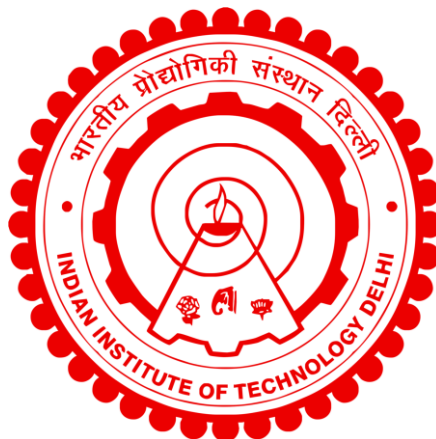


**AN INVESTIGATION OF DIRECT LASER ABLATION
AND SCANNING INTERFERENCE LITHOGRAPHY
TECHNIQUES FOR EFFICIENT AND HIGH-PRECISION
FABRICATION OF PHOTONIC SENSORS**

SHITAL DEVINDER



**CENTER FOR SENSORS INSTRUMENTATION AND CYBER PHYSICAL
SYSTEM ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
MARCH 2026**

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

by

Shital Devinder

Centre for Sensors, Instrumentation and Cyber Physical System

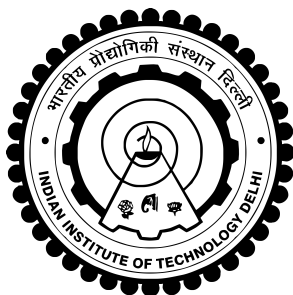
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HAUZ KHAS, NEW DELHI-110016 INDIA

MARCH 2026

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.



Prof. Joby Joseph
Professor
Optics and Photonic Centre
IIT Delhi, 110016

New Delhi
March 2026

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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°C 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 चिपर्ड 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 चिपर्ड 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 di-

rect 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

CERTIFICATE	iv
ACKNOWLEDGEMENTS	v
ABSTRACT	vii
Organization of the thesis	xi
List of figures	xxviii
List of tables	xxix
1 Introduction to Laser Material Interaction in the Preview of Sensor Fabrication	1
1.1 Introduction	1
1.2 Evolution of Lasers for material processing	3
1.3 Fundamentals of Laser-Material Interaction	6
1.3.1 Properties of Lasers	7
1.3.2 Light propagation in materials	9
1.3.3 Laser Matter Interaction	10
1.3.4 Material Modification by Photothermal Processes	13
1.3.5 Ablation by Photothermal Process	15
1.3.6 Photopolymerization	19
1.4 Materials for Laser Processing	20
1.4.1 Optical Properties of Materials Influencing Laser Processing	22
1.4.2 Brief overview of applications covered in this research	23
1.5 Research Gaps and Motivation	24

1.5.1	Identified Gaps	24
1.5.2	Motivation for the Study	25
1.6	Research Objectives	26
1.6.1	Logical Flow from Fundamental Principles to Advanced Applications	27
2	UV laser induced graphene foam for energy harvesting, proximity sensing and tuneable optical filters	28
2.1	UV-LIG-Based Perfect Broadband Absorber for solar energy harvesting . .	28
2.2	Background and Literature Review	31
2.3	Current Studies on Photothermal Materials and STEGs	32
2.4	Materials and Methods	33
2.4.1	Materials Used	33
2.4.2	Direct Laser Writing System	34
2.4.3	Preparation Process	35
2.5	Characterization Techniques	36
2.6	Results and Discussion	38
2.6.1	Structural Properties of UV-LIG	38
2.6.2	Optical and Photothermal Properties	40
2.7	Performance of UV-LIG-based STEG	42
2.8	Comparative Analysis	45
2.9	Prospects for Future Research and Technology Development	46
2.10	Laser-Written Graphene Foam for Touch, Proximity, and Liquid Level Detection	47
2.11	Background on Capacitive Sensors in Modern Technology	47
2.12	Emergence of Flexible, Graphene-Based Sensors as a Cost-Effective Solution	49
2.13	Objectives of the Study	50
2.14	Material and Methods	51
2.14.1	Materials Used	51
2.14.2	Laser-Induced Graphene Foam (LIGF) Generation Process	51
2.15	Characterization Techniques	53
2.16	Working Principles	54
2.16.1	Capacitive sensor fundamentals and detection method	54

2.17	Simulation Validation Using COMSOL	56
2.18	Results and Discussion	56
2.18.1	Proximity Sensing Performance	56
2.18.2	Touch Sensing Capability	57
2.18.3	Liquid Level Detection	58
2.19	Advantages and Applications of LIGF-Based Capacitive Sensors	58
2.20	Laser-Induced Graphene heater for Guided Mode Resonance-Based Tunable Optical Filters	61
2.21	Design and Fabrication	64
2.21.1	GMR Filter	64
2.21.2	LIG Microheaters	64
2.21.3	Characterization	65
2.22	Device Assembly and Operational Principles	67
2.22.1	Results and discussion	68
2.23	Conclusion	69
3	Direct laser ablation of ITO thin films for photonic device fabrication	71
3.1	Introduction	71
3.2	Objectives of the Study	73
3.3	Fundamentals of Laser Material Interaction	73
3.4	Optical properties of Indium Tin Oxide (ITO)	77
3.4.1	Cleaning and Post-treatment Processes	78
3.5	Laser System and Experimental Setup	80
3.6	Characterization Results	83
3.7	Surface Plasmon Resonance (SPR) Sensors using DLA of ITO	85
3.7.1	Sensitivity Analysis and Practical Implications	87
3.8	Challenges, Limitations, and Future Perspectives	89
3.9	Direct laser ablated ITO based chirped SPR sensors	90
3.10	Design and Fabrication of ITO-Based Chirped Gratings	92
3.11	Comparison with Uniform Grating SPR Sensors	93
3.12	Sensing Performance and Applications	96
3.13	Future Directions	98

3.14	Conclusion	99
4	Large-Area Grating Fabrication Using Scanning Laser Interference Lithography	101
4.1	Introduction	101
4.2	Objective of the Study	105
4.3	Experimental Method	105
4.4	Results and Discussion	111
4.4.1	Comparison with Traditional Methods	113
4.4.2	Potential for Complex Structures	115
4.4.3	Considerations and Areas for Improvement	115
4.4.4	Conclusion	116
4.5	Future work	117
5	Intensity tracking-based GMR detection modality using diffraction grating and CMOS array	118
5.1	Introduction	118
5.2	Design and Fabrication of GMR Sensor	121
5.3	Working of CMOS-Based Detection System	124
5.4	Experiment and Results	126
5.5	Advantages over Traditional Systems:	129
5.6	Applications and Future Prospects	131
5.7	Conclusion	131
6	Conclusions and scope for future research	133
6.1	Limitations of the techniques	135
6.2	Comparison of SPR and GMR Sensing Platforms	136
6.3	Scope for Future Research	137
6.4	Guidance for Future Researchers	139
6.5	Outlook	139
	References	156
	Publications	159

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 ₃ N 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

List of Figures

1.1	Historical timeline of laser development for material processing.	3
1.2	Properties of a laser source in contrast to a thermal source.	7
1.3	(a) Photochemical and Photothermal process (b) Laser material interaction mechanism: depicting bond breaking without heating, bond breaking followed by heating and combination of two processes	11
1.4	(a) Laser ablation of material as a result of heating due to interaction. (b) Photochemical degradation of the material on account of laser interaction. (c) Chemical modification of the photosensitive material under the light of suitable wavelength.	13
1.5	Ablation of material by photothermal process involving (a) heating (b) Vaporization (c) plasma formation and (d) ablation or material removal. . . .	15
1.6	(a) Laser induced graphene based broadband absorber. (b) Laser induced graphene based tactile and liquid level detection sensors (c) Grating coupled SPR sensor fabrication using direct laser ablation of ITO. (d) Very large area grating prepared using scanning laser interference lithography.	23
2.1	Schematic illustrating solar energy harvesting using Photovoltaic (PV) and Solar Thermoelectric Generator (STEG) technologies, highlighting conversion mechanisms and efficiency pathways. Typical crystalline silicon photovoltaic systems achieve power conversion efficiencies exceeding 20%, whereas practical solar thermoelectric generators generally operate at efficiencies of a few percent, reflecting their fundamentally different energy conversion mechanisms.	29
2.2	SEM image of the cross-sectional view of PI Tape, verifying its thickness and the thickness of the adhesive layer. (b) Reflection, transmission, and absorption spectra of the commercially available PI tape.	34
2.3	(a) Schematic illustration of the direct laser scribing setup, highlighting key components such as laser steering mirrors, the focusing objective, and precision translation stages used to control sample positioning. (b) The figure showcases the formation of Laser-Induced Graphene (LIG) following both a single scan and a double scan process. The double scan results in the development of a distinctive pyramid-like surface structure, which significantly enhances the light absorption capabilities of the LIG surface.	35

2.4	(a) SEM image of the UV-LIG surface after the single surfaces can be seen. (b) Cross-sectional SEM view of the UV-LIG surfaces shows the foamy UV-LIG. (c) - (f) SEM images showing the UV-LIG surface viewed at a tilted angle. (g) Light-trapping mechanism of the transformed surface.	39
2.5	(a) Raman spectra for the obtained UV-LIG surface. (b) X-ray diffraction data for the UV-LIG powders scraped from the UV-LIG surface. (c) The EDAX data for the UV-LIG surface. (d) XPS data plots for PI (Kapton) and the UV-LIG surface. (e) HR-TEM image for UV-LIG. (f) HR-TEM image for the marked box in Figure 2.4(e).	40
2.6	(a) Reflection, transmission, and absorption spectra for the UV-LIG surface. The surface shows 99% absorption for the entire solar spectral range. (b) Images showing a 4 $\times$ 3.5 cm ² UV-LIG surface with black ensures perfect absorption throughout the region. (c) The water contact angle for the UV-LIG surface. (d) Photothermal heating of the UV-LIG surface and the resulting temperature evolution with time.	41
2.7	(a) depicts a schematic of the UV-LIG-based STEG. (b) shows images of the STEG mounted on the translation stage during UV-LIG generation. The insets in Figure 2.7 (b) illustrate the complete STEG device. (c) presents the open-circuit voltage across the STEG for 1 sun, 1.5 sun, and 2 sun. (d) demonstrates the output voltage stability during on-off input cycles at 1 sun.	43
2.8	(a) shows the voltage variation with load, (b) the corresponding current variation, and (c) the power variation. (d) This is an STEG image under 1 sun illumination with water flowing through the heatsink channel at 0.8 L/min. The yellow arrows point toward the flow of water in the channel. (e) This is an LED powered by the STEG under 1 sun illumination, with a joules recursion circuit to boost the current.	44
2.9	(a) Illustration of the preparation process for the LIG-based interdigitated planar capacitor. (b) Visualization of the fringing effect in the planar capacitor, highlighting how dielectric materials enhance field line density and capacitance. (c) Schematic of the LIG-based touch sensor demonstrating capacitance measurement upon touch, (d) LIG based liquid level sensor schematic with an accompanying plot depicting capacitance variations as water level rises.	52
2.10	(a) Raman spectrum showcasing the distinctive features confirming LIG generated on a PI substrate with a 410 nm diode laser. (b) XPS data plot highlighting the pronounced concentration of Carbon compared to Nitrogen and Oxygen within the LIG electrodes. (c) SEM micrograph revealing the seamless and continuous formation of LIG across the targeted electrode region. (d) HR-TEM image confirming the presence of graphene structures in the laser-treated areas on the PI surface.	53

2.11	(a) The schematic diagram of an electrical circuit and the process of collecting data using a microcontroller (Arduino Uno). (b) The change in capacitance relative to the proximity of a human hand to the sensor. (c) A graph displaying the data from multiple touches on the sensor over a period of 1 min. (d) An enlarged display of the red box depicted in (c). (e) The experimental data (represented in black) and the linear fit (shown in red) for liquid level sensing utilizing the LIGF planar capacitor.	57
2.12	(a) GMR structure explaining phase detection. A 1D subwavelength grating coupled to a waveguide to form the GMR structure. (b) Schematic illustrating the complete LIG-based tunable filter, comprising a GMRF with its substrate side facing forward. The grating side of the GMRF is coated with PDMS (yellow), while a LIG heater (black) is positioned at the back, connected to a regulated power supply. The inset in the top right corner provides a cross-sectional view of the GMR filter, highlighting its dimensional characteristics.	62
2.13	(a) Schematic illustration of the LIG heater preparation process. (b) Step-by-step sequence of the GMRF filter fabrication process.	65
2.14	Characterization of the Tunable Filter Elements (LIG and GMRF): (a) Raman spectra of the heater surface, confirming distinctive graphene peaks, and (b) reflection spectra of the GMRF, showcasing a sharp filtering response at 810 nm.	66
2.15	(a) Image of the bare LIG heater. (b) LIG heater covered with Kapton tape, with a thermocouple attached for temperature measurement. (c) Experimental plot showing temperature variation of the LIG surface with applied voltage. (d) Thermal image of the LIG heater surface at the maximum applied voltage (12V). The image shows an even temperature across the surface, except near the electrode contacts where the temperature differs due to lower resistance in that area.	67
2.16	Spectral Response of the Tuneable Filter: (a) Reflection spectrum at the start and end of the tuning cycle (inset shows the filter assembly); (b) Resonant wavelength variation of GMRF with applied voltage to the LIG heater under the filter's cover layer.	68
3.1	(a) Absorbance measurements for the indium tin oxide (ITO) thin films[154]. (b) Ellipsometry data from the ITO thin film used in the experiments. . .	77
3.2	(a) Cleaning the ITO sample with isopropyl alcohol (IPA) (b) Thoroughly washing the laser-ablated grating with piranha solution, a mixture of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) in a 3:1 ratio (c) Gold coating the sample using thermal evaporation	79
3.3	(a) Schematic illustration of the DLA setup. (b) Visualization of light coupling into the ITO film, evident at the edges of the ITO sample, indicating precise focus. (c) Diagram depicting photothermal expansion resulting in the removal of ITO from the surface. (d) Photograph of four fabricated grating regions with varying periodicities on the ITO sample, subsequently coated with gold for SPR.	81

3.4	(a) Schematic representation of the laser ablation process for ITO. (b) Photograph of the actual experimental setup. (c) 1D grating sample fabricated via direct laser ablation of ITO. (d) SEM image of the sample without post-ablation treatment. (e) SEM image of the sample following a 2-minute piranha wash. (f) SEM image of the sample after optimized laser scanning and post-ablation treatments.	82
3.5	(a) Image displaying the laser-ablated grid pattern on the ITO sample, with laser power varying vertically and scanning speed varying horizontally. (b) SEM top view of the 1 μm grating structure. (c) Optical profiler measurement showing the grating's surface profile and roughness. (d) FESEM cross-sectional view highlighting the sinusoidal shape of the grating. (f) Graph illustrating how grating height changes with laser power. (g) Plot showing the relationship between the grating's fill fraction and the laser beam's power density.	83
3.6	(a) Simulation window displaying the transverse view of a sinusoidal grating with a 100, nm gold coating. (b) FESEM image of the fabricated sinusoidal grating on an ITO film, with an inset showing the grating regions on the sample. (c) Transverse-section FESEM image confirming the sinusoidal structure of the grating surface. (d) Image of the sample after gold coating, with red circles indicating the regions where the mechanical profiler was used to measure the gold layer thickness. (e) Plot of mechanical profiler data demonstrating the 100, nm gold coating thickness on the sample surface. (f) Comparison plot of simulated reflectance and corresponding experimental results, showing strong agreement.	86
3.7	(a) A schematic illustration of the SPR detection setup, which enables the measurement of refractive index variations on the sensor surface. The accompanying image on the right depicts the sensor integrated within a custom cavity designed to facilitate the flow of a sample liquid over the sensor's surface. (b) The reflectance of the SPR sensor chip is shown, revealing a dip at the wavelength of interest. (c) The results of the refractive index sensing experiment conducted on the SPR chip's surface. (d) The sensitivity curve showing the variation of resonance wavelength of SPR chip with varying refractive index of the cover medium.	88
3.8	(a) Top view schematic of a chirped SPR sensor, illustrating the periodic variation along the grating grooves. (b) Experimental setup schematic for detecting chirped grating-coupled SPR signal using a CMOS camera. (c) Representation of the sensor image under collimated laser beam irradiation. (d) Plot of the intensity variation along the chirp direction.	91
3.9	Schematic presentation of the fabrication process followed for the chirped grating coupled SPR sensor fabrication.	92

3.10	Experimental Verification of the Proposed Chirped SPR Sensor (a) Optimization Process: Creation of multiple chirped SPR regions with different periodicities to identify the suitable grating for the target laser wavelength. (b) Image of the optimized chirped grating (10 mm $\times$ 5mm) designed to produce an SPR intensity dip at the center of the sample width under near-normal incidence. (c) Photograph of the gold-coated chirped SPR sensor. (d) Data Visualization: (left) Image of the chirped SPR sensor illuminated with a 1064 nm collimated laser beam; (middle) Line plot showing intensity distribution along the chirp direction; (right) Plot illustrating the variation of intensity minima over time. (e) Experimental Results: Graph showing changes in the SPR intensity dip over time as the concentration of sugar solution on the sensor surface varies.	97
4.1	Various lithography techniques illustrated: (a) Optical Lithography, (b) Electron Beam (e-beam) Lithography, (c) Nanoimprint Lithography, (d) Laser Interference Lithography with a Two-Beam Setup, (e) Direct Laser Writing, (f) Two-Photon Lithography, and (g) Laser Interference Lithography using Lloyd's Mirror Setup.	102
4.2	Existing Laser Interference Lithography Setups schematics for large-area grating fabrication: (a) Lloyd's mirror configuration with two-beam interference lithography, showcasing the interference phenomenon and the periodicity dependence on wavelength and interference angle (inset); (b) Lloyd's mirror setup utilizing collimated light producing straight line fringes; (c) configuration with an expanded spherical beam producing hyperbolic fringes; (d) proposed scanning laser interference lithography using Lloyd's mirror in conjunction with a cylindrical lens and a translating setup.	104
4.3	(a) Schematic diagram illustrating the expanded laser beam utilizing a cylindrical lens. (b) Measured intensity image data with a corresponding profile plot, demonstrating uniformity across a 5 cm width after propagating over a distance of one meter.	106
4.4	Schematic of the proposed method for large-area grating fabrication. A laser beam is expanded using a small focal length cylindrical lens and propagated over a significant distance to achieve uniform intensity and phase at the photoresist-coated sample plane. The expanded beam is directed onto a Lloyd's mirror setup mounted on a translation stage, allowing the interference pattern to sweep across the entire photoresist-coated sample. The red dot inside the black circle indicates the translation direction of the Lloyd's mirror setup. Gray images with arrows on the right depict progression of the interference pattern, which forms the polymerized grating pattern on the photoresist-coated sample.	108

4.5	Simulation to Estimate Periodicity Changes in Cylindrical Beam Interference: (a) This section illustrates the wavefronts of two interfering beams at the sample plane. The plot on the right demonstrates how the periodicity changes along the length of the interfering beams. (b) A schematic diagram is provided to show the conceptual layout of the interferometer, clearly representing its components and arrangement. (c) The schematic describes the Lloyd's mirror configuration, where the traditional mirror is substituted with a long strip of front-coated mirror. The sample is mounted separately on a linear translation stage. Additionally, the image on the right displays the actual experimental setup used in the study.	110
4.6	Results of large grating fabrication using the proposed setup. (a) A 1-inch SiO_2 1-inch photoresist grating sample prepared with the proposed method. (bd) Cross-sectional FESEM images of the photoresist grating. (e) SEM image showing the varying fill-fraction grating resulting from accelerated translation of the translation stage. (f) Large-area 2-inch SiO_2 2-inch grating image achieved using this method.	112
5.1	Detection modalities explored for sensing GMR signals include: (a) Wavelength scanning methods [74], (b) GMR phase detection using interferometric methods [153], (c) Spectral interferometry for GMR phase detection,[11] and (d) Single-wavelength intensity-based detection schemes for guided-mode resonance sensors[155].	119
5.2	(a) Schematic illustration of the Guided Mode Resonance (GMR) phenomenon. (b) Simulated reflectivity data for the GMR sensor in the TE (767.1 nm)/TM (811.7 nm) configuration for 0° incidence angle. (c) Experimental TE (810.6nm) reflectivity data obtained from the GMR sensor used in the study, validating the simulated results. (d) Atomic Force Microscopy (AFM) image of a specific section of the GMR surface, revealing the nanoscale surface topology where values against the axis ($x=2.7 \mu\text{m}$) represents the width of the cropped region. (e) Corresponding profile plot from the AFM data along the red dotted line as shown in figure 2(d), detailing surface profile where values against the axis ($x=2.7 \mu\text{m}$ and $z = 0.17 \mu\text{m}$) represents the width of the cropped region. (f) Simulated electromagnetic field profiles for both TM (767.1 nm) and TE (811.7 nm) polarizations, respectively for a Si_3N_4 grating with periodicity 500 nm, grating height 120 nm and 80 nm thick Si_3N_4 waveguide at normal incidence, demonstrating the distribution and intensity of the optical fields within the GMR structure under each polarization condition.	122

-
- 5.3 (a) This image illustrates the detailed procedural steps undertaken for the fabrication of the diffraction grating, including substrate preparation, photoresist application, exposure to laser interference patterns by scanning method as described in previous chapter, and development to achieve the desired grating structure. (b-c) These images present Field Emission Scanning Electron Microscope (FESEM) data, providing both top-view (b) and cross-sectional view (c) perspectives of the fabricated diffraction grating. The top-view image reveals the uniformity and periodicity of the grating lines, while the cross-sectional view highlights the depth, profile, and structural integrity of the grating features, essential for assessing the effectiveness of the fabrication process. (d) This picture showcases the final fabricated diffraction grating, produced through laser interference lithography. 123
- 5.4 (a) Schematic of the optical arrangement for a typical EOM spectrometer covering a broad wavelength range. (b) Typical variation in the GMR signal due to the attachment of small concentrations of biological entities on the surface of a functionalized chip. 125
- 5.5 Schematic representation of the Guided Mode Resonance (GMR) detection setup. The GMR sample is illuminated by a collimated broadband LED source, and the reflected light is directed by optical components (diffraction grating and focusing lens) to be collected on a CMOS sensor and intensity spot. Variations in the refractive index of the GMR cover medium cause shifts in the centroid position of the intensity spot on the CMOS sensor, enabling precise refractive index sensing. 126
- 5.6 Schematic of the experimental setup used for refractive index sensing constituting a source (LED with 100 μm pinhole), a polarizer, a beam splitter, a diffraction grating, a focusing lens and a 2D CMOS sensor. The inset illustrates the surface of GMR sensor. (b) Experimental data showcasing the centroid position shift over time. The data points represent raw measurements, while the red curve illustrates the low-pass filtered data, highlighting the overall trend and minimizing high-frequency noise for clearer interpretation. (c) Experimental data depicting the relationship between the centroid position and the refractive index of the sugar solutions used during the experiment. 128
-

List of Tables

2.1	Performance evaluation of various solar thermoelectric generators (STEGs) under 1 sun illumination.	45
2.2	Qualitative cost–benefit comparison of UV-LIG absorbers with representative photothermal absorber technologies used in STEG systems.	46
2.3	Comparison of laser-induced graphene (LIG/LIGF) based capacitive sensors with representative conventional capacitive sensor technologies.	59
4.1	Comparison of representative laser interference lithography (LIL) approaches for large-area grating fabrication.	114