ROBUST ENTANGLED-PHOTON SOURCES BASED ON PPKTP FOR ROTATIONAL-MISALIGNMENT-RESILIENT FREE-SPACE QKD

OMSHANKAR

DEPARTMENT OF PHYSICS

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Robust entangled-photon sources based on ppKTP for rotational-misalignment-resilient free-space QKD

by

OMSHANKAR

Department of Physics

Submitted

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to the

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Dedicated to my grandfather and my loving family.....

Certificate

This is to certify that the thesis entitled **"Robust entangled-photon sources based on ppKTP for rotational-misalignment-resilient free-space QKD"**, submitted by **OMSHANKAR** 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 standards that meet 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 my knowledge.

Prof. Joyee Ghosh
Associate Professor, Department of Physics
Indian Institute of Technology Delhi
New Delhi, 110016

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Abstract

Polarization-entangled photon-based quantum key distribution (QKD has witnessed significant advancements; however, its practical implementation often necessitates that users maintain a shared reference frame. This requirement introduces considerable technical overhead, as it demands continuous monitoring and alignment of the reference frames between communicating parties. We demonstrate a potential solution to overcome such rotational misalignment by exploiting two degrees of freedom of entangled photons, i.e. polarization and orbital angular momentum (OAM to generate rotationally invariant hybrid entangled photons. The thesis begins by establishing the foundational concepts of quantum processes, particularly spontaneous parametric down-conversion (SPDC and the derivation of the Schmidt decomposition of the biphoton quantum state and two-photon amplitude function. This foundation serves as a basis for the understanding of various concepts introduced in subsequent chapters, which delve into the development of polarization-entangled photon sources through SPDC and its characterization through second-harmonic generation (SHG. The investigation includes discussions on pump beam focusing, polarization inhomogeneity effects, and the transition of phase-matching conditions. We experimentally showcase the generation of high-brightness, temporally and spectrally correlated photons, validated by measuring the polarization correlation. Further chapters focus on the practical implementation and testing of quantum key distribution (QKD protocols, with a detailed analysis comparing the single-photon and entangled-photon-based approaches under various channel losses. Theoretical investigations aid in selecting the optimal protocol for free-space QKD applications, with a preference for the BBM92 protocol due to its robustness against higher channel losses. The experimental implementation of the BBM92 protocol, following the theoretical investigation and leveraging a polarization-entangled photon source, validates its effectiveness in establishing a secret key with high-performance metrics. Moreover, the thesis explores innovative strategies for quantum communication by leveraging the multiple degrees of freedom of correlated/entangled photons, such as polarization and orbital angular momentum, to overcome the reference frame misalignment challenges. This approach involves encoding qubits into rotationally invariant hybrid states using liquid crystal devices, demonstrating robustness against reference frame rotations and enabling alignment-free quantum communication. Overall, the thesis contributes to advancing the understanding and practical implementation of quantum measurements, entanglement sources, and communication

protocols, with implications for quantum cryptography, quantum key distribution, and alignment-free quantum communication systems.

सार

पिछले कुछ सालों में फोटॉन के ध्रुवीकरण-उलझन पर आधारित क्वांटम कुंजी वितरण (क्यूकेडी) के क्षेत्र में महत्वपूर्ण प्रगति देखी गई है, हालाँकि, इसके व्यावहारिक कार्यान्वयन के लिए अक्सर यह आवश्यक हो जाता है कि उपयोगकर्ता एक साझा संदर्भ फ्रेम बनाए रखें। एक साझा संदर्भ फ्रेम बनाए की आवश्यकता के कारण संचार करने वाले पक्षों के बीच संदर्भ फ्रेम की निरंतर निगरानी और संरेखण की जरूरत होती है जो हमारे तकनीकी व्यय को बढ़ा देती है| हम इस शोध प्रबंध में अपरिवर्तनीय घूर्णन-विषयक संकर-उलझन पर आधारित फोटॉनों को उत्पन्न करने के लिए फोटॉनों की स्वतंत्रता की दो कोटिया, यानी ध्रुवीकरण और कक्षीय कोणीय संवेग (ओएएम) का उपयोग करके इस तरह के घूर्णन कुसरेखण को दूर करने के लिए एक संभावित समाधान प्रस्तुत करते हैं। यह शोध क्वांटम प्रक्रियाओं, विशेष रूप से स्वतःस्फूर्त पैरामीट्रिक डाउन-रूपांतरण (एसपीडीसी) और बाइफोटोन क्वांटम अवस्था तथा दो-फोटॉन आयाम कार्य के श्मिट अपघटन की व्युत्पत्ति की मूलभूत अवधारणाओं को स्थापित करने से शुरू होती है। यह बाद के अध्यायों में प्रस्तुत की गई विभिन्न अवधारणाओं की समझ के लिए एक आधार के रूप में कार्य करता है, जिसमें हम एसपीडीसी के माध्यम से ध्रुवीकरण में उलझे हुए फोटॉन के स्रोतों के विकास तथा आवृत्ति दोहरीकरण (एसएचजी) के माध्यम से एसपीडीसी के लक्षणो का वर्णन गहराई से करते हैं। यह शोध पंप बीम फोकसिंग, ध्रुवण असमानता प्रभावों, और चरण-मिलान स्थितियों के परिवर्तन पर चर्चा करता है। हम प्रयोगात्मक रूप से उच्च-उज्ज्वलता, समय और वर्णक्रमीय रूप से सहसंबद्ध फोटॉनों की उत्पत्ति को प्रदर्शित करते हैं, जिसे ध्रुवण सहसंबंध मापकर सत्यापित किया गया है। आगे के अध्यायों में क्यूकेडी प्रोटोकॉल के व्यावहारिक कार्यान्वयन और परीक्षण पर ध्यान केंद्रित किया गया है, जिसमें एकल-फोटॉन और उलझे हुए-फोटॉन आधारित दृष्टिकोणों की विभिन्न चैनल हानियों के अंतर्गत विस्तृत तुलना की गई है। सैद्धांतिक अध्ययन फ्री-स्पेस क्यूकेडी अनुप्रयोगों के लिए उपयुक्त प्रोटोकॉल का चयन करने में मदद करता है, जिसमें बीबीएम92 प्रोटोकॉल को उच्च चैनल हानियों के खिलाफ इसकी मजबूती के कारण प्राथमिकता दी गई है। सैद्धांतिक अध्ययन के पश्चात बीबीएम92 प्रोटोकॉल के प्रयोगात्मक कार्यान्वयन और ध्रुवण-उलझे हुए फोटॉन स्रोत का उपयोग करके इसकी प्रभावशीलता को एक उच्च प्रदर्शन मेट्रिक्स के साथ गुप्त कुंजी स्थापित करने में सत्यापित किया गया है। इसके अतिरिक्त, शोध क्वांटम संचार के लिए नवीन रणनीतियों का अन्वेषण करता है, जिसमें सहसंबद्ध/उलझे हुए फोटॉनों की कई स्वतंत्रताओं, जैसे ध्रुवण और ऑर्बिटल एंगुलर मोमेंटम का लाभ उठाया जाता है, ताकि संदर्भ फ्रेम असंतुलन की चुनौतियों को दूर किया जा सके। यह दृष्टिकोण लिक्विड क्रिस्टल उपकरणों का उपयोग करके रोटेशनली इनवेरिएंट हाइब्रिड स्टेट्स में क्यूबिट्स को एन्कोड करता है, जो संदर्भ फ्रेम के घुमावों के प्रति मजबूतता प्रदर्शित करता है और संरेखन-मुक्त क्वांटम संचार को सक्षम बनाता है। कुल मिलाकर, यह शोध क्वांटम माप, उलझन स्रोतों, और संचार प्रोटोकॉल के सैद्धांतिक और व्यावहारिक कार्यान्वयन को आगे बढ़ाने में योगदान देता है, जिसका प्रभाव क्वांटम क्रिप्टोग्राफी, क्वांटम कुंजी वितरण, और संरेखन-मुक्त क्वांटम संचार प्रणालियों पर पड़ता है।

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Abbreviations

CW	**C**ontinuous **W**ave
SHG	**S**econd **H**armonic **G**eneration
SH	**S**econd **H**armonic
PMT	**P**hase **M**atching **T**emperature
OAM	**O**rbital **A**ngular **M**omentum
PBS	**P**olarizing **B**eam **S**plitter
HWP	**H**alf-**W**ave **P**late
QWP	**Q**uarter-**W**ave **P**late
BS	**B**eam-**S**plitter
VHWP	**V**ortex **h**alf-**W**ave **P**late
SPDC	**S**pontaneous **P**arametric **D**own-**C**onversion
FWHM	**F**ull-**W**idth **H**alf **M**axima
ppKTP	**p**eriodically **p**oled **P**otassium **T**itanyl **P**hosphate
ppLN	**p**eriodically **p**oled **L**ithium **N**iobate
CAR	**C**oincidences-to-**A**ccidentals **R**atio
SFWM	**S**pontaneous **F**our-**W**ave **M**ixing
TCSI	**T**wo **C**rystal **S**agnac **I**nterferometer
PSI	**P**olarization **S**agnac **I**nterferometer
MZI	**M**ach-**Z**ehnder **I**nterferometer
EMCCD	**E**lectron **M**ultiplying **C**harge-**C**oupled **D**evice
CCD	**C**harge-**C**oupled **D**evice
CC	**C**ompensating **C**rystal
FM	**F**lip **M**irror
TCSPC	**T**ime-**C**orrelated **S**ingle **P**hoton **C**ounting
CHSH	**C**lauser-**H**orne-**S**himony-**H**olt
QKD	**Q**uantum **K**ey **D**istribution

QC	**Q**uantum **C**ommunication
RSA	**R**ivest–**P**odolsky–**A**dleman
EPR	**E**instein–**S**hamir–**R**osen
FSO	**F**ree–**S**pace **O**ptical
BB84	**B**ennett and **B**rassard 1984 Protocol
BBM92	**B**ennett, **B**rassard, and **M**ermin 1992 Protocol
E91	**E**kert 1991 Protocol
SNSPD	**S**uperconducting **N**anowire **S**ingle **P**hoton **D**etector
SPAD	**S**ingle-**P**hoton **A**valanche **D**etector
QBER	**Q**uantum **B**it **E**rror **R**ate
JSA	**J**oint **S**pectral **A**amplitude
JSI	**J**oint **S**pectral **I**ntensity
HG	**H**ermite **G**aussian
LG	**L**aguerre-**G**aussian
BG	**B**essel-**G**aussian
AG	**A**iry-**G**aussian
CGH	**C**omputer-**G**enerated **H**ologram
HOM	**H**ong-**O**u-**M**andel
BPM	**B**irefringent **P**hase **M**atching
QPM	**Q**uasi **P**hase **M**atching

Symbols

c	Speed of light in vacuum
ϵ_0	Dielectric permittivity of free-space
μ_0	magnetic permeability of free-space
k_0	Wavevector in free space
ω	Angular frequency
$\hbar$	Reduced Planck‘s constant
l	Orbital angular momentum in units of $2\pi\hbar$
J	total angular momentum
s_z	spin angular momentum in units of $2\pi\hbar$
$\chi^{(1,2)}$	first/second-order nonlinear susceptibility coefficient
$\|\Psi^-\rangle$	Bell state representing entangled photon pairs
H/V	Horizontal/Vertical polarization states
D/A	Diagonal/Antidiagonal polarization states
N_{error}	Number of erroneous photon coincidences
N_{total}	Total photon coincidences (correct + erroneous)
QBER	Quantum Bit Error Rate
$\lambda_p, \lambda_s, \lambda_i$	Wavelength of pump, signal and idler photons
$\mathbf{P}$	Electric polarization vector
$\mathbf{E}$	Electric field vector
$\mathbf{B}$	Magnetic field vector
$\mathbf{J}$	current density vector
$\mathbf{D}$	displacement field vector
$\hat{\mathbf{E}}^{(+)}/\hat{\mathbf{E}}^{(-)}$	positive/negative frequency parts of the field operator
$\hat{H}_{\text{int}}$	Interaction Hamiltonian
Φ	Bi-photon amplitude function

$\hat{a}, \hat{a}^\dagger$	creation and annihilation operator
$S_p(\omega_p)$	spectral distribution
σ_p	frequency bandwidth of the pump beam
Δk	Momentum mismatch
ΔT	Crystal temperature deviation
P	Pump power
S_B	Source brightness of the source
S_λ	Spectral brightness of the source
V	Visibility of two-photon interference
F	Fidelity of the quantum state
C	Concurrence as a measure of entanglement
$\omega_p, \omega_s, \omega_i$	Angular frequencies of pump, signal and idler photons
$\mathbf{k_p}, \mathbf{k_s}, \mathbf{k_i}$	Wavevectors of the pump, signal and idler photons
$\mathbf{q_p}, \mathbf{q_s}, \mathbf{q_i}$	transverse components of the wavevectors
$\Delta\omega$	Frequency detuning
L	Length of the nonlinear crystal
d_{eff}	Effective nonlinear coefficient
η	Detection efficiency
r	Radial index of the LG mode
ϕ	azimuthal angle
z	Propagation distance
o, e	ordinary and extraordinary polarization
Λ	poling period of the crystal
$P(\theta_1, \theta_2)$	probability of an entangled state in a projection basis (θ_1, θ_2)
ρ	density matrix of a quantum state
S	CHSH-Bell parameter
q	vortex charge of Q-plate
L	length of the crystal