न्यूनतम करने और संगत परिणाम प्राप्त करने के लिए **अभिसरण अध्ययन (convergence studies)** किए गए हैं। साथ ही, विश्लेषणात्मक विधियों और मौजूदा संख्यात्मक कार्यों के साथ तुलना द्वारा इस दृष्टिकोण की पुष्टि की गई है।

सारांशतः, इस शोध ने संख्यात्मक सिमुलेशन क्षेत्र में एक महत्वपूर्ण योगदान दिया है, जहाँ **पूर्ण वेक्टर नॉन-पैराक्सियल तरंग प्रसार और मनमाने आकार के वेवगाइड्स** के लिए **मोडल गणना (modal computation)** हेतु नई विधियों का विकास किया गया है।

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ABBREVIATIONS

ABC - Absorbing Boundary Conditions

BPM - Beam Propagation Method

EMET- Eigenmode expansion technique

FD - Finite-Difference

FDBC - Field Domain Boundary Condition

FD-BPM - Finite difference-beam propagation method

FDSSNP - Finite-Difference Split-Step Non-Paraxial

FDTD - Finite Difference Time Domain

FEM- Finite Element Method

FFT - Fast Fourier Transform

FFT-BPM - Fast Fourier transform-beam propagation method

PML - Perfectly Matched Layer

SSNP - Split step non paraxial

TBC - Transparent Boundary Conditions

TE - Transverse Electric

TIR - Total Internal Reflection

TM - Transverse Magnetic

SYMBOLS

General Symbols

x, y, z : Cartesian coordinates

t : Time

c : Speed of light in a vacuum

ω : Angular frequency

k : Wave number

λ : Wavelength

ν : Frequency

n : Refractive index

Vector Fields

\vec{E} : Electric field vector

\vec{H} : Magnetic field vector

\vec{D} : Electric displacement field

\vec{B} : Magnetic flux density

\vec{P} : Polarization vector

\vec{M} : Magnetization vector

Waveguide Parameters

n : Refractive index of material

Δ : Relative index difference

V : Normalized frequency parameter

β : Propagation constant

Modes and Fields

TE: Transverse electric mode

TM: Transverse magnetic mode

HE: Hybrid electric mode

EH: Hybrid magnetic mode

E_x, E_y, E_z : Electric field components

H_x, H_y, H_z : Magnetic field components