Final report for project "Quantum communication based on next-generation optical fibers"
Ceniit – 2018-2024

• A summary of the most important scientific results.

The project has directly funded several scientific results in the area of quantum communication and foundations of quantum information employing few-mode optical fibers. We have demonstrated the propagation, dynamic generation and measurement of orbital angular momentum (OAM) quantum states all done within optical fibers, having important consequences for quantum communication using spatially-encoded quantum states. This was my initial plan to carry out when the project began.

However other opportunities arose, and I pursued them expanding the applications covered by the project. One notable case was the demonstration of quantum random number generators using OAM quantum states with few-mode fibers and perovskite light emitting diodes. The project was also extended to the certification of entanglement using photonic integrated circuits. A final new area of expansion has been the development of a storage device for photonic quantum states based on a poled fiber phase modulator, done in collaboration with RISE. This last result is very promising as a way to develop storage buffers for the quantum internet, and we will continue to work on this project.

The project has also been instrumental in establishing the quantum technologies laboratory at ISY.

• A summary of the degrees and promotions the project has contributed to.

The project allowed me to obtain the degree of Docent in Information Coding in 2020, as well as to submit an application (currently under external review as of March 2025) to Senior Associate Professor.

• A summary of the masters thesis works that have been performed within the project.

Multiple theses have been carried out in the project. The following have focused on quantum communication using few-mode fibers:

- Jakov Krniv, M. Sc. Student in Applied Physics, "Investigation of Multimode Interference in Heterogeneous Fiber Structures", defended June 2024.
- Hilma Karlsson, M. Sc. Student in Applied Physics "Space-Division-Multiplexing Platform for a Delayed-Choice Experiment", defended 13th June 2023.
- Oscar Pihl, M. Sc. Student in Applied Physics "Characterization and Stabilization of Transverse Spatial Modes of Light in Few-Mode Optical Fibers", defended 13th June 2023.
- Daniel Spegel-Lexne, M. Sc. Student in Applied Physics, "Design and Construction of a Multi-Port Beamsplitter Based on Few-Mode-Fibers", defended 23rd May 2022.

The following have been done on security aspects of information, with the research work done at Sectra Communications, part of the industrial collaboration of this project:

- Markus Alvila, M. Sc. Student in Electrical Engineering and Applied Physics, "A Performance Evaluation of Post-Quantum Cryptography in the Signal Protocol", 07th June 2019. 30 credits.
- Henning Gideskog, M. Sc. Student in Applied Physics, "Viability of Post Quantum Digital Signatures on Field Programmable Gate Arrays", defended 11th June 2024. 30 credits.
- Viktor Lindström, M. Sc. Student in Applied Physics, "Near-interface Cryptography and its Applications on Modern Communication Platforms", defended 11th June 2024. 30 credits.

• A summary of persons funded by the project.

The project has partially funded the PI's own time (between 10-20% on average during the project), and about 30% of the time of Joakim Argillander over two years of his PhD work, working on quantum random number generation with few-mode fibers.

• A summary of which industrial connections the project has had and how scientific results have been transferred to the industrial partners. In those cases where scientific results have directly affected commercial products, this should be emphasized.

During the project I have kept close contact with Niklas Johansson, research manager at Sectra Communications as well as Adjunct Assistant Lecturer (20%) at ISY, where we have discussed the possible interest of Sectra on quantum random number generators. The research performed was then optimized to produce devices that could be small enough to be potentially be useful for Sectra. More specifically effort was done in this direction together with the group of Feng Gao at IFM to develop a generator based on perovskite materials. Unfortunately, this work has not progressed much due to a lack of needed funding. We are currently looking for other funding opportunities.

• A summary of connections with other CENIIT projects and possible common results.

I am currently collaborating with Onur Günlü (project 23.01), where we are trying new security metrics for quantum communication devices based on information theoretical methods. We are currently jointly applying for other funding opportunities to carry out this research.

• A description of the extent the project has contributed to creating a new research group.

This project's start coincided shortly after my arrival at LiU, when I began establishing the quantum technologies laboratory. Zenith's funding has been instrumental in allowing the creation of a new experimental group on quantum technologies at ISY and LiU, which did not exist before my arrival. The funding obtained in this project, allowed me to fund partially my time, allowing me to dedicate more for experimental research, as well as funding some of the equipment needed in the lab, and partial time of one of my PhD students. Furthermore with the Zenith funding I was able to secure additional funding in the form of a QuantERA project (part of the EU ERA-NET programs), where I was the coordinator, VR and Vinnova funding.

• A list of publications and patents.

Peer reviewed articles:

1. D. Spegel-Lexne, S. Gómez, J. Argillander, M. Pawłowski, P. R. Dieguez, A. Alarcón, **G. B. Xavier**, "Experimental demonstration of the equivalence of entropic uncertainty with wave-particle duality", Science Advances **10**, adr2007 (2024).

2. F. B. L. Santagiustina, C. Agnesi, A. Alarcón, A. Cabello, **G. B. Xavier**, P. Villoresi and G. Vallone, "Experimental post-selection loophole-free time-bin and energy-time nonlocality with integrated photonics", Optica **11,** 498 (2024).

3. A. Alarcón, S. Gómez, D. Spegel-Lexne, J. Argillander, J. Cariñe, G. Cañas, G. Lima and **G. B. Xavier**, " All-in-fiber dynamic orbital angular momentum mode sorting", ACS Photonics 10, 3700 (2023).

4. J. Argillander, A. Alarcón, C. Bao, C. Kuang, G. Lima, F. Gao and **G. B. Xavier**, ”Quantum random number generation based on a perovskite emitting diode”, Communications Physics **6**, 157 (2023).

5. A. Alarcón, J. Argillander, D. Spegel-Lexne and **G. B. Xavier**, “Dynamic Generation of Photonic Spatial Quantum States with an All-Fiber Platform”, Optics Express **31**, 10673 (2023).

6. S. Sarmiento, S. Etcheverry, J. Aldama, I. H. Lopez, L. T. Vidarte, **G. B. Xavier**, D. A. Nolan, J. S. Stone, M. J. Li, D. Loeber and V. Pruneri, "Continuous-Variable Quantum Key Distribution over 15 km Multi-Core Fiber", New Journal of Physics **24**, 063011 (2022).

7. J. Argillander, A. Alarcón and **G. B. Xavier**, "A tunable quantum random number generator based on a fiber-optical Sagnac interferometer", Journal of Optics **24**, 064010 (2022).

8. A. Alarcón, J. Argillander, G. Lima and **G. B. Xavier**, ”Few-mode fibre technology fine-tunes losses in quantum communication systems”, Physical Review Applied **16,** 034018 (2021).

9. J. Cariñe, S. Gómez, G. F. Obregón, E. S. Gómez, M. Figueroa, G. Lima and **G. B. Xavier**, “Post-measurement adjustment of the coincidence window in quantum optics experiments”, IEEE Access **9**, 94010 (2021).

10. P. Mironowicz, G. Cañas, J. Cariñe, E. S. Gómez, J. F. Barra, A. Cabello, **G. B. Xavier**, G. Lima and M. Pawlowski, “Quantum randomness protected against detection loophole attacks”, Quantum Information Processing **20**, 1 (2021).

11. A. Alarcon, P. Gonzalez, J. Carine, G. Lima and **G. B. Xavier**, “Polarization-independent single-photon switch based on a fiber-optical Sagnac interferometer for quantum communication networks”, Optics Express **28**, 33731 (2020).

12. R. Lin, A. Udalcovs, O. Ozolins, X. Pang, L. Gan, M. Tang, S. Fu, S. Popov, T. Ferreira da Silva, **G. B. Xavier**, and J. Chen, ``Telecommunication Compatibility Evaluation for Co-existing Quantum Key Distribution in Homogenous Multicore Fiber", IEEE Access **8**, 78836 (2020).

13. J. Carine, G. Canas, P. Skrzypczyk, I. Supic, N. Guerrero, T. Garcia, L. Pereira, M. A. S.-Prosser, **G. B. Xavier**, A. Delgado, S. P. Walborn, D. Cavalcanti and G. Lima, ``Multi-port beamsplitters based on multi-core optical fibers for high-dimensional quantum information", Optica **7**, 542 (2020).

14. **G. B. Xavier** and G. Lima, “Quantum information processing with space-division multiplexing optical fibres”, Communications Physics **3**, 9 (2020).

Conference papers:

1. M. Clason, J. Argillander, D. Spegel-Lexne and **G. B. Xavier**, “Visibility of a 220 km Long Deployed Optical Fiber Sagnac Interferometer”, accepted as an oral presentation at CLEO 2025.

2. J. Argillander, D. Spegel-Lexne, M. Clason and **G. B. Xavier**, “Quantum Random Number Generator With Spatially Encoded Photonic Qutrits”, accepted as a poster presentation at CLEO 2025.

3. “D. Spegel-Lexne, JMB Pereira, A. Alarcon, J. Argillander, M. Clason, Å. Claesson, K. H. Tow, W. Margulis and **G. B. Xavier** “Storage Buffer of Polarization Quantum States Based on a Poled-Fiber Phase Modulator”, accepted as an oral presentation at CLEO 2025.

4. J. M. B. Pereira, D. Spegel-Lexne, A. Alarcón, O. Tarasenko, Å. Claesson, K. H. Tow, W. Margulis, and **G. B. Xavier**, "All-fiber Optical Pulse Storage Using Poled Fiber Modulators," in CLEO 2024, Technical Digest Series (Optica Publishing Group, 2024), paper SM1B.1.

5. S. Gómez, D. Spegel-Lexne, J. Argillander, H. Karlsson, M. Pawłowski, P. R. Dieguez, A. Alarcón, and **G. B. Xavier**, "Orbital Angular Momentum Wave-Particle Duality in a Few-Mode Optical Fiber Platform," in CLEO 2024, Technical Digest Series (Optica Publishing Group, 2024), paper JW2A.134.

6. J. Argillander, A. Alarcón, C. Bao, C. Kuang, G. Lima, F. Gao and **G. B. Xavier**. “Secure quantum random number generation with perovskite photonics”, Proceedings Volume 12911, Quantum Computing, Communication, and Simulation IV, SPIE Quantum West, 129111B (2024)

7. A. Alarcon, J. Argillander, D. Spegel-Lexne and **G. B. Xavier**, “Quantum Random Number Generation Based on Spatial Modal Superposition over Few-Mode-Fibers”, Frontiers in Optics, paper JTu5A.28 (2022).

8. J. Argillander, A. Alarcon and **G. B. Xavier**, “All-fiber Dynamically Tunable Beamsplitter for Quantum Random Number Generators”, Latin America Optics and Photonics Conference, paper Th1A.2 (2022).

9. **G. B. Xavier**, "Quantum Communications", XXXIX Brazilian Symposium on Telecommunications and Signal Processing, Fortaleza 26-29 September 2021, **Invited Tutorial**.

10. **G. B. Xavier**, I workshop on quantum communication and computation (WQuantum), part of the XXXIX Brazilian Symposium on Computer Networks and Distributed Systems, Uberlandia – Brazil, 16-20th August 2021. **Invited speaker.**

11. A. Alarcon, J. Argillander and **G. B. Xavier**, "Creating spatial states of light for quantum information with photonic lanterns", Optica (Formerly Optical Society of America – OSA) Applied Industrial Optics, July 2021, held in hybrid mode, Washington DC, paper W2A.2.

12. A. Alarcon and **G. B. Xavier**, “A few-mode Mach-Zehnder interferometer for quantum communication applications”, OSA Frontiers in Optics + Laser Science APS/DLS 2020, held virtually, 14th-17th September 2020, paper LM1F.6

13. **G. B. Xavier**, “Quantum communication with optical fibers”, Optics, Photonics and Upcoming Methods & Applications (OPUMA) 2019 conference, 29th July – 2nd August, Ciudad de Mexico, Mexico. **(Invited speaker)**.

14. **G. B. Xavier**, “Quantum information with multi-core fibers”, Workshop on Information Optics 2019, 1st-5th July 2019, Stockholm, Sweden. **(Invited speaker)**.

15. R. Lin, L. Gan, A. Udalcovs, O. Ozolins, X. Pang, L. Shen, S. Popov, M. Tang, S. Fu, W. Tong, D. Liu, T. Ferreira da Silva, **G. B. Xavier** and J. Chen, “Spontaneous Raman Scattering Effects in Multicore Fibers: Impact on Coexistence of Quantum and Classical Channels”, 2019 Optical Fiber Communications Conference and Exhibition (OFC), 3rd-7th March 2019, San Diego, USA, Paper M4C.2.

16. R. Liu, A. Udalcovs, O. Ozolins, X. Pang, L. Gan, L. Shen, M. Tang, S. Fu, S. Popov, C. Yang, W. Tong, D. Liu, T. Ferreira da Silva, **G. B. Xavier**, and J. Chen, "Telecom Compatibility Validation of Quantum Key Distribution Co-existing with 112 Gbps/**λ**/core Data Transmission in Non-Trench Multicore Fiber", European Conference on Optical Communication (ECOC) 2018, 23rd-27th September 2018, Rome, Italy, Paper We1A.3.