

**DEVELOPMENT OF SPECKLE NOISE REDUCTION
DEVICES FOR LASER BASED PROJECTION IMAGING
AND UNIFORM ILLUMINATION**

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**DEPARTMENT OF PHYSICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

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DEPARTMENT OF PHYSICS

Submitted

in fulfilment of the requirement for the degree of Doctor of Philosophy

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI,
DECEMBER 2022**

Dedicated to,

My Elder Brother, “Dhyan Singh”

&

My Sister’s son, “Harshit Singh”

CERTIFICATE

This is to certify that the thesis entitled “**DEVELOPMENT OF SPECKLE NOISE REDUCTION DEVICES FOR LASER BASED PROJECTION IMAGING AND UNIFORM ILLUMINATION**” is submitted by **Mr. Virendra Kumar** to the Department of Physics, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**. This thesis is a bonafide record of the research carried out by him under my guidance and supervision. In my opinion, the thesis has reached the standards fulfilling the requirement for the submission relating to the degree.

The contents of the 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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ABSTRACT

Optical devices and instruments have reached to a new high of quality, accuracy, and precision after the invention of lasers. It is because lasers possess numerous optical, electrical, and other properties for example, they have high spatial-temporal coherence, narrow spectral linewidth, high flux density, long lifetime, compact size, low energy consumption, and high energy efficiency. Despite of having so many properties, lasers and laser-based devices are encountered with a problem of occurrence of speckles. Speckles are high contrast fine scale granular patterns of light intensity that are originated from mutual interference of highly coherent scattered light. Speckles lead to inhomogeneous illumination of objects. A compact and efficient system that can combine various fundamental techniques for effective speckle reduction is desired.

In this thesis, we have developed a compact, low-cost, multi-color diode laser-based illumination system for displays and laser projectors. Our innovative approach is based on spatially structured and temporally varying beams. In this setup, we have generated structured diverging beams using a diffractive optical element based electromechanical system that produce spatial, angular, and temporal diversity. The beams were collected by a large diameter plano-convex lens and focussed on the input of a vibrating multimode fiber bundle based device. We found that with our system, the laser speckle contrast was reduced from 0.65 to 0.02 which is an order of magnitude speckle reduction.

The problem of laser speckles becomes more challenging when the objective is to develop high-power laser systems as high lumen laser applications require. We address such challenges by reporting a compact design and step-by-step development scheme of a laser speckle reduction system. The scheme comprises a metallic ball-mirror connected with a mechanically dynamic and thermally conductive heat sink system. Highly reflecting ball-

mirror was coated with a transparent thick film of ZnO nanoparticle embedded epoxy adhesive that provides volume scattering, and the layer was sandblasted to achieve surface scattering as well. TracePro simulations demonstrate the efficiency enhancement in the system due to an involvement of a pyramidal reflector. Speckle contrast reduction was experimentally achieved by 0.0248 for red, 0.0298 for green, and 0.0213 for blue laser diodes.

Optical systems are generally very sensitive to vibrations as most of the speckle reduction techniques are based on mechanical motion of some optical components, but it produces blurring effect in the imaging system due to vibrations. Solving this problem, we have developed a mechanical vibration free method and device for speckle reduction by using a cylindrical diffuser inside a reflective pyramidal cavity. The pyramidal cavity was developed using a 3D printer and highly-reflecting metallic mirrors. The system is highly effective for speckle suppression due to the coherence reduction via multiple internal reflections of light scattered from the surface of a rod-shaped cylindrical diffuser placed inside the pyramidal reflective cavity. At the output of pyramidal cavity, a diffuser plate was fixed to further homogenize the illumination. Reduced speckle contrast using the proposed system was observed up to 2%, which is nearly equivalent to a mechanically moving diffuser system. The developed device does not consume any electrical energy and it is completely vibration-free.

Speckle-free white light illumination from lasers is generally achieved by using a combination of red, green, and blue lasers but at the cost of some losses in the light intensity. Another method of white light generation is the combination of blue laser and yellow phosphor by down-conversion approach. Using this method, we have developed a headlamp prototype that comprises a set of four cylindrical diffusers, and a phosphor plate inside a pyramidal cavity reflector. The scattered light from cylindrical diffusers interacts with a

remote phosphor plate that prevents phosphor resin burning. The pyramidal cavity reflector plays an important role to make the laser light uniform and speckle free via spatial and angular diversity. The white light received from the headlamp module was almost speckle free with a computed speckle contrast of 5%. The developed devices within this thesis can be broadly used to develop speckle-free laser-based projectors, high precision microscopes and automotive smart-headlamps.

सार

लेज़रों के आविष्कार के बाद प्रकाशीय युक्तियों और उपकरणों ने गुणवत्ता और सटीकता की नयी ऊंचाइयों को छुआ है। ऐसा इसलिए है, क्योंकि लेज़रों में कई प्रकाशीय, विद्युत एवं अन्य गुण विद्यमान होते हैं, उदाहरण के लिए, उनमें उच्च आकाशीय-सामयिक कला संबद्धता, स्पेक्ट्रम रेखा की संकीर्ण चौड़ाई, उच्च फ्लक्स घनत्व, लम्बा जीवनकाल, सूक्ष्म आकार, कम ऊर्जा खपत तथा उच्च ऊर्जा दक्षता आदि होते हैं। इतने सारे प्रकाशीय और विद्युत गुण होने के बावजूद, लेजर तथा लेजर-आधारित उपकरणों में धब्बेदार-रौशनी (स्पेकल्स) होने की समस्या पाई जाती है। स्पेकल्स प्रकाश की तीव्रता के उच्च कंट्रास्ट फाइन स्केल दानेदार पैटर्न हैं जो अत्यधिक कलासंबद्ध बिखरे हुए प्रकाश के पारस्परिक व्यतिकरण से उत्पन्न होते हैं। स्पेकल्स की वजह से वस्तुएं एक समान रूप से प्रतिदीप्त नहीं हो पाती हैं। इसके लिए ऐसी कॉम्पैक्ट और कुशल प्रणाली की आवश्यकता है, जो विभिन्न मौलिक तकनीकों का एकसाथ प्रयोग करके स्पेकल्स को प्रभावी रूप से कम कर सके।

इस शोध-प्रबंध में, हमने डिस्प्ले और लेजर प्रोजेक्टर के लिए एक कॉम्पैक्ट, कम लागत वाली, बहु-रंग डायोड-लेजर आधारित रोशनी प्रणाली विकसित की है। हमारा नवाचार आकाशीय संरचनात्मक एवं सामयिक परिवर्तित प्रकाश पुंजों पर आधारित है। इस व्यवस्था में, हमने एक विवर्तनिक प्रकाशीय तत्व आधारित विद्युत-यांत्रिकी प्रणाली का उपयोग करके संरचित डायवर्जिंग प्रकाश पुंज उत्पन्न किए हैं जो आकाशीय, कोणीय और सामयिक विविधता उत्पन्न करते हैं। प्रकाश पुंजों को एक बड़े व्यास वाले समतलोत्तल लेंस द्वारा एकत्र किया गया, और एक कम्पित मल्टीमोड फाइबर बंडल आधारित डिवाइस के इनपुट पर केंद्रित किया गया। हमने पाया कि हमारे सिस्टम ने, लेजर स्पेकल कंट्रास्ट को 0.65 से घटाकर 0.02 कर दिया जो की वांछित स्पेकल रिडक्शन की कोटि का है।

लेजर स्पेकल्स की समस्या तब और अधिक चुनौतीपूर्ण हो जाती है जब उद्देश्य उच्च-शक्ति वाली लेजर प्रणाली को विकसित करना होता है। इसकी आवश्यकता उच्च ल्यूमेन वाले लेजर अनुप्रयोगों में होती है। हमने ऐसी चुनौतियों का समाधान करते हुए एक लेजर स्पेकल रिडक्शन प्रणाली के कॉम्पैक्ट डिज़ाइन और चरण-दर-चरण विकास योजना को प्रस्तुत किया है। इस योजना में एक यांत्रिक रूप से गतिशील और ऊष्मीय चालक हीट सिंक प्रणाली एवं एक धातु के गोलाकार दर्पण का प्रयोग किया गया है। अत्यधिक परावर्तक गोलाकार दर्पण पर ZnO नैनोपार्टिकल युक्त एपॉक्सी गोंद की एक पारदर्शी मोटी फिल्म को

लेपित किया गया था जो आयतन प्रकीर्णन प्रदान करती है, और पृष्ठ प्रकीर्णन प्राप्त करने के लिए परत को खुदरा किया गया था। ट्रेसप्रो सिमुलेशन पिरामिडीय परावर्तन के प्रभाव के कारण से होने वाली प्रणाली की दक्षता में वृद्धि को प्रदर्शित करता है। प्रयोगात्मक परीक्षण में स्पेकल कंट्रास्ट का मान लाल रंग के लिए 0.0248, हरे रंग के लिए 0.0298 और नीले रंग के लेजर डायोड के लिए 0.0213 तक कम हुआ।

प्रकाशीय यंत्र आमतौर पर कम्पनों के प्रति बहुत अधिक संवेदनशील होते हैं क्योंकि स्पेकल कम करने वाली अधिकांश तकनीकें, उसमें लगे प्रकाशीय घटकों के यांत्रिक कंपन पर आधारित होती हैं, लेकिन यह कंपन किसी इमेजिंग प्रणाली में धुंधला प्रभाव पैदा करते हैं। इस समस्या को हल करते हुए, हमने एक परावर्तक पिरामिडीय गुहिका के अंदर एक बेलनाकार विसारक का उपयोग करके स्पेकल कम करने के लिए एक यांत्रिक कंपन-मुक्त विधि एवं उपकरण विकसित किया है। पिरामिडीय गुहिका को 3-डी प्रिंटर और अत्यधिक परावर्तक धात्विक दर्पणों का उपयोग करके विकसित किया गया था। पिरामिडीय परावर्तक गुहिका के अंदर रखे छड़ के रूप के बेलनाकार विसारक के पृष्ठ से प्रकीर्णित प्रकाश के कई आंतरिक परावर्तन के माध्यम से कला संबद्धता में कमी के कारण यह प्रणाली स्पेकल कम करने के लिए अत्यधिक प्रभावी है। पिरामिडीय गुहिका से प्राप्त प्रकाश को और अधिक समरूप बनाने के लिए एक विसारक प्लेट लगाई गई थी। प्रस्तावित प्रणाली का उपयोग करते हुए स्पेकल कंट्रास्ट को 2% तक के मान तक कम किया गया, जो यांत्रिक रूप से चलने वाले विसारक (डिफ्यूज़र) प्रणाली की कोटी का है। विकसित उपकरण किसी भी विद्युत ऊर्जा की खपत नहीं करता है और यह पूरी तरह से कंपन मुक्त है।

लेज़रों से धब्बे रहित श्वेत प्रकाश की रोशनी आमतौर पर लाल, हरे और नीले रंग के लेज़रों के संयोजन का उपयोग करके प्राप्त की जाती है, लेकिन प्रकाश की तीव्रता में कुछ हानि की कीमत पर। श्वेत प्रकाश उत्पन्न करने की एक अन्य विधि डाउन-रूपांतरण द्वारा नीले लेजर और पीले फॉस्फोर का संयोजन भी है। इस पद्धति का उपयोग करते हुए, हमने एक हेडलैम्प प्रोटोटाइप विकसित किया है जिसमें चार बेलनाकार डिफ्यूज़र का एक सेट और एक पिरामिडीय गुहिका परावर्तक के अंदर एक फॉस्फोर प्लेट शामिल है। बेलनाकार डिफ्यूज़र से प्रकीर्णित प्रकाश एक दूरस्थ फॉस्फोर प्लेट के साथ अंतः क्रिया करता है जो फॉस्फोर मिश्रित गोंद को जलने से रोकता है। पिरामिडीय गुहिका परावर्तक आकाशीय और कोणीय विविधता के माध्यम से लेजर प्रकाश को एक समान और धब्बा मुक्त बनाने में महत्वपूर्ण भूमिका निभाता है। हेडलैम्प मॉड्यूल से प्राप्त सफेद रोशनी में स्पेकल कंट्रास्ट का मान

लगभग 5% तक प्राप्त किया गया। इस शोध-प्रबंध में विकसित किये गए उपकरणों का उपयोग व्यापक रूप से धब्बे-मुक्त लेजर-आधारित प्रोजेक्टर, उच्च परिशुद्धता वाले माइक्रोस्कोप और ऑटोमोटिव स्मार्ट-हेडलैम्प विकसित करने के लिए किया जा सकता है।

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List of Abbreviations

DHM	Digital Holographic Microscopy
QPM	Quantitative Phase Microscopy
OCT	Optical Coherence Tomography
SMLM	Single-Molecule Localization Microscopy
VLC	Visible Light Communication
DOE	Diffractive Optical Element
MEMS	Micro-Electro-Mechanical System
MMFB	Multi-Mode Fiber Bundle
FDS	Fully Developed Speckle
PDF	Probability Density Function
CCD	Charged Coupled Device
TIRF	Total Internal Reflection Fluorescence
TIR	Total Internal Reflection
FOV	Field-Of-View
FFI	Flat Field Illumination
SRLM	Super-Resolution Localization Microscopy
CMOS	Complementary Metal-Oxide-Semiconductor
DPSS	Diode-Pumped Solid-State

SSL	Solid State Lighting
RGB	Red-Green-Blue
HD	High Definition
LED	Light Emitting Diode
DC	Direct Current
BSDF	Bidirectional Scattering Distribution Function
BRDF	Bidirectional Reflectance Distribution Function
BTDF	Bidirectional Transmittance Distribution Function
DMD	Digital Micromirror Device
BMW	Bavarian Motor Works
CNC	Computer Numerical Control
PLA	Polylactic Acid
YAG	Yttrium Aluminum Garnet
DLP	Digital Light Processing
RF	Radio Frequency