FABRICATION AND OPTICAL STUDIES OF POROUS SILICON-BASED PHOTONIC STRUCTURES

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

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FABRICATION AND OPTICAL STUDIES OF POROUS SILICON-BASED PHOTONIC STRUCTURES

by

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Submitted

in fulfillment of the requirements for the degree of

Doctor of Philosophy

to the



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To my Parents

CERTIFICATE

This is to certify that the thesis entitled, "**Fabrication and Optical Studies of Porous Silicon-based Photonic Structures"** *being submitted by* **Mr. Mohd Shanu**, *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 in full to any other University or Institute for the award of any degree or diploma.



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(Mohd Shanu)

ABSTRACT

This thesis explores the one-dimensional (1D) porous silicon (PSi) photonic structures which have been fabricated via a cost-effective, top-down electrochemical approach. This thesis includes linear, nonlinear, and ultrafast optical studies, and some of the photonic structures have been used in sensing and photonic applications. A systematic study is presented by combining the transfer matrix method (TMM) and finite element method (FEM) based COMSOL Multiphysics simulations to simulate the photonic structures, visualize the field propagation, and support various experimental results in the thesis.

Free-standing porous silicon (FS-PSi) microcavities are fabricated so that they can be used to do measurements which are based on transmission-mode. Using a femtosecond laser, their third-order nonlinear optical (NLO) properties and the transient absorption spectroscopy (TAS) measurements have been done, and interesting results have been found. A FS-PSi microcavity has been utilized to record the reflection and transmission kinetics simultaneously for real-time sensing applications of small-chain alcohols. This highlights the advantages of FS-PSi microcavities for low-dielectric analytes over electrical sensors.

Complementary studies on organic porphyrin have been done to explore the nonlinear optical studies by focusing on the multi-photon absorption in Q bands over a broad range of 400-1600 nm, which has not been previously explored. Later, this porphyrin solution has been utilized to impregnate the PSi optical microcavity to study the interaction between them as a hybrid system. These kind of systems can be used for tunable light sources and optoelectronic applications. To utilize the PSi microcavity for this hybrid application, a systematic cavity mode tuning has been done from near UV-Vis to the NIR region. At the end of the thesis, aperiodic 1D photonic structures like Fibonacci structures have also been fabricated and compared with the periodic DBR and microcavity.

All these comprehensive studies of the 1D porous silicon photonic structures can open new avenues to explore fundamental aspects as well as the novel and advanced photonic and optoelectronic applications.

सामान्य सारांश

यह शोध प्रबंध एक-आयामी पोरस सिलिकॉन आधारित फोटोनिक संरचनाओं का अध्ययन प्रस्तुत करता है, जिन्हें एक किफायती, टॉप-डाउन इलेक्ट्रोकेमिकल प्रक्रिया द्वारा निर्मित किया गया है, साथ ही उनकी रैखिक, गैर-रैखिक और अल्ट्राफास्ट प्रकाशिकी विशेषताओं तथा सेंसरिंग और फोटोनिक अनुप्रयोगों में उनके प्रदर्शन का प्रदर्शन भी किया गया है। फोटोनिक संरचनाओं के अभिकल्प, क्षेत्र प्रसार के दृश्यांकन, और शोध प्रबंध में वर्णित विविध प्रायोगिक परिणामों के समर्थन हेतु ट्रांसफर मैट्रिक्स मेथड और फाइनाइट एलिमेंट मेथड आधारित कॉमसोल मल्टीफिजिक्स सिमुलेशनों को सम्मिलित करते हुए एक सुव्यवस्थित फ्रेमवर्क प्रस्तुत किया गया है।

अत्यधिक डोप्ड पी-प्रकार सिलिकॉन का उपयोग करते हुए, बहु-परत मुक्त-स्थापित पोरस सिलिकॉन माइक्रोकैविटीज़ का निर्माण किया गया, जिससे सब्सट्रेट की बाधाओं के बिना ट्रांसमिशन-मोड में मापन संभव हो सका। फेम्टोसेकंड लेज़र का उपयोग कर उनकी तृतीय-क्रम गैर-रैखिक प्रकाशकीय विशेषताओं तथा ट्रांज़िएंट एब्ज़ॉर्प्शन स्पेक्ट्रोस्कोपी मापों को पहली बार प्रदर्शित किया गया। एक मुक्त-स्थापित पोरस सिलिकॉन माइक्रोकैविटी का उपयोग लघु-श्रृंखला अल्कोहॉल्स के वास्तविक-समय सेंसरिंग अनुप्रयोगों हेतु परावर्तन और प्रसारण गतिकी को एकसाथ अभिलेखित करने में किया गया, जो निम्न-डाइलेक्ट्रिक एनालाइट्स के लिए विद्युत सेंसरों पर इसके लाभों को रेखांकित करता है।

एक कार्बनिक पॉर्फिरिन पर पूरक अध्ययन किए गए, जिनमें ४००-१६०० नैनो मीटर के व्यापक स्पेक्ट्रल दायरे में क्यू बैंड्स में बहु-फोटॉन अवशोषण पर विशेष ध्यान सहित गैर-रैखिक प्रकाशकीय गुणों की पड़ताल की गई, जो पूर्व में अन्वेषित नहीं था। तत्पश्चात, इसी पॉर्फिरिन को पोरस सिलिकॉन ऑप्टिकल माइक्रोकैविटी के साथ संयोजित कर एक हाइब्रिड प्लेटफ़ॉर्म निर्मित किया गया, जिसने चयनात्मक उत्सर्जन वर्धन प्रदर्शित किया, फोटोनिक नियंत्रण का प्रमाण दिया, तथा ट्यूनेबल प्रकाश स्रोतों और ऑप्टोइलेक्ट्रॉनिक अवयवों की दिशाओं की ओर संकेत किया। इस हाइब्रिड अनुप्रयोग में पोरस सिलिकॉन माइक्रोकैविटी के उपयोग हेतु, अनुनादी कैविटी मोड का व्यवस्थित ट्यूनिंग किया गया, जिसके तहत मोड को निकट अल्ट्रा वॉयलेट-दृश्यमान से इन्फ्रारेड के पास क्षेत्र तक स्थानांतरित किया गया। शोध प्रबंध के अंत में, फाइबोनाची जैसी एक-आयामी एपीरियोडिक फोटोनिक संरचनाओं का निर्माण कर उनका आवधिक वितरित ब्रैग रिफ्लेक्टर और माइक्रोकैविटी के साथ तुलनात्मक अध्ययन प्रस्तुत किया गया।

इन एक-आयामी पोरस सिलिकॉन-आधारित फोटोनिक संरचनाओं के इन व्यापक अध्ययनों से मौलिक पहलुओं की खोज के साथ-साथ नवीन एवं उन्नत फोटोनिक तथा ऑप्टोइलेक्ट्रॉनिक अनुप्रयोगों के लिए नई संभावनाएँ उद्घाटित होती हैं।

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Chapter 3: Fabrication, Optical Nonlinearities, and Ultrafast Dynamics of Free-Standing Porous Silicon-based Optical Microcavities

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Chapter 6: Fabrication and Optical Studies of Hybrid and Aperiodic Porous Silicon-based 1D Photonic Structures

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Abbreviations

1D, 2D, and 3D	One-dimension, Two-dimension, and Three-dimension
LASER	Light Amplification by Stimulated Emission of Radiation
PC	Photonic Crystal
Si	Silicon
PSi	Porous Silicon
FS-PSi	Free-Standing Porous Silicon
DBR	Distributed Bragg Reflector
TMM	Transfer Matrix Method
EM	Electromagnetic
TE	Transverse Electric
TM	Transverse Magnetic
n	Refractive Index
n_L/n_H	Low/High Refractive Index
n_S	Refractive Index of Spacer/Defect Layer
eV/keV	Electron Volt/ Kilo Electron Volt
nm/μm/cm	Nanometers/Micrometers/Centimeters
a.u./arb.units	Arbitrary Units
fs/ps/ns	Femtosecond/Picosecond/Nanosecond
CW	Continuous Wave
FWHM	Full Width at Half Maximum
UV, Vis	Ultraviolet, Visible
NIR	Near Infrared
IR	Infrared
SEM	Scanning Electron Microscopy
FE-SEM	Field Emission Scanning Electron Microscopy
GSB	Ground State Bleaching
PIA	Photo-Induced Absorption
PIB	Photo-Induced Bleaching
ESA	Excited State Absorption
SA	Saturation of Absorption
RSA	Reverse Saturation of Absorption
NLO	Nonlinear Optics
1PA	One-Photon Absorption
2PA	Two-Photon Absorption
3PA	Three-Photon Absorption
4PA	Four-Photon Absorption
MPA	Multi-Photon Absorption
TAS	Transient Absorption Spectroscopy
TRS	Transient Reflection Spectroscopy
TCSPC	Time Correlated Single Photon Counting
OPA	Optical Parametric Amplifier
SCG	Supercontinuum Generation

Symbols

c	Speed of light
h	Planck's Constant
k	Wave vector
L_{eff}	Effective sample length
α_0	Linear absorption coefficient
β	Two-photon absorption coefficient
γ	Three-photon absorption coefficient
δ	Four-photon absorption coefficient
λ	Wavelength of light
$\chi^{(1)}$	Linear dielectric susceptibility
$\chi^{(2)}$	Second-order dielectric susceptibility
$\chi^{(3)}$	Third-order dielectric susceptibility
ω	Angular frequency
ϕ	Nonlinear phase shift
n_0	Linear refractive index
n_2	Nonlinear refractive index