Nonlinear quantum logic with colliding graphene plasmons

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Abstract: We present a theoretical study of a quantum logic gate based on two colliding plasmons in a single graphene nanoribbon with an intrinsic optical nonlinearity. The gate performance is only limited by the plasmon lifetime. © 2023 The Author(s)

One main challenge of photonic quantum computing is the realization of two-qubit photonic gates. In Ref. [1] Shapiro formulated the limitations of nonlinear photonic gates, establishing fundamental boundaries for particles with linear dispersion relations undergoing an interaction by a local Kerr-nonlinearity. It is currently a challenge how to circumvent these problems in an integrated photonic platform; however, it has been shown that electromagnetically-induced transparency with Rydberg atoms [2] or discrete networks of cavities [3] can overcome the Shapiro limits.

Plasmon polaritons occur at metal-dielectrics interfaces when light hybridizes with the collective oscillations of conduction electrons. These quasi-particles concentrate the electromagnetic energy into volumes far below the free space wavelength of the excitation light [4, 5]. It has been shown shown that graphene is a promising material platform, supporting long-lived and electrically-tunable plasmons while also providing strong intrinsic optical nonlinearities [6]. These features make it perfectly suitable for integrated photonic gates with small footprints.

Here, we propose an integrated controlled-Z (CZ) gate that circumvents the Shapiro theorem by using the enhanced dispersion relation of graphene plasmons and the strong nonlinear two plasmon absorption (TPA) in a single graphene nanoribbon [7]. We present a multi mode treatment of a gate based on the collision of two counter propagating plasmons in contrast to previous single mode treatments [8]. In an equivalent but simplified picture, this interaction can be viewed as a single plasmon interacting with a reflective potential. In the limit of strong interactions, the Lieb and Liniger model for massive bosons can be applied [9]. Assuming realistic plasmon lifetimes, we find a surprisingly robust gate performance that is only limited by the lifetime of the plasmons.

In our proposed system we assume that light with the frequency ω is converted into graphene plasmons which then propagate through a graphene nanoribbon (see fig. 1(a)). The ribbon is characterized by the length L and the width W ≪ L, where W is also much smaller than the incident light wavelength. This results in highly-confined plasmons in the quasistatic limit. We model the graphene nanoribbon by the two-dimensional linear conductivity of bare graphene in the local limit of the random phase approximation, and we then determine the resulting modes. Throughout our work, we assume kW = 1. The transverse confinement of the plasmon modes along the ribbon results in multiple branches in the dispersion relation (see fig. 1(c)). All dispersion relations exhibit a smaller slope than the light line. The plasmon modes with n > 1 can be well described by an effective mass model. Modeling the plasmons as massive quasiparticles allows us to describe their propagation in the second-quantization formalism by the effective Hamiltonian H0. The interaction of the plasmons via TPA can be
Fig. 1. (a) Material platform: two counter propagating plasmons in a single graphene nanoribbon, characterized by the widths $W$ and the lengths $L$ scatter via a TPA process. The process can be described in the relative coordinate system as a scattering event on a delta potential. (b) Schematic of band structure of electronic doped graphene with $\hbar \omega < E_F - \hbar \nu k$, single plasmon absorption is permitted by Pauli blocking, TPA is allowed via interband transition. (c) Dispersion relation of the first three modes in the graphene nanoribbon with $E_F = 0.1 \text{eV}$ and $W = 20 \text{nm}$. The vertical line marks $kW = 1$ and the dashed line the effective mass model.

captured with:

$$\mathcal{H} = \mathcal{H}_0 - \frac{\gamma_2}{2} \sum_{\eta \in R,L} \int dy \hat{a}^\dagger_{\eta}(y) \hat{a}^\dagger_{\eta}(y) \hat{a}_{\eta}(y) \hat{a}_{\eta}(y).$$ (1)

where $\gamma_2$ is the TPA rate per length, $\hat{a}_{R,L}(y)$ and $\hat{a}^\dagger_{R,L}(y)$ are annihilation and creation operators for a right-propagating (left-propagating) plasmon at position $y$ and $\bar{v}_g = \bar{v}_g - (\hbar/m)k_p$.

When operating the gate in the range $\hbar \nu k < \hbar \omega < 2E_F - \hbar \nu k$ no inter- or intraband transitions can be excited by single plasmons (see fig. 1(b)). The main decoherence processes are scattering events at defects or phonons, while we define the single-plasmon absorption rate as $\gamma = \alpha_0 / Q$, where $Q$ is the quality factor. When determining the reflection and transmission coefficients, we observe that the flat bands of the plasmon modes with $n > 1$ enhance the interaction. A reflection of the plasmons always leads to a relative phase shift of $\pi$. This allows us to define the fidelity of the gate as the probability to obtain the same output pulse as input pulse with an additional phase shift. However, a more complete description can be given by the success probability which takes into account the plasmon damping via the single-plasmon absorption rate. In the end we achieve, with experimentally observed quality factors of $Q = 100$, a success probability of $P_{\text{success}} \approx 20\%$ with a fidelity $> 0.97$, while for a quality factor of 1000 (which have been predicted theoretically) we find $P_{\text{success}} \approx 50\%$.

We have shown that it is possible to engineer the dispersion relation of plasmons in graphene nanoribbon to enhance their interaction and overcome the Shapiro limitations for nonlinear photonic gates. Our proposed gate only limited by the single-plasmon absorption rate, making graphene nanoribbons to an interesting and novel route towards quantum logic gates.

References

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