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High-Dimensional Spatial-Mode Quantum Logic Gates

RESEARCHERS

Kangrui Wang, **Dawei Lyu**, **Qianke Wang**, **Chengkun Cai**, **Tianhao Fu**, **Jue Wang**, **Jun Liu** (jun_liu@hust.edu.cn) and **Jian Wang** (jwang@hust.edu.cn), Huazhong University of Science and Technology, China, and Optics Valley Laboratory, China

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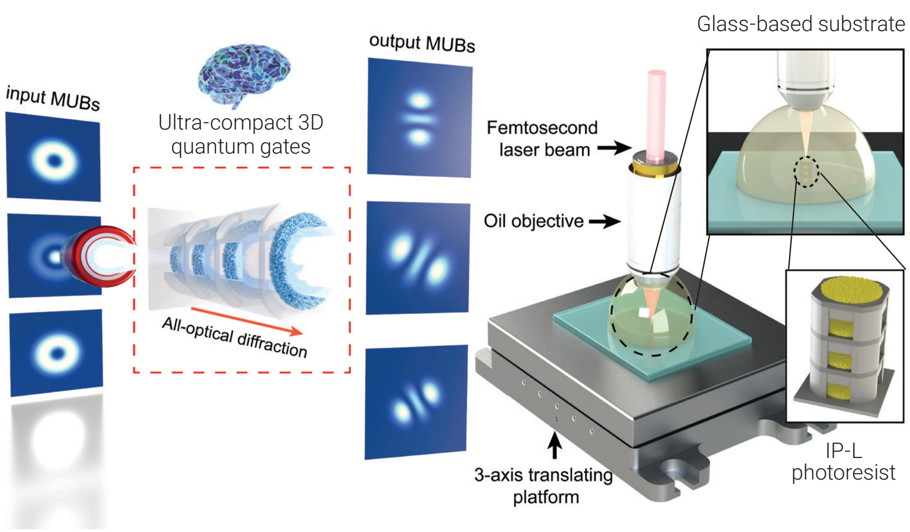
Photons, as robust carriers of quantum bits, are well suited for quantum computing but suffer from weak photon–photon interactions. To overcome this, spatial modes offer a promising degree of freedom for encoding high-dimensional qubits. Diffractive neural networks (DNNs) provide compact and efficient control of photonic states, enabling scalable quantum operations.

We previously introduced a spatial-mode-based quantum gate using DNNs to realize high-fidelity, deterministic and universal transformations. Qubits encoded in spatial modes were manipulated experimentally with a spatial light modulator (SLM), validating this approach.

Building on this framework, we demonstrate high-dimensional quantum gates on SLMs and femtosecond laser–written 3D polymer devices. The DNNs, composed of trainable phase layers, were optimized through computer-based modeling. On the SLM platform, we realized 3D Hadamard, 3D X and CNOT gates with process fidelities above 99%.[1] Furthermore, a compact three-qubit Toffoli gate, encoded in polarization and orbital angular momentum, achieved 97.3% truth table visibility and 94.1% fidelity. These results confirm the feasibility, performance and scalability of DNN-based photonic quantum gates.[2]

In parallel, by combining DNNs with a fabrication method such as femtosecond laser direct writing (FLDW), we can manipulate spatial modes at the micrometer level.[3] Thus, we made a polymer-based multi-plane light converter quantum device using FLDW with two-photon polymerization (TPP), offering submicrometer precision and high alignment accuracy.[4] The device exhibits a lateral pixel size of ~1.58 μm, a feature resolution of ~1.6 μm, and a vertical resolution of 100 nm, with an overall footprint of approximately 160 × 160 × 150 μm³. Its four-layer diffractive structure ensures accurate phase modulation, while scanning electron microscopy confirmed well-defined morphology and layer spacing. Experimental characterization through single-photon quantum process tomography demonstrated the successful implementation of a 3D Hadamard gate, achieving a fidelity of ~90%. This level of performance, previously achievable only in bulky free-space optical systems, is now realized in a micrometer-scale 3D integrated device. By combining ultracompact geometry, high fabrication precision and reliable functionality, the approach not only validates the feasibility of on-chip high-dimensional quantum logic but also establishes a route toward scalable, low-loss and reconfigurable photonic quantum processors for future quantum information technologies, demonstrating high performance and scalability in integrated high-dimensional quantum logic.

By emphasizing device-level integration and ultracompact design, our work advances beyond bulk-optics implementations. Leveraging the abundant dimensional resources of photons, the demonstrated spatial-mode quantum gates provide a novel paradigm for quantum computing. This approach facilitates low-cost, programmable quantum computation and can be employed to validate quantum algorithms and explore complex quantum phenomena. OPN



Left: The high-dimensional quantum gates in photonic spatial modes. Right: TPP-based FLDW fabrication device.