STUDY AND IMPLEMENTATION OF PHASE AND POLARIZATION ENCODED QUANTUM KEY DISTRIBUTION IN ALL-GUIDED-WAVE GEOMETRY

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by

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"What I do not know, I do not think I know"
- Socrates, Apology 21d

Dedicated to my parents and teachers

Certificate

This is to certify that the thesis entitled **"Study and Implementation of Phase and Polarization Encoded Quantum Key Distribution in All-Guide-Wave Geometry"**, submitted by **Nishant Kumar Pathak** 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 contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of our knowledge.

Prof. Bhaskar Kanseri
Thesis Supervisor
Department of Physics,
Indian Institute of Technology Delhi.

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Abstract

This thesis presents a detailed investigation into the development and implementation of quantum communication systems, focusing on phase and polarization-encoded quantum key distribution (QKD) at telecommunication wavelengths.

The study demonstrates the feasibility and robustness of Differential Phase Shift (DPS) QKD by implementing high-frequency (GHz) phase encoding for QKD over significant distances. It showcases the successful transmission of quantum keys through laboratory and real-world environments, overcoming challenges associated with long-distance communication. The work establishes a reliable framework for extending QKD systems to longer ranges through meticulous optimization of key experimental parameters, including error sources and phase overlaps.

The research further explores the generation and distribution of entangled photons. The experiments use guided-wave structures based on periodically poled lithium niobate (PPLN) waveguides. This experimental work demonstrates the potential of entangled photons for use in quantum communication protocols. Integrating such systems into existing optical networks provides a clear pathway for scalable quantum networks.

A critical aspect of this thesis is the investigation of the simultaneous propagation of quantum and classical signals within the same optical fiber. This study addresses one of the crucial challenges in integrating quantum communication with traditional telecommunication systems by analyzing the effect of classical signal transmission on entanglement quality. By optimizing experimental conditions, including the selection of wavelengths and power levels, the coexistence of classical data and quantum signals is achieved with minimal degradation in quantum properties, enabling hybrid communication networks and leveraging the strengths of both technologies.

This research bridges theory and practice in quantum communication by demonstrating scalable quantum state management for secure networks. It offers key insights into protocol design and shows how integrating quantum technologies with telecom infrastructure can enhance security and scalability for diverse applications.

सार

प्रस्तुत शोध प्रबंध दूरसंचार तरंगदैर्ध्य पर कला एवं ध्रुवण आधारित क्वांटम कुंजी वितरण (क्यूकेडी) पर केंद्रित, क्वांटम संचार प्रणालियों के विकास और क्रियान्वयन का विस्तृत अध्ययन प्रस्तुत करता है।

अध्ययन में उच्च आवृत्ति (गीगाहर्ट्ज़ स्तर) कला कूटलेखन का उपयोग करके डिफरेंशियल फेज़ शिफ्ट (डीपीएस) क्यूकेडी की व्यवहार्यता और दृढ़ता को सिद्ध किया गया है, जिसे लंबी दूरी तक क्यूकेडी के लिए प्रयोग में लाया गया है। यह प्रयोगशाला और वास्तविक परिवेश दोनों में लंबी दूरी में आने वाली संचार संबंधी चुनौतियों को पार करता हुआ क्वांटम कुंजियों के सफल वितरण को दर्शाता है। यह शोध कार्य त्रुटियों के स्रोतों और कालाओं के अधिव्यापन जैसे महत्वपूर्ण प्रायोगिक घटकों का अनुकूलन करके, क्यूकेडी प्रणालियों को अधिक दूरी तक विस्तारित करने की एक विश्वसनीय रूपरेखा स्थापित करता है।

यह शोध इंटैंगल हुए प्रकाशाणुओं (फोटॉन) की उत्पत्ति और वितरण की दिशा में भी गहन अन्वेषण करता है। प्रयोगों में आवर्ती ध्रुवित लिथियम नियोबेट (पीपीएलएन) तरंग-पथकों पर आधारित निर्देशित तरंग संरचनाओं का प्रयोग किया गया है। यह प्रायोगिक कार्य यह दर्शाता है कि क्वांटम संचार प्रणाली में इंटैंगल हुए प्रकाशाणुओं का उपयोग एक व्यवहारिक संभावना है। ऐसे प्रणालियों को मौजूदा प्रकाश तन्तु संजाल में एकीकृत करने से बड़े पैमाने पर क्वांटम संजालों के लिए एक स्पष्ट मार्ग प्रशस्त होता है।

इस शोध प्रबंध का एक महत्वपूर्ण पक्ष यह है कि क्वांटम और पारंपरिक संकेतों को एक ही प्रकाश तन्तु में एक साथ प्रेषित करने की व्यवहार्यता का अध्ययन किया गया है। यह अध्ययन पारंपरिक दूरसंचार प्रणालियों के साथ क्वांटम संचार को एकीकृत करने में आने वाली महत्वपूर्ण चुनौतियों में से एक को संबोधित करता है, विशेषकर यह कि पारंपरिक संकेतों के संचरण से इंटैंग्लमेंट की गुणवत्ता पर क्या प्रभाव पड़ता है। तरंगदैर्ध्य और शक्ति स्तरों का सावधानीपूर्वक चयन करके प्रायोगिक परिस्थितियों का अनुकूलन कर, क्वांटम गुणों में न्यूनतम हानि के साथ पारंपरिक आंकड़ों और क्वांटम संकेतों की सह-अस्तित्व प्राप्त की गई है, जिससे दोनों तकनीकों की सामूहिक शक्ति के साथ एक संकर संचार संजाल संभव हो सका है।

यह शोध क्वांटम संचार के सैद्धांतिक और व्यावहारिक पहलुओं के बीच की खाई को पाटते हुए, सुरक्षित संजालों के लिए आरोह्य क्वांटम अवस्था प्रबंधन को सिद्ध करता है। यह प्रणाली विधि के संदर्भ में महत्वपूर्ण अंतर्दृष्टियाँ प्रदान करता है और यह दर्शाता है कि किस प्रकार क्वांटम तकनीकों को दूरसंचार अवसंरचना में एकीकृत कर सुरक्षा और विस्तार क्षमता को विविध अनुप्रयोगों के लिए बेहतर बनाया जा सकता है।

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5.5 (a) Effect of classical channel power on visibility and CAR The theoretical curves for visibility for 1(solid), 4(dashed), 16(dotted) times the obtained coincidence rate, CC, is shown in blue keeping the visibility same. (b) Impact of classical channel power on the CHSH Bell parameter and secure key rate for entanglement based BBM92 QKD protocol. (below). The corresponding theoretical curves for 1(solid), 4(dashed), and 16(dotted) times CC are shown. The horizontal green line shows the quantum-classical threshold in the above figures. . . . 120

Abbreviations

AES	**A**dvanced **E**ncryption **S**tandard
ATT	**A**ttenuator
BB	**B**ennett-**B**rassard (BB84)
BBM	**B**ennett-**B**rassard-**M**ermin (BBM92)
BCH	**B**aker–**C**ampbell–**H**ausdorff
BPSK	**B**inary **P**hase **S**hift **K**eying
BS	**B**eam **S**plitter
CAR	**C**oincidence to **A**ccidental **R**atio
CHSH	**C**lauser-**H**orne-**S**himony-**H**olt
COW	**C**oherent **O**ne **W**ay
CW	**C**ontinuous **W**ave
DCF	**D**ispersion **C**ompensating **F**iber
DET	**Det**ector
DPS	**D**ifferential **P**hase **S**hift
DSF	**D**ispersion **S**hifted **F**iber
ECC	**E**lliptic **C**urve **C**ryptography
EPR	**E**instein-**P**odolsky-**R**osen
FPGA	**F**ield **P**rogrammable **G**ate **A**rray
FTTH	**F**iber **t**o **t**he **H**ome
FWHM	**F**ull **W**idth at **H**alf **M**aximum
HOM	**H**ong-**O**u-**M**andel
HWP	**H**alf **W**ave **P**late
IM	**I**ntensity **M**odulator
IoT	**I**nternet **o**f **T**hings
ITU	**I**nternational **T**elecommunication **U**nion
LN	**L**ithium **N**iobate

MDI	**M**easurement **D**evice **I**ndependent
MON	**M**onitor
MZI	**M**ach **Z**ehnder **I**nterferometer
PBS	**P**olarizing **B**eam **S**plitter
PC	**P**olarization **C**ontroller
PM	**P**hase **M**odulator
PMD	**P**olarization **M**ode **D**ispersion
PNR	**P**hoton **N**umber **R**esolving
PNS	**P**hoton **N**umber **S**plitting
PPLN	**P**eriodically **P**oled **L**ithium **N**iobate
PQC	**P**ost **Q**uantum **C**ryptography
QAM	**Q**uadrature **A**mplitude **M**odulation
QBER	**Q**uantum **B**it **E**rror **R**ate
QKD	**Q**uantum **K**ey **D**istribution
QPK	**Q**uantum **P**rivate **K**ey
QPM	**Q**uasi **P**hase **M**atching
QPSK	**Q**uadrature **P**hase **S**hift **K**eying
QC	**Q**uantum **C**hannel
RF	**R**adio **F**requency
RRDPS	**R**ound **R**obin **D**ifferential **P**hase **S**hift
RSA	**R**ivest-**S**hamir-**A**dleman
SHG	**S**econd **H**armonic **G**eneration
SNSPD	**S**uperconducting **N**anowire **S**ingle **P**hoton **D**etector
SPDC	**S**pontaneous **P**arametric **D**own-**C**onversion
TF	**T**win **F**ield
ULL	**U**ltra-**L**ow **L**oss
VOA	**V**ariable **O**ptical **A**ttenuator
WDM	**W**avelength **D**ivision **M**ultiplexing/**M**ultiplexer

Symbols

f	Frequency
σ_ω	Spectral Width
τ	Gate Width
$H_2(x)$	Binary Entropy Function
η	Efficiency
$g^{(2)}$	Normalized second-order correlation
c	Speed of light in vacuum
k	Wave-vector in free space
l_c	Temporal coherence length
λ	Wavelength
V	Visibility
Q	Quantum Bit Error Rate
$\bar{n}, \mu$	Mean photon number
ν	Pulse repetition rate
η	Efficiency