Selected Research Cover Letter——On-chip Quantum Communication for the Quantum Internet

My research focuses on advancing quantum information science through integrated quantum photonics and its applications in secure communication, sensing, and information processing. I aim to transform foundational breakthroughs in quantum physics into practical, scalable technologies. For the large-scale secure deployment of communication and sensing integrated quantum resources in the quantum internet, my research focuses on three areas: high-performance on-chip continuous-variable quantum communication devices and system mechanisms, quantum-secure semi-device-independent on-chip quantum random number generation, and the practical security of quantum resources.

I. High-Performance On-Chip Continuous Variable Quantum Key Distribution for the Quantum Internet

(1) 100 km-Level Continuous Variable Quantum Key Distribution Based on On-Chip Light Sources

Integrated photonic chips for quantum key distribution (QKD) offer high scalability and stability, making them a promising solution for the construction of global quantum communication networks. The integration of on-chip quantum light sources has been a key challenge for fully integrated QKD systems, particularly for continuous variable quantum key distribution (CV-QKD) systems that rely on coherent detection, which demands extremely stringent requirements for light sources. Since the GG02 protocol was proposed 20 years ago, the challenge of integrating light sources has persisted. Through fundamental mechanism and technological innovations, I have, for the first time, proposed and realized two on-chip tunable lasers suitable for CV-QKD, building a high-performance quantum key distribution system. Benefiting from high output power, fine tunability, and narrow linewidth, this system ensures precise shot-noise-limited detection of quantum signals, wavelength alignment of the non-homodyne lasers, and suppression of untrusted excess noise. The system achieves a real-time secure key rate of 0.75 Mb/s over 50 km of optical fiber and a secure transmission distance of over 100 km.

Specifically, I proposed a novel approach to integrate continuous variable quantum light sources for local local oscillator (LLO)-CV-QKD systems on a chip. First, by utilizing III-V materials on silicon nitride and a new mechanism based on the detuning load effect, a feedback loop structure was developed to narrow the Lorentzian linewidth to about 2 kHz, meeting the stringent requirements for precise control and evolution of quantum states on a chip. Second, Vernier microring resonators were used for highly efficient mode filtering, with a long-range tunability of over 70 nm and a continuous fine-tuning resolution of 30 GHz, achieving a side-mode suppression ratio of up to 75 dB. This overcame the challenge of aligning the slight frequency difference between non-homodyne quantum states and the local oscillator over long distances. Third, by utilizing silicon nitride as the waveguide material, which has low loss and a high nonlinear threshold, we achieved an on-chip output power of up to 47.3 mW, overcoming the power damage limitations of traditional materials like lithium niobate. Supported by these innovations, the system achieved a real-time secure key rate of 0.75 Mbps over a 50 km optical fiber distance and a 0.14 kbps key rate over 100 km.

This work was published as the cover article in the top-tier journal Photonics Research (IF: 7.254), where it was selected as a cover feature by the journal's editor, IEEE/AAAS/APS Fellow and Washington University professor Lan Yang. This breakthrough has also been positively cited by Austrian Academy of Sciences member and APS/OSA Fellow Professor Philip Walther, Danish quantum physicist Professor Tobias Gehring, Academician Peng Kun-Chi from Shanxi University’s State Key Laboratory of Quantum Optics and Quantum Devices, and was featured in the Peking University-Huawei Quantum Lab white paper. Additionally, this work was cited by Light: Science & Applications (IF: 27.2) and Applied Physics Reviews (IF: 11.9), and was covered by major media outlets such as Tencent News, Sohu, Sina Weibo, and the Chinese Laser Press. It was also selected for display by the National Key Laboratory of Optical Fiber Communication Networks and New Optical Communication Systems as part of their "14th Five-Year Plan Key Achievements" during its “Science and Technology Open Week.”

(2) Fully Integrated Continuous Variable Quantum Key Distribution Chip

Continuous variable quantum key distribution (CV-QKD) offers advantages such as high channel capacity and strong compatibility with existing optical communication infrastructure, making it a key technology for quantum secure communication. Quantum photonic technology presents a promising solution for developing low-cost, miniaturized, portable, scalable, and highly stable CV-QKD systems. However, achieving high performance and security with fully integrated CV-QKD chips remains a significant challenge. This study reports the latest advances in the practical security, high-performance light source integration, and optoelectronic integration of on-chip CV-QKD systems. This work was presented as an invited talk at the 2023 PIERS conference and was published as a first-author paper.

II. High-Security On-Chip Quantum Random Number Generation for the Quantum Internet

(3) High-Speed Source-Device-Independent Quantum Random Number Generator Chip

Quantum resources inherently provide true randomness, which has significant applications in cryptography, scientific simulations, and computing. Silicon photonic chips offer a superior platform for the large-scale, low-cost deployment of next-generation quantum systems. However, the potential vulnerabilities of chips can pose security challenges, particularly the risk of hacking, which threatens the secure generation of quantum random numbers. I proposed and implemented the first on-chip source-device-independent quantum random number generator (SDI-QRNG), which ensures system security through distortion-free detection of quantum resources, successfully eliminating classical noise interference. In actual chip environments, I introduced on-chip criteria to estimate secure entropy, ensuring system security. The SDI-QRNG chip achieved a secure bit rate of 146.2 Mbps in a packaged system and 248.47 Gbps on a bare chip, with all extracted secure bits passing the NIST randomness tests.

This innovation solves the challenge of securely extracting intrinsic randomness from quantum resources for large-scale quantum network deployments and further supports the development of new devices, such as field-deployed continuous variable quantum communication chips. This work was published in Photonics Research as the cover article and was selected as Editor’s Pick by IEEE Fellow Lan Yang. It was also featured on the homepage of Shanghai Jiao Tong University’s official website, alongside news of SJTU students Sun Yingsha and Wang Chuqin winning gold at the 2024 Paris Olympics. Additionally, this work was widely covered by media outlets such as Quantum Insider and China Laser Press, marking a significant breakthrough in the field of quantum random number generator chips.

III. Practical Security Research on On-Chip Quantum Resources for the Quantum Internet

(4) Practical Security of On-Chip Continuous Variable Quantum Key Distribution

The integration of on-chip CV-QKD systems is a key technological route for building high-performance, low-cost quantum key distribution systems, with significant potential for constructing quantum metropolitan networks. However, as systems shrink down to the micro- and nanoscale, many macroscopic physical effects could pose potential security risks. I investigated the practical security of on-chip CV-QKD systems at both the source and detection ends, revealing that the imperfections of chip modulators could threaten system security. I proposed two preliminary countermeasures to address these issues. This work was published as a first-author paper in Physical Review A and was listed as a global significant advancement by QuantumCTek. This work was also highly praised by Quantum Insider, which stated that it "pioneered the practical security research of on-chip quantum key distribution systems."

(5) Forced Carrier Perturbation Opens a Loophole for On-Chip Continuous Variable Quantum Key Distribution Systems

At the detection end, my research demonstrated that forced carrier perturbation could lead to security risks in on-chip CV-QKD systems. In traditional studies, the quantum efficiency of detectors is often assumed to be constant. However, in on-chip systems, due to waveguide inhomogeneity and free-carrier absorption, the quantum efficiency dynamically changes. I proposed a detector model based on chips, showing through simulations that changes in quantum efficiency could reduce system security. I also proposed two countermeasures to address this issue. This research was published in Optics Express, breaking the traditional assumption that detector quantum efficiency can be pre-calibrated, and suggested stricter consideration of practical security in the development of on-chip CV-QKD systems.