TELECOM-BAND QUANTUM PHOTONIC STATE PREPARATION VIA DISPERSION ENGINEERING IN SOI NANOWAVEGUIDES

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Telecom-band quantum photonic state preparation via dispersion engineering in SOI nanowaveguides

by

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Dedicated to my grandfather

Certificate

This is to certify that the thesis entitled **"Telecom-band quantum photonic state preparation via dispersion engineering in SOI nanowaveguides"**, submitted by **Shivani Sharma** 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 our 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.

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"If I have seen further, it is by standing on the shoulders of giants" - Isaac Newton

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Abstract

The thesis aims to design quantum photonic sources based on CMOS-compatible silicon-on-insulator (SOI) waveguides capable of generating diverse quantum light states at telecommunication wavelengths via spontaneous four-wave mixing (SFWM). The extensive dispersion engineering capabilities enabled by the high refractive-index-contrast in such waveguide structures are effectively harnessed to show the generation of nonclassical photonic states, useful for various quantum applications. We present designs for SOI nanowaveguides with a standard film thickness of 220-nm that could generate spectrally bright frequency-correlated photon pairs spanning nearly the entire telecom spectrum (∼1250-1750 nm), utilizing the continuous-band phase matching. We also exploited the discrete phase-matched sidebands far detuned from the pump, in addition to group-velocity matching between the pump and generated photons, to theoretically demonstrate the conditional preparation of spectrally pure heralded single photons. We proposed tunable generation of filter-free spectrally pure (Purity > 95%) near-ideal single photons in the O-, E-, and S-bands of the telecom range, in standard SOI waveguides. The devices can be directly used in linear optical quantum computing (LOQC) networks and prepare-and-measure quantum key distribution (QKD) protocols. Extending to another degree of freedom of photons, we demonstrated the possible generation of near-perfect polarization-entangled photon pairs over a broad (∼ 100 nm) range of wavelengths around 1550 nm in SOI waveguides with a non-standard thickness of 280 nm. The effect of polarization mode dispersion (PMD) is also studied to show that the use of relatively narrow pump bandwidths (<10 GHz) can still maintain entanglement over waveguide lengths up to 7 mm. These promising cm-scale devices for broadband entanglement (frequency and polarization) generation could be efficiently employed in multi-channel QKD via frequency multiplexing, thereby improving the data rates in quantum communication. Further, we presented a semi-classical numerical model for computing the impact of the Langevin noise, induced due to the linear scattering loss and nonlinear losses like two-photon absorption (TPA) and free carrier absorption (FCA), on the quality of biphoton quantum correlations in silicon waveguides. Our model is more general compared to the previous analytical models, particularly for including dispersion and wavelength-dependent losses, and more accurate for noise

estimation in the high-photon-flux regime such as optical parametric amplifiers and squeezed state generation.

Therefore, the thesis proposes simple designs for SFWM-based sources for the generation of diverse telecom-band quantum states that could in principle be employed to implement quantum logic operations or distribute secret keys for communication via low-loss silica optical fibers. Direct generation of the quantum photonic states is proposed in contrast to the relatively involved post-processing techniques for heralding or entangling photons. The thesis is a significant advancement towards the ultimate goal of manipulating single/entangled photons on a single chip that integrates the light source, waveguides for quantum state generation, filtering devices, modulators, and single-photon detectors.

सार

थीसिस का उद्देश्य CMOS–संगत सिलिकॉन–ऑन–इंसुलेटर (SOI) वेवगाइड्स के आधार पर क्वांटम फोटोनिक स्रोतों को डिजाइन करना है जो स्वत: चार–तरंग मिश्रण (SFWM) के माध्यम से दूरसंचार तरंग दैर्ध्य पर विविध क्वांटम प्रकाश उत्पन्न करने में सक्षम हैं। ऐसी वेवगाइड संरचनाओं में उच्च अपवर्तक–सूचकांक–कंट्रास्ट द्वारा सक्षम व्यापक वर्ण–विक्षेपण इंजीनियरिंग क्षमताओं को विभिन्न क्वांटम अनुप्रयोगों के लिए उपयोगी, गैर–चिरसम्मत फोटोनिक अवस्था के उत्पन्न को दिखाने के लिए प्रभावी ढंग से उपयोग किया जाता है। हम 220–nm की मानक फिल्म मोटाई के साथ SOI नैनोवेवगाइड के लिए डिज़ाइन प्रस्तुत करते हैं जो निरंतर–बैंड चरण मिलान का उपयोग करके लगभग पूरे टेलीकॉम स्पेक्ट्रम ($\sim$1250–1750 nm) में फैले उज्ज्वल आवृत्ति–सहसंबद्ध फोटॉन जोड़े उत्पन्न कर सकते हैं। हमने सैद्धांतिक रूप से आवृत्ति में शुद्ध हेराल्ड एकल फोटॉनों की सशर्त तैयारी को प्रदर्शित करने के लिए, पंप और उत्पन्न फोटॉन के बीच समूह–वेग मिलान के अलावा, पंप से दूर अलग किए गए असतत चरण–मिलान वाले साइडबैंड का भी उपयोग किया। हमने मानक SOI वेवगाइड्स में टेलीकॉम रेंज के ओ–, ई– और एस–बैंड में फिल्टर–मुक्त आवृत्ति रूप से शुद्ध (शुद्धता $> 95\%$) के निकट–आदर्श एकल फोटॉनों की ट्यून करने योग्य उत्पन्न का प्रस्ताव रखा। उपकरणों का उपयोग सीधे रैखिक ऑप्टिकल क्वांटम कंप्यूटिंग (LOQC) नेटवर्क और क्वांटम कुंजी वितरण (QKD) प्रोटोकॉल तैयार करने और मापने में किया जा सकता है। फोटॉन की स्वतंत्रता की एक और डिग्री तक विस्तार करते हुए, हमने गैर–मानक 280–nm मोटाई के साथ SOI वेवगाइड में 1550 nm के आसपास तरंग दैर्ध्य की एक विस्तृत ($\sim$ 100 nm) रेंज पर लगभग पूर्ण ध्रुवीकरण–इनटंगल हुए फोटॉन जोड़े की संभावित उत्पन्न का प्रदर्शन किया। यह दिखाने के लिए ध्रुवीकरण मोड (PMD) के प्रभाव का भी अध्ययन किया गया है कि अपेक्षाकृत संकीर्ण पंप बैंडविड्थ ($<$10 GHz) का उपयोग अभी भी 7 mm तक की वेवगाइड लंबाई पर इनटंगलमेंट बनाए रख सकता है। ब्रॉडबैंड इनटंगलमेंट (आवृत्ति और ध्रुवीकरण) उत्पन्न के लिए इन आशाजनक cm–स्केल उपकरणों को आवृत्ति मल्टीप्लेक्सिंग के माध्यम से मल्टी–चैनल QKD में कुशलतापूर्वक नियोजित किया जा सकता है, जिससे क्वांटम संचार में डेटा दरों में सुधार होगा। इसके अलावा, हमने सिलिकॉन वेवगाइड में क्वांटम सहसंबंध में बाइफोटोन की गुणवत्ता पर रैखिक बिखरने के नुकसान और दो–फोटॉन अवशोषण (TPA) और मुक्त वाहक अवशोषण (FCA) जैसे गैर–रैखिक नुकसान के कारण प्रेरित लैंग्विन नॉइज़ के प्रभाव की गणना के लिए एक अर्ध–चिरसम्मत संख्यात्मक मॉडल प्रस्तुत किया। हमारा मॉडल पिछले विश्लेषणात्मक मॉडल की तुलना में अधिक सामान्य है, विशेष रूप से वर्ण–विक्षेपण और तरंग दैर्ध्य–निर्भर हानियों को शामिल करने के लिए, और ऑप्टिकल पैरामीट्रिक एम्पलीफायरों और स्कुईज़ी अवस्था उत्पन्न जैसे उच्च–फोटॉन–फ्लक्स में नॉइज़ अनुमान के लिए अधिक सटीक है।

निष्कर्ष के तौर पर, थीसिस विविध टेलीकॉम–बैंड क्वांटम अवस्था की पीढ़ी उत्पन्न के लिए SFWM–आधारित स्रोतों के लिए सरल डिजाइन का प्रस्ताव करती है, जिन्हें सैद्धांतिक रूप से क्वांटम लॉजिक

संचालन को लागू करने या कम–नुकसान वाले सिलिका ऑप्टिकल फाइबर के माध्यम से संचार के लिए गुप्त कुंजी वितरित करने के लिए नियोजित किया जा सकता है। क्वांटम फोटोनिक अवस्थाओं की प्रत्यक्ष उत्पन्न फोटॉन को हेराल्डिंग या इनटंगलेमेंट के लिए अपेक्षाकृत जटिल पोस्ट–प्रोसेसिंग तकनीकों के विपरीत प्रस्तावित है। थीसिस एकल चिप पर एकल/इनटंगल हुए फोटॉन में हेरफेर करने के अंतिम लक्ष्य की दिशा में एक महत्वपूर्ण प्रगति है जो प्रकाश स्रोत, क्वांटम अवस्था उत्पन्न के लिए वेवगाइड, फ़िल्टरिंग डिवाइस, मॉड्यूलेटर और एकल–फोटॉन डिटेक्टरों को एकीकृत करता है।

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List of Abbreviations and Acronyms

ASGVM	**As**ymmetric **G**roup-**V**elocity **M**atching
BOX	**B**urried **Ox**ide
BWF	**B**iphoton **W**ave **F**unction
CAR	**C**oincidental-to-**A**ccidental **R**atio
CE	**C**onversion **E**fficiency
CMOS	**C**omplex **M**etal-**O**xide **S**emiconductor
EBL	**E**lectron **B**eam **L**ithography
EDFA	**E**rbium **D**oped **F**iber **A**mplifier
FCA	**F**ree **C**arrier **A**bsorption
FC	**F**iber **C**oupler
FWHM	**F**ull **W**idth **H**alf **M**aximum
FWM	**F**our-**W**ave **M**ixing
GVD	**G**roup-**V**elocity **D**ispersion
GVM	**G**roup-**V**elocity **M**atching
JSA	**J**oint **S**pectral **A**mplitude
JSI	**J**oint **S**pectral **I**ntensity
LOQC	**L**inear **O**ptical **Q**uantum **C**omputing
OSA	**O**ptical **S**pectrum **A**nalyzer
PC	**P**olarization **C**ontroller
PEF	**P**ump **E**nvelope **F**unction
PMF	**P**hase **M**atching **F**unction
PMD	**P**olarization **M**ode **D**ispersion
QIC	**Q**uantum **I**nformation and **C**ommunication
QKD	**Q**uantum **K**ey **D**istribution

RIE	**R**eactive **I**on **E**tching
SEM	**S**canning **E**lectron **M**icroscope
SFWM	**S**pontaneous **F**our-**W**ave **M**ixing
SGVM	**S**ymmetric **G**roup-**V**elocity **M**atching
SOI	**S**ilicon-**o**n-**I**nsulator
SPDC	**S**pontaneous **P**arametric **D**own **Conversion**
SpRS	**Sp**ontaneous **R**aman **S**cattering
SVD	**S**ingular **V**alue **D**ecomposition
TE	**T**ransverse **E**lectric
TM	**T**ransverse **M**agnetic
TPA	**T**wo-**P**hoton **A**bsorption
WDM	**W**avelength **D**ivision **M**ultiplexing

List of Symbols

ω	Angular frequency
ν	Frequency
c	Speed of light in vacuum
λ	Wavelength
χ	Electric susceptibility
$\vec{\mathrm{k}}$	Wavevector in free space
β	Propagation constant inside the waveguide
n_2	Nonlinear Kerr coefficient
$\mathrm{n}_{\mathrm{eff}}$	Effective refractive index
$\mathrm{A}_{\mathrm{eff}}$	Effective mode area
β_1	Inverse group velocity
β_2	Group-velocity dispersion
β_4	Fourth-order dispersion
ψ	Quantum state
F	Joint spectral amplitude
S	Joint spectral intensity
α	Linear scattering loss
γ	Effective nonlinearity
$\Delta\beta$	Phase mismatch
L	Waveguide length
P_{p}	Pump power
σ_{p}	Pump bandwidth
θ_{si}	Phase-matching function angle with the signal axis
$\widehat{a}$	Annihilation operator
$\mathrm{g}^{(2)}$	Normalized second-order correlation
K	Schmidt mode number

P	Spectral purity
C	Concurrence
β_{TPA}	TPA coefficient
α_{FCA}	FCA coefficient