

# Integrated Photonics and Metasurfaces for Quantum Computing and Sensing

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Optical control of quantum matter from trapped atoms and ions to quantum dots and defects is foundational for quantum information science and technology. We present our work on scalable, robust, and multifunctional nanophotonic interfaces to trap neutral atoms or address trapped ions. Our platform combines metasurfaces with integrated photonics to replace bulk optical elements in a batch-fabricated microsystem, ultimately enabling cold atom clocks and quantum computers. Metasurfaces are ultrathin, planar arrays of subwavelength resonators providing precise, spatially-varying control over phase and amplitude within a single lithographic layer. Complex wavefront transformations – beam shaping, tight focusing, and polarization conversion – are realized in CMOS-compatible components with multi-functional capability within a single layer. For trapped-ion quantum computing, photonic integrated circuits route light to individual ions via on-chip waveguides, with metasurface elements providing beam shaping, polarization control, and NA-matched focusing directly above trap electrodes. This enables multi-wavelength functionality – simultaneously handling Doppler cooling, qubit manipulation, and state detection – while metasurface-based fluorescence collection removes the need for large, high-NA objectives. For neutral atom quantum computing, we integrate high-NA dielectric metasurfaces to deterministically generate tweezer arrays of over 10,000 sites from a single engineered wavefront, achieving trap depth uniformity and intensity homogeneity critical for consistent gate fidelities. In atomic clock architectures, metasurface outcouplers deliver polarization-controlled fields for state preparation and narrow-line cooling within a single planar element. To address the challenging inverse design problem of satisfying multi-objective constraints simultaneously, we apply reinforcement learning to navigate the high-dimensional nanostructure parameter space, demonstrated in designing metasurfaces for a miniaturized magneto-optical trap.

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