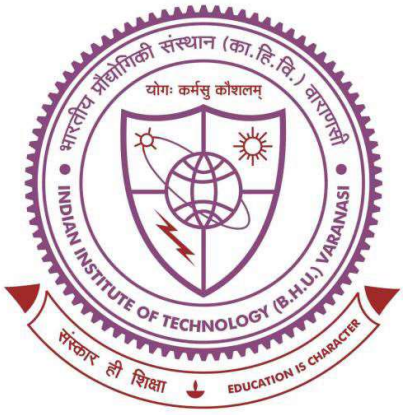
HELICAL MODES AND POLARIZATION GUIDING TO DELIVER OPTICAL INFORMATION THROUGH RANDOM SCATTERER: LOOKING THROUGH RANDOMNESS



A thesis submitted in partial fulfillment for the

Award of Degree

Doctor of Philosophy

in

Physics

by

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December, 2022

CERTIFICATE

It is certified that the work contained in the thesis titled **"**Helical modes and polarization guiding to deliver optical information through random scatterer: Looking through randomness**"** by Tushar Sarkar has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of the comprehensive examination, candidacy, and SOTA for the award of a Ph.D. Degree.

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DECLARATION BY THE CANDIDATE

I, ***"Tushar Sarkar"***, certify that the work embodied in this thesis is my own bona fide work carried out by me under the supervision of **"*Dr. Rakesh Kumar Singh*"** from **"*January 2019*"** to ***"December 2022"***, at the **"*DEPARTMENT OF PHYSICS*"**, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credit to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, thesis, *etc*., or available on websites and have not included them in this thesis and have not cited as my work.

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It is certified that the above statement made by the student is correct to the best of my knowledge.

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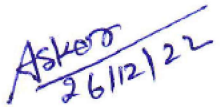

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"गुरू ब्रह्मा गुरू विष्णु, गुरु देवो महेश्वरा गुरु साक्षात परब्रह्म, तस्मै श्री गुरुवे नमः"

No one who achieves success does so without acknowledging the help of others. The wise and confident acknowledge this help with gratitude.

Alfred North Whitehead

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Sincerely

(Tushar Sarkar)

This thesis is dedicated to all those who have chosen excellence over success.

Confidence and doubt are like two bulls in a car—either confidence is going to stay or your doubts or insecurities are going to stay, but there is not room for both to remain.

Keith Johnson

Success is no accident. It is hard work, perseverance, learning, studying, sacrifice, and most of all, love of what you are doing or learning to do.

Pele

Welcome To World of Optics

Dedicated

To

My Beloved

Family

"No amount of money or success can take the place of time spent with your family"

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PREFACE

The objective of the research presented in the thesis is to investigate issues and challenges of the random scattering of light and present our new results. The thesis reports new experimental schemes with helical modes of light and polarization to faithfully deliver and recover the information through a random scattering media. Polarization guiding and encoding information into one of the orthogonal polarization modes of the light work as a pilot-assisted strategy to deliver coherent light through a random scattering medium and consequently see through the scatterer by polarization correlation.

The research work presented in this thesis has been divided into **six** chapters.

Chapter 1 presents an introduction on the information optics and delivering coherent optical signals through the free space and scattering media. This chapter starts a discussion on the coherent optical signals, wavefront shaping, and mode composition of the light in information optics. Apart from using the conventional method to examine the plane wave composition in the optics, we discuss and give special emphasis to the helical modes of light in the information optics. The role of helical modes and holography in the processing of optical information is also discussed. However, inhomogeneity of refractive index distributions in the scattering path scrambles the optical signal without any direct resemblance to the desired information and hence makes conventional optical methods nearly redundant. Intensive research efforts have been made to address this fundamental, yet practical, problem, and many different techniques have been put forward. This chapter covers the challenges of faithful delivery of optical signals through random light, different techniques, limitations, and the role of coherence in optics through randomness particularly on looking through randomness.

In **Chapter 2,** we propose two different techniques to quantitatively determine the helical mode of the beam scrambled by a random scattering medium. In the first technique, the SPs of the randomly scattered field is exploited to recover complex polarization correlation function (CPCF) which adduces the information of the helical beam. The two-point correlation of the SPs provides a 4-by-4 matrix with sixteen elements. Out of these sixteen elements, only four elements of the matrix are used to obtain real and imaginary parts of the CPCF. This technique requires six measurements to evaluate the SPs from the randomly scattered fields using a polarizer and quarter-wave plate (QWP) in the experiment. The use of a QWP in the Stokes polarimetry demands proper calibration in power to avoid unnecessary influence on the state of polarization (SOP) mapping owing to the absorption of light by the QWP. Therefore, the second technique is built on the principle of using limited SPs without the QWP and quantitatively retrieves the helical mode from the random light in a lensless configuration. The correlation of the first three SPs of the random light combined with digital phase shifting for the recovery of helical mode. The correlation of the first three SPs forms a 3-by-3 matrix that contains nine elements. Out of these nine elements, only two elements of the matrix along with four phase-shifting are applied to recover the helical mode from the random light. This helps to design a highly stable experimental setup. Detailed theoretical frameworks, numerical simulations, and experimental results of these techniques are discussed.

Chapter 3 presents two different techniques for the recovery and sorting of the composition of helical modes propagating through the random scattering media. The first technique uses the all SPs of the scattered polarized field to evaluate the higher-order polarization correlation and subsequently the CPCF. The complex amplitude of the composition of the helical modes is extracted from the random light using the CPCF. In comparison to the previous chapter, here we demonstrate the recovery of the composition

of helical modes and their weightage in different optical signals. The two-point correlation of the Stokes fluctuations assists to design a highly stable non-interferometric configuration to recover compositions of helical modes from the random light. Another experimental set-up free from the QWP is also built to design a new lensless non-interferometric experimental geometry for recovery of the composition of OAM modes from the random light. This technique employs the limited SPs which are measured by only a linear polarizer. The correlation of the limited SPs of the random light along with three-step phase shifting is used to evaluate the complex Fourier coefficient (CFC). The CFC helps to extract the complex amplitude of the compositions of helical modes. The orthogonal projection method is further used to sort the different integer OAM modes in terms of the OAM power spectrum from the recovered complex amplitude. The detailed theoretical models, numerical simulations, and experimental results of these techniques are explained.

Chapter 4 describes a new approach to estimating the helical mode of the beam from the non-imaged randomly scattered pattern. SPs of the random light are used and higher-order correlations between SPs fluctuations are evaluated in this approach. This provides a 4-by-4 correlation matrix that contains sixteen elements. Out of these sixteen elements, only one element is considered to build a theoretical basis and subsequently applied for the estimation of the helical mode of the incident optical signal. We design a highly stable experimental geometry in a coaxial propagation of two orthogonal polarization states of the light to estimate the helical mode from the speckle pattern. The topological charge of the helical beam is estimated by counting the number of petals in the correlation function of the Stokes parameter. A detailed theoretical model, numerical simulation of the experimental situation with Stokes correlation, and experimental results are presented to test and confirm our approach.

Chapter 5 presents two different correlation holography approaches with randomly polarized light for 3D optical information recovery. Here, we demonstrate two different strategies on how to use depolarization for the reconstruction of the correlation holography. In the first approach, the higher-order polarization correlation of the randomly polarized light is exploited to design an in-line correlation holography technique through the random scattering media. Only two SPs of the randomly polarized light are employed to evaluate the CPCF and this recovers the complex amplitude using higher-order polarization correlations. This is a new method for lensless and in-line complex field reconstruction in correlation holography. In the second approach, only a single SP of randomly polarized light is combined with digital phase shifting to build a robust and compact lensless in-line holography reconstruction method with the random light. The higher-order polarization correlation is used to obtain the real part of the CPCF from the SP of the randomly polarized light. The four-phase shifting method is combined with real parts of the CPCF to appraise the CFC and consequently in the reconstruction of the hologram. The detailed theoretical analysis, numerical simulations, and experimental tests of these two techniques are described in the chapter.

The conclusions of the overall study have been summarized in the last **chapter 6**. We discuss the role of polarization correlation in the recovery of OAM modes and in unconventional holography techniques to deliver and recover optical information with randomness. This Chapter also comprises further future research plans on this topic, particularly on encoding, non-line of sight (NLOS), and underwater imaging.