Quantum controlled-Z gate for weakly interacting qubits

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Entangling two-qubit quantum gates are essential for universal quantum computing and quantum information processing. However, the available inter-qubit coupling is often only weak and limited by decoherence or other factors. Moreover, in hybrid architectures connecting physically different qubits, one can have only a limited amount of control over one of the systems. Schemes that would allow us to circumvent these obstacles and engineer highly entangling quantum gates under such unfavourable conditions are therefore highly desirable.

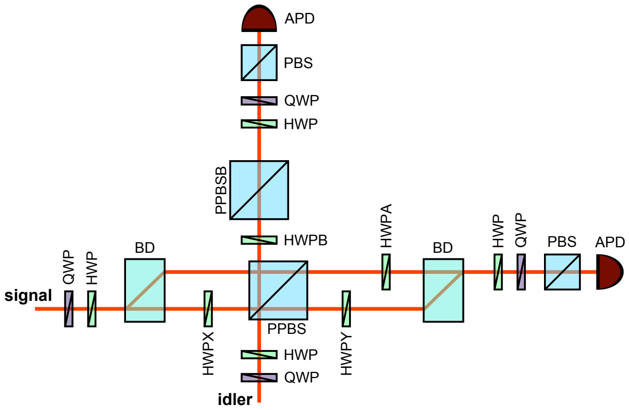

FIG. 1. Experimental setup. HWP - half-wave plate, QWP - quarter-wave plate, PPBS - partially polarizing beam splitter with nominal reflectances $R_V = 1/3$ and $R_H = 0$ for vertical and horizontal polarizations, respectively, PBS - polarizing beam splitter, BD - calcite beam displacer that spatially separates vertical and horizontal polarizations, APD - single-photon detector.

Here we propose and experimentally demonstrate a scheme for conditional implementation of a maximally entangling quantum controlled-Z gate between two qubits whose coupling can be arbitrarily weak. We show that the weak inter-qubit coupling can be enhanced by quantum interference. Both before and after the inter-qubit interaction, one of the qubits is coherently coupled to an auxiliary quantum level, and finally it is projected back onto qubit subspace. Remarkably, this procedure enhances the inter-qubit interaction strength although the coupling to auxiliary quantum level can be considered as a local bypass that allows the qubit to partly avoid the interaction with the other qubit. Since this bypass is introduced only for one of the qubits, the scheme is suitable for hybrid architectures such as atomic clouds or optomechanical oscillators coupled to light, where one of the systems is more difficult to address and manipulate. We explicitly illustrate this general method for two typical and highly relevant inter-qubit interactions: First, a conditional phase shift occurring e.g. in spin-spin coupling, and, second, a beam-splitter type of coupling between two bosonic modes.

We have experimentally demonstrated this technique using a linear optical setup with weak interferometric coupling between single-photon qubits, see Fig. 1. This platform of linear optical quantum gates operating in the coincidence basis [1–5] provides a suitable testbed for verifying the practical feasibility of our method, which is ultimately intended mainly for spin-spin interactions and hybrid configurations exhibiting limited coupling strength between light and matter. The experiment provides a key check of robustness of our procedure against various experimental imperfections and parasitic residual interactions. We characterize the performance of the CZ gate by a Hofmann lower bound [6, 7] on quantum gate fidelity F, and we carry out a complete quantum process tomography [8, 9] of the gate at the optimal operating point where the success probability and gate fidelity are maximized. The experimentally determined gate fidelity $F = 0.846$ is consistent with our theoretical model that accounts for imperfect two-photon interference with visibility $\mathcal{V} = 0.94$ and an imperfection of the central partially polarizing beam splitter PPBS which exhibited a small nonzero reflectance for horizontally polarized photons, while ideally it should be perfectly transmitting for horizontally polarized light.

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