ABSTRACT

This thesis presents developments in quantum information technologies and their applications to both quantum networks and fundamental physics. It is organized into three parts. Part I focuses on the design and implementation of state-of-the-art sources and detectors for quantum networks. Key contributions include the development of photon-number-resolving superconducting nanowire detectors and their application to heralded single-photon generation and photon-number discrimination; a high-rate multiplexed entangled photon-pair source for quantum key distribution; and on-chip balanced homodyne detectors for the detection of squeezed light. I describe how phased arrays can facilitate wireless quantum communications by introducing the concept of "quantum phased arrays" and present the first large-scale optoelectronic phased array receiver on a chip capable of interfacing with nonclassical light, with first demonstrations of coherent imaging and beamforming of squeezed states of light. Part II details the construction of quantum network testbeds at Caltech and Fermilab, designed to realize scalable architectures for the quantum internet. These systems demonstrate high-fidelity quantum teleportation over 45 km of optical fiber and entanglement swapping with time-bin qubits. The experiments are supported by the development of theoretical models that guide system optimization. I also present demonstrations of entanglement distribution at Caltech and remote sites at Fermi and Argonne National Labs with picosecond-level clock synchronization, representing milestones toward the deployment of quantum networking infrastructure across national laboratories. Part III investigates how quantum networks can be used to probe fundamental questions in physics. I report the first experimental generation of GHZ states with time-bin qubits, towards the deployment of multipartite entanglement distribution in real-word networks for tests of quantum mechanics and distributed sensing. Finally, I present the first experimental realization of a traversable wormhole teleportation protocol implemented on a quantum processor, a step in the program of quantum gravity in the lab. I conclude with an outlook and discuss future directions of this work.