Below-Threshold Error Reduction in Single Photons through Photon Distillation

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Photonic quantum computers use the bosonic statistics of photons to construct, through quantum interference, the large entangled states required for measurement-based quantum computation. Therefore, any which-way information present in the photons will degrade quantum interference and introduce errors. While quantum error correction can address such errors in principle, it is highly resource-intensive and operates with a low error threshold, requiring numerous high-quality optical components. We experimentally demonstrate scalable, optimal photon distillation as a substantially more resource-efficient strategy to reduce indistinguishability errors in a way that is compatible with fault-tolerant operation. Photon distillation is an intrinsically bosonic, coherent error-mitigation technique which exploits quantum interference to project single photons into purified internal states, thereby reducing indistinguishability errors at both a higher efficiency and higher threshold than quantum error correction. We observe unconditional error reduction (i.e., below-threshold behavior) consistent with theoretical predictions, even when accounting for noise introduced by the distillation gate, thereby achieving actual net-gain error mitigation under conditions relevant for fault-tolerant quantum computing. We anticipate photon distillation will find uses in large-scale quantum computers. We also expect this work to inspire the search for additional intrinsically bosonic error-reduction strategies, even for fault-tolerant architectures.

We experimentally demonstrate the distillation of single photons, using an optimal, scalable protocol directly implementable in a fault-tolerant photonic quantum computer. We utilize quantum interference in an integrated silicon-nitride photonic optical circuit with high precision to entangle multiple copies of a state with finite partial distinguishability, and we make a measurement projecting to a single copy of a distilled state. We find a reduction in photon indistinguishability error by a factor of $R = 2.2$, demonstrating that our protocol is running below threshold. Even taking into account the excess noise of our gate, we find an error reduction of $R = 1.2$, demonstrating net-gain error mitigation under realistic conditions, showing this protocol is ready to be implemented in quantum computers. We calculate the effects of implementing this gate in photonic quantum computers, considering currently existing sources. Optimizing the gate for the lowest-indistinguishability photon source reported so far, we estimate a reduction in the total number of photon sources required to construct a logical qubit by a factor of 4. This solution utilizes a combination of QEC and photon distillation, emphasizing the complementarity of the two. Since photon sources are by far the most numerous components of the quantum computer, this combination directly corresponds to an equivalent reduction in the bill of materials. Furthermore, we find that with photon distillation, quantum-dot single-photon sources, which suffer strongly from indistinguishability errors between independent sources, can be reduced to below the error correction threshold.