NANOPHOTONICS AND PLASMONICS BASED BIOSENSORS

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NANOPHOTONICS AND PLASMONICS BASED BIOSENSORS

by

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in fulfillment of the requirements of the degree of Doctor of Philosophy

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DEDICATED

TO

MY FAMILY

CERTIFICATE

This is to certify that the thesis entitled "Nanophotonics and Plasmonics Based Biosensors" being submitted by **Ms. Akanksha Ninawe** 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 Ms. Akanksha Ninawe. Ms. Akanksha Ninawe 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

Nanophotonics is a widely researched area that investigates light-matter interactions at a nanometer scale and plasmonics is one major subset in the field of nanophotonics that essentially deals with optical manipulation of light on engineered nanostructures and metamaterials. The incorporation of plasmonically engineered subwavelength nanostructures or metamaterials which can lead to optical manipulation and thus enhanced light-matter interactions resulting in various applications requires easy fabrication implementation. With the latest advances in nanofabrication technology, fabrication of subwavelength dimensions of nanostructures has become feasible using sophisticated top-down and bottom-up fabrication approaches. Further, the cost effectiveness is an important factor which should be taken into consideration in the implementation of plasmonic nanostructures and wafer-scalable metamaterials. The optical manipulation in designed subwavelength structures becomes realizable by controlling several dimensional parameters. The primary goal of this thesis is to study plasmonic sensors based on nanostructures and metamaterials majorly for three plasmonic applications, namely, surface-enhanced infrared absorption spectroscopy, narrowband absorber metamaterial and chiro-plasmonic sensing.

The first part of the thesis numerically investigates plasmonic nanostructures for efficient surface enhanced infrared absorption (SEIRA) substrates based on several configurations of bowtie nanoring and crossed-bowtie nanoring nanoantennas with embedded bowtie nanoantennas and crossed-bowtie nanoantennas. The numerical modelling is carried out using Finite-difference Time Domain (FDTD) simulations for studying the spectral properties of the nanostructures, including the spectral response in the desired spectral regime and electric field

distribution at the plasmon resonances noted in the proposed nanostructures. The SEIRA enhancement factor is found to be ~ 1.7×10^5 which is substantially large compared to the previously reported enhancement factor values for bowtie nanoantennas or nanoring antennas.

The second part of this thesis presents a numerical modelling of simple structure for narrowband absorption in mid-infrared regime. The structure is based on simple design of a diabolo antenna which can be easily fabricated using a two-step fabrication process, essentially, a lithography and metallization process, as opposed to typical absorber designs employed tri-layered metal-insulator-metal based configurations. The two metasurfaces employed are ‘Babinet’ counterparts. The lithography step can be easily carried out using a photon polymerization laser direct write technique followed by a metallization process. The numerical modelling is carried out using Finite Element Method (FEM).

Finally, the third application studied is based on investigations of chiro-plasmonic metamaterials exhibiting giant chiro-optical responses. The chiral films, upon experimental investigations have shown a giant chiral response, the largest ever reported for a wafer-scalable chiro-plasmonic films. The samples in the study have shown large morphological variations which are inherent due to the bottom-up fabrication process employed for fabrication of the films. The experimental findings are correlated with computational models which are numerically investigated using Finite Element Method (FEM). The information from the computational predictions and its concurrence with the experimental data is highly relevant for enantiomer selective identification and sensing applications since the wafer scalable nanostructured films considered in this study are inherently porous easily allowing the diffusion of chiral molecules in regions of enhanced chiral electromagnetic hotspots.

This thesis work thus investigates key research areas of great interest to the scientific community in the field of nanophotonics and plasmonics and light-matter interactions at nanoscale focusing on applications pertaining to surface enhanced infrared absorption spectroscopy, narrowband absorption metamaterials and chirality detection using wafer-scalable metamaterials.

सारांश

नैनोफोटोनिक्स एक व्यापक रूप से शोध किया गया क्षेत्र है जो नैनोमीटर पैमाने पर प्रकाश-पदार्थ अंतःक्रियाओं की जांच करता है और नैनोफोटोनिक्स के क्षेत्र में प्लास्मोनिक्स एक प्रमुख उपसमुच्चय है जो अनिवार्य रूप से इंजीनियर नैनोस्ट्रक्चर और मेटामटेरियल्स पर प्रकाश के ऑप्टिकल हेरफेर से संबंधित है। प्लास्मोनिक रूप से इंजीनियर सबवेवलेंथ नैनोस्ट्रक्चर या मेटामटेरियल्स का समावेश जो ऑप्टिकल हेरफेर को जन्म दे सकता है और इस प्रकार विभिन्न अनुप्रयोगों के परिणामस्वरूप बढ़े हुए प्रकाश-पदार्थ की बातचीत को आसान निर्माण कार्यान्वयन की आवश्यकता होती है। नैनोफाइब्रिकेशन तकनीक में नवीनतम प्रगति के साथ, परिष्कृत टॉप-डाउन और बॉटम-अप फैब्रिकेशन दृष्टिकोणों का उपयोग करके नैनोस्ट्रक्चर के सबवेवलेंथ आयामों का निर्माण संभव हो गया है। इसके अलावा, लागत प्रभावशीलता एक महत्वपूर्ण कारक है जिसे प्लास्मोनिक नैनोस्ट्रक्चर और वेफर-स्केलेबल मेटामटेरियल्स के कार्यान्वयन में ध्यान में रखा जाना चाहिए। डिज़ाइन किए गए सबवेवलेंथ संरचनाओं में ऑप्टिकल हेरफेर कई आयामी मापदंडों को नियंत्रित करके साकार हो जाता है। इस थीसिस का प्राथमिक लक्ष्य तीन प्लास्मोनिक अनुप्रयोगों, अर्थात् सतह-वर्धित अवरक्त अवशोषण स्पेक्ट्रोस्कोपी, नैरोबैंड अवशोषक मेटामटेरियल और कायरो-प्लास्मोनिक सेंसिंग के लिए प्रमुख रूप से नैनोस्ट्रक्चर और मेटामटेरियल पर आधारित प्लास्मोनिक सेंसर का अध्ययन करना है।

थीसिस का पहला भाग कुशल सतह वर्धित अवरक्त अवशोषण (SEIRA) सबस्ट्रेट्स के लिए संख्यात्मक रूप से प्लास्मोनिक नैनोस्ट्रक्चर की जांच करता है, जो कि बोटाई नैनोरिंग और क्रॉस-बोटाई नैनोरिंग नैनोएन्टेनस के कई कॉन्फ़िगरेशन के आधार पर एम्बेडेड बोटाई नैनोएंटेना और क्रॉस- बोटाई नैनोएंटेनस के साथ होता है। संख्यात्मक मॉडलिंग को नैनोस्ट्रक्चर के वर्णक्रमीय गुणों का अध्ययन करने के लिए परिमित-

अंतर समय डोमेन (FDTD) सिमुलेशन का उपयोग करके किया जाता है, जिसमें वांछित वर्णक्रमीय शासन में वर्णक्रमीय प्रतिक्रिया और प्रस्तावित नैनोस्ट्रक्चर में नोट किए गए प्लास्मोन प्रतिध्वनि पर विद्युत क्षेत्र वितरण शामिल है। SEIRA एन्हांसमेंट फैक्टर ~ 1.7×10^5 पाया गया है जो कि बोटाई नैनोएंटेना या नैनोरिंग एंटेना के लिए पहले बताए गए एन्हांसमेंट फैक्टर वैल्यू की तुलना में काफी बड़ा है।

इस थीसिस का दूसरा भाग मध्य-अवरक्त शासन में नैरोबैंड अवशोषण के लिए सरल संरचना का एक संख्यात्मक मॉडलिंग प्रस्तुत करता है। संरचना एक डायबोलो एंटीना के एक साधारण डिजाइन पर आधारित है जिसे आसानी से दो-चरण निर्माण प्रक्रिया का उपयोग करके बनाया जा सकता है, अनिवार्य रूप से, एक लिथोग्राफी और धातुकरण प्रक्रिया, त्रि-स्तरित धातु-इन्सुलेटर-धातु आधारित कॉन्फ़िगरेशन नियोजित विशिष्ट अवशोषक डिज़ाइनों के विपरीत। नियोजित दो मेटासर्फेस 'बेबिनेट' समकक्ष हैं। धातुकरण प्रक्रिया के बाद फोटॉन पोलीमराइजेशन लेजर डायरेक्ट राइट तकनीक का उपयोग करके लिथोग्राफी चरण को आसानी से किया जा सकता है। परिमित तत्व विधि (एफईएम) का उपयोग करके संख्यात्मक मॉडलिंग की जाती है।

अंत में, अध्ययन किया गया तीसरा आवेदन काइरो-प्लास्मोनिक मेटामटेरियल्स की जांच पर आधारित है जो विशाल कायरो-ऑप्टिकल प्रतिक्रियाओं को प्रदर्शित करता है। प्रायोगिक जांच पर कायरल फिल्मों ने एक विशाल कायरल प्रतिक्रिया दिखाई है, जो वेफर-स्केलेबल काइरो-प्लास्मोनिक फिल्मों के लिए अब तक की सबसे बड़ी रिपोर्ट है। अध्ययन में नमूनों ने बड़ी रूपात्मक विविधताएं दिखाई हैं जो फिल्मों के निर्माण के लिए नियोजित बॉटम-अप फैब्रिकेशन प्रक्रिया के कारण अंतर्निहित हैं। प्रयोगात्मक निष्कर्षों को कम्प्यूटेशनल मॉडल के साथ सहसंबद्ध किया जाता है, जिन्हें परिमित तत्व विधि (एफईएम) का उपयोग करके संख्यात्मक रूप से जांचा जाता है। कम्प्यूटेशनल भविष्यवाणियों की जानकारी और प्रायोगिक डेटा के साथ इसकी सहमति एनैन्टीओमर चयनात्मक पहचान और संवेदन अनुप्रयोगों के लिए अत्यधिक प्रासंगिक है क्योंकि इस अध्ययन में मानी जाने वाली वेफर स्केलेबल नैनोस्ट्रक्टेड फिल्में स्वाभाविक रूप से झरझरा

होती हैं, जो आसानी से बढ़े हुए कायरल इलेक्ट्रोमैग्नेटिक हॉटस्पॉट के क्षेत्रों में कायरल अणुओं के प्रसार की अनुमति देती हैं।

इस प्रकार यह थीसिस कार्य नैनोफोटोनिक्स और प्लास्मोनिक्स के क्षेत्र में वैज्ञानिक समुदाय के लिए बहुत रुचि के प्रमुख अनुसंधान क्षेत्रों की जांच करता है और वेफर-स्केलेबल मेटामटेरियल्स का उपयोग करके सतह वर्धित अवरक्त अवशोषण स्पेक्ट्रोस्कोपी, नैरोबैंड अवशोषण मेटामटेरियल्स और कायरलिटी डिटेक्शन से संबंधित अनुप्रयोगों पर ध्यान केंद्रित करते हुए नैनोस्केल पर प्रकाश-पदार्थ बातचीत करता है।

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