

PLASMONIC DEVICES BASED ON NANOSTRUCTURES AND NANOANTENNAS

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**PLASMONIC DEVICES BASED ON NANOSTRUCTURES
AND NANOANTENNAS**

by

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Dedicated to

Family and Friends

CERTIFICATE

This is to certify that the thesis entitled “Plasmonics devices based on nanostructures and nanoantennas” being submitted by **Mr. Nitin Gupta** to the **Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, is a record of bonafide research work carried out by him. Mr. Nitin Gupta 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

Plasmonics nanostructures and nanoantennas have been widely studied and employed for the development of various optical devices. Two physical phenomena, surface plasmon polaritons (SPPs) and localized surface plasmons (LSPs), have been harnessed to develop several types of optical sensors and integrated optical devices. This thesis primarily focuses on developing platforms for surface-enhanced Raman scattering (SERS) based sensors and the study of plasmonic switches for near-field switching.

Firstly, the nanohole arrays such as bowtie nanohole array, bridged-bowtie nanohole arrays, and crossed bridged-bowtie nanohole arrays in a thin gold film have been studied for the development of SERS substrates. Finite-difference time-domain (FDTD) simulations were carried out to study the effects of various geometrical parameters as well as the polarization of light on the performance of the devices. The FDTD simulations show that the bridge-bowtie nanohole array and crossed bridged-bowtie nanohole array exhibit large electromagnetic enhancement of SERS and have the SERS enhancement spread over a much larger area than what could be present in SERS substrates consisting of nanopillar arrays or nanopillar plasmonic nanoantennas.

The second plasmonic device studied in this thesis comprises of a bowtie nanoantenna in the vicinity of a symmetric plasmonic nanogroove or an asymmetric plasmonic nanogroove. FDTD simulations show that the electric field enhancement of a bowtie nanoantenna is significantly improved via interaction between the bowtie nanoantenna and the SPPs from the nanogroove. Bowtie nanoantenna in the vicinity of a single asymmetric plasmonic nanogroove produces a SERS electromagnetic enhancement factor (EMEF) of 10^{10} ; three orders of magnitude higher

than SERS EMEF of a stand-alone bowtie nanoantenna and one order of magnitude higher than SERS EMEF of bowtie nanoantenna in the vicinity of a single symmetric plasmonic nanogroove.

The third plasmonic device proposed in this thesis is based on the combination of a Yagi-Uda nanoantenna and a bowtie nanoantenna, that can enable on-chip implementation of plasmon-enhanced light-matter interaction processes such as SERS. In this device, a localized source is employed to excite the Yagi-Uda nanoantenna, which in turn drives the bowtie nanoantenna. FDTD simulations were employed to obtain the radiation characteristics of the Yagi-Uda nanoantenna and the electric field enhancements in the vicinity of the bowtie nanoantenna excited by the Yagi-Uda nanoantenna. The electric field enhancements in the bowtie nanoantenna that is driven by a Yagi-Uda nanoantenna are compared with those for direct excitation of the bowtie nanoantenna by a dipole source or by plane wave source. The effect of various geometrical parameters of the nanoantennas on the device performance have been studied.

Finally, a novel plasmonic switch based on plasmonic nanoantennas lying on top of a thin film of a phase change material such as vanadium dioxide (VO_2), such that the near-field properties of these nanoantennas can be actively switched by varying the phase of the VO_2 film. The FDTD simulations are carried out first to demonstrate that the near-field intensity in the vicinity of the plasmonic nanoantennas can be substantially switched by changing the phase of the VO_2 film from the semiconductor state to the metallic state. In addition, we also show that the intensity of emission from a nanoemitter placed in the gap between the two arms of a plasmonic nanoantenna can be significantly switched by changing the phase of the VO_2 . To quantify the switching of emission from the nanoemitters placed in the near-field of the

nanoantennas, we have defined and calculated a parameter, called FESR, the ratio of fluorescent enhancement factors in the on-state and off-state of the plasmonic switch.

सार

विभिन्न ऑप्टिकल उपकरणों के विकास के लिए प्लास्मोनिक्स नैनोस्ट्रक्चर और नैनोएंटेना का व्यापक रूप से अध्ययन और उपयोग किया गया है। कई प्रकार के ऑप्टिकल सेंसर और एकीकृत ऑप्टिकल उपकरण विकसित करने के लिए दो भौतिक घटनाएं, सतह प्लास्मोन पोलरिटोन (एसपीपी) और स्थानीयकृत सतह प्लास्मोन (एलएसपी) का उपयोग किया गया है। यह थीसिस मुख्य रूप से सतह-संवर्धित रमन स्कैटरिंग (एसईआरएस) आधारित सेंसर के लिए प्लेटफॉर्म के विकास और निकट-क्षेत्र स्विचिंग के लिए प्लास्मोनिक स्विच के अध्ययन पर केंद्रित है।

सबसे पहले, एक पतली सोने की फिल्म में बनाये गए नैनोहोल एरेज जैसे कि बोताई नैनोहोल एरेज, ब्रिज- बोताई नैनोहोल एरेज, और ब्रिज- बोताई नैनोहोल एरेज का अध्ययन एसईआरएस सबस्ट्रेट्स के विकास के लिए किया गया है। विभिन्न ज्यामितीय मापदंडों के प्रभावों के साथ-साथ उपकरणों के प्रदर्शन पर प्रकाश के ध्रुवीकरण के प्रभावों का अध्ययन करने के लिए परिमित-अंतर समय-डोमेन (एफडीटीडी) सिमुलेशन किए गए थे। एफडीटीडी सिमुलेशन से पता चलता है कि ब्रिज- बोताई नैनोहोल एरे और क्रॉस-ब्रिज-बॉटी नैनोहोल एरे एसईआरएस के बड़े इलेक्ट्रोमैग्नेटिक एन्हांसमेंट को प्रदर्शित करते हैं और एसईआरएस एन्हांसमेंट नैनोपिलर एरेज या नैनोपिलर प्लास्मोनिक नैनोएंटेना से युक्त एसईआरएस सबस्ट्रेट्स में मौजूद होने की तुलना में बहुत बड़े क्षेत्र में फैला हुआ है। इस थीसिस में अध्ययन किए गए दूसरे प्लास्मोनिक उपकरण में एक सममित प्लास्मोनिक नैनोग्रूव या एक असममित प्लास्मोनिक नैनोग्रूव के आसपास के क्षेत्र में एक बोताई नैनोएंटेना शामिल है। एफडीटीडी सिमुलेशन से पता चलता है कि बोताई नैनोएंटेना और नैनोग्रूव से उत्पन्न हुए एसपीपी के बीच परस्पर क्रिया के माध्यम से एक बोताई नैनोएंटेना के विद्युत क्षेत्र में काफी बेहतर वृद्धि होती है। एकल असममित प्लास्मोनिक नैनोग्रूव के आसपास के क्षेत्र में बोताई नैनोएंटेना 10^{10} का एसईआरएस इलेक्ट्रोमैग्नेटिक एन्हांसमेंट फैक्टर (ईएमईएफ) पैदा करता है; जोकि एक अकेले बोताई नैनोएंटेना के एसईआरएस ईएमईएफ से 10^3 गुना और एकल सममित प्लास्मोनिक नैनोग्रूव के आसपास के क्षेत्र में बोताई नैनोएंटेना के एसईआरएस ईएमईएफ से दस गुना अधिक है।

इस थीसिस में प्रस्तावित तीसरा प्लास्मोनिक उपकरण एक यागी-उडा नैनोएंटेना और एक बोताई नैनोएंटेना के संयोजन पर आधारित है, जो एसईआरएस जैसे प्लास्मोन-वर्धित प्रकाश-पदार्थ परस्पर क्रिया के ऑन-चिप

कार्यान्वयन को सक्षम कर सकता है। इस उपकरण में, यागी-उडा नैनोएंटेना को उत्तेजित करने के लिए एक स्थानीय स्रोत का उपयोग किया जाता है, जो बदले में बोताई नैनोएंटेना को संचालित करता है। यागी-उडा नैनोएंटेना की विकिरण विशेषताओं और यागी-उडा नैनोएंटेना द्वारा उत्तेजित बोताई नैनोएंटेना के आसपास के क्षेत्र में विद्युत क्षेत्र में वृद्धि प्राप्त करने के लिए एफडीटीडी सिमुलेशन किए गए हैं। यागी-उडा नैनोएंटेना द्वारा संचालित बोताई नैनोएंटेना के विद्युत क्षेत्र के संवर्द्धन की तुलना, द्विध्रुवीय स्रोत द्वारा या प्लेन वेव स्रोत द्वारा संचालित बोताई नैनोएंटेना के विद्युत क्षेत्र के संवर्द्धन से की गयी है। उपकरण के प्रदर्शन पर नैनोएंटेना के विभिन्न ज्यामितीय मापदंडों के प्रभाव का अध्ययन किया गया है।

अंत में, वैनेडियम डाइऑक्साइड जैसे फेज चेंज मटेरियल की एक पतली फिल्म के ऊपर स्थित प्लास्मोनिक नैनोएंटेना पर आधारित एक नए प्लास्मोनिक स्विच, जोकि इन नैनोएंटेना के निकट-क्षेत्र गुणों को सक्रिय रूप से स्विच कर सकता है, का अध्ययन किया है। एफडीटीडी सिमुलेशन का उपयोग यह प्रदर्शित करने के लिए किया गया है कि प्लास्मोनिक नैनोएंटेना के आसपास के क्षेत्र में निकट-क्षेत्र की तीव्रता को वैनेडियम डाइऑक्साइड फिल्म के चरण को सेमीकंडक्टर अवस्था से धातु अवस्था में बदलकर सार्थक रूप से स्विच किया जा सकता है। इसके अलावा, हम यह भी दिखाते हैं कि एक प्लास्मोनिक नैनोएंटेना की दो भुजाओं के बीच के स्थान में रखे गए नैनो एमिटर से उत्सर्जन की तीव्रता को वैनेडियम डाइऑक्साइड के चरण को बदलकर सार्थक रूप से स्विच किया जा सकता है। नैनोएंटेना के निकट-क्षेत्र में रखे गए नैनोमीटर से उत्सर्जन के स्विचिंग को मापने के लिए, हमने एफईएसआर नामक एक पैरामीटर, जो प्लास्मोनिक स्विच के ऑन-स्टेट और ऑफ-स्टेट में फ्लोरोसेंट एन्हांसमेंट का अनुपात है, को परिभाषित किया है और उसकी गणना की है।

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Glossary

SP: Surface plasmon

SPP: Surface Plasmon Polariton

SPPs: Surface Plasmon Polaritons

LSP: Localized surface plasmon

LSPs: Localized surface plasmons

LSPR: Localized surface plasmon resonance

SERS: Surface-enhanced Raman scattering

FDTD: Finite-difference time-domain CTAB:

Cetyltrimethyl ammonium bromide

EF: enhancement factor

PL: Plasmonic lens

EM: Electromagnetic

RBN: Ring-bowtie nanoantenna

RRN: Ring-rhombus nanoantenna

FESR: Fluorescent enhancement switching ratio