FABRICATION, LINEAR, AND NONLINEAR OPTICAL STUDIES OF SILICON-BASED APERIODIC AND PERIODIC PHOTONIC STRUCTURES

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by

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in fulfillment of the requirements of the degree of
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To the Almighty, my Parents & Teachers…

CERTIFICATE

This is to certify that the thesis entitled, "**Fabrication, Linear, and Nonlinear Optical Studies of Silicon-Based Aperiodic and Periodic Photonic Structures"** *being submitted by* **Mr. Albin Kuriakose**, *to the Indian Institute of Technology Delhi, New Delhi, for the award of the degree of* **Doctor of Philosophy** *in Physics is a record of bonafide research work carried out by him under my supervision and guidance. He has fulfilled the requirements for submission of the thesis, which to the best of my knowledge has reached the requisite standard.*

The material contained in the thesis has not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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Albin Kuriakose

ABSTRACT

Owing to tremendous interest in new trends in photonics, *silicon*-based photonic structures are of tremendous interest for ultrafast nonlinear optical devices. Specifically, non-stoichiometric a:SiN_x provide structurally tuneable optical characteristics and bandgap engineering capabilities which is highly suited for integrated device technology. The thesis is highly motivated for exploring varieties of aperiodic and periodic wavelength-ordered nonstoichiometric a:SiN_x multilayered photonic structures of that have been of interest to research from past decades due to the ability to manipulate the light-matter interactions.

The thesis presents a comprehensive understanding of the structural, linear and ultrafast nonlinear optical properties of various a:SiN_x based aperiodic and periodic photonic structures such as distributed Bragg reflectors (DBR) and optical microcavities and their respective constituent a:SiN_x thin films. The results demonstrate that the stochiometric composition in a:SiN_x plays a crucial role in tailoring both linear and nonlinear optical responses as well as ultrafast carrier dynamics, thereby offering a route for controlled bandgap and refractive index engineering. Exclusively, the linear and nonlinear optical features of a:SiN_x based aperiodic and periodic1D photonic structures are strongly influenced by the disparities in optical field confinement due to the geometrical invariance. Effect of photonic *minibands* and *cavity mode* in the third-order nonlinear responses are studied extensively using various rigorous experimentations. Thesis emphasises the influence of photonic modes and fractal resonances in manipulating and enhancing nonlinear optical responses of photonic architectures with inherent N/Si related defect energy levels. All the experimental results are fully supported by the Transfer Matrix Method (TMM) simulations, numerical estimations and theoretical fits. The thesis also explores the potential of high-intensity pulsed lasers for large-area mass-production 2D periodic photonic structure fabrication on silicon surfaces to demonstrate broadband antireflective and diffraction capabilities.

The thesis establishes a unified understanding of how compositional and structural control in a:SiN_x can be leveraged to achieve tunable and ultrafast optical functionalities by developing various photonic architectures. The findings contribute to the advancement of next-generation silicon-compatible photonic devices for both linear and nonlinear optical applications.

सारांश

फोटोनिक्स के नए रुझानों में अत्यधिक रुचि के कारण, सिलिकॉन-आधारित फोटोनिक संरचनाएँ अल्ट्राफास्ट नॉनलाइनियर ऑप्टिकल उपकरणों के लिए अत्यधिक रुचिकर हैं। विशेष रूप से, नॉन-स्टोइकोमेट्रिक $a:SiN_x$ संरचनात्मक रूप से ट्यूनेबल ऑप्टिकल विशेषताएँ और बैंडगैप इंजीनियरिंग क्षमताएँ प्रदान करता है जो एकीकृत उपकरण प्रौद्योगिकी के लिए अत्यधिक उपयुक्त हैं। यह शोध प्रबंध विभिन्न प्रकार की अआवर्ती और आवर्ती तरंगदैर्ध्य-क्रमित नॉनस्टोइकोमेट्रिक $a:SiN_x$ बहुस्तरीय फोटोनिक संरचनाओं की खोज के लिए अत्यधिक प्रेरित है, जो प्रकाश-पदार्थ अंतःक्रियाओं को नियंत्रित करने की क्षमता के कारण पिछले दशकों से अनुसंधान के लिए रुचिकर रही हैं।

यह शोध प्रबंध विभिन्न $a:SiN_x$ आधारित आवर्ती और आवर्ती फोटोनिक संरचनाओं, जैसे वितरित ब्रैग परावर्तक (DBR) और प्रकाशिक सूक्ष्मगुहाओं, और उनके संबंधित घटक $a:SiN_x$ पतली फिल्मों के संरचनात्मक, रैखिक और अति तीव्र अरैखिक प्रकाशीय गुणों की एक व्यापक समझ प्रस्तुत करता है। परिणाम दर्शाते हैं कि a:SiNx में स्टोकियोमेट्रिक संरचना रैखिक और अरैखिक प्रकाशीय प्रतिक्रियाओं के साथ-साथ अति तीव्र वाहक गतिकी को अनुकूलित करने में महत्वपूर्ण भूमिका निभाती है, जिससे नियंत्रित बैंडगैप और अपवर्तनांक इंजीनियरिंग के लिए एक मार्ग उपलब्ध होता है। विशेष रूप से, a:SiNx आधारित आवर्ती और आवर्ती 1D फोटोनिक संरचनाओं की रैखिक और अरैखिक प्रकाशीय विशेषताएँ ज्यामितीय अपरिवर्तनशीलता के कारण प्रकाशीय क्षेत्र परिरोध में असमानताओं से अत्यधिक प्रभावित होती हैं। तृतीय-क्रम अरैखिक प्रतिक्रियाओं में फोटोनिक मिनीबैंड और कैविटी मोड के प्रभाव का विभिन्न कठोर प्रयोगों द्वारा व्यापक अध्ययन किया गया है। शोध प्रबंध अंतर्निहित N/Si संबंधित दोष ऊर्जा स्तरों वाले फोटोनिक आर्किटेक्चर की अरैखिक प्रकाशिक प्रतिक्रियाओं में हेरफेर और वृद्धि करने में फोटोनिक मोड और फ्रैक्टल अनुनादों के प्रभाव पर बल देता है। सभी प्रयोगात्मक परिणाम ट्रांसफर मैट्रिक्स विधि (TMM) सिमुलेशन, संख्यात्मक अनुमानों और सैद्धांतिक फिट द्वारा पूरी तरह से समर्थित हैं। शोध प्रबंध ब्रॉडबैंड एंटीरिफ्लेक्टिव और विवर्तन क्षमताओं को प्रदर्शित करने के लिए सिलिकॉन सतहों पर बड़े क्षेत्र में बड़े पैमाने पर उत्पादन वाली 2D आवधिक फोटोनिक संरचना निर्माण हेतु उच्च-तीव्रता वाले स्पंदित लेज़रों की क्षमता का भी पता लगाता है।

कुल मिलाकर, यह शोध-प्रबंध इस बात की एक एकीकृत समझ स्थापित करता है कि विभिन्न फोटोनिक आर्किटेक्चर विकसित करके $a:SiN_x$ में संरचनागत और संरचनात्मक नियंत्रण का उपयोग कैसे किया जा सकता है ताकि ट्यूनेबल और अल्ट्राफास्ट ऑप्टिकल कार्यात्मकताएँ प्राप्त की जा सकें। ये निष्कर्ष रैखिक और अरैखिक दोनों प्रकार के ऑप्टिकल अनुप्रयोगों के लिए अगली पीढ़ी के सिलिकॉन-संगत फोटोनिक उपकरणों के विकास में योगदान करते हैं।

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Appendix

Abbreviations

LED	: Light Emitting Diode
QD	: Quantum Dot
PSi	: Porous Silicon
PECVD	: Plasma Enhanced Chemical Vapor Deposition
RF	: Radio Frequency
1D, 2D, and 3D	: One-dimension, Two-dimension, and Three-dimension
DBR	: Distributed Bragg Reflector
TMM	: Transfer Matrix Method
PBG	: Photonic Bandgap
ns	: Nanosecond
ps	: Picosecond
fs	: Femtosecond
SA	: Saturation of Absorption
RSA	: Reverse Saturation of Absorption
XPS	: X-ray Photoelectron Spectroscopy
XRD	: X-ray Diffraction
XRR	: X-ray Reflectivity
FESEM	: Field Emission Scanning Electron Microscopy
AFM	: Atomic Force Microscopy
FWHM	: Full Width at Half Maximum
UV, Vis	: Ultraviolet, Visible
NIR	: Near Infrared
OPA	: Optical Parametric Amplifier
CPA	: Chirped pulse amplification
OA	: Open Aperture
CA	: Closed Aperture
TAS	: Transient Absorption Spectroscopy

Symbols

h	: Planck's Constant
ν	: Frequency
k	: Wave vector
λ	: Wavelength
L_{eff}	: Effective sample length
α_0	: Linear absorption coefficient
β	: Two-photon nonlinear absorption coefficient
γ	: Three-photon nonlinear absorption coefficient
$\chi^{(1)}$	: Linear dielectric susceptibility
$\chi^{(2)}$	: Second-order dielectric susceptibility
$\chi^{(3)}$	: Third-order dielectric susceptibility
$\Delta\phi$	: Nonlinear refraction phase shift
$\Delta\varphi$	: Nonlinear absorption phase shift
n_0	: Linear refractive index
n_2	: Nonlinear refractive index