AN INVESTIGATION OF DIRECT LASER ABLATION AND SCANNING INTERFERENCE LITHOGRAPHY TECHNIQUES FOR EFFICIENT AND HIGH-PRECISION FABRICATION OF PHOTONIC SENSORS

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An Investigation of Direct Laser Ablation and Scanning Interference Lithography Techniques for Efficient and High-Precision Fabrication of Photonic Sensors

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Dedicated to my Family and Friends.

CERTIFICATE

This is to certify that the thesis titled **An Investigation of Direct Laser Ablation and Scanning Interference Lithography Techniques for Efficient and High-Precision Fabrication of Photonic Sensors**, submitted by **Mr. Shital Devinder**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by him under my supervision and guidance. He has fulfilled the requirements for the submission of the thesis, which to the best of my knowledge has reached the required standard. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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– Shital Devinder

ABSTRACT

This doctoral research investigates laser-based micro- and nanofabrication techniques for the realization of cost-effective, scalable, and high-precision sensors and energy devices. The growing demand for compact, high-sensitivity optical sensors, sustainable energy harvesting devices, and low-cost diagnostic platforms has intensified the need for fabrication methods that can simultaneously offer precision, scalability, and material versatility. Laser-based techniques, including direct laser ablation (DLA) and scanning interference lithography (SIL), enable maskless patterning, localized material modification, and rapid process optimization while maintaining compatibility with a broad range of functional materials. The work focuses on direct laser ablation (DLA) and scanning interference lithography (SIL) as flexible alternatives to conventional lithographic methods, enabling rapid prototyping and large-area fabrication with reduced processing complexity.

Ultraviolet laser-induced graphene (UV-LIG) structures are developed for broadband solar absorption and multifunctional sensing applications. The fabricated UV-LIG surfaces exhibit optical absorption exceeding 99% across the solar spectrum and reach temperatures of approximately 90^oC under one-sun illumination. When integrated with a thermoelectric generator, the system produces an output voltage of 273.9 mV, demonstrating its viability for solar thermoelectric energy harvesting. In addition, interdigitated UV-LIG electrodes are employed for capacitive sensing, achieving touch response exceeding 49%, proximity detection up to 170 mm, and liquid level sensing with a resolution of 0.97 mm.

The thesis further presents surface plasmon resonance (SPR) sensors fabricated via direct laser ablation of indium tin oxide (ITO) films followed by metal coating. Sinusoidal grating profiles generated through DLA exhibit enhanced resonance quality compared to rectangular gratings. A chirped grating-coupled SPR configuration is introduced, enabling spatially resolved sensing with a measured positional sensitivity of approximately 6 mm/RIU, allowing wavelength-encoded sensing without the use of a spectrometer.

Scanning interference lithography is employed to fabricate inch-scale periodic, apodized, and chirped gratings using a minimal optical setup, offering a scalable alternative to electron-beam and direct laser writing techniques for large-area nanostructuring. Finally, an intensity-tracking-based guided mode resonance (GMR) detection scheme is demonstrated using laser-fabricated diffraction gratings and a CMOS sensor, achieving a sensitivity of 2.02 mm/RIU while eliminating the need for expensive spectrometers.

Overall, this work establishes laser-based fabrication as a versatile and scalable approach for developing high-sensitivity photonic sensors and energy devices, providing experimentally validated performance metrics and clear advantages in cost, scalability, and system simplicity compared to conventional fabrication and detection methodologies.

सार (Abstract)

प्रस्तुत शोधकार्य किफायती, स्केलेबल तथा उच्च-परिशुद्धता सेंसर एवं ऊर्जा उपकरणों के विकास हेतु लेज़र-आधारित माइक्रो एवं नैनो-निर्माण तकनीकों के विस्तृत अध्ययन पर केंद्रित है। कॉम्पैक्ट एवं उच्च-संवेदनशील ऑप्टिकल सेंसरों, सतत ऊर्जा-संग्रह उपकरणों तथा कम-लागत निदान प्लेटफॉर्मों की बढ़ती मांग के कारण ऐसे निर्माण तरीकों की आवश्यकता उत्पन्न हुई है जो एक साथ उच्च परिशुद्धता, स्केलेबिलिटी तथा सामग्री-बहुलता प्रदान कर सकें। इस संदर्भ में, प्रत्यक्ष लेज़र एब्लेशन (Direct Laser Ablation – DLA) तथा स्कैनिंग इंटरफेरेंस लिथोग्राफी (Scanning Interference Lithography – SIL) जैसी लेज़र-आधारित तकनीकें मास्क-रहित पैटर्निंग, स्थानीयकृत सामग्री संशोधन तथा तीव्र प्रक्रिया अनुकूलन को सक्षम बनाती हैं, साथ ही विभिन्न कार्यात्मक सामग्रियों के साथ व्यापक संगतता भी प्रदान करती हैं। यह शोध पारंपरिक लिथोग्राफी विधियों के प्रभावी विकल्प के रूप में DLA एवं SIL की भूमिका को स्थापित करता है, जो कम प्रक्रिया जटिलता के साथ तीव्र प्रोटोटाइपिंग एवं बड़े-क्षेत्र निर्माण को संभव बनाती हैं।

इस शोध के अंतर्गत पराबैंगनी लेज़र-प्रेरित ग्रेफीन (Ultraviolet Laser-Induced Graphene – UV-LIG) संरचनाओं का विकास ब्रॉडबैंड सौर अवशोषण तथा बहुउपयोगी संवेदन अनुप्रयोगों हेतु किया गया है। विकसित UV-LIG सतहें सौर स्पेक्ट्रम में 99 प्रतिशत से अधिक प्रकाशीय अवशोषण प्रदर्शित करती हैं तथा एक-सूर्य (one-sun) प्रकाशन अवस्था में लगभग 90 °C तापमान तक पहुँचती हैं। थर्मोइलेक्ट्रिक जनरेटर के साथ इनके एकीकरण पर प्रणाली द्वारा 273.9 mV का आउटपुट वोल्टेज प्राप्त हुआ, जो सौर थर्मोइलेक्ट्रिक ऊर्जा-संग्रह अनुप्रयोगों के लिए इसकी व्यवहार्यता को प्रमाणित करता है। इसके अतिरिक्त, इंटरडिजिटेटेड UV-LIG इलेक्ट्रोडों का उपयोग कैपेसिटिव सेंसिंग हेतु किया गया, जिसमें 49 प्रतिशत से अधिक टच-प्रतिक्रिया, 170 मिमी तक निकटता पहचान तथा 0.97 मिमी विभेदन क्षमता के साथ द्रव-स्तर संवेदन प्राप्त की गई।

शोधप्रबंध में इंडियम टिन ऑक्साइड (Indium Tin Oxide – ITO) पतली परतों पर प्रत्यक्ष लेज़र एब्लेशन के उपरांत धातु कोटिंग द्वारा निर्मित सरफेस प्लास्मोन रेज़ोनेंस (Surface Plasmon Resonance – SPR) सेंसरों का भी विवरण प्रस्तुत किया गया है। DLA द्वारा निर्मित साइनसॉइडल ग्रेटिंग प्रोफाइल, आयताकार ग्रेटिंग्स की तुलना में उन्नत रेज़ोनेंस गुणवत्ता प्रदर्शित करते हैं। एक चिर्प्ड ग्रेटिंग-युग्मित SPR विन्यास प्रस्तावित किया गया है, जो स्थानिक रूप से विभेदित सेंसिंग को सक्षम बनाता है तथा लगभग 6 मिमी/RIU की स्थितीय संवेदनशीलता प्रदान करता है, जिससे स्पेक्ट्रोमीटर के बिना तरंगदैर्घ्य-एन्कोडित सेंसिंग संभव हो पाती है।

आगे, स्कैनिंग इंटरफेरेंस लिथोग्राफी का उपयोग न्यूनतम ऑप्टिकल सेटअप के माध्यम से इंच-स्केल आवधिक, एपोडाइज़्ड तथा चिर्प्ड ग्रेटिंग्स के निर्माण हेतु किया गया है, जो बड़े-क्षेत्र नैनो-संरचनाकरण के लिए इलेक्ट्रॉन-बीम तथा प्रत्यक्ष लेज़र लेखन तकनीकों का एक स्केलेबल विकल्प प्रस्तुत करता है। अंततः, लेज़र-निर्मित विवर्तन ग्रेटिंग्स एवं CMOS सेंसर का उपयोग करते हुए एक तीव्रता-ट्रैकिंग आधारित गाइडेड मोड रेज़ोनेंस (Guided Mode Resonance – GMR) डिटेक्शन योजना प्रदर्शित की गई है, जिसमें 2.02 मिमी/RIU की संवेदनशीलता प्राप्त हुई तथा महंगे स्पेक्ट्रोमीटर की आवश्यकता समाप्त हो जाती है।

समग्र रूप से, यह शोध लेज़र-आधारित निर्माण तकनीकों को उच्च-संवेदनशील फोटोनिक सेंसरों एवं ऊर्जा उपकरणों के विकास हेतु एक बहुमुखी, स्केलेबल तथा व्यावहारिक दृष्टिकोण के रूप में स्थापित करता है। प्रस्तुत कार्य पारंपरिक निर्माण एवं डिटेक्शन पद्धतियों की तुलना में लागत-प्रभावशीलता, स्केलेबिलिटी तथा प्रणाली-सरलता के स्पष्ट लाभों को दर्शाता है तथा प्रयोगात्मक रूप से सत्यापित प्रदर्शन मापदंड उपलब्ध कराता है।

Organization of the Thesis

The proposed thesis consists of the following chapters. A brief overview of the chapters is provided here.

Chapter 1: The introductory chapter of the proposed thesis offers a detailed description of the research issue, highlighting its importance within the broader field and identifying the specific research gap the study intends to fill. It also outlines the main research questions, objectives, and hypotheses guiding the inquiry. Furthermore, the chapter presents a concise overview of the thesis framework, providing the reader with a definitive guide to the organization and progression of the next chapters.

Chapter 2: The chapter deals with UV laser-induced graphene (LIG) foam for energy harvesting, proximity sensing, and tunable optical filters. Thermoelectric technology is increasingly pivotal for the conversion of solar energy, contributing to the growth of green energy resources. This work presents a perfect broadband solar absorber that utilizes UV-LIG prepared on a polymer material. This absorber exhibits exceptional light absorption (>99%) across the full solar spectrum and achieves a temperature of $90.4°C$ with 1 sun irradiation in less than 60 seconds. When combined with a thermoelectric generator (TEG), the structured UV-LIG absorber outperforms other materials in power generation, achieving a remarkable output voltage of 273.9 mV, making it a promising solution for solar-thermoelectric conversion systems.

The next section deals with low-cost, interdigitated capacitive sensors fabricated using direct laser-written graphene foam for touch, proximity, and liquid level detection. This work explores the fabrication of a low-cost interdigitated capacitive sensor for touch, proximity, and liquid level detection. This chapter introduces planar capacitive sensors based on laser-induced graphene foam (LIGF), characterized by their flexibility, high sensitivity, energy efficiency, and cost-effectiveness. These sensors operate on the principle of the fringing field effect, in which the electric field extends beyond the boundaries of planar capacitor electrodes. Capacitance variations are detected as changes occur in the permittivity of the surrounding medium or the distribution of electric charges. The developed LIGF-based touch sensor showed an average touch response of more than 49%, and it can detect the presence of human hands up to a maximum distance of 170mm. An extended design demonstrated liquid level detection with an accuracy of 0.97mm. The LIGF electrode-based capacitive sensor is suitable for modern technology and devices due to its ability to detect dielectric materials, contactless operation, long-range sensing, low power consumption, and environmental friendliness.

Guided Mode Resonance-Based Tunable Filter Utilizing the Thermo-Optic Effect of PDMS through LIG Microheaters: This section focuses on developing thermo-optic tuneable guided mode resonance (GMR) filters using laser-induced graphene (LIG) microheaters to achieve real-time spectral tuning with high sensitivity and precision. Tuneable filters are crucial for various optical applications, including microscopy, communication, imaging, sensing, and lightning. They also provide wavelength-switching capability, which is essential for real-time multiplexing and manipulation of optical signals. The current work focuses on the fabrication and evaluation of thermo-optic tunable spectral filters based on guided mode resonance phenomena, providing a decent response in the visible spectrum range.

Chapter 3: This chapter introduces direct laser ablation of ITO thin films for photonic sensor fabrication. The chapter deals with the investigation of a novel direct laser ablation (DLA) process for fabricating highly sensitive photonic sensors based on the phenomenon of surface plasmon resonance (SPR). This study presents a simple and far-fetched approach to fabricating surface plasmon resonance (SPR) sensors using indium tin oxide (ITO) thin films. The sinusoidal grating-coupled SPR shows a higher quality factor and sensitivity than a rectangular grating-coupled SPR. The structures were simulated using a commercial grade 3D electromagnetic simulator operating on the "finite-difference-time domain" method, and the performance of both gratings was evaluated. The fabrication process involves direct ablation of ITO films with a focused laser beam generating photonic structures on the ITO film. The patterned surface is then covered with metals like gold, resulting in a gold grating. ITO is chosen because of its transparency at visible wavelengths and high absorption in the UV region of the spectrum. The poor thermal conductivity of ITO thin films contributes to a smaller heat-affected zone even when ablated with a continuous-wave CW laser. Unlike conventional methods, laser ablation leaves an impression of the laser intensity profile that results in the sinusoidal surface profile of the grating surface.

The second part of this chapter presents a new and cost-effective approach to encourage the use of photonic biosensors. The challenge lies in developing a low-cost, compact and autonomous device that is durable and can be operated by untrained users in field conditions. The proposed method introduces an innovative chirped grating coupled SPR sensor, which generates resonance signal and converts spectral information into spatial data using the same sensor chip. This sensor can be easily integrated into a small, mass-producible device that is durable, affordable, and requires minimum alignment. The device is engineered to function under unpredictable and real-world conditions. Despite its low cost, the sensor demonstrated a positional sensitivity of 6 mm/RIU for the bulk refractive index.

Chapter 4: The chapter deals with large-area grating fabrication using scanning interference lithography. A key challenge in nanostructured surface fabrication is scaling up to produce large-area gratings. This chapter presents an innovative approach that combines interference lithography with mechanical scanning, enabling the production of large-area gratings that can enhance biosensing, energy harvesting, and photonic applications. The proposed method is a significant advancement in nanofabrication, introducing a novel approach for generating large nanostructured gratings. A $405nm$ laser beam is converted into a light line using a cylindrical lens, achieving a uniform intensity and phase. This line illuminates Lloyd's mirror set-up, producing interference fringes on a photoresist-coated substrate. Controlled motion along these fringes ensures precise replication of the grating pattern across the sample. This method facilitates the creation of extensive grating structures on photoresist-coated surfaces with adjustable grating parameters, for example, variation of the grating pitch can be achieved through simple adjustments to the incident beam's angle. Unlike conventional methods, this method requires only a high-precision linear translation stage, a modestly powered laser source, and minimal optical components, offering enhanced flexibility and efficiency. Additionally, it serves as a simple procedure to produce apodized (varying fill-fraction) and chirped grating structures, which are otherwise intricate to fabricate and can only be realized using sophisticated techniques like e-beam lithography and direct laser writing.

Chapter 5: This chapter focuses on intensity tracking-based guided mode resonance (GMR) for refractive index sensing. It introduces an innovative intensity-based detection method for GMR sensors that eliminates the reliance on costly spectrometers. The setup employs an in-house developed diffraction grating, fabricated through scanning interference lithography, as detailed in a previous chapter, coupled with an affordable CMOS array. This combination enables high-sensitivity refractive index sensing, paving the way for more cost-effective and accessible biosensing technologies. The core technique utilizes a silicon nitride (Si_3N_4) GMR chip, meticulously fabricated using e-beam lithography, to detect changes in the refractive index. The sensitivity of this system is quantified by the slope of the linear relationship between the intensity spot position on the CMOS sensor and variations in the refractive index. For the developed set-up, this sensitivity is measured to be 2.02 mm/RIU. This approach not only significantly reduces operational costs but also improves the overall sensitivity of the system, making it a promising solution for future biosensing applications.

Chapter 6: This concluding chapter delves into the transformative potential of photonic and nanofabrication technologies, bridging fundamental research with real-world applications. Highlights key advancements in laser-induced graphene (LIG) technologies made during the research work, direct laser ablation (DLA), nanostructured grating fabrication, and guided mode resonance (GMR) detection systems. The chapter also describes the importance of the proposed fabrication methods in sustainable energy and sensing technologies, the precision of DLA in microfabrication, and the scalability of novel nanofabrication methods. In addition, the development of compact and cost-effective GMR detection systems showcases applications in diagnostics and environmental monitoring. The chapter concludes with future research avenues, focusing on material optimization and interdisciplinary integration to enhance device performance and broaden application scopes.

Contents

Abbreviations

AFM	Atomic Force Microscopy
CMOS	Complementary Metal-Oxide-Semiconductor
CW	Continuous Wave
DLA	Direct Laser Ablation
EBL	Electron-Beam Lithography
EDAX	Energy-Dispersive X-ray Spectroscopy
EOM	Electro-Optic Modulation
FESEM	Field Emission Scanning Electron Microscopy
FFT	Fast Fourier Transform
FDTD	Finite Difference Time Domain
FWHM	Full Width at Half Maximum
GMR	Guided Mode Resonance
HAZ	Heat-Affected Zone
HR-TEM	High-Resolution Transmission Electron Microscopy
ITO	Indium Tin Oxide
LED	Light Emitting Diode
LIG	Laser-Induced Graphene
LOD	Limit of Detection
NA	Numerical Aperture
NIL	Nanoimprint Lithography
NIR	Near-Infrared
PECVD	Plasma-Enhanced Chemical Vapor Deposition
PDMS	Polydimethylsiloxane
PI	Polyimide
POC	Point-of-Care
QF	Quality Factor
RI	Refractive Index
RIU	Refractive Index Unit
RIE	Reactive Ion Etching
SEM	Scanning Electron Microscopy
Si_3N_4	Silicon Nitride
SiO_2	Silicon Dioxide
SIL	Scanning Interference Lithography
SLA	Stereolithography
SLM	Single Longitudinal Mode
SPR	Surface Plasmon Resonance
STEG	Solar Thermoelectric Generator
TEG	Thermoelectric Generator
UV	Ultraviolet
XPS	X-ray Photoelectron Spectroscopy
XRD	X-Ray Diffraction

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