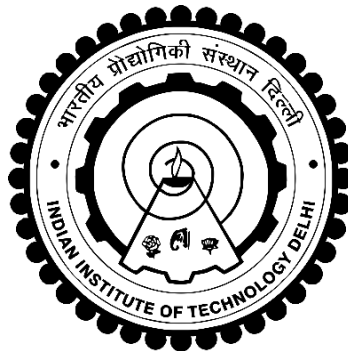


**STUDIES ON NON-RADIATIVE
METAMATERIALS FOR TERAHERTZ
PHOTONICS**

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**DEPARTMENT OF PHYSICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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STUDIES ON NON-RADIATIVE METAMATERIALS FOR TERAHERTZ PHOTONICS

by

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Department of Physics

Submitted

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



INDIAN INSTITUTE OF TECHNOLOGY DELHI
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“The highest education is that which does not merely give us information but makes our life in harmony with all existence.” – Rabindranath Tagore

Dedicated to my parents...

Certificate

This is to certify that the proposed thesis titled “**STUDIES ON NON-RADIATIVE METAMATERIALS FOR TERAHERTZ PHOTONICS**”, being submitted by **Mr. Subhajit Karmakar** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements, which to our knowledge, have reached the requisite standard for the submission of this thesis. The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

Dated: August 2022

Place: New Delhi, India



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Subhajit Karmakar

Subhajit Karmakar

Abstract

Metamaterial ('beyond the natural material') is artificially contrived subwavelength structure which was conceived to realize several unusual and exceptional properties which were not viable in nature. The applications of metamaterials are not only limited to electromagnetism, but they are expanded towards acoustic, mechanical, optical, thermal, electrical, transport, and in other several applications. The merit of metamaterials is drawn from their geometrical designs, imperative of the constructive materials. Electromagnetic metamaterials are used in diverse electromagnetic spectrum (from microwave to optical domain) depending upon the dimension of structures and design variations. Imperative of metamaterial structures, the efficiency of them is limited due to their associated inherent losses. One of the dominant losses in such electromagnetic structures is radiative loss, which generates when electromagnetic waves interact with such artificial materials. Such loss is a major degrading factor specifically in applications where energy conservation, low-power applications, and high efficacy operations are required. Such study, i.e., non-radiative metamaterials for microwave and optical domains are evident in the scientific community; but, for terahertz photonics, exploration of such designs or structures demand extensive investigation, which is believed to be one of the cornerstones for realization of advanced, highly efficient, next-generation terahertz devices and components to be applied in different integrated electronic circuitry and optical devices.

In this present thesis, our aim is to experimentally and theoretically (numerically) demonstrate different design concepts of non-radiative metamaterials for terahertz applications. Major focus of this thesis is to mitigate (control and decrease) radiation losses from terahertz metamaterials by realization of different non-radiative phenomena (like Fano resonances, Bound states (BICs), electromagnetic anapoles etc.) and simultaneously tailoring the nature and properties of the hybridized resonances with suitable geometric and dynamic tuning. For practical applications, we evince high quality (Q) factor based Fano resonance with large detectable intensity which can also be differentially tuned with different external excitations (for example, differential response with applied polarizations is dynamically tuned by electronic means). Larger Q-factor implies lower radiation loss and larger energy confinement

in the device. In general, excitation of Fano resonances were always being excited with structurally broken symmetry. We further demonstrate excitation of asymmetric line shaped Fano resonances in the absence of structural asymmetry by employing broadside coupled stacked metamaterial structures. Such structural configurations have the unique advantage in confining energy to a significant extent compared to planar metamaterials or metasurfaces, and results in strong terahertz-matter interaction and ultra-sensitive sensing performances. Moreover, in periodic metamaterial structures, lattice constant (coupling of metamaterials' resonances with lattice mode) and structural asymmetry are the major factor depicting the nature and line shape of resonances which govern the radiation loss associated with it. With variation of lattice constant of metamaterials, the hybridized resonances can be transformed from radiative to non-radiative states and vice versa. Furthermore, structural asymmetry is a major governing factor in the coupled metamaterials to tailor radiation loss. In general, increasing asymmetry leads to higher radiation loss from the devices. We do a detailed study on structural asymmetry in near field coupled metasurfaces and demonstrate excitation of several non-radiative states like BICs, electric and magnetic Fano resonances, anapoles at different structural asymmetry values (both low and high), which yields principally from mode hybridization. Moreover, by operating at large asymmetry regime, we postulate the criteria to induce artificial transverse magnetism in a non-magnetic straight metallic wire, which provides scientific community with the foremost concept of 'magnetic wire'.

The practical employability of such terahertz metamaterials can be enhanced by inducing dynamic reconfigurable ability in it. An important dynamic tuning scheme which is still not much explored in terahertz metamaterials is magnetic tuning. Magnetically reconfigurable designs are specifically useful for metal-based structures where we need to modulate the conductivity of metal films, which would not be feasible by most of the existing schemes (viz. electrical, optical, mechanical (MEMS) tuning etc.). In this context, we demonstrate the magnetic modulation of non-radiating resonances in metamaterials, which can be very useful for several practical applications for realization and enhancement of performances for both optically thick (above-skin depth) and thin (sub-skin depth) photonic devices. Moreover, our proposed device which consists of ferromagnetic (FM)/ non-magnetic (NM) metals-based patterned superlattice structure and works on the concept of electron spin dependent magneto-transport phenomena; results to a unique combination of photonics with spintronics concept at

terahertz domain. This proposition also establishes a unique criterion to magnetically tune (enhance) non-magnetic responses (resonances) with the exploitation of electron spin dynamics. Therefore, this thesis yields the prospective dimensions to realize several non-radiative passive and dynamic (electronic and magnetic means) reconfigurable resonant hybridized metamaterials to be applied in diverse applications of terahertz photonics.

सार

मेटामटेरियल ('प्राकृतिक पदार्थ से परे') कृत्रिम रूप से निर्मित अनु-तरंग-दैर्घ्य संरचना हैं जिनकी कल्पना कई असामान्य और असाधारण गुणों को महसूस करने के लिए की गई थी जो प्रकृति में व्यवहार्य नहीं थे। मेटामटेरियल्स के अनुप्रयोग न केवल विद्युत-चुंबकत्व तक सीमित हैं, बल्कि उन्हें ध्वनिक, यांत्रिक, प्रकाशविज्ञान, उष्णता सम्बन्धी, विद्युतीक, परिवहन और अन्य जगह अनुप्रयोगों में विस्तारित किया गया है। मेटामटेरियल्स की योग्यता उनके ज्यामितीय बनावट, निर्माणकारी सामग्रियों की अनिवार्यता से ली गई है। विद्युत-चुम्बकीय मेटामटेरियल्स का उपयोग विभिन्न विद्युत चुम्बकीय वर्णक्रम (माइक्रोवेव से प्रकाशिक विकिरण तक) में किया जाता है जो संरचनाओं के आयाम और बनावट विविधताओं पर निर्भर करता है। मेटामटेरियल संरचनाओं की अनिवार्यता, उनके संबंधित अंतर्निहित नुकसान के कारण उनकी कार्यक्षमता सीमित है। ऐसी विद्युत-चुम्बकीय उपकरण में प्रमुख नुकसानों में से एक विकिरण हानि है, जो तब उत्पन्न होती है जब विद्युत-चुम्बकीय तरंगें ऐसी कृत्रिम सामग्री के साथ परस्पर क्रिया करती हैं। इस तरह का नुकसान विशेष रूप से उन अनुप्रयोगों में एक प्रमुख हासमान कारक है जहां ऊर्जा संरक्षण, कम-शक्ति अनुप्रयोगों, और उच्च प्रभावकारिता संचालन की आवश्यकता होती है। इस तरह के अध्ययन, यानी माइक्रोवेव और प्रकाशिक विकिरण के लिए गैर-विकिरणीय मेटामटेरियल वैज्ञानिक समुदाय में स्पष्ट हैं; लेकिन, टेराहर्ट्ज़ फोटोनिक्स के लिए, इस तरह के बनावट या संरचनाओं के अन्वेषण के लिए व्यापक जांच की आवश्यकता होती है, जिसे विभिन्न एकीकृत इलेक्ट्रॉनिक सर्किट और प्रकाशिकी उपकरण में लागू किए जाने वाले उन्नत, अत्यधिक कुशल, अगली पीढ़ी के टेराहर्ट्ज़ उपकरणों और घटकों की प्राप्ति के लिए आधारशिला में से एक माना जाता है।

इस वर्तमान थीसिस में, हमारा उद्देश्य प्रयोगात्मक और सैद्धांतिक रूप से (संख्यात्मक रूप से) टेराहर्ट्ज़ अनुप्रयोगों के लिए गैर-विकिरणीय मेटामटेरियल्स की विभिन्न बनावट अवधारणाओं को प्रदर्शित करना है। इस थीसिस का मुख्य फोकस विभिन्न गैर-विकिरणीय घटनाओं (जैसे फैनो अनुनाद, बाउंड स्टेट्स (बीआईसीएस), विद्युत-चुम्बकीय एनापोल आदि) की प्राप्ति द्वारा टेराहर्ट्ज़ मेटामटेरियल्स से विकिरण हानियों को कम (नियंत्रण और कमी) करना है और साथ ही साथ, उपयुक्त ज्यामितीय और गतिशील ट्यूनिंग के साथ संकरित अनुनाद के प्रकृति और गुणों को नियंत्रण करना है। व्यावहारिक अनुप्रयोगों के लिए, हम बड़ी तौर पर पता लगाने योग्य तीव्रता के साथ उच्च गुणवत्ता (क्यू) कारक आधारित फ़ानो अनुनाद को विकसित करते हैं, जिसे विभिन्न बाहरी उत्तेजनाओं के साथ अलग-अलग परिवर्तन किया जा सकता है (उदाहरण के लिए, लागू ध्रुवीकरण के साथ अंतर प्रतिक्रिया गतिशील रूप से इलेक्ट्रॉनिक माध्यमों से परिवर्तन की जाती है)। बड़ा क्यू-कारक कम विकिरण हानि और उपकरण में बड़ी ऊर्जा संग्रह का तात्पर्य है। सामान्य तौर पर, फ़ानो अनुनाद की उत्तेजना हमेशा संरचनात्मक

रूप से टूटी हुई समरूपता से उत्साहित होती थी। हम आगे व्यापक युग्मित स्टैकड मेटामटेरियल संरचनाओं को नियोजित करके संरचनात्मक विषमता की अनुपस्थिति में असममित रेखा के आकार के फ़ानो अनुनाद के उत्तेजना को प्रदर्शित करते हैं। इस तरह के संरचनात्मक विन्यासों में प्लानर मेटामटेरियल्स या मेटासर्फ़ेस की तुलना में ऊर्जा को एक महत्वपूर्ण सीमा तक सीमित करने में अद्वितीय लाभ होता है, और इसके परिणामस्वरूप मजबूत टेराहर्ट्ज़-पदार्थ परस्पर क्रिया और अत्यंत-संवेदनशील संवेदन प्रदर्शन होते हैं। इसके अलावा, आवधिक मेटामटेरियल संरचनाओं में, लैटिस स्थिरांक (लैटिस मोड के साथ मेटामटेरियल के अनुनादों का युग्मन) और संरचनात्मक विषमता, अनुनादों की प्रकृति और रेखा के आकार को दर्शाने वाले प्रमुख कारक हैं जो इससे जुड़े विकिरण हानि को नियंत्रित करते हैं। मेटामटेरियल्स के लैटिस स्थिरांक की भिन्नता के साथ, संकरित अनुनादों को विकिरण से गैर-विकिरणीय अवस्थाओं में और इसके विपरीत रूपांतरित किया जा सकता है। इसके अलावा, संरचनात्मक विषमता युग्मित मेटामटेरियल्स में दर्जी विकिरण हानि के लिए एक प्रमुख शासी कारक है। सामान्य तौर पर, विषमता बढ़ने से उपकरणों से उच्च विकिरण हानि होती है। हम निकट क्षेत्र युग्मित मेटासर्फ़ेस में संरचनात्मक विषमता पर एक विस्तृत अध्ययन करते हैं और कई गैर-विकिरण वाले अवस्था जैसे बीआईसी, इलेक्ट्रिक और चुंबकीय फ़ानो अनुनाद, एनापोल को विभिन्न संरचनात्मक विषमता मूल्यों (निम्न और उच्च दोनों) पर प्रदर्शित करते हैं, जो मुख्य रूप से मोड संकरण से उत्पन्न होता है। इसके अलावा, बड़े विषमता में संचालन करके, हम एक गैर-चुंबकीय सीधे धातु के तार में कृत्रिम अनुप्रस्थ चुंबकत्व को प्रेरित करने के लिए मानदंड निर्धारित करते हैं, जो वैज्ञानिक समुदाय को 'चुंबकीय तार' की अग्रणी अवधारणा प्रदान करता है।

ऐसे टेराहर्ट्ज़ मेटामटेरियल्स की व्यावहारिक प्रयोज्यता को इसमें गतिशील पुनःविन्यास करने योग्य क्षमता को प्रेरित करके बढ़ाया जा सकता है। एक महत्वपूर्ण गतिशील परिवर्तन योजना जो अभी भी टेराहर्ट्ज़ मेटामटेरियल्स में बहुत अधिक खोजी नहीं गई है वह चुंबकीय परिवर्तन है। चुंबकीय रूप से पुनःविन्यास योग्य डिजाइन धातु-आधारित संरचनाओं के लिए विशेष रूप से उपयोगी होते हैं जहां हमें धातु फिल्मों की चालकता को संशोधित करने की आवश्यकता होती है, जो कि अधिकांश मौजूदा योजनाओं (जैसे विद्युत, प्रकाशिकी, यांत्रिकी (एमईएमएस) तरीका से परिवर्तन आदि) द्वारा संभव नहीं होगा। इस संदर्भ में, हम मेटामटेरियल्स में गैर-विकिरण अनुनादों के चुंबकीय मॉड्यूलेशन को प्रदर्शित करते हैं, जो प्रकाशिकी तरीका से मोटी (सुपर-स्किन गहराई) और पतली (उप-स्किन गहराई) फोटोनिक उपकरण, दोनों के लिए प्रदर्शन की प्राप्ति और वृद्धि के लिए कई व्यावहारिक अनुप्रयोगों के लिए बहुत उपयोगी हो सकता है। इसके अलावा, हमारा प्रस्तावित उपकरण जिसमें लौह-चुंबकीय (एफएम)/ गैर-चुंबकीय (एनएम) धातु-आधारित प्रतिरूप वाली सुपरलैटिस संरचना शामिल है और इलेक्ट्रॉन स्पिन निर्भर मैग्नेटो-ट्रांसपोर्ट घटना की अवधारणा पर काम करता है; ओ टेराहर्ट्ज़ डोमेन पर स्पिंट्रॉनिक्स अवधारणा के साथ फोटोनिक्स के एक अद्वितीय संयोजन के परिणाम है। यह प्रस्ताव इलेक्ट्रॉन स्पिन गतिकी के शोषण के साथ गैर-चुंबकीय प्रतिक्रियाओं (अनुनाद) को चुंबकीय रूप से बदलने (बढ़ाने) के लिए एक अद्वितीय

मानदंड भी स्थापित करता है। इसलिए, यह थीसिस टेराहर्ट्ज फोटोनिक्स के विविध अनुप्रयोगों में लागू होने के लिए कई गैर-विकिरणशील निष्क्रिय और गतिशील (इलेक्ट्रॉनिक और चुंबकीय साधन) पुनःविन्यास करने योग्य गुंजयमान संकरित मेटामटेरियल्स का एहसास करने के लिए संभावित आयाम उत्पन्न करता है।

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List of Abbreviations

ACIS	Association for computer and information science
ASM	Anti-symmetric mode
BIC	Bound state in continuum
CST	Computer simulation technology
EHF	Extremely high frequency
FDTD	Finite difference time domain
FEM	Finite element method
FFT	Fast Fourier transformation
FIT	Finite integral technique
FOM	Figure of merit
GMR	Giant magnetoresistance
LMM	Left metamaterial mode
QCL	Quantum cascade laser
MDI	Modulation index
MEMS	Micro electromechanical system
MM	Metamaterial
MoM	Method of moments
NEMS	Nano electromechanical system
PEC	Perfect electric conductor
PhC	Photonic crystal
RMM	Right metamaterial mode
SC	Spectral contrast

SM	Symmetric mode
SRR	Split ring resonator
TDS	Time domain spectroscopy
THz	Terahertz
TLM	Transmission line method