

NANOPHOTONIC SENSORS AND DEVICES

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NANOPHOTONIC SENSORS AND DEVICES

by

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CERTIFICATE

This is to certify that the thesis entitled “Nanophotonic Sensors and Devices” being submitted by Ms. **Yashna Sharma** 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 her. She 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, which deals with the interaction of light with matter, at a nanoscale, has led to the development of several techniques which have revolutionized many fields of science and engineering. The physical phenomena that result from this light-matter interaction, like surface plasmons, localized surface plasmons and coupled plasmons amongst others, have been utilized for the development of highly sensitive and specific sensors and for the development of novel optical devices at the sub-wavelength scales. The work done in this thesis focuses primarily on the development of such nanophotonic, more specifically, nano plasmonic sensors and devices.

The primary part of this thesis is based on the development of robust, reproducible and highly sensitive sensors capable of multiplexed detection. These sensors are based on surface enhanced Raman spectroscopy (SERS) – a process where the weak Raman signals from an analyte molecule are enhanced in the presence of metallic nanostructures, leading to an effective trace-level detection. At the same time, these substrates offer multiplexing, with high spectral resolution, due to the very narrow line-widths of the Raman spectra. Many novel SERS substrates are numerically analyzed, by using Finite Difference Time Domain (FDTD) modeling, to study the effect of structural parameters, polarization of the incident light and the angle of the incident light, on the SERS enhancement offered by these substrates. The first amongst these - a metallic nanoline- nanoparticle SERS substrate – is a hybrid SERS substrate which can be fabricated by a combination of lithography and self assembly processes. An exhaustive numerical analysis is done for these substrates. Self assembly of metallic nanoparticles inside metallic nanolines is demonstrated as a proof-of-concept for the fabrication of these substrates, and subsequent SERS measurements are done to estimate the amount of SERS enhancement offered by these substrates. The second SERS substrate proposed in this thesis is based on oblique gold nanofingers inside triangular gold nanowires. Numerical analysis using FDTD is carried out and discussed, along with a possible fabrication approach. The third kind of SERS substrate demonstrated in this thesis is a 'nanopillar inside nanohole' array fabricated on a large area. The multiplexed detection of two nitro-based explosive compounds- Dinitrotoluene (2,4-DNT) and Trinitrotoluene (2,4,6-TNT) is demonstrated through this substrate, by employing a portable Raman spectrometer.

In addition, a novel nanowire-based nanolens array — which aids in the focusing of light into tight spots — is also proposed in this thesis, which can be employed for SERS-based sensing. The funneling of fields, in this substrate, leads to development of areas of high E-field intensity, which can be utilized for SERS sensing. A comprehensive FDTD based analysis for these SERS substrates has been done in this thesis.

Another sensor proposed as a part of this thesis, is a palladium based plasmonic hydrogen sensor and is based on the capability of palladium lattice to swell and change optical properties in the presence of hydrogen. A plasmonic ‘gold nanowire array on a palladium layer deposited on gold substrate’ is proposed and is numerically analyzed. Plasmonic waveguide modes are coupled in the narrow grooves between the nanowires, and lead to field enhancement. The thin layer of palladium, changes its dielectric properties, on exposure to various hydrogen concentrations, thus leading to a change in the optical and plasmonic behaviour of these waveguide modes. This change in optical properties of the system is exhibited in the reflectance spectra calculated at different hydrogen concentrations. The sensitivity of this sensor is evaluated using an exhaustive numerical analysis, based on Rigorous Coupled Wave Analysis (RCWA), which analyzes the shift in the wavelength of minimum reflection for the system, before and after exposure to hydrogen.

In addition to nano-photonics sensors, other nanophotonic devices like optical switches have emerged due to their high speeds and miniaturized size. The later part of this thesis is based on the numerical analysis of one such nanophotonic device, i.e., a vanadium dioxide based optical switch. A smart optical switch based on vanadium dioxide, a phase change material is proposed, which exhibits switching and modulation behavior not only in the visible region of the spectrum, but also in the near-IR and IR regimes with an advantage of ultrafast switchability. Plasmonic narrow groove nano-gratings— coated with a thin layer (2-10 nm) of VO₂ — are proposed and numerically analyzed. These switches can couple incident light into plasmonic waveguide modes, even at normal incidence and thus alleviate the need for using heavy angle dependent mechanisms like the prism-coupling.

सार

नैनोफोटोनिक्स, जो नैनोस्केल पर पदार्थ के साथ प्रकाश की परस्पर क्रिया से संबंधित है, ने कई तकनीकों के विकास के लिए नेतृत्व किया है, जिसने विज्ञान और इंजीनियरिंग के कई क्षेत्रों को क्रांतिकारित किया है। प्रकाश और पदार्थ की परस्पर क्रिया के परिणामस्वरूप होने वाले सतह प्लासमॉनस और स्थानीयकृत सतह प्लासमॉन का उपयोग बेहद संवेदनशील और विशिष्ट सेंसर के विकास के लिए किया जाता है। उनका उपयोग उप-तरंग दैर्ध्य तराजू पर नए ऑप्टिकल उपकरणों के विकास के लिए भी किया गया है। इस थीसिस में किए गए काम मुख्य रूप से ऐसे नैनो-प्लासमोनिक सेंसरों और उपकरणों के विकास पर केंद्रित हैं।

इस थीसिस का प्राथमिक भाग मल्टीप्लेक्जड डिटेक्शन के लिए सक्षम, मजबूत और अत्यधिक संवेदनशील सेंसर के विकास पर आधारित है। ये सेंसर सतह पर बढ़ाए हुए रमन स्पेक्ट्रोस्कोपी (एसईआरएस) पर आधारित हैं जो एक प्रभावी ट्रेस-स्तर का पता लगाने के लिए अग्रणी है। यह एक ऐसी प्रक्रिया है जहां धातु नैनोस्ट्रक्चर की मौजूदगी में विश्लेषक अणु के कमजोर रमन संकेतों को बढ़ाया जाता है। साथ ही, रमन स्पेक्ट्रा के बहुत ही संकीर्ण रेखा-चौड़ाई के कारण इन सबस्ट्रेट्स को उच्च वर्णक्रमीय संकल्प के साथ मल्टीप्लेक्स सेंसिंग की सुविधा मिलती है। इस थीसिस में, परिमित अंतर समय डोमेन (एफडीटीडी) मॉडलिंग का उपयोग करके कई नए एसईआरएस सबस्ट्रेट्स का संख्यात्मक विश्लेषण किया गया है। संरचनात्मक मापदंडों के प्रभाव का अध्ययन करने के लिए, घटना प्रकाश की ध्रुवीकरण और घटना प्रकाश के कोण, इस सबस्ट्रेट द्वारा प्रस्तुत एसईआरएस वृद्धि पर, संख्यात्मक मॉडलिंग को नियोजित किया गया है। पहला प्रस्तावित सबस्ट्रेट एक धातु नैनोलाइन-नैनोपार्टिकल एसईआरएस सबस्ट्रेट है जो एक संकर एसईआरएस सबस्ट्रेट है और इसे लिथोग्राफी और स्वयं सभा प्रक्रियाओं के संयोजन द्वारा निर्मित किया जा सकता है। इन सबस्ट्रेट्स के लिए एक विस्तृत संख्यात्मक विश्लेषण किया गया है। धातु के नैनोलाइनों के अंदर धातु नैनोकणों के स्व-विधानसभा को इन सबस्ट्रेट्स के निर्माण के लिए अवधारणा के प्रमाण के रूप में दिखाया गया है। इन सबस्ट्रेट्स द्वारा की गई एसईआरएस वृद्धि की मात्रा का अनुमान लगाने के लिए एसईआरएस माप भी किए गए हैं। इस थीसिस में प्रस्तावित दूसरे एसईआरएस सबस्ट्रेट त्रिकोणीय सोने के नैनो तारों के अंदर तिरछे सोने के नैनोफिंगर्स पर आधारित है। एफडीटीडी का इस्तेमाल करते हुए संख्यात्मक विश्लेषण किया गया है और एक संभावित निर्माण दृष्टिकोण पर चर्चा की गई है। इस थीसिस में प्रदर्शित तीसरे प्रकार के एसईआरएस सबस्ट्रेट नैनो छिद्रों के अंदर नैनो खंभे की एक सरणी है जो एक बड़े क्षेत्र पर निर्मित है। दो नाइट्रो-आधारित विस्फोटक यौगिकों- डायनेट्रोटोलुएन (2,4-डीएनटी) और त्रिनिट्रोटोट्यूलेन (2,4,6-टीएनटी) का मल्टीप्लेक्जड डिटेक्शन इस सबस्ट्रेट के माध्यम से प्रदर्शित किया गया है। इन मापों के लिए पोर्टेबल रमन स्पेक्ट्रोमीटर को नियोजित किया गया है।

इसके अलावा, इस शोध में एक नया नैनोवायर आधारित नैनोलेंस सरणी भी प्रस्तावित है जिसे एसईआरएस आधारित संवेदन के लिए इस्तेमाल किया जा सकता है। यह नैनोलेंस सरणी प्रकाश को तंग स्थानों में केंद्रित करता है। इस सबस्ट्रेट में फ्रील्ड के फ़नलिंग से उच्च विद्युत क्षेत्र की तीव्रता के क्षेत्रों का निर्माण होता है। इन एसईआरएस सबस्ट्रेट के लिए एक व्यापक एफडीटीडी आधारित विश्लेषण इस थीसिस में किया गया है।

इस थीसिस के एक हिस्से के रूप में प्रस्तावित एक और संवेदक, एक पैलेडियम आधारित प्लासमोनिक हाइड्रोजन सेंसर है। यह हाइड्रोजन की उपस्थिति में पैलेडियम धातु के ऑप्टिकल गुणों में परिवर्तन पर आधारित है। सोने की सबस्ट्रेट पर जमा एक पैलेडियम परत पर एक 'सोने की नैनोवर सरणी' का संख्यात्मक विश्लेषण किया गया है। प्लासमोनिक वेवगाइड मोड नैनोयर्स के बीच संकीर्ण खांचे में उत्साहित हैं और इन मोडों के उत्साह से विद्युत चुम्बकीय क्षेत्र की वृद्धि होती है। पैलेडियम की पतली परत हाइड्रोजन के विभिन्न सांद्रता के संपर्क में अपनी ऑप्टिकल गुण बदलती है। इसके परिणामस्वरूप इन वेवगाइड मोडों के प्लासमोनिक व्यवहार में बदलाव आता है। सिस्टम के ऑप्टिकल गुणों में यह परिवर्तन विभिन्न हाइड्रोजन सांद्रता पर प्रतिबिंबित स्पेक्ट्रा में प्रदर्शित किया गया है। इस संवेदक की संवेदनशीलता का आकलन कठोर युग्मक वेव विश्लेषण (आरसीडब्ल्यूए) के आधार पर, एक संपूर्ण संख्यात्मक विश्लेषण का मूल्यांकन किया गया है। हाइड्रोजन से पहले और बाद में न्यूनतम प्रतिबिंब के तरंग दैर्ध्य में बदलाव का विश्लेषण किया गया है।

नैनो-फोटोनिक सेंसरों के अतिरिक्त, ऑप्टिकल स्विच जैसे अन्य नैनोफोटोनिक डिवाइस हाल ही में उनकी उच्च गति और लघु आकार के कारण उभरे हैं। इस थीसिस के बाद का भाग एक वैनेडियम डाइऑक्साइड आधारित ऑप्टिकल स्विच के संख्यात्मक विश्लेषण पर आधारित है जो एक नैनोफोटोनिक डिवाइस है। वैनेडियम डाइऑक्साइड पर आधारित एक स्मार्ट ऑप्टिकल स्विच प्रस्तावित है, जो न केवल स्पेक्ट्रम के दृश्य क्षेत्र में स्विचिंग और मॉड्यूलेशन व्यवहार को दर्शाता है, बल्कि इसे आईआर और आईआर के निकट स्थितियों में प्रदर्शित करता है। यह अल्ट्राफास्ट स्विचबिलिटी का लाभ भी प्रदान करता है। वैनेडियम डाइऑक्साइड की पतली परत (2-10 एनएम) के साथ लेपित प्लैस्मोनी संकी नाली नैनो-ग्रेटिंग, के संख्यात्मक विश्लेषण किए गए हैं। यहां तक कि प्रकाश जो शून्य डिग्री कोण पर इन स्विच पर सीधे गिर जाता है वेवगाइड मोड में जोड़ा जा सकता है। इस प्रकार, वे प्रिज्म-युग्मन जैसे भारी, कोण निर्भर तंत्रों का उपयोग करने की आवश्यकता को कम करते हैं।

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