Generation of frequency entanglement with an effective quantum dot-waveguide two-photon quadratic interaction

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Abstract

In this study, we propose a novel approach for generating frequency entanglement between two single photons using a quantum dot embedded in a waveguide, called Frengate shaping frequency entangling gate [1,2]. This process utilizes a four-level atomic structure that suppresses single-photon processes while enhancing two-photon transitions. We employ a Markovian scattering formalism to show that the quantum dot interaction reshapes an initially separable two-photon input state into a frequency-entangled output state, without the need for auxiliary photons, post-selection, or strong optical pumping. Theoretical results reveal a quadratic two-photon Hamiltonian that describes the light-matter interaction [1,2], enabling efficient frequency entanglement generation. Our model takes into account realistic experimental conditions and shows a significant improvement in the probability of success compared to conventional nonlinear optical sources [2]. Additionally, we demonstrate that the system can generate frequency-bin qudit states by shaping the two-photon coupling, offering flexibility for both continuous and discrete time-frequency encodings [2]. Finally, we discuss potential applications of frequency entanglement in quantum metrology [3] and quantum computing [4]. In quantum metrology, frequency entangled state using the Frengate allow generating probe reaching the Heisenberg scaling for estimating time and frequency parameters. In particular, we show that there is an interplay between particle-number and time-frequency degrees of freedom defines the ultimate precision of such probes [3]. In quantum computing, the Frengate analogizes traditional beam-splitters with non-linear frequency beam-splitters, entangling photon frequencies and enabling time-frequency Gaussian Boson Sampling [4]. This protocol, though not feasible for near-term experiments, illustrates how different quantum resources can lead to the same information processing outcomes, extending the versatility of quantum systems [4].

References

[1] Alushi, U., and al PRX Quantum **4**, 030326 (2023)

[2] Meguebel.M , and al Optica Quantum **3**, 617 (2025).

[3] Descamps, E., et al Phys. Rev. Lett. **131**, 030801 (2023).

[4] Fabre, N. et al Quantum Information Processing **25**, 7 (2025).

Figures

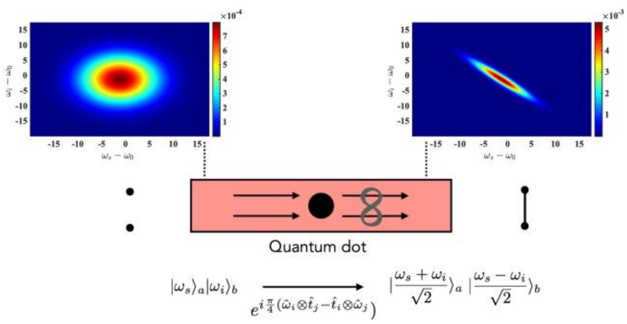

Figure 1: Schematic of Frengate. Starting from two separable single photon, the quantum dot embedded into a waveguide served as a mediator of frequency photon-photon entanglement.