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Synopsis Of

Generation, Modulation and Detection of Phase Structured Laser Beams for Sensing Application

A Thesis

To be submitted by

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For the award of the degree

Of

DOCTOR OF PHILOSOPHY

1 Abstract

Electromagnetic radiation carries energy and momentum. The momentum may involve linear and angular part. Light from laser can carry angular momentum of two types called spin angular momentum associated to polarization and orbital angular momentum associated to spatial distribution.

Circularly polarized beam and Laguerre-Gaussian (LG) beam holds spin and orbital angular momentum (OAM) respectively. The history of the study conducted on angular momentum of light can be dated back to 1909's when Poynting proposed that when polarization state of light changes from linear to circular, there should also be a transfer of orbital angular momentum with optical systemPoynting (1909); Yao and Padgett (2011). OAM can have different helicity in modes. The total number of helical modes is represented by topological charge of the beam (m). LG beams carry phase singularity at the center and hence called as vortex beams. LG beams find application in optical tweezing O'Neil and Padgett (2001), free space data transmission Wang *et al.* (2012), bio-sensingAshrafi and Linquist (2019); Shi *et al.* (2017).

In this work, various viable methods for LG beam generation is proposed and demonstrated. The tunability of thermal lens in nanofluid by electrical or optical means allowed for dynamic lenses for beam shaping. Further a new type of common path interferometer called Thermo-optica refraction interferometer (TORI) is proposed. LG beam propagation through milk as medium is studied as a function of its phase structure deterioration. The deterioration in phase structure is quantified and used to measure fat content in milk.

2 Objectives

The objectives of the research work are as follows:

(a) To design and develop an economical method for generating Laguerre-Gaussian(LG) beams with variable topological charges.

(b) To understand the properties of Laguerre Gaussian beams and their interaction with different media as a function of their topological charge.

(c) To develop a sensing modality using LG beam as illuminating source.

3 Existing Gaps Which Were Bridged

The research gaps that were bridged in the work:

(a) The accessibility to affordable phase and diffractive elements is limited owing to the fabrication complexity and associated materials.

(b) Low cost and tunable solution for Hermite Gaussian like beam generation other than spatial light modulator and digital micromirror device.

(c) Optically induced thermal lenses in nanofluids can be a potential method for dynamic lens system. The control and tunability of these thermal lenses are not studied well. Further, the electrical modality for thermal lens generation is not well explored for beam shaping.

(d) Astigmatic Optical mode converters are useful for beam mode conversion with high efficiency. But the lenses used in such mode converters are static. A dynamically tunable lens by means of optical and electrical modality can allow switchable mode conversion.

(e) A new type of common path interferometry is proposed which is not limited by its usage due to small sample and reference beam separation. .

4 Most Important Contributions

4.1 Generation of the Laguerre Gaussian beam using simple optical elements

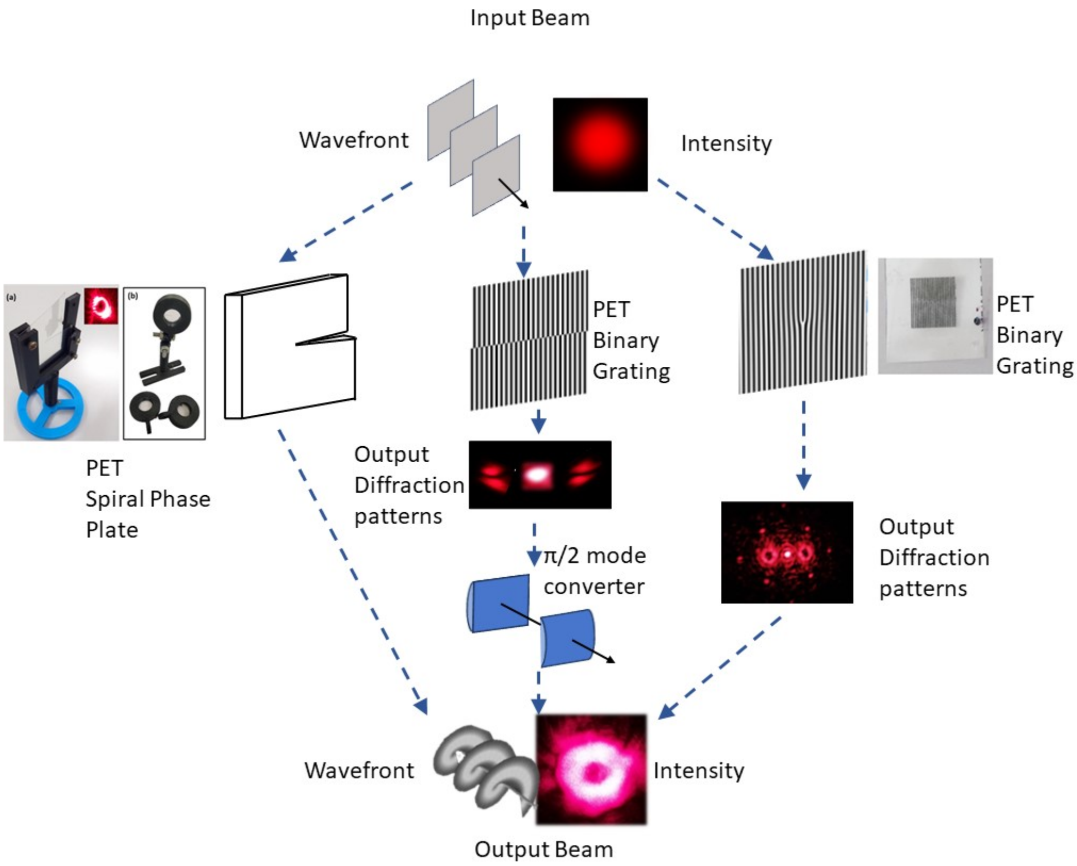

Figure 1: Methods to generate Laguerre Gaussian beam

PET sheets are most commonly found plastic sheets used as overhead projector sheets. These sheets are affordable and available in various thickness. The refractive index of PET transparent sheets is 1.5651 . This is also flexible for different azimuthal angles which is important for generating OAM beams. PET sheets allow clean shear cuts with fine edges which is important to have a clean beam profile after transmission. Further, the absorption is minimum in the visible spectrum (450nm to 700nm) which will cause less impact on propagation losses of the beam. PET sheets are cut in square from using scissors and mounted over 3D printed holders as shown in Figure. The screw can be used for adjusting the spiral phase to achieve tunable topological charge of LG beams. The angles were changed upto $10°$.

Binary amplitude gratings are diffractive optical elements with regions of high and low intensity transmission. The diffraction and the output beam pattern in these gratings can be controlled using the parameters such as pitch, relative fringe shifts, duty cycle of the grating material of grating substrate. This gives better control to generate low topological charges of orbital angular momentum of beams, that include Hermite Gaussian and Laguerre gaussian beams.

4.2 A phenomenon to generate Hermite Gaussian structured beams

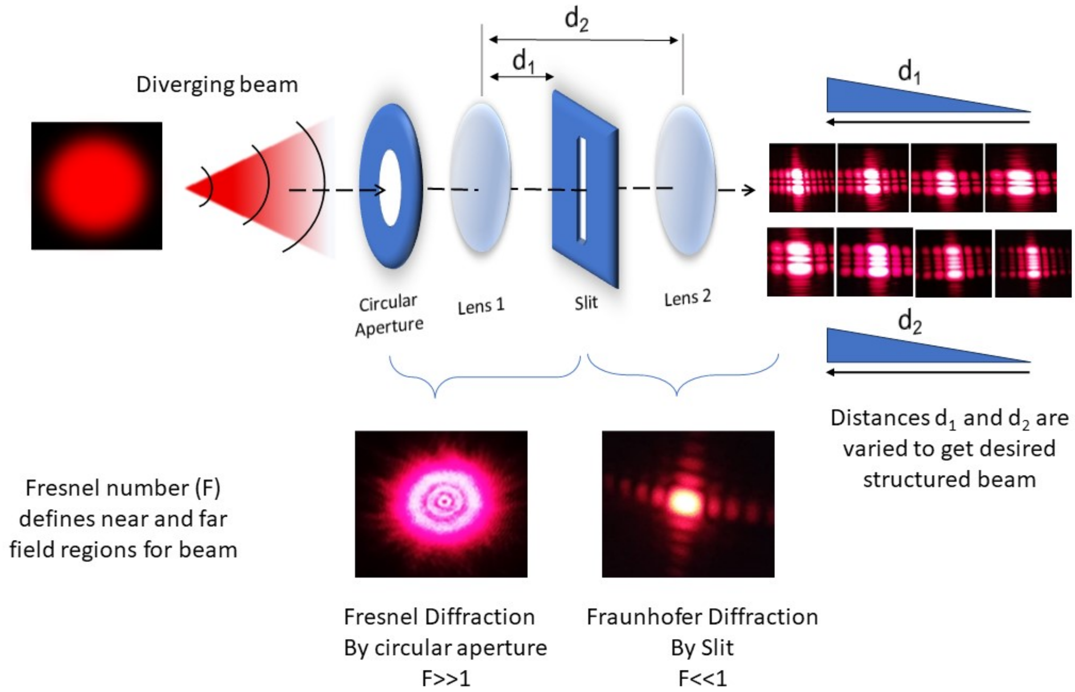

Figure 2: Synergic Fresnel and Fraunhofer diffraction

Diffraction, arising from the wave-like nature of light, manifested at edges. The well-known diffraction phenomena, namely Fresnel and Fraunhofer, have diverse individual applications. However, the combined effects of these two phenomena have not been thoroughly studied and understood, despite their importance in comprehending compound optical instruments. This research investigates and demonstrates the synergistic patterns resulting from the combination of Fresnel and Fraunhofer diffractions. The observed combined diffraction patterns exhibit characteristics similar to Hermite-Gaussian Beam intensity distributions, as validated through both simulations and experimental results. This work contributes to a deeper understanding of complex diffraction in optical instruments and offers a pathway for robust fabrication of micro gratings (Shetty and Bingi, 2020).

4.3 Imaging and measurement of thermal lens region within nanofluid

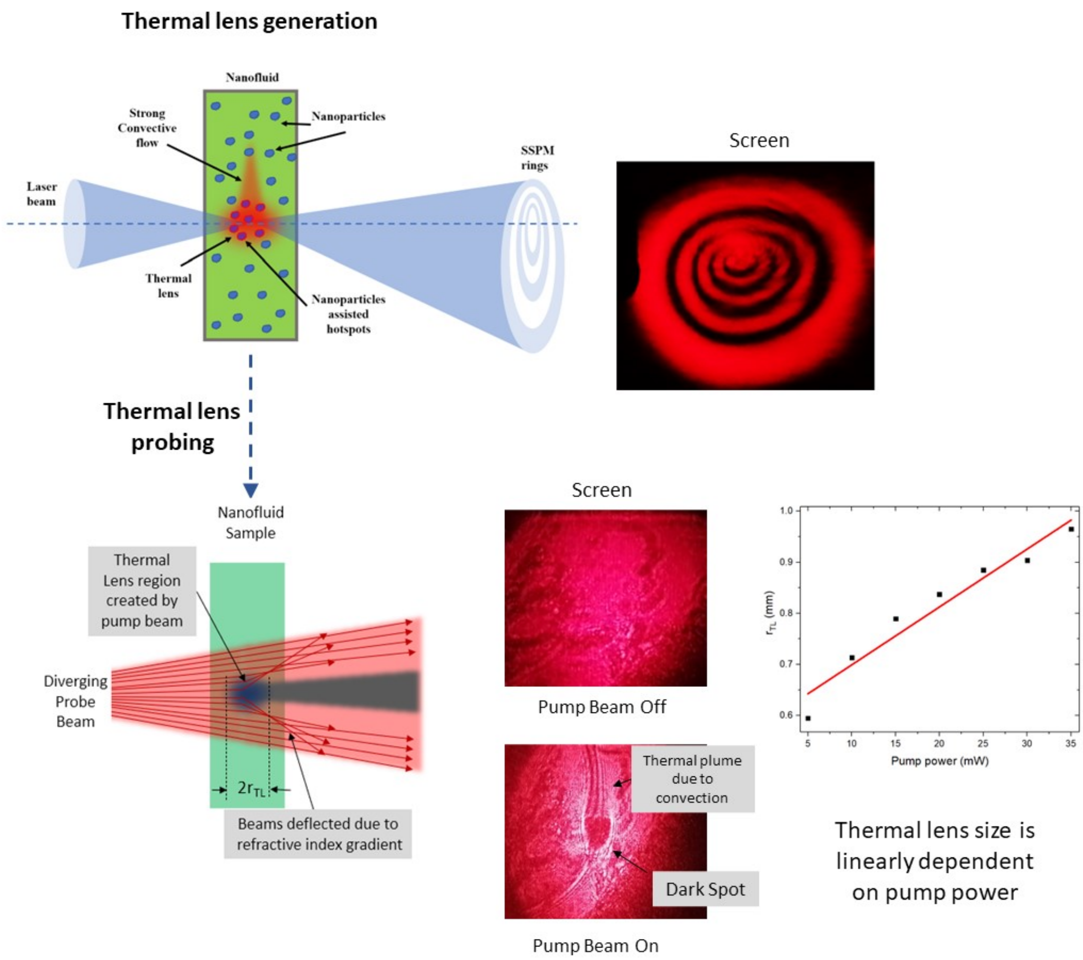

Figure 3: Thermal lens generation in nanofluid and its probing

The remarkable nonlinear optical response exhibited by two-dimensional (2D) nanomaterials such as Molybdenum disulfide (MoS_2) has garnered significant attention. In this study, we investigate the formation of thermal lenses in dispersions of MoS_2 nanoflakes using a pump-probe configuration with mode mismatch. By observing the intensity patterns of the pump and probe beams, we gain visual insights into the temporal evolution of photothermal lens formation. The influence of MoS_2 nanoflake concentration on the thermo-optic properties of the dispersions is explored using thermal lens spectroscopy. Additionally, a novel technique based on thermo-optic refraction is proposed for measuring the size of the thermal lens region. It is observed that the size of the thermal lens region increases with higher pump power. Leveraging the observed thermal lens modulation, we successfully demonstrate a "normally on" all-optical switch that exhibits exceptional modulation of the output beam signal by the pump beam(Shetty *et al.*, 2021*a*) .

4.4 Near vicinity thermal lens optics with respect to Laguerre Gaussian beams

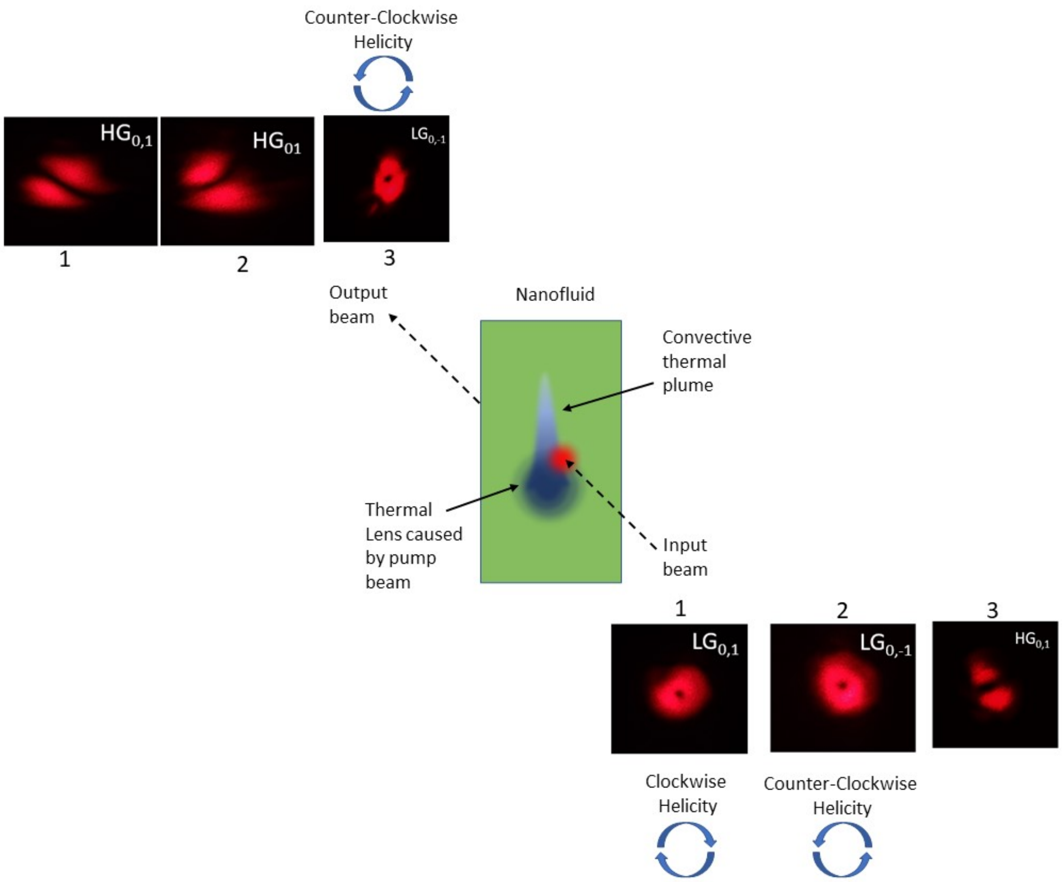

Figure 4: Mode conversion after transmission through thermal lens

This study highlights the importance of temporally switchable optical mode conversion in optical communication and computing applications. We have successfully developed an optically switchable mode converter based on thermo-optic refraction. To achieve this, we utilized MoS_2 nanofluid as medium, where a thermal microlens is formed by focusing a laser beam (referred to as the pump beam). Above the focal point of the pump beam within the nanofluid, a convective thermal plume is generated, which acts as an astigmatic thermal lens. Through experimentation, it was observed that the thermal lens causes the conversion of Laguerre-Gaussian (LG) beams into Hermite-Gaussian (HG) beams, and vice versa, when they pass through it. Consequently, this mode converter enables the easy determination of the topological charge of the LG beam. A theoretical explanation for this mode transformation by considering the different optical paths experienced by the Fourier components of the LG beam as it propagates through the convective plume is provided (Shetty *et al.*, 2021*b*).

4.5 An electrically controllable mode converter for topological charge measurement

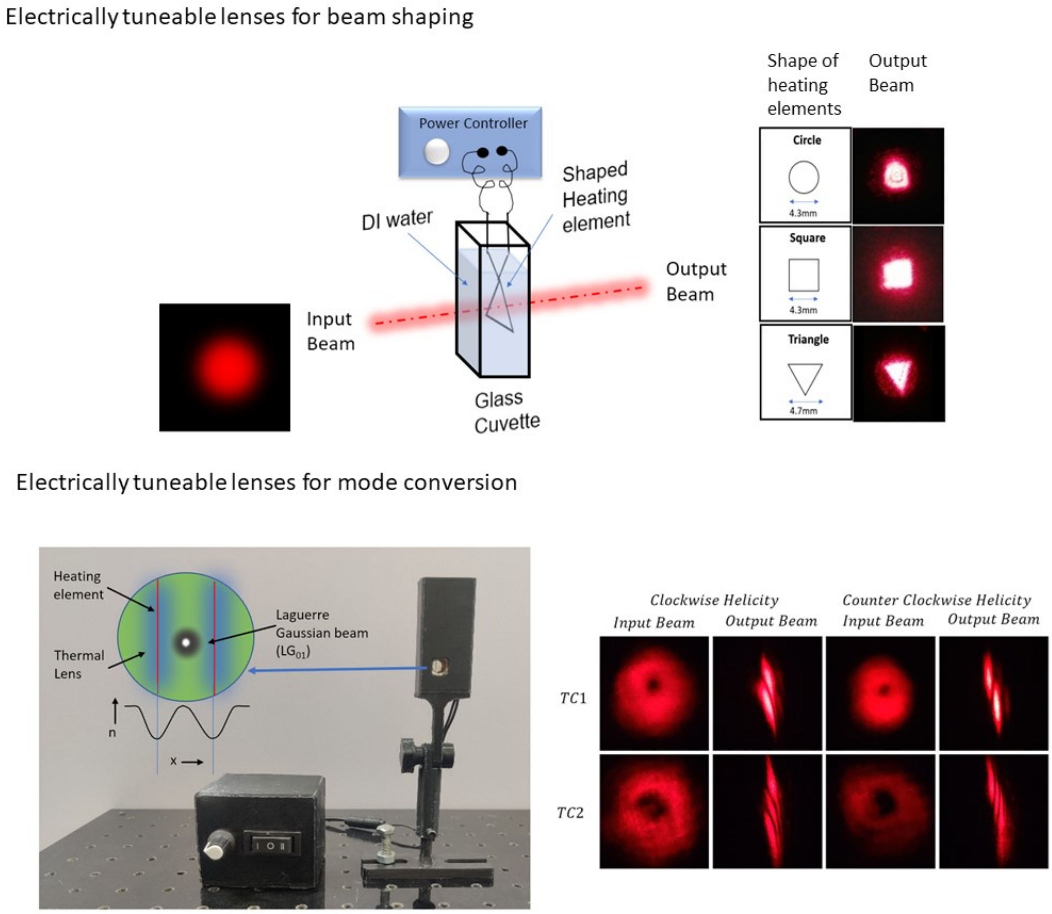

Figure 5: Electrically generated thermal lenses for beam structureing and mode conversion

Heating elements with distinctive shapes immersed in a fluid have the ability to generate thermal lenses in their vicinity. The strength of these thermal lenses is directly proportional to the current passing through the heating elements. By bending the elements into common shapes such as squares, circles, and triangles, structured beams can be generated. Moreover, when multiple heating elements are arranged in a parallel configuration, a cylindrical lens-like profile is formed within the liquid medium. This profile can be effectively utilized for mode conversion purposes.

4.6 A new common path interferometric method called Thermo optic refraction interferometry

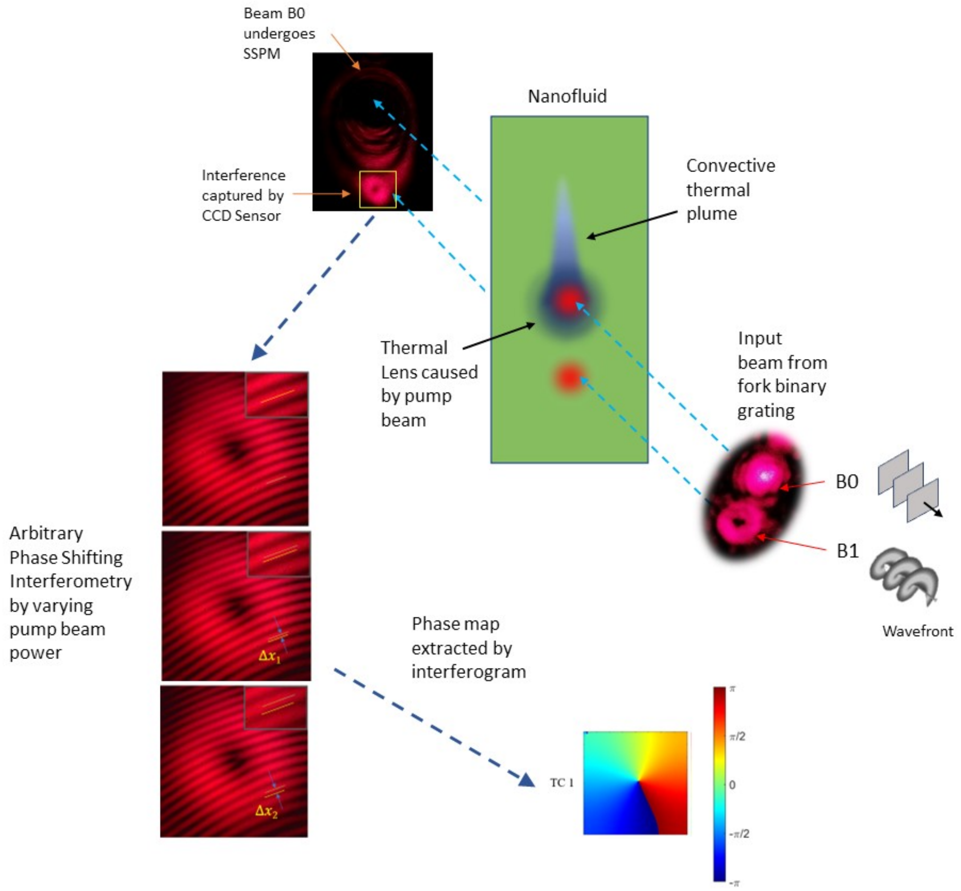

Figure 6: Thermo optic refraction interferometer

Common path interferometers (CPI) are highly valuable for their compactness and ability to resist vibrations. However, a common challenge in CPI arises from the small separation between the reference and sample beams. This limitation makes it difficult to send a reference beam through a sample, hindering the ability to study the interaction of beams with materials based on their phase structure. This research introduces a promising solution that opens up new possibilities for interferometry. The study proposes and demonstrates a novel approach utilizing thermo-optic refraction to enable both beams to pass through the sample and investigate the phase degradation resulting from their relative interaction within the material medium.

Termed thermo-optic refraction interferometry (TORI), this technique leverages the phenomenon of thermal lensing to superpose a higher order vortex beam with a non-vortex beam. By optically pumping the non-vortex beam, controlled expansion is induced. The interaction between the expanding non-vortex beam and the vortex beam within the sample generates an output interferogram. Analyzing the phase deterioration exhibited in the output interferogram provides insights into the medium-induced phase changes (Shetty *et al.*, 2023).

4.7 A milk fat detection methodology using TORI

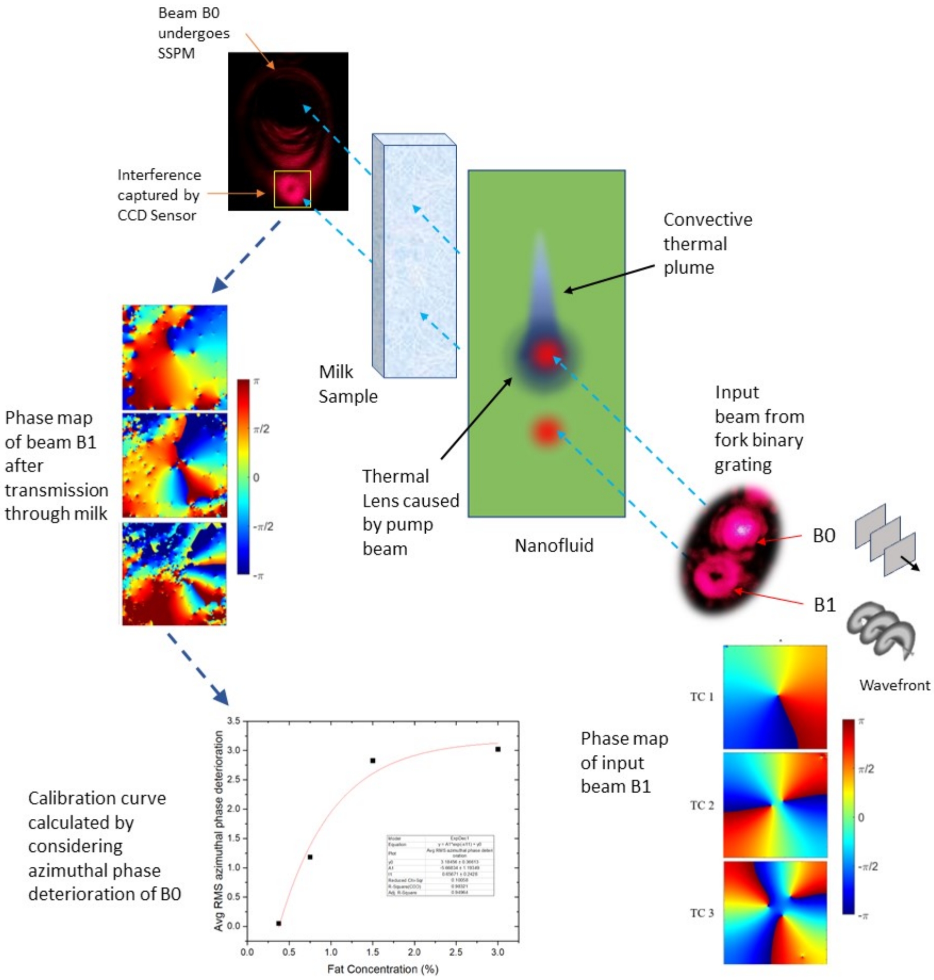

Figure 7: Milk Fat estimation using Thermo optic refraction interferometer

To illustrate the effectiveness of TORI , the experiments were conducted using milk samples and measured the root mean square (RMS) azimuthal phase deterioration of the orbital angular momentum (OAM) beam. The results showcase the potential of this technique to study phase variations driven by the medium. By overcoming the limitations of traditional CPI setups, this innovative approach broadens the capabilities of interferometric analysis (Shetty *et al.*, 2023).

5 Conclusions

(a) Synergic effect of Fresnel and Fraunhofer diffractions revealed notable disparities in intensity distributions compared to the conventional diffraction. Through simulations and experimental findings, the research highlighted the importance of compound diffraction effects and their potential in enhancing our comprehension of optical instruments.

(b) A pump-probe setup is employed to visually investigate the temporal changes in the thermal lens (TL) region within MoS_2 dispersions. The collapse of diffraction rings in the transmitted pump beam confirmed the presence of a vertical convective heat flow. Additionally, it was observed that the TL region decreased by 38.4% as the pump power varied from 35 to 5 mW. The thermo-optic properties of MoS_2 dispersions were explored using the thermal lens spectroscoplic technique, revealing an increase in the temperature coefficient of the refractive index with higher concentrations of MoS_2 nanoflakes. Leveraging the thermo-optic refraction as an optical modulation tool, the study successfully demonstrated an "normally on" all-optical switch using MoS_2 dispersions, showcasing excellent output beam modulation capabilities. These findings suggest potential applications for low-power micro-optical devices based on single monolayer MoS_2 in future research.

(c) An optically switchable mode converter utilizing thermo-optic refraction is demonstrated. The converter enables easy measurement of the helicity and topological charge of the LG beam. Theoretical analysis reveals that the mode transformation occurs due to variations in optical paths experienced by Fourier components of the LG beam during propagation through a convective plume. With its switchable nature and these unique properties, the mode converter holds potential as a valuable tool in free space optical communication and quantum computing applications.

(d) A new type of common path interferometer is demonstrated and it is called as thermo-optic refraction interferometer (TORI). The TORI employs the thermal lensing phenomenon to interfere two optical fields, where one of the fields is a vortex beam. By controlling the power of the pump beam, phase shifting interferometry can be achieved using TORI. Analysis of the phase maps extracted from the interferograms reveals that the phase structure of higher Topological charge (TC) beams experiences greater deterioration. The root mean square (RMS) azimuthal phase deterioration indicates that the beams undergo varying levels of deterioration radially, depending on their TC. Consequently, beams with higher topological charges (>2) exhibit greater sensitivity to phase deterioration, making them suitable for probing very low concentrations of scatterers. This method has the potential to pave the way for a novel form of common path interferometry, enabling the measurement of relative phase changes between vortex and non-vortex beams.

6 Organization of the Thesis

The proposed outline of the thesis is as follows:

(a) Chapter 1: Introduction

(b) Chapter 2: Viable and Affordable Methods for Structured Beam Generation

(c) Chapter 3: Thermal Lensing for in-situ Structured Beam Tunability

(d) Chapter 4: Thermo optic refraction based switchable optical mode converter

(e) Chapter 5: Electrically Generated Thermal Lenses for LG Beam Shaping and Mode Conversion.

(f) Chapter 6: Vortex phase analysis using thermo-optic refraction interferometry

(g) Chapter 7: Conclusion and Future Scope

7 List of Publications

I. **REFEREED JOURNALS BASED ON THE THESIS**

1. P. P. Shetty and J. Bingi, "Demonstration of synergic Fresnel and Fraunhofer diffraction for application to micrograting fabrication," Opt. Laser Technol., vol. 130, no. April, p. 106340, 2020, doi: 10.1016/j.optlastec.2020.106340.
2. P. P. Shetty, M. Babu, D. N. Maksimov, and J. Bingi, "Thermo-optic refraction in MoS_2 medium for 'Normally on' all optical switch," Opt. Mater. (Amst)., vol. 112, p. 110777, Feb. 2021, doi: 10.1016/j.optmat.2020.110777
3. P. P. Shetty, D. N. Maksimov, M. Babu, S. R. Bongu, and J. Bingi, "Thermo-optic refraction based switchable optical mode converter," J. Quant. Spectrosc. Radiat. Transf., vol. 274, p. 107867, 2021, doi: 10.1016/j.jqsrt.2021.107867.
4. P. P. Shetty, Hemalatha V, M. Babu, and J. Bingi, "Vortex phase deterioration common path interferometry" *Journal of Optics*, 25, 085601, (2023).

II. **PRESENTATIONS/PUBLICATIONS IN CONFERENCES (Others)**

1. Jayachandra Bingi, Pritam P Shetty, "Fourier transform speckle lithography for structural biomimicry", Poster presentation, DAE-BRNS National Laser Symposium-19.
2. Mahalingam Babu, Pritam Shetty, Jayachandra Bingi, " Study of Optical Switching in MoS_2 Nanosheets based on Spatial Self Phase Modulation." Poster presentation- National Photonics Symposium (NPS)-2020.
3. Shetty, P. P., Krupakhar, G., & Bingi, J. (2021). Multi-inspirational Design for Additively Manufacturable Products. In Design for Tomorrow—Volume 3 (pp. 189-199). Springer, Singapore.

4. Pritam P Shetty, Jayachandra Bingi," Thermo-optic refraction interferometry for milk turbidity estimation using optical vortex beam", Oral Presentation, Pacific Rim Conference on Lasers and Electro-Optics (CLEO-PR 2022), Japan.
5. Anik Sarkar, Pritam P Shetty, Jayachandra Bingi," Optical vortex beam assisted milk adulteration detection using alginate thin film ", Poster Presentation, International Conference on Advances in Biopolymers and Composites: Health, Environment, and Energy(ABC-HEE 2022), MNNIT, Prayagraj.
6. Ashwanth P, Pritam P Shetty, Jayachandra Bingi," Geometrical beam shaping by electrically tunable thermal lensing", Poster Presentation, Conference on Optics, Photonics & Quantum Optics (COPaQ 2022), IIT Roorkee.
7. Pritam P Shetty, Jayachandra Bingi," Thermo-Optic Refraction Based Optical Mode Multiplexer for Free Space Optical Communication", Oral Presentation, Optica Laser Congress 2022, Spain

III. **Patent Published**

1. Pritam Shetty, Jayachandra Bingi, "Electrically switchable optical mode converter, 2021," Indian Patent, Application No. 202141007641.

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2. **O'Neil, A. T.** and **M. J. Padgett** (2001). Axial and lateral trapping efficiency of laguerre–gaussian modes in inverted optical tweezers. *Optics Communications*, **193**(1-6), 45–50.
3. **Poynting, J. H.** (1909). The wave motion of a revolving shaft, and a suggestion as to the angular momentum in a beam of circularly polarised light. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, **82**(557), 560–567.
4. **Shetty, P. P.**, **M. Babu**, **D. N. Maksimov**, and **J. Bingi** (2021*a*). Thermo-optic refraction in mos2 medium for "normally on" all optical switch. *Optical Materials*, **112**, 110777.
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7. **Shetty, P. P.**, **H. V**, **M. Babu**, and **J. Bingi** (2023). Vortex phase deterioration common path interferometry. *Journal of Optics*.
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