

DESIGN AND MODELING OF PLASMONIC NANOANTENNAS AND NANOPROBES

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DESIGN AND MODELING OF PLASMONIC NANOANTENNAS AND NANOPROBES

by

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CERTIFICATE

This is to certify that the thesis entitled “Design and Modeling of Plasmonic Nanoantennas and Nanoprobes” being submitted by Mr. **Priten Bipinbhai Savaliya** 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

In this thesis, the design and modeling of plasmonic nanoantennas and nanoprobe have been described for various application of the electromagnetic wave manipulation at the nanoscale level. The application of these nanoantennas includes surface-enhanced Raman scattering sensors, fluorescence-enhanced scattering sensors, scanning near-field optical microscopy probes, nano-optic switches, plasmonic metamaterials, solar cells, photodetectors, plasmonics interconnects and many more. Several nanoantenna designs have been proposed and compared for electric field enhancement, resonance wavelength tuning, switching in electric field enhancement, switching in resonance wavelength and for switching in radiation emission patterns. In this thesis, we propose the design of switchable plasmonic nanoantennas (SPNs) that can be employed for optical switching in the near-infrared regime. The proposed SPNs consist of nanoantenna structures made up of a plasmonic metal (gold) such that these nanoantennas are filled with a switchable material (vanadium dioxide). We compare the results of these SPNs with inverted SPN structures that consist of gold nanoantenna structures surrounded by a layer of vanadium dioxide (VO_2) on their outer surface. These nanoantennas demonstrate switching of electric-field intensity enhancement (EFIE) between two states (On and Off states), which can be induced thermally, optically or electrically. The On and Off states of the nanoantennas correspond to the metallic and semiconductor states, respectively of the VO_2 film inside or around the nanoantennas, as the VO_2 film exhibits phase transition from its semiconductor state to the metallic state upon application of thermal, optical, or electrical energy. We employ finite-difference time-domain (FDTD) simulations to demonstrate switching in the EFIE for four different SPN geometries — nanorod-dipole, bowtie, planar trapezoidal toothed log-periodic, and rod-disk — and compare their near-field distributions for the On and Off states of the SPNs. Intensity switching ratios between 5.5 and 7 were demonstrated for the different dimensions of the dipole SPNs, while the intensity switching ratios for the bowtie and the rod-disk SPN structures were found to be lying between ~ 4.5 and 6.5. We also demonstrate that the resonance wavelength of the EFIE spectra gets substantially modified when these SPNs switch between the two states. In this thesis, we also describe active steering of radiation patterns by complex nanoantenna structures — called steerable nanoantennas (SNs) in this thesis — formed by a combination of multiple Yagi-Uda

nanoantennas and thin films of a phase change material (VO_2). The radiation patterns of these nanoantennas can be actively steered upon tunably changing the phase of the VO_2 thin films from the semiconductor phase to the metallic phase. Moreover, the nanoantennas being described in this thesis enable steering of the radiation patterns 'in the plane' of the nanoantennas. In this thesis, we demonstrate that the maximum achievable steering of the radiation pattern is 90° for a two-element steerable nanoantenna when the phase of the VO_2 thin film is changed from the semiconductor phase to the metallic phase. Moreover, it was observed that the radiation pattern of the steerable nanoantennas being proposed in our thesis can be designed to be much more directed as compared to previously reported steerable nanoantennas. By employing a four element steerable nanoantenna, we also demonstrate a full 360° active steering of the radiation pattern. The steerable nanoantennas can find applications in areas such as tunable on chip plasmonic interconnects, networks on chip, or for selective excitation of fluorophores on a sensor chip. In this thesis, we also demonstrated that the EM field enhancement in tapered optical fibers (TOFs) containing the PNs on their tips is much greater than the EM enhancement in TOFs without the PNs. We also show that a metal coating present on the tip of the tapered fiber can lead to a further increase the EM enhancement for the TOFs containing PNs on their tips.

सार

इस थीसिस में, नैनोस्केल स्तर पर इलेक्ट्रोमैग्नेटिक वेव हेरफेर के विभिन्न अनुप्रयोग के लिए प्लास्मोनिक नैनोएंटीना और नैनोसंवेदन टिप के डिजाइन और मॉडलिंग का वर्णन किया गया है। इन नैनोएंटीना के अनुप्रयोग में सतह-संवर्धित रमन स्कैटरिंग सेंसर, फ्लोरेसेंस-एनहांसिंग बिखरने वाले सेंसर, निकट-क्षेत्र ऑप्टिकल माइक्रोस्कोपी जांच, नैनो-ऑप्टिक स्विच, प्लास्मोनिक कृत्रिमपदार्थ, सौर सेल, फोटोडेटेक्टर्स, प्लास्मोनिक इंटरकनेक्ट और कई अधिक शामिल हैं। कई नैनोएंटीना डिजाइन प्रस्तावित किए गए हैं और उनकी तुलना इलेक्ट्रिक फील्ड एन्हांसमेंट, रेजोनेंस वेवलेंथ ट्यूनिंग, इलेक्ट्रिक फील्ड एन्हांसमेंट में स्विचिंग, रेजोनेंस वेवलेंथ में स्विचिंग और रेडिएशन एमिशन पैटर्न में स्विच करने के लिए की गई है। इस थीसिस में, हम स्विचबल प्लास्मोनिक नैनोएंटीना (एसपीएन) के डिजाइन का प्रस्ताव करते हैं, जिसे निकट-अवरक्त क्षेत्र में ऑप्टिकल स्विचिंग के लिए नियोजित किया जा सकता है। प्रस्तावित एसपीएन में प्लास्मोनिक धातु (सोना) से बनी नैनोएंटीना संरचनाएं होती हैं, जैसे कि ये नैनोएंटीना एक स्वेच्छापूर्ण सामग्री (वैनेडियम डाइऑक्साइड) से भरे होते हैं। हम इन एसपीएन के परिणामों की तुलना उल्टे एसपीएन संरचनाओं से करते हैं, जिसमें सोने की नैनोएनेटेना संरचना होती है, जो उनकी बाहरी सतह पर वैनेडियम डाइऑक्साइड (VO_2) की एक परत से घिरी होती है। ये नैनोएंटीना दो अवस्था (ऑन और ऑफ अवस्था) के बीच विद्युत-क्षेत्र की तीव्रता बढ़ाने (ईएफआईई) के स्विचिंग को प्रदर्शित करते हैं, जो कि थर्मली, वैकल्पिक रूप से या विद्युत रूप से प्रेरित हो सकते हैं। नैनोएंटीना के ऑन और ऑफ अवस्था धातु और अर्धचालक अवस्था के अनुरूप होते हैं, क्रमशः नैनोएंटीना के अंदर या उसके आसपास VO_2 फिल्म के रूप में VO_2 फिल्म थर्मल, ऑप्टिकल, या के आवेदन के लिए अपने अर्धचालक अवस्था से धातु अवस्था तक चरण संक्रमण दिखाती है। विद्युत ऊर्जा। हम चार अलग-अलग एसपीएन ज्यामितीयों के लिए ईएफआईई में स्विचिंग प्रदर्शित करने के लिए परिमित-अंतर समय-डोमेन (एफडीडीटी) सिमुलेशन का उपयोग करते हैं - नैनोरोड- द्विध्रुवीय, बोटार्ई, प्लेनर ट्रेपेज़ोइडल दांतेदार लॉग-आवधिक, और रॉड-डिस्क - और उनके निकट-क्षेत्र वितरण की तुलना करें एसपीएन के ऑन और ऑफ अवस्था। 5.5 और 7 के बीच तीव्रता स्विचिंग अनुपात को द्विध्रुवीय एसपीएन के विभिन्न आयामों के लिए प्रदर्शित किया गया था, जबकि आंत और रॉड-डिस्क एसपीएन संरचनाओं के लिए तीव्रता स्विचिंग अनुपात ~ 4.5 और 6.5 के बीच झूठ पाए गए थे। हम यह भी प्रदर्शित करते हैं कि जब ये SPN दोनों अवस्था के बीच स्विच करते हैं, EFIE स्पेक्ट्रा की प्रतिध्वनि तरंगदैर्घ्य काफी हद तक संशोधित हो जाती है। इस थीसिस में, हम जटिल नैनोएनेटेना संरचनाओं द्वारा विकिरण पैटर्न के सक्रिय स्टीयरिंग का भी वर्णन करते हैं - इस थीसिस में स्टीयरेबल नैनोएंटीना (एसएन) कहा जाता है - एक चरण परिवर्तन सामग्री (VO_2) के कई यागी-उदय नैनोएनेटेनेस और पतली फिल्मों के संयोजन द्वारा गठित। इन नैनोएंटीना के विकिरण पैटर्न को सक्रिय रूप से अर्धचालक चरण से धातु चरण तक VO_2 पतली फिल्मों के चरण को बदलने पर सक्रिय किया जा सकता है। इसके अलावा, इस थीसिस में वर्णित किया जा रहा नैनो नैनोएंटीना के 'प्लेन' में विकिरण पैटर्न के स्टीयरिंग को सक्षम करता है। इस थीसिस में, हम यह प्रदर्शित करते हैं कि विकिरण पैटर्न की अधिकतम प्राप्त करने योग्य स्टीयरिंग 90° दो-तत्व वाले स्टीयरेबल नैनोएनेटेन के लिए है जब VO_2 पतली फिल्म के अवस्था को सेमीकंडक्टर अवस्था से धातु अवस्था में बदल दिया जाता है। इसके अलावा, यह देखा गया कि हमारी थीसिस में प्रस्तावित किए जा रहे स्टीयरेबल नैनोएंटीना के विकिरण पैटर्न को पहले से रिपोर्ट किए गए नैनोएंटीना की तुलना में बहुत अधिक निर्देशित किया जा सकता है। एक चार तत्व स्टीयरेबल नैनोएनेटेन को नियोजित करके, हम विकिरण पैटर्न का पूर्ण 360° सक्रिय स्टीयरिंग भी प्रदर्शित करते हैं। स्टीयरेबल नैनोएनेटेनेस चिप प्लास्मोनिक इंटरकनेक्ट पर ट्यून करने योग्य, चिप पर नेटवर्क या सेंसर चिप पर फ्लोरोफोर्स के चयनात्मक उत्तेजना के लिए क्षेत्रों में आवेदन पा सकते हैं। इस थीसिस में, हमने यह भी प्रदर्शित किया कि उनके सुझावों पर पीएन युक्त पतला ऑप्टिकल फाइबर (टीओएफ) में ईएम क्षेत्र वृद्धि पीएन के बिना टीओएफ में ईएम वृद्धि की तुलना में बहुत अधिक है। हम यह भी बताते हैं कि टेप किए गए फाइबर की नोक पर मौजूद एक धातु की कोटिंग टीओएफ के लिए उनके सुझावों पर पीएन युक्त ईएम वृद्धि को और बढ़ा सकती है।

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ABBREVIATIONS

AR = Aspect Ratio

EM = Electromagnetic

EFIE = Electric Field Intensity Enhancement

FDTD = Finite Difference Time Domain

FIB = Focused Ion Beam

I_{off} = Intensity in Off state

I_{on} = Intensity in On state

LSPR = Localised Surface Plasmon Resonance

PEF = Plasmonics-Enhanced Fluorescence

PML = Perfectly Matched Layers

RCWA = Rigorous Coupled Wave Analysis

SERS = Surface Enhanced Raman Scattering

SN=Switchable nanoantenna

SNOM = Scanning Near-field Optical Microscopy

SPN = Switchable Plasmonic Nanoantenna

SPP = Surface Plasmon Polariton

SPRI = Surface Plasmon Resonance Imaging

TM = Transverse Magnetic

TOF= Tapered Optical Fiber

VO_2 = Vanadium Dioxide

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