FIBER-INTEGRATED PPLN-WAVEGUIDE-BASED QUANTUM LIGHT SOURCES FOR LOW-QBER QUANTUM COMMUNICATION AND SENSING APPLICATIONS

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Dedicated to my family...

Certificate

This is to certify that the thesis entitled **"Fiber-integrated PPLN-waveguide-based quantum light sources for Low-QBER quantum communication and sensing applications"**, submitted by **Akanksha Angural** 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 her under my supervision and guidance. The thesis has reached the 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.

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Abstract

The generation, characterization, and application of non-classical states of light is fundamental to state-of-the-art quantum communication and sensing technologies. This thesis focuses on the development and performance optimization of fiber-integrated, periodically poled lithium niobate (ppLN) ridge-waveguide–based quantum light sources tailored for both discrete-variable (DV) and continuous-variable (CV) applications. These sources are intended for real-time implementation in secure quantum communication and sensing systems. All sources developed in this work are realized using single pass spontaneous parametric down-conversion (SPDC) in magnesium-oxide-doped periodically poled lithium niobate (MgO:ppLN) ridge waveguides. We first systematically explore type-II quasi-phase-matched MgO:ppLN waveguide for DV characterization, enabling the generation of narrowband, spectral and polarization-correlated biphotons at 1560 nm with high spectral brightness ($\sim 5 \times 10^6$ pairs/s/mW/nm), coincidence-to-accidental ratio (~ 427) and comparatively narrow emission bandwidth (~ 2.4 nm) along with strong spectral correlations revealed by joint spectral intensity measurements. Since type-II SPDC generates orthogonally polarized photons, temporal distinguishability may arise due to anisotropy and fiber-integration of the source. Hence, subsequent investigations address how detection system parameters, including single-photon detector quantum efficiency, dead time, and time-correlator bin width impact the measured photon statistics and temporal quantum correlations. while introducing birefringence compensation. Analytical modeling and experimental validation demonstrate that optimized detection conditions can yield exceptionally high temporal cross-correlations ($g_{si}^{(2)}(0) \sim 10^4$) and near-unity raw Hong–Ou–Mandel interference visibilities ($\sim 99 \pm 1\%$), demonstrating the intrinsic indistinguishability and quality of the generated photon pairs. Building on this foundation, we further present the realization of a robust, fiber-integrated polarization-entangled photon-pair source. One highlight of this thesis is that using the same system and setup, this source is capable of generating both bosonic ($|\psi^+\rangle$) and fermionic ($|\psi^-\rangle$) Bell states. This is achieved by controlling the phase symmetry between the two arms after splitting the photon pairs, rendering the source switchable between the two states. The generated entangled states exhibit high raw concurrence ($> 92\%$), raw fidelity ($> 95\%$), and low QBER ($< 3\%$), with strong violation of the CHSH inequality ($S > 2.65$), confirming their potential for secure quantum key distribution and quantum networking. We further extend the scope of this thesis to the generation and characterization of quantum squeezed states in

the telecom C-band using a fully guided MgO:ppLN waveguide-based source presenting the first indigenous waveguide squeezer at telecom wavelengths. Theoretical analyses of balanced homodyne detection (BHD) circuits are performed for two configurations- a current subtraction design with a differential fine tuning circuit and adjustable bias voltage, and a variable gain design with an additional differential amplifier. This enables a study of the best configuration for enhanced transimpedance gain, high bandwidth and low electronic noise, which can thereby be employed for improving squeezed-state detection sensitivity. Utilizing this BHD circuit, an operational study of fully-guided single-mode squeezing in the telecom C-band is done using a Zn-indiffused MgO:ppLN ridge waveguide (using type-0 SPDC), achieving -1.81 ± 0.05 dB of measured squeezing (corresponding to -4.11 ± 0.05 dB of generated squeezing), notably using off-the-shelf components. The quantum utility of the source under real-time noise constraints is investigated and quantified through a computation of the purity, Von-Neumann entropy and quantum Fisher information, showing enhancement in phase sensing. Additionally, entanglement potential, Duan's inseparability criterion and quantum teleportation fidelity are also computed. All these parameters, establish quantitative benchmarks for evaluating the performance of such guided-wave sources. Overall, this work demonstrates fiber-integrated waveguide-based sources as compact, stable, and scalable building blocks capable for quantum communication, metrology, and sensing applications in practical telecom environments for both DV and CV classifications.

सार

प्रकाश की नॉन-क्लासिकल अवस्थाओं का सृजन, विशेषण तथा अनुप्रयोग आधुनिक क्वांटम संचार और संवेदन प्रौद्यो-गिकियों की एक मूलभूत आवश्यकता है। यह शोधप्रबंध फाइबर-समेकित, आवधिक रूप से ध्रुवीकृत लिथियम नायोबेट (पीपीएलएन) रिज-तरंगमार्ग आधारित क्वांटम प्रकाश स्रोतों के विकास और प्रदर्शन के अनुकूलन पर केंद्रित है, जिन्हें डिस्क्रीट-वेरिएबल (डीवी) तथा कंटिन्यूअस-वेरिएबल (सीवी) दोनों अनुप्रयोगों के लिए तैयार किया गया है। ये स्रोत सुरक्षित क्वांटम संचार और संवेदन प्रणालियों में वास्तविक समय कार्यान्वयन के लिए अभिकल्पित हैं। इस कार्य में विकसित सभी स्रोत मैग्नीशियम-ऑक्साइड-मिश्रित आवधिक ध्रुवीकृत लिथियम नायोबेट (एमजीओ:पीपीएलएन) रिज-तरंगमार्गों में एकल-पास स्वस्फूर्त पैरामीट्रिक डाउन-परिवर्तन (एसपीडीसी) के माध्यम से साकार किए गए हैं। सर्वप्रथम डीवी विशेषण हेतु टाइप-द्वितीय अर्ध-फेज-सामंजस्यित एमजीओ:पीपीएलएन तरंगमार्ग का व्यवस्थित अध्ययन किया गया, जिससे 1560 नैनोमीटर पर संकीर्ण-वर्णक्रमीय, वर्णक्रम तथा ध्रुवण-सहसंबद्ध द्वि-फोटॉनों का सृजन संभव होता है। इनकी उच्च वर्णक्रमीय दीप्ति $\sim 5 \times 10^6$ युग्म/सेकंड/मिलिवाट/नैनोमीटर), सह-घटना से आकस्मिक अनुपात (~ 427) तथा तुलनात्मक रूप से संकीर्ण उत्सर्जन वर्णपट्टी चौड़ाई (~ 2.4 नैनोमीटर) प्राप्त हुई, साथ ही संयुक्त वर्ण-क्रमीय तीव्रता मापन से प्रबल वर्णक्रमीय सहसंबंध भी प्रकट हुए। चूँकि टाइप-द्वितीय एसपीडीसी परस्पर लम्बवत ध्रुवीकृत फोटॉन उत्पन्न करता है, अतः स्रोत की दिशात्मक असमानता और फाइबर-समेकन के कारण समयगत पृथकता उत्पन्न हो सकती है। इसलिए आगे के अध्ययन यह दर्शाते हैं कि डिटेक्शन तंत्र के पैरामीटर — जैसे एकल-फोटॉन डिटेक्टर की क्वांटम दक्षता, निष्क्रिय समय और समय-सहसंबंधक की बिन चौड़ाई मापी गई फोटॉन सांख्यिकी तथा समयगत क्वांटम सहसंबंधों को किस प्रकार प्रभावित करते हैं, साथ ही द्विविचलन क्षतिपूर्ति भी प्रस्तुत की गई है। विश्लेषणात्मक मॉडलन और प्रयोगात्मक प्रमाणीकरण से यह प्रदर्शित होता है कि अनुकूलित डिटेक्शन परिस्थितियों में अत्यंत उच्च समयगत पार-सहसंबंध ($g_{si}^{(2)}(0) \sim 10^4$) तथा लगभग एकात्मक हांग–ऊ–मैंडल व्यतिकरण दृश्यता ($99 \pm 1\%$) प्राप्त होती है, जो उत्पन्न फोटॉन युग्मों की अंतर्निहित अविभेद्यता और उच्च गुणवत्ता को प्रमाणित करती है। इसी आधार पर एक सुदृढ़, फाइबर-समेकित, ध्रुवण-संयोजित फोटॉन-युग्म स्रोत का साकार प्रस्तुत किया गया है। इस शोध की प्रमुख विशेषता यह है कि समान प्रणाली और सेटअप से यह स्रोत दोनों बोसोनिक ($|\psi^+\rangle$) तथा फर्मियोनिक ($|\psi^-\rangle$) बेल अवस्थाएँ उत्पन्न कर सकता है। यह फोटॉन युग्मों के विभाजन के पश्चात दोनों भुजाओं के मध्य चरण सममिति को नियंत्रित कर प्राप्त किया गया है, जिससे स्रोत को दोनों अवस्थाओं के बीच स्विच योग्य बनाया जा सकता है। उत्पन्न संयोजित अवस्थाएँ उच्च कच्ची सहसम्बद्धता ($> 92\%$), उच्च कच्ची विशुद्धता ($> 95\%$) तथा निम्न क्यूबीईआर ($< 3\%$) प्रदर्शित करती हैं। साथ ही सीएचएसएच असमानता का प्रबल उल्लंघन ($S > 2.65$) इनके सुरक्षित क्वांटम कुंजी वितरण और क्वांटम नेटवर्किंग में उपयोग की पुष्टि करता है।इस शोध का विस्तार आगे दूरसंचार सी-बैंड में क्वांटम संपीडित अवस्थाओं के सृजन और विशेषण तक किया गया, जिसके लिए एक पूर्णतः निर्देशित एमजीओ:पीपीएलएन तरंगमार्ग आधारित स्रोत का उपयोग किया गया, जो दूरसंचार तरंगदैर्घ्य पर प्रथम स्वदेशी तरंगमार्ग संपीडक प्रस्तुत करता है। संतुलित होमोडाइन अभिज्ञापन परिपथों का सैद्धांतिक विश्लेषण दो विन्यासों हेतु किया गया -(1) धारा-घटाव आधारित विन्यास, जिसमें विभेदक सूक्ष्म-संयोजन परिपथ और समायोज्य बायस वोल्टेज सम्मिलित हैं, (2) परिवर्ती प्रवर्धन आधारित विन्यास, जिसमें अतिरिक्त विभेदक प्रवर्धक जोड़ा गया है। इससे सर्वोत्तम विन्यास का निर्धारण संभव हुआ, जो उच्च ट्रांसइम्पीडेंस प्रवर्धन, अधिक बैंडचौड़ाई और न्यून इलेक्ट्रॉनिक शोर प्रदान करता है, जिससे संपीडित अवस्था पहचान संवेदनशीलता

में वृद्धि की जा सके। इस परिपथ का उपयोग करते हुए दूरसंचार सी-बैंड में पूर्णतः निर्देशित एकल-मोड संपीडन का अध्ययन जिंक-प्रसारित एमजीओ:पीपीएलएन रिज-तरंगमार्ग में किया गया, जिसमें -1.81 ± 0.05डेसीबेल का मापा गया संपीडन प्राप्त हुआ, जो -4.11 ± 0.05 डेसीबेल उत्पन्न संपीडन के अनुरूप है, और यह सब मानक व्यावसायिक अवयवों के प्रयोग से संभव हुआ। वास्तविक समय शोर प्रतिबंधों के अंतर्गत स्रोत की क्वांटम उपयोगिता का मूल्यांकन शुद्धता, वॉन-न्यूमैन एंट्रॉपी तथा क्वांटम फिशर सूचना के माध्यम से किया गया, जिससे चरण संवेदन में उन्नति प्रदर्शित हुई। इसके अतिरिक्त संयोजन संभाव्यता, डुआन की अविभाज्यता कसौटी तथा क्वांटम टेलीपोर्टेशन विश्वसनीयता की भी गणना की गई। ये सभी पैरामीटर ऐसे निर्देशित-तरंग स्रोतों के प्रदर्शन मूल्यांकन हेतु मात्रात्मक मानक स्थापित करते हैं। समग्र रूप से यह कार्य फाइबर-समेकित तरंगमार्ग आधारित स्रोतों को संक्षिप्त, स्थिर और स्केलेबल क्वांटम निर्माणखंड के रूप में स्थापित करता है, जो व्यावहारिक दूरसंचार परिवेश में डीवी तथा सीवी दोनों वर्गीकरणों हेतु क्वांटम संचार, मापन तकनीक और संवेदन अनुप्रयोगों में सक्षम सिद्ध होते हैं।

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Abbreviations

DV	**D**iscrete **V**ariable
CV	**C**ontinuous **V**ariable
SPDC	**S**pontaneous **P**arametric **D**own-**C**onversion
SFWM	**S**pontaneous **F**our-**W**ave **M**ixing
NV	**N**itrogen-**V**acancy
QKD	**Q**uantum **K**ey **D**istribution
CV-QKD	**C**ontinuous **V**ariable **Q**uantum **K**ey **D**istribution
SHG	**S**econd **H**armonic **G**eneration
ppLN	**P**eriodically **P**oled **L**ithium **N**iobate
MgO:ppLN	**M**agnesium-**O**xide **P**eriodically **P**oled **L**ithium **N**iobate
LNOI	**L**ithium **N**iobate **O**n **I**nsulator
JSI	**J**oint **S**pectral **I**ntensity
JSA	**J**oint **S**pectral **A**mplitude
CAR	**C**oincidence-**T**o-**A**ccidental **R**atio
CSR	**C**oincidence-**T**o-**S**ignal **R**atio
HOM	**H**ong–**O**u–**M**andel
QBER	**Q**uantum **B**it **E**rror **R**ate
CHSH	**C**lauser–**H**orne–**S**himony–**H**olt
QFI	**Q**uantum **F**isher **I**nformation
QST	**Q**uantum **S**tate **T**omography
PC	**P**olarization **C**ontroller
PBS	**P**olarizing **B**eam **S**plitter
FPBS	**F**iber **P**olarization **B**eam **S**plitter
IOF	**I**nline **O**ptical **F**ilter
DTF	**D**igital **T**unable **F**ilter
PMT	**P**hase **M**atching **T**emperature

SPD	**S**ingle **P**hoton **D**etector
SNSPD	**S**uperconducting **N**anowire **S**ingle-**P**hoton **D**etector
APD	**A**valanche **P**hotodiode
TDC	**T**ime-**T**o-**D**igital **C**onverter
LO	**L**ocal **O**scillator
RF	**R**adio **F**requency
DC	**D**irect **C**urrent
AC	**A**lternating **C**urrent
BHD	**B**alanced **H**omodyne **D**etection
TIA	**T**rans**I**mpedance **A**mplifier
ABV	**A**djustable **B**ias **V**oltage
FFT	**F**ast **F**ourier **T**ransform
SMF	**S**ingle **M**ode **F**iber
MMF	**M**ulti **M**ode **F**iber
WDM	**W**avelength **D**ivision **M**ultiplexing
DWDM	**D**ense **W**avelength **D**ivision **M**ultiplexing
ITU	**I**nternational **T**elecommunication **U**nion
PMD	**P**olarization **M**ode **D**ispersion
PDL	**P**olarization **D**ependent **L**oss
ODL	**O**ptical **D**elay **L**ine
DDL	**D**ifferntial **D**elay **L**ine
SNR	**S**ignal-**T**o-**N**oise **R**atio
ESA	**E**lectronic **S**pectrum **A**nalyzer

Symbols

c	speed of light in vacuum
ϵ	permittivity / dielectric constant
ϵ_0	vacuum permittivity
μ_0	vacuum permeability
$\chi^{(1)}$	linear susceptibility
$\chi^{(2)}$	second-order nonlinear susceptibility
k	wavevector
k_0	free-space wavevector
k_p, k_s, k_i	pump, signal, idler wavevectors
n	refractive index
n_{eff}	effective refractive index
n_r	reference refractive index
ω	angular frequency
$\omega_p, \omega_s, \omega_i$	pump, signal, idler frequencies
λ	wavelength
$\lambda_p, \lambda_s, \lambda_i$	pump, signal, idler wavelengths
Δk	phase mismatch
$\Delta\omega$	frequency detuning
$\Delta\lambda$	spectral bandwidth
τ	temporal delay
$\Delta\tau$	temporal walk-off
η	efficiency (detection / conversion)
Γ	nonlinear overlap factor
Φ	biphoton amplitude
$g_{si}^{(2)}(0)$	zero-delay cross-correlation
S	CHSH Bell parameter+Von Neumann entropy

F	quantum-state fidelity
C	concurrence
V	interference visibility
K	Schmidt number
P	pump power / polarization
E	electric field
B	magnetic field
D	electric displacement field
J	current density
$a, a^\dagger$	annihilation and creation operators
$E^{(+)}, E^{(-)}$	positive/negative frequency field operators
H_{int}	interaction Hamiltonian
ρ	density matrix
$P(\theta_1, \theta_2)$	projection probability
l	orbital angular momentum index
r	radial mode index
ϕ	azimuthal angle
z	propagation distance
o, e	ordinary and extraordinary photons
Λ	poling period
L	crystal length
S_λ	spectral brightness
S_B	source brightness
N_{error}	erroneous coincidence counts
N_{total}	total coincidence counts
μ	state purity
ν	symplectic eigenvalue
r	squeezing parameter
$S(\omega)$	noise spectrum
S_x, S_p	quadrature noise spectra
V_x, V_p	quadrature variances
$\hat{x}, \hat{p}$	quadrature operators
ξ	loss factor
T, R	transmission and reflection coefficients
$\bar{n}$	mean photon number

θ	measurement phase
$\delta\phi$	phase estimation error
ϕ_{LO}	local oscillator phase
M	number of measurements
σ	standard deviation
σ_{el}	electronic noise
σ_{shot}	shot noise
I_{sig}	signal photocurrent
I_{diff}	difference photocurrent
G	gain (electronic)
τ_d	detector dead time
τ_c	coincidence window
R_{dc}	dark-count rate
η_{det}	detector quantum efficiency
η_{fiber}	fiber coupling efficiency
η_{sys}	total system efficiency