Measurement-induced nonlinearities — an algorithmic way to construct quantum gates from linear-optics networks

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Quantum information processing with light on the single-photon level suffers from the difficulty that arises when one wants two photons to interact with each other. In quantum electrodynamics, this is a fourth-order process in the fine structure constant. Even in nonlinear optics, third-order (Kerr) nonlinearities present in some dielectric media are too small in magnitude to render such processses useful for quantum information purposes.

Despite these fundamental difficulties, there exist intrinsic nonlinearities in projective measurements. These effects have long been used in connection with conditional quantum-state engineering and a vast amount of literature exists on this subject. However, Knill, Laflamme and Milburn were the first who pointed out the potential usefulness of these conditional schemes for quantum information processing.

Our work is concerned with the fundamental question concerning the types of (nonlinear) operators that can be realised with the help of linear-optics networks given restricted resources such as single-photon Fock states and single-photon detectors. We can show that there exist classes of operations that can be realised easily and effectively. Hereby we mean that there exists a constructive algorithm to generate the relevant networks and that the associated conditional probabilities do not necessarily scale exponentially with increasing complexity of the gate operation. All these operators act within single Fock layers, for which the controlled-phase gate and the 'swap' operation are the simplest nontrivial examples. We will argue that, within the framework of linear-optics quantum information processing, it is rather disadvantegeous to focus on the usual information-theoretic set of universal quantum gates which is not at all adapted to the somewhat restricted powers of the unitary networks. As for the generation of specific operations, we restrict ourselves to the experimentally relevant case of single-photon detections and stay away from the highly inefficient vacuum 'detection'. We will explicitly construct particularly useful operations such as the controlled-phase gate and the 'swap' gate, whereby the latter can be easily shown to be deterministic.