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Deterministic Photonic Entangling Quantum Gates

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Abstract: We propose a scheme to realise deterministic two-qubit entangling gates in photonic platforms. Our results provide a pathway towards the realization of a universal quantum computing architecture based on light-matter interactions in polariton systems.

Universal quantum computation (QC) relies on the ability to perform arbitrary single-qubit rotations and two-qubit entangling operations, such as the controlled-NOT (CNOT) gate. In this respect, linear optical networks [1] offer the possibility to realize single-qubit and two-qubit *probabilistic* entangling quantum gates, as in the case of the CNOT gate [2]. Deterministic computing in photonic systems could be possible in the presence of strong photon-photon interactions, such as those observed at the onset of photon-blockade. However, achieving such a strong-interacting regime experimentally remains a significant challenge [3], and experimental demonstrations are still lacking.

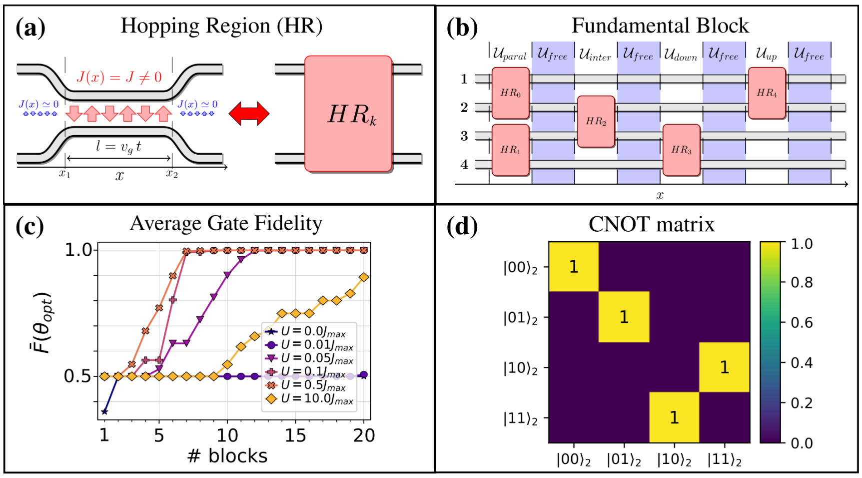

Fig. 1 (a) Hopping Region: polaritons propagating along the x direction are linearly coupled due to proximity interaction between adjacent waveguides. **(b)** Fundamental Block: basic unit used in our scheme to obtain the target two-qubit entangling gate where four waveguides are suitably connected via several hopping regions (HR_k , k=0,1,...,4) . **(c)** Average Gate Fidelity: behavior of the output average gate fidelity as function of the number of blocks used in the parametrized circuit for different values of the Kerr nonlinearity U (J_{max}= 1). **(d)** CNOT matrix: example of the optimal output transfer matrix obtained with our scheme with an average gate fidelity F=99.96% (U=0.5 J_{max} , 12 blocks).

In our study [4] we explore an alternative approach to deterministic QC based on photonic systems with distributed Kerr nonlinearities, a scenario that could be obtained in practice by means of propagating exciton-polaritons. Such hybrid light-matter quasiparticles exhibit strong nonlinearities compared to standard optoelectronics materials, while being amenable to confinement and manipulation in integrated nanophotonic structures. We show that, in the dual-rail encoding paradigm, by carefully designing the linear interactions between a set of waveguides constituting the building block of our circuit (Fig. 1a, b), on the increasing of the number of concatenated blocks it is possible to devise interferometers which implement deterministic two-qubit entangling gates with high-fidelity, for instance the CNOT gate, *e.g.*, Fig. 1 c, d. In particular, the optimized gate implementations exhibit optimal performance for intermediate interaction strengths without requiring access to the photon-blockade regime.

Our findings, combined with the ability to perform arbitrary single-qubit rotations in photonic platforms, provide a pathway towards the realization of a universal quantum computing architecture.

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[2] E. Knill, R. Laflamme, and G. J. Milburn, "A scheme for efficient quantum computation with linear optics", Nature **409**,46–52 (2001).
[3] J. H. Shapiro, "Single-photon Kerr nonlinearities do not help quantum computation", Phys. Rev. A **73**, 062305 (2006).
[4] F. Scala, D. Nigro, and D. Gerace, "Deterministic entangling gates with nonlinear quantum photonic interferometers", Commun Phys **7**, 118 (2024).