

NOVEL INTEGRATED PHOTONIC DEVICES

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NOVEL INTEGRATED PHOTONIC DEVICES

By

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CERTIFICATE

This is to certify that the thesis entitled “Novel Integrated Photonic Devices” being submitted by **Mr. Arun Thomas** to the **Department of Electrical Engineering, Indian Institute of Technology Delhi**, for the award of the degree of *Doctor of Philosophy* in Electrical Engineering, is a record of bonafide research work carried out by him. He has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results contained in this thesis have 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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ABSTRACT

This thesis is a summary of the detailed theoretical studies of several novel plasmonic nanostructures, and proposes these structures for applications such as optical switching, plasmonic interconnects and waveguides, thickness sensing, and biological and chemical sensing. We first performed a numerical study using (finite difference time domain, i.e. FDTD simulations) of a plasmonic nanoparticle-spacer-plasmonic film structure and then compared the results of this study with the results of a full-wave analytical solution. Further, we investigated a plasmonic nanowire array-spacer-plasmonic film structure by carrying out numerical calculations (using rigorous coupled wave analysis, i.e. RCWA, simulations). These two nanostructure systems could be employed as highly sensitive plasmonic sensors for thickness sensing and for chemical and biological molecular detection. Further, we proposed the plasmonic nanowire array-spacer layer-plasmonic film structure as a tunable plasmonic switch using a phase-change material as the spacer layer. Moreover, we studied the different kinds of plasmonic waveguides and calculated the different modes (mode profiles as well as the effective refractive index associated with the different modes) supported by these waveguides. The objective of this study was to investigate the trade-off between propagation lengths and effective mode area for these plasmonic waveguides. Some of the short- to medium- range plasmonic waveguide structures studied included: A single plasmonic nanowire – having different geometrical cross-section – over a plasmonic metal film with a dielectric spacer in between them, a pair of plasmonic nanowires over a plasmonic metal film with a dielectric spacer in between, a pair of cylindrical plasmonic nanowires, and a single cylindrical plasmonic nanowire. Some of the long-range plasmonic waveguide structures studied included: (i) hybrid plasmonic waveguides (HPWs) consisting of triangular shaped silicon nanowires on either side of a plasmonic thin film, with a dielectric spacer between the silicon nanostructures and the plasmonic thin film, and (ii)

HPWs consisting of diamond shaped silicon nanowires on a silica-coated silicon substrate on one side of a plasmonic thin film a square-shaped silicon nanowires on the other side of a plasmonic thin film, with a dielectric spacer between the silicon nanostructures and the plasmonic thin film. Although most of the work described in this thesis is in the area of plasmonics, we also carried out a study of an actively modulated ring resonator-based power splitter for photonic interconnects.

सार

यह थीसिस कई उपन्यास प्लास्मोनिक नैनोस्ट्रक्चर के विस्तृत सैद्धांतिक अध्ययनों का सारांश है और ऑप्टिकल स्विचिंग, प्लास्मोनिक इंटरकनेक्ट्स और वेवगाइड, मोटाई सेंसिंग और जैविक और रासायनिक सेंसिंग जैसे अनुप्रयोगों के लिए इन संरचनाओं का प्रस्ताव है। हमने सबसे पहले एक प्लासमोनिक नैनोकण-स्पेसर-प्लास्मोनिक फिल्म संरचना का (परिमित अंतर समय डोमेन, यानी एफ-डी-टी-डी सिमुलेशन) उपयोग करके एक संख्यात्मक अध्ययन किया और फिर इस अध्ययन के परिणामों की तुलना एक पूर्ण-लहर विश्लेषणात्मक समाधान के परिणामों से की। इसके अलावा, हमने संख्यात्मक गणनाओं (कठोर युग्मित लहर विश्लेषण, अर्थात आरसीडब्ल्यूए, सिमुलेशन) का उपयोग करके एक प्लास्मोनिक नैनोवायर सरणी-स्पेसर-प्लास्मोनिक फिल्म संरचना की जांच की। इन दो नैनोस्ट्रक्चर सिस्टम को मोटाई संवेदन के लिए और रासायनिक और जैविक आणविक पता लगाने के लिए बेहद संवेदनशील प्लास्मोनिक सेंसर के रूप में कार्यरत किया जा सकता है। इसके अलावा, हमने प्लासमोनिक नैनोवायर सरणी-स्पेसर परत-प्लास्मोनिक फिल्म संरचना को एक ट्यूनेबल प्लास्मोनिक स्विच के रूप में प्रस्तावित किया है, जो स्ट्रक्चर परत के रूप में चरण-परिवर्तन सामग्री का उपयोग करता है। इसके अलावा, हमने विभिन्न प्रकार के प्लास्मोनिक वेवगाइड का अध्ययन किया और इन वेवगाइड द्वारा समर्थित विभिन्न मोडों (मोड प्रोफाइल और साथ ही प्रभावी तरीके से प्रभावी अपवर्तक सूचक) की गणना की। इस अध्ययन का उद्देश्य प्रचारों के बीच अदला-बदली की जांच करना था, इन प्लासमोनिक वेवगाइड के लिए प्रचार लंबाई के बीच का

नियंत्रण प्रभावी क्षेत्र है। कुछ छोटे-से-मध्यम-श्रेणी वाले प्लास्मोनिक वेवगाइड संरचनाओं में शामिल हैं: एक एकल प्लासामोनिक नैनोवायर, जिसमें एक प्लैसमोनिक धातु की फिल्म के ऊपर एक अलग-अलग ज्यामितीय क्रॉस-सेक्शन होता है, जिसमें एक पराविद्युत स्पेसर होता है, जो एक प्लैसमोनिक धातु फिल्म पर प्लास्मोनिक नैनोवायर बीच में एक पराविद्युत स्पेसर के साथ, बेलनाकार प्लास्मोनिक नैनोवायर की एक जोड़ी, और एक एकल बेलनाकार प्लास्मोनिक नैनोवायर। अध्ययन की लंबी अवधि वाली प्लास्मोनिक वेवगाइड संरचनाओं में से कुछ में शामिल हैं: (i) हाइब्रिड प्लास्मोनिक वेवगाइड (एच-पी-डब्ल्यू-एस) जिसमें प्लास्मोनिक पतली फिल्म के दोनों तरफ त्रिकोणीय आकार के सिलिकॉन नैनोवायर होते हैं, जिसमें सिलिकॉन नैनोस्ट्रक्चर और प्लास्मोनिक पतली फिल्म के बीच एक पराविद्युत स्पेसर होता है, और (ii) एचपीडब्ल्यू एक प्लैसमोनिक पतली फिल्म के एक तरफ एक सिलिका-लेपित सिलिकॉन सबस्ट्रेट पर हीरा के आकृति वाले सिलिकॉन नैनोवायर से मिलते हैं, एक प्लास्मोनिक पतली फिल्म के दूसरी तरफ एक वर्ग के आकार के सिलिकॉन नैनोवायर, जिसमें सिलिकॉन नैनोस्ट्रक्चर के बीच एक पराविद्युत स्पेसर होता है और प्लास्मोनिक पतली फिल्म यद्यपि इस शोध में वर्णित अधिकांश काम प्लास्मोनिक्स के क्षेत्र में हैं, हमने फोटोनिक इंटरकनेक्ट्स के लिए एक सक्रिय रूप से मिश्रित रिंग गुंजयमान यंत्र आधारित बिजली अलगाने वाला यंत्र का अध्ययन भी किया है।

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ABBREVIATIONS

FDTD	=	Finite Difference Time Domain
SERS	=	Surface Enhanced Raman Scattering
PEF	=	Plasmonics-Enhanced Fluorescence
SAMs	=	Self-Assembled Monolayers
LBL	=	Layer-By-Layer
PML	=	Perfectly Matched Layers
AR	=	Aspect Ratio
EM	=	Electromagnetic
DAC	=	Digital to Analog Converter
FIB	=	Focused Ion Beam
FDE	=	Finite-Difference Eigen-mode
RCWA	=	Rigorous Coupled Wave Analysis
LRSP	=	Long Range Surface Plasmon Polariton
SRSP	=	Short Range Surface Plasmon Mode
IMI	=	Insulator-Metal-Insulator
MIM	=	Metal-Insulator-Metal
SPP	=	Surface Plasmon Polariton
CPPs	=	Channel Plasmon Polaritons
SP	=	Surface Plasmon
LSPR	=	Localised Surface Plasmon Resonance
HPWs	=	Hybrid Plasmonic Waveguides
VO ₂	=	Vanadium Dioxide
IMT	=	Insulator-to-Metal Transition
TM	=	Transverse Magnetic
CAD	=	Computer Aided Design