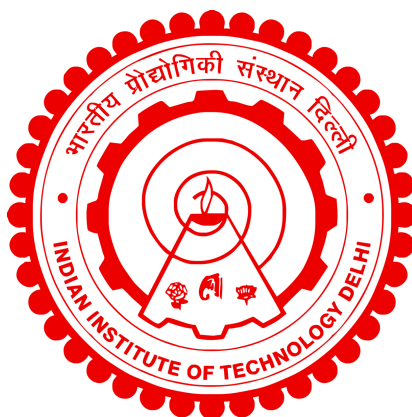


**STATISTICAL AND PROPAGATION STUDIES OF
OPTICAL FIELDS HAVING TUNABLE
COHERENCE-POLARIZATION FEATURES**

HEMANT KUMAR SINGH



DEPARTMENT OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2024

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by

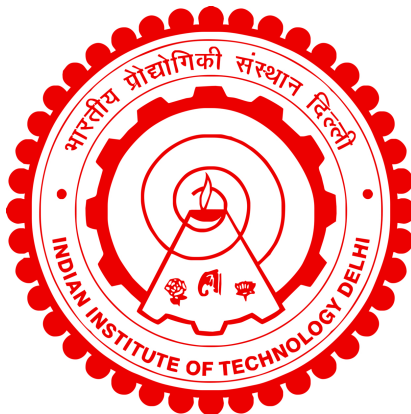
HEMANT KUMAR SINGH

Department of Physics

Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2024

Dedicated to My Loving Maa, Little Sister, and all My Teachers

Certificate

This is to certify that the thesis entitled “**statistical and propagation studies of optical fields having tunable coherence-polarization features**”, submitted by **Hemant Kumar Singh** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in Physics, is a record of the original, bonafide research work carried out by him under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results in this thesis have not been submitted in part or in full to any other University or Institute for awarding any degree or diploma to the best of our knowledge.

Jul 29, 2024

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“No one who achieves success does so without acknowledging the help of others”–A. N. Whitehead

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Abstract

This thesis contains theoretical and experimental methods to investigate the characteristics of partially coherent and partially polarized classical optical fields and their impact on statistical features and propagation through random media (e.g., atmospheric and oceanic turbulence). We start by constructing and examining a source with tunable coherence and polarization characteristics. An unpolarized laser beam passes through a balanced Mach-Zehnder interferometer to control the polarization features. Coherence attributes of the source are manipulated using the spot size at the rotating ground glass diffuser surface. The generated source covers almost all of the range of coherence and polarization. Furthermore, we verify the validity of the van Cittert Zernike theorem for various multi-scattered sources. The tunable coherence and polarization source is further used to understand the statistical features of the electromagnetic beam propagation through the polluted smoke environment. Interestingly, the study reveals that the two-point correlation in spatial position, for scalar case degree of coherence and vector case electromagnetic degree of coherence, deteriorates as the beam propagates through a smoke channel. Meanwhile, the polarization of the source remains unaffected through the smoke environment. The developed tunable polarization source is free from the correlation between the orthogonal (x - y correlation) components (due to the unpolarized laser source). For later studies, we used two kinds of polarization sources: (a) uncorrelated and (b) correlated sources to investigate the degree of cross-polarization (DOCP) of the source across the beam radius. The findings indicate that modifying the coherence and polarization characteristics of the input source has a notable impact on the DOCP across the beam radius. Further, we investigate the Stokes fluctuation correlation and Stokes scintillation parameters for an electromagnetic Gaussian-Schell model beam (EMGSM). The experimental study discloses that both the coherence and polarization of the input source severely affect the Stokes fluctuation correlation and scintillations. So, the Stokes scintillation parameters can be controlled by controlling the coherence and polarization features of the input source. Then, such beams with controlled Stokes scintillation parameters can be used as per the requirement of the user. Finally, we also explore the oceanic turbulence medium for the propagation of EMGSM. This theoretical work explores the impact of coherence and polarization on the Stokes scintillations of the beam. The results manifest that coherence and polarization are important factors in controlling the Stokes scintillation parameters through the marine turbulent channel. These foundational investigations into coherence, polarization, and their unification are anticipated to propel the realms of classical and quantum optics significantly.

सार

यह शोध आंशिक रूप से सुसंगत और आंशिक रूप से ध्रुवीकृत पारंपरिक प्रकाश क्षेत्रों की विशेषताओं की जांच करने के लिए सैद्धांतिक और प्रायोगिक विधियों को समाहित करता है और उनके सांख्यिकीय गुणों तथा यादृच्छिक माध्यम (जैसे वायुमंडलीय और समुद्री विक्षोभ) के माध्यम से प्रचार पर उनके प्रभाव को शामिल करता है। हम एक स्रोत का निर्माण और जांच करके प्रारंभ करते हैं जिसमें सुसंगतता और ध्रुवीकरण विशेषताओं को समायोजित किया जा सकता है। एक अप्रकाशित लेजर बीम संतुलित मैक-जेन्डर व्यतिकरणमापी से होकर गुजरती है ताकि ध्रुवीकरण विशेषताओं को नियंत्रित किया जा सके। स्रोत की सुसंगतता विशेषताओं को घूर्णनशील कांच विसारक सतह पर बिंदु आकार का उपयोग करके नियंत्रित किया जाता है। उत्पन्न स्रोत सुसंगतता और ध्रुवीकरण की लगभग पूरी श्रृंखला को कवर करता है। इसके अलावा, हम विभिन्न बहु-विच्छेदक स्रोतों के लिए वैन सिटरट जर्नाइक प्रमेय की वैधता की पुष्टि करते हैं। सुसंगतता और ध्रुवीकरण स्रोत का उपयोग प्रदूषित धुएं के वातावरण के माध्यम से विद्युतचुंबकीय बीम प्रसार की सांख्यिकीय विशेषताओं को समझने के लिए किया जाता है। दिलचस्प बात यह है कि अध्ययन से पता चलता है कि धुएं के चैनल के माध्यम से बीम के प्रचार के साथ स्थानिक स्थिति में द्वि-बिंदु संबंध, अदिश मामले में सुसंगतता की डिग्री और सदिश मामले में विद्युतचुंबकीय सुसंगतता की डिग्री, खराब हो जाती है। इस बीच, धुएं के वातावरण के माध्यम से स्रोत का ध्रुवीकरण अप्रभावित रहता है। चूंकि उत्पन्न ध्रुवीकरण स्रोत में लंबवत (x-y संबंध) घटकों के बीच कोई संबंध नहीं है (अप्रकाशित लेजर स्रोत के कारण)। इसलिए, बाद में हमने दो प्रकार के ध्रुवीकरण स्रोतों का उपयोग किया: (क) असंबद्ध और (ख) संबंधित स्रोतों का उपयोग करके स्रोत के बीम त्रिज्या के पार क्रॉस-ध्रुवीकरण की डिग्री की जांच की। निष्कर्ष इंगित करते हैं कि इनपुट स्रोत की सुसंगतता और ध्रुवीकरण विशेषताओं को संशोधित करने से बीम त्रिज्या के पार क्रॉस-ध्रुवीकरण (डीओसीपी) की डिग्री पर उल्लेखनीय प्रभाव पड़ता है। आगे, हमने विद्युतचुंबकीय गॉसियन-शेल मॉडल बीम (ईएमजीएसएम) के लिए स्टोक्स अस्थिरता संबंध और स्टोक्स स्पंदन मापदंडों की जांच की। प्रायोगिक अध्ययन से पता चलता है कि इनपुट स्रोत की सुसंगतता और ध्रुवीकरण दोनों ही स्टोक्स अस्थिरता संबंध और स्पंदनों को गंभीर रूप से प्रभावित करते हैं। इसलिए, इनपुट स्रोत की सुसंगतता और ध्रुवीकरण विशेषताओं को नियंत्रित करके स्टोक्स स्पंदन मापदंडों को नियंत्रित किया जा सकता है। फिर, नियंत्रित स्टोक्स स्पंदन मापदंडों वाले ऐसे बीम का उपयोग उपयोगकर्ता की आवश्यकता के अनुसार किया जा सकता है। अंत में, हमने ईएमजीएसएम के प्रचार के लिए समुद्री विक्षोभ माध्यम की भी खोज की। यह सैद्धांतिक कार्य समुद्री विक्षोभ चैनल के माध्यम से स्टोक्स स्पंदनों के नियंत्रण में सुसंगतता और ध्रुवीकरण के प्रभाव की जांच करता है। परिणाम दर्शाते हैं कि सुसंगतता और ध्रुवीकरण समुद्री विक्षोभ चैनल के माध्यम से स्टोक्स स्पंदन मापदंडों को नियंत्रित करने में महत्वपूर्ण कारक हैं। सुसंगतता, ध्रुवीकरण और उनके एकीकरण पर ये मौलिक अनुसंधान क्लासिकल और क्वांटम प्रकाशिकी के क्षेत्रों को महत्वपूर्ण रूप से आगे बढ़ाने उच्च की संभावना रखते हैं।

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Abbreviations

BS	B eam S plitter
CCD	C harged C oupled D evice
CSD	C ross S pectral D ensity
DOC	D egree of C oherence
DOP	D egree of P olarization
DOCP	D egree of C ross P olarization
EM	E lectromagnetic
EMDOC	E lectromagnetic D egree of C oherence
EMGSM	E lectromagnetic G aussian S chell M odel
FSO	F ree S pace O ptical
GS	G eneralized S tokes
HBT	H anbury B rown T wiss
HWP	H alf W ave P late
MZI	M ach Z ehnder I nterferometer
NDF	N eutral D ensity F ilter
OTG	O ptical T urbulence G enerator
PBS	P olarizing B eam S plitter
PD	P hoto D etector
Q	Q uarter Wave Plate
RGGD	R otating G round G lass D iffuser
SI	S agnac I nterferometer
TS	T elescopic S ystem
YDS	Y oung D ouble S lit

Symbols

E	Electric field
k	Wavevector
$I(\mathbf{r})$	Intensity
$S(\mathbf{r}, \omega)$	Spectral density
$W(\mathbf{r}_1, \mathbf{r}_2, \omega)$	Cross-spectral density function
$\gamma(\mathbf{r}_1, \mathbf{r}_2, \tau)$	Complex degree of coherence
$\mu(\mathbf{r}_1, \mathbf{r}_2, \omega)$	Spectral degree of coherence
c	Speed of light in vacuum
ω	Angular frequency
λ	Wavelength
V	Visibility
$\gamma(\tau)$	Temporal degree of coherence
$J(\mathbf{r}, t)$	Polarization matrix
$S_n(\mathbf{r}, \omega)$	Stokes parameters in space-frequency domain
$\mathcal{S}_n(\mathbf{r}_1, \mathbf{r}_2, \omega)$	Generalized Stokes parameters in space-time domain
$\eta_n(\mathbf{r}_1, \mathbf{r}_2, \omega)$	Space-frequency Coherence Stokes parameters normalized by zeroth usual Stokes parameters
$D_{nn}^N(\mathbf{r}, \omega)$	Space-frequency normalized Stokes scintillation parameters