Minimizing resource overhead in fusion-based quantum computation using hybrid spin-photon devices

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Fault-tolerant quantum computation (FTQC) is indispensable to execute the most impactful quantum algorithms, such as prime factorization and chemical simulations. To achieve fault tolerance, the modularity enabled by photonic architectures is promising: numerous identical, small devices can be fabricated independently and interconnected via photonic links to scale computational power. A leading paradigm for photonic FTQC is fusion-based quantum computing (FBQC) [1], a variant of measurement-based quantum computing where small photonic resource states are first generated then measured jointly in a fusion network. But in photon-based quantum computing, photon loss is the dominant source of error, and FBQC is fault-tolerant only provided that the supplied resource states are produced with a small per-photon loss probability. Designing schemes to generate resource states with minimal resource overhead and minimal loss is thus instrumental in designing an efficient photonic quantum computer.

In this work, we introduce two schemes to construct a resource state useful for FBQC, namely the (2,2)-Shor-encoded 6-ring state. We benchmark these schemes against existing approaches, by estimating their minimal hardware requirements for FTQC in terms of number of photon sources needed to achieve the on-demand generation of the resource state. We show that a group of 12 deterministic single-photon sources containing a single matter qubit degree of freedom can produce the target resource state near-deterministically by exploiting entangling gates that are repeated until success (RUS) [2]. The approach is fully modular, eliminates the need for lossy large-scale multiplexing, and reduces the overhead for resource-state generation by several orders of magnitude compared to architectures using heralded single-photon sources (HSPS) and probabilistic linear-optical entangling gates. Our work shows that the use of deterministic single-photon sources embedding a matter qubit substantially shortens the path towards FTQC with photons.

This submission is based on the preprint [3].

References

[1] S. Bartolucci *et al.*, *Nat. Commun.*, **14** (2023) 912
[2] Y. Lim *et al.*, *Phys. Rev. Lett.*, **95** (2005) 030505
[3] S. Wein *et al.*, arXiv: 2412.08611 (2024)

Figures

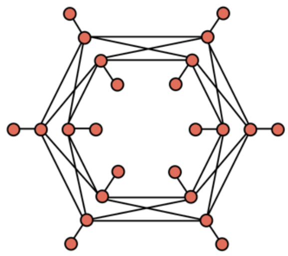

Figure 1: (2,2)-Shor-encoded 6-ring state

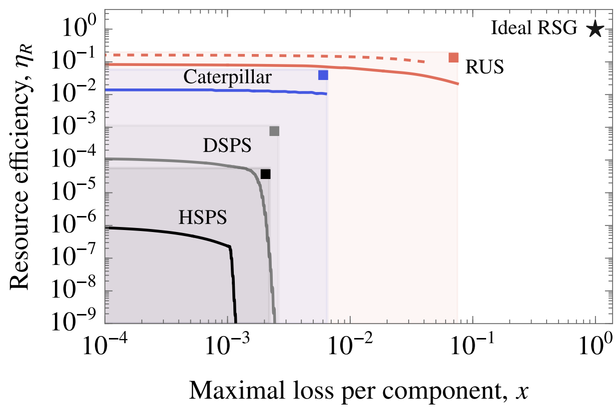

Figure 2: Resource efficiency and maximal loss that each architecture can tolerate when generating the state depicted in Fig. 1. The most efficient one, RUS, tolerates more loss and is at least 5 orders of magnitude more efficient than the standard approach based on HSPS.