On the Modeling of Quantum Photonic and Electronic Devices

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Abstract

Quantum electronic and photonic devices form the foundation of emerging technologies in quantum communication, sensing, and computing. This talk outlines their theoretical modeling, focusing on two distinct device platforms: quantum cascade lasers (QCLs) as mid-infrared and terahertz light sources, and superconducting traveling-wave parametric amplifiers (TWPAs) for qubit readout in circuit quantum electrodynamics. QCLs show strong potential for applications in free-space optical communication and spectroscopy. We introduce self-consistent modeling approaches that combine quantum transport with classical electromagnetics to accurately capture charge carrier dynamics and optical field generation. Our recent work advances the understanding of frequency comb formation and soliton dynamics in QCLs, enabling compact, low-power spectrometer designs. In parallel, we develop second-quantized models of superconducting TWPAs, key components for high-fidelity, single-shot qubit readout in superconducting quantum computers. By analytically describing nonlinear wave-mixing and dispersion effects, these models show excellent agreement with experimental observations and yield valuable insights into the amplifier's quantum noise performance. Together, these efforts reveal fundamental physical parallels between photonic and electronic quantum systems and support the development of next-generation quantum technologies.

Bio

Michael Haider received an engineer's degree in electrical engineering from the HTL Salzburg, Austria, in 2010. From 2011 to 2014, he studied electrical and computer engineering at the Technical University of Munich (TUM), Germany, earning the B.Sc. degree, followed by the M.Sc. degree in 2016. In March 2016, he joined the Institute for Nanoelectronics at TUM as a Research Associate, where his work focused on the theoretical modeling and characterization of stochastic electromagnetic fields. He completed his doctoral degree (Dr.-Ing.) in November 2019 with highest distinction (*summa cum laude*). His dissertation was awarded the VDE ITG Dissertationspreis 2020 for outstanding academic achievement. In April 2019, Dr. Haider joined the Computational Photonics Group at TUM as a group leader and Habilitation candidate. Since October 2023, he has held a permanent position as Senior Staff Scientist (*Akademischer Rat*) and serves as Deputy Group Leader. His work focuses on the theoretical and numerical modeling of quantum photonic and optoelectronic devices. Dr. Haider's research spans optical and microwave regimes and includes applications in quantum optics, photonic device engineering, and quantum information processing. He has developed stochastic quantum methods for modeling coherent and dissipative light–matter interactions, with emphasis on charge-carrier dynamics in quantum cascade lasers and nonlinear optical processes. A major focus of his work is the modeling of superconducting quantum systems, particularly the microwave signal amplification chain used in qubit readout. He investigates and optimizes traveling-wave parametric amplifiers, accounting for realistic imperfections such as losses, noise, and impedance mismatches. Dr. Haider has led several research projects, including the modeling of non-classical light emission from quantum cascade lasers in the mid-infrared and terahertz regimes, the development of stochastic phase-space approaches for quantum photonic devices, the quantum modeling of superconducting amplifier chains, and symbolic-numeric co-simulation techniques for Bosonic quantum systems. He has strong expertise in numerical simulation, analytical methods, and symbolic computation, with applications ranging from time-domain modeling and stochastic differential equations to perturbative and hybrid quantum–classical approaches. Dr. Haider has co-authored more than 100 scientific publications in journals and conference proceedings. He regularly reviews for renowned journals and conferences in quantum optics, photonics, and microwave engineering. He has also successfully organized workshops at major MTT-S and AP-S events. His work is frequently presented at international conferences across photonics, quantum electronics, and applied physics. He is a member of the IEEE and actively collaborates across disciplines at the intersection of engineering and quantum science.

Host

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