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Graphene Nonlinearities for Quantum Computing

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Abstract:

There is no doubt that the next great technological revolution will be brought about by the development of quantum technology. There are different approaches to build a universal quantum computer; from cold atoms or trapped ions, all the way to photons or superconducting circuits. Although these architectures are quite disparate, they each have many advantages and disadvantages. Therefore, it is not yet clear which the winning horse will be. In photonic quantum computing, the weak interaction of photons with their environment provides extremely long coherence times that could enable the realization of complex and intricate quantum algorithms. On top of this, they already allow one to transmit quantum information over very long distances with unbeatable speed and security. However, at the same time, this weak interaction with their surroundings hinders photon-photon interactions. As a result, the main drawback of photonic quantum computing is the lack of deterministic single-photon sources and quantum logic gates. Nevertheless, these challenges could be overcome by strong nonlinearities at the single-photon level.

In this thesis, I have worked both towards deterministic single-photon sources and quantum logic gates by taking advantage of the strong nonlinearity of graphene. On one hand, I propose a novel universal square-root of SWAP gate based on surface plasmons in graphene nanoribbons, whose strong nonlinearity provides a two-plasmon absorption larger than the single-plasmon absorption. This gives rise to a Zeno effect that prevents the system from evolving into failure states of the gate. The 99% success probability of our proposed gate could bring us closer to deterministic quantum gates, which would enable universal and scalable quantum computation. The strong two-plasmon absorption that this gate requires arises from the plasmon-assisted third-order nonlinearity in graphene, which has been predicted to be unprecedentedly high but has not yet been observed.

To this end, we have experimentally explored the third-order nonlinearity in graphene by combining plasmons in graphene-metal heterostructures. Although the observed nonlinearity is not yet strong enough to drive nonlinear processes at the single-photon level, we measured an enhancement of 1500 on the third-harmonic signal and we found evidence of graphene plasmons present in the optical nonlinearity. This clearly indicates the potential of graphene to perform nonlinearities at the single-photon level.

Finally, parallel to the graphene investigations, we have implemented the first counterfactual communication protocol that relies on the Zeno effect to transmit a message without a weak trace of the photons travelling in the same direction. This experiment was carried out on a silicon-on-insulator nanophotonic processor, whose stability and tunability allowed us to counterfactually send a message from Bob to Alice while single-photons traveled from Alice to Bob with a bit error rate below 1%.