Arbitrary d-dimensional Pauli X-Gates of a flying Qudit

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Abstract

High-dimensional degrees of freedom of photons can encode more quantum information than their two-dimensional counterparts. Here we show a method to perform lossless arbitrary high-dimensional Pauli X-gates on the orbital angular momentum of single photon. The number of involved interferometers scales logarithmically with the dimension, which is important for practical implementation. The X-gate consists of a cyclic permutation of qudit basis vectors, and, together with the Z-gate, forms the basis for performing arbitrary transformations.

High-dimensional quantum systems allow for encoding, transmitting and processing more than qubits system. However, performing well-defined manipulations in multilevel systems is significantly more challenging than for qubits. Laguerre-Gaussian modes of light, carrying orbital angular momentum (OAM), represent an alternative to polarization that has been applied a lot in high-dimensional quantum domains. The X gate in high-dimensional Hilbert spaces takes the form of a cyclic permutation of the computational basis vectors. For a fixed basis in a d-dimensional space the cyclic transformation transforms each basis state into its nearest neighbour in a clockwise manner with the last state being transformed back to the first one. While efficient methods for realizing a four-dimensional cyclic transformation in both classical and quantum realms have been experimentally demonstrated, for an arbitrary dimension such methods are still missing.

Here we present setups of X gates for arbitrary d-dimensional qudits represented by the OAM of single photons [1]. When developing the general method we took inspiration from designs generated by the computer program MelvinṠchemes produced by the method can be implemented in the laboratory using accessible optical components, such as holograms and OAM beam splitters (OAM-BSs). Importantly, the number of OAM-BSs scales logarithmically with the dimension of the cycle, which is relevant for their experimental implementation. As shown in Figure 1. A cyclic transformation in a given d-dimensional space is defined for a specific basis, but also for other sets of states without adaptation of the experimental setup. The structure of the setups generated by our method is very symmetric. Figure 2 shows the ten-dimensional X-gate. Consequently, if the photon has a sufficiently large coherence length, the original setup can be considerably simplified.

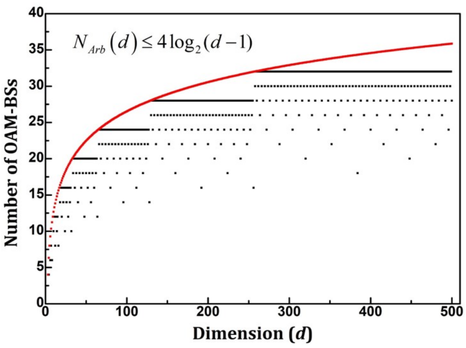

Figure 1: The number of OAM-BSs scales logarithmically with the dimension d.

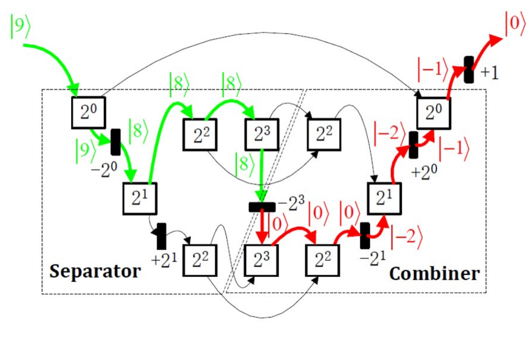

Figure 2: The experimental setup for the X-gate in the 10-dimensional space.

[1] Xiaoqin Gao, Mario Krenn, Jaroslav Kysela, and Anton Zeilinger, *Arbitrary d-dimensional Pauli X gates of a flying qudit*, Phys. Rev. A **99**, 023825 (2019).