Quantum Optics with Graphene Plasmons

PHY 552: Quantum Optics Term Paper

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Abstract: *Two recent papers in the area of Quantum Optics with Graphene are reviewed. They propose to use strong confinement of surface plasmons in graphene nanostructures to enhance the light matter interaction. It has been theoretically shown that in such a system it might be possible to observe nonlinear interactions down to single photon level and also observe Plasmonic Vacuum Rabi splitting.*

Introduction

Traditionally Nonlinear Optical processes were studied under intense laser illumination because the nonlinear terms in the polarization that are responsible for these effects are quite small. For example, a typical Kerr type nonlinearity which gives rise to intensity dependent phase shifts is effective only when there are at least 10^{10} photons[1]. Therefore, these effects are essentially classical in nature. An emerging frontier of Quantum Optics is the study of nonlinear process in the limit of few photons, where the quantum nature of photons is explicitly manifested. A major driving force for this interest is the potential applications in quantum computing and quantum logic. Photons are ideal candidates for quantum information processing because they can easily be produced, measured and detected. They also do not interact with the environment making them robust against decoherence. Unfortunately this is exactly why it is also hard to build logic gates from single photons.

Quantum nonlinear processes down to single photons were first demonstrated in atomic vapor systems, where the electronic transitions are associated with huge nonlinearities. To overcome the strong absorption associated with the resonance schemes based on Electromagnetically Induced Transparency (EIT) in cold atoms were used[2]. A common feature of these schemes is the suppression of linear absorption by and enhancement of nonlinear susceptibility by quantum interference of probe beams. Subsequently quantum nonlinear optics were demonstrated using superconducting qubits[3] and photonic crystals[4]. In an exciting recent development Peyronel et al. demonstrated a system which transmits single photons but is opaque to two photons[5]. Most of the demonstrations of quantum nonlinear optics have been in cold atoms so far. It is technologically enticing to move towards solid state devices. Naturally this is much more challenging due to ubiquitous strong interactions and broadening in solids. Graphene a 2D lattice of carbon atoms has some unique electrical and optical properties. Recently Gullans and coworkers analyzed the potential of using graphene for quantum nonlinear optics. The main idea of this work is that by confining single photons to an extremely small volume and with extremely long times it would be possible to enhance the probability of interaction between them. They consider a surface plasmon cavity and estimate the mobility required to see quantum effects. In the following sections we provide a brief review of the paper "Single Photon Nonlinear Optics with Graphene Plasmons" PRL 111, 247401 (2013)[6].

Surface Plasmons in Graphene for Quantum Nonlinear Optics

Surface plasmons are charge density oscillations excited on a graphene sheet by the incident field. These surface plasmons have attracted a lot of attention because of their ability to confine electromagnetic energy into dimensions much smaller than wavelength of light. With right momentum matching, surface plasmons can be excited on a graphene sheet with the plasmon wavelength given by

$$\lambda_p \approx \lambda_0 \alpha \frac{E_F}{E_P} \frac{4}{\varepsilon_r + 1}$$

where, λ_0 is the free space wavelength, α is the fine structure constant, E_F is the Fermi energy, E_P is the plasmon energy and ε_r is the dielectric constant of the substrate[7]. It has been demonstrated that plasmon wavelength is about 40-60 times smaller than the free space wavelength. In the direction perpendicular to graphene sheet these plasmons have a decay constant of $2\pi/\lambda_P$, meaning that plasmons can be confined to a much smaller dimension than free space wavelength. Gullans et. al., propose a surface plasmon cavity which will exhibit strong nonlinear phase shifts so that a single photon would excite the cavity resonances.

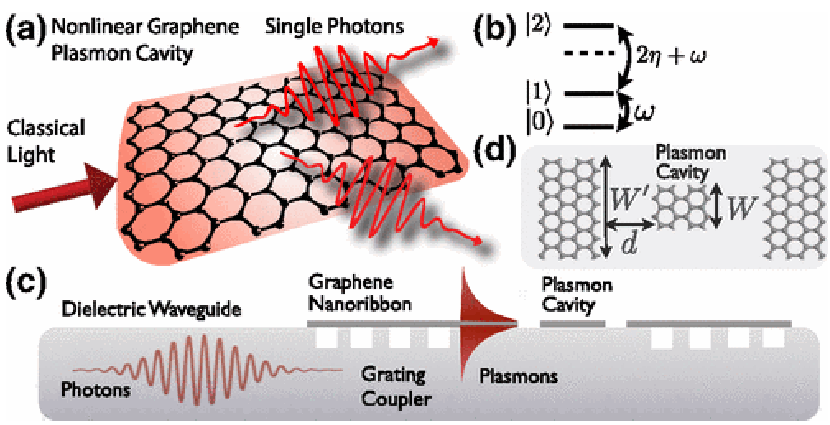

Fig. 1 Schematic illustration of the proposed experimental setup. Free space light would be first coupled to graphene plasmons by means of a grating. These plasmons then couple to a graphene nanodisk plasmon cavity which exhibit a strong nonlinear phase shifts. The nonlinear interaction between first and second photon is 2η and sufficient to cause resonant excitation.

The Hamiltonian of this graphene cavity can be described in the quantum regime by $H_0 = \left(\omega_q - i\kappa/2 + \eta_q(n_q - 1)\right)n_q$, where ω_q is the resonance frequency, n_q is the number of photons and η_q is the interaction energy. The resonance frequency is given by $\omega_q + \eta_q(n_q - 1)$, which is dependent on the photon number. The interaction parameter η_q quantifies the additional cost of exciting two photons versus one photon. The authors show in their paper that the interaction energy for graphene will be inversely proportional to area of the graphene nanodisk, and for sufficiently small cavities the condition shown in Fig. 1 can be met. Fig. 2(a) shows the two-plasmon shift calculated for different sized cavities. It can be seen that for sufficiently small cavities and high mobility it is possible to reach the quantum nonlinear regime where the two-plasmon

shift is greater than 1. They also calculate the second order correlation function $g^{(2)}(t)$, which indicates high mobility graphene nanodisk can emit single photons.

The authors also calculate the transmission and reflection through the cavity consisting of a nano-ribbon and nanodisk shown in Fig. 1. Under ideal conditions the cavity should transmit single photons and reflect multiple photons. This can be numerically seen from Fig. 3 (b-c) showing bunching of reflected photons and anti-bunching of transmitted photons. Further, the scattering rate in the cavity should be inversely related to Fermi energy E_F, which can be from Fig. 3(a) where transmission increases for lower value of mobility at larger Fermi energy.

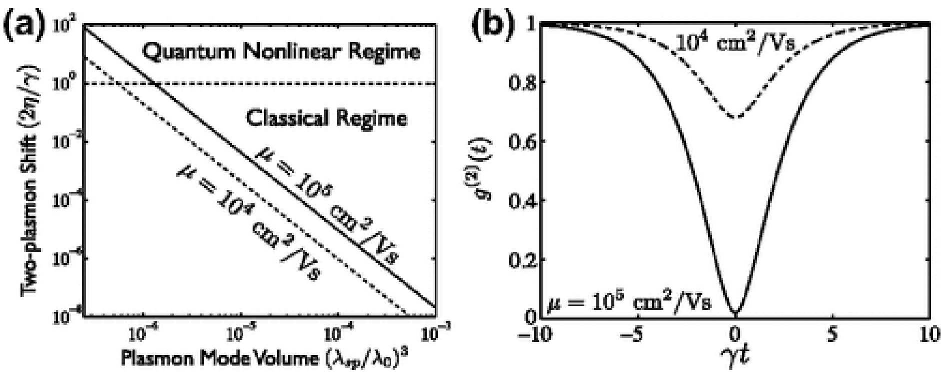

Fig. 2 (1) Estimation of Two-plasmon shift of resonant frequency showing that it might be possible to achieve quantum nonlinear regime with high mobility and small mode volume. (b) The second order auto-correlation function showing single photon behavior for high mobility.

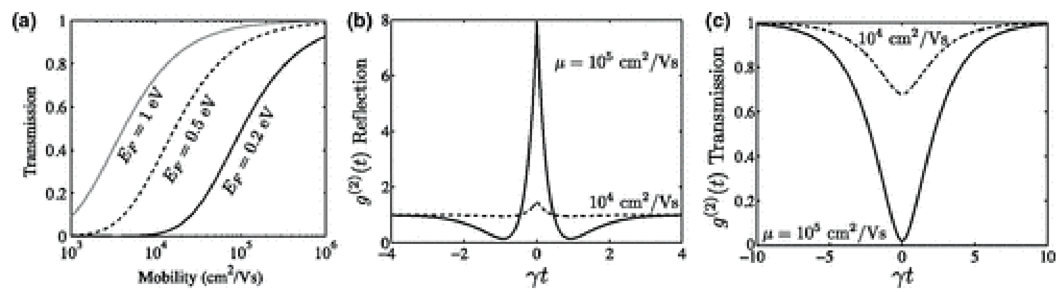

Fig. 3 (a) Impurity scattering decreases with increasing Fermi energy resulting in larger transmission for the same value of mobility. (b-c) Calculations showing bunched photons in reflection and anti-bunched photons in transmission.

Other quantum applications: Plasmonic Vacuum Rabi Splitting

Another similar research direction is the study of Vacuum Rabi Splitting when an emitter is placed in close vicinity of a Graphene Nanodisk supporting surface plasmons. This has been reported by Koppens et. al., in the paper "Graphene Plasmonics: A platform for strong light matter interaction" Nano Letters (2012)[8]. They analyze the decay of an emitter emitting at $\hbar\omega_0 = 0.3eV$ using the Jaynes-Cummings approach discussed in the class. The Hamiltonian of the system can be expressed as $H=H_0+H_{int}+H_{ext}$, where the non-interacting part is given by

$$H_0 = \hbar\omega_p\left(a^+a + \frac{1}{2}\right) + \hbar\omega_0\sigma^+\sigma - i\hbar\frac{\kappa}{2}a^+a - i\hbar\frac{\Gamma_0}{2}\sigma^+\sigma$$

consisting of plasmon mode of energy $\hbar\omega_P$ and it's creation and annihilation operators, the unperturbed quantum emitter and also both radiative (Γ_0) and inelastic (κ) decay channels. The interacting part of Hamiltonian is given by $H_{\text{int}} = i\hbar g\left(a^+\sigma - a\sigma^+\right)$ and H_{ext} is the external field. When g> (Γ_0 ,κ) then strong coupling effects should be seen and an excited emitter should undergo vacuum Rabi oscillations at the frequency g. The authors calculated the factor g/κ over a range of frequencies and disk radii and conclude that the strong coupling regime is robust over a wide range of parameters since g/κ is greater than 1. They further calculate the extinction cross-section and observe the anti-crossing behavior characteristic of Rabi splitting.

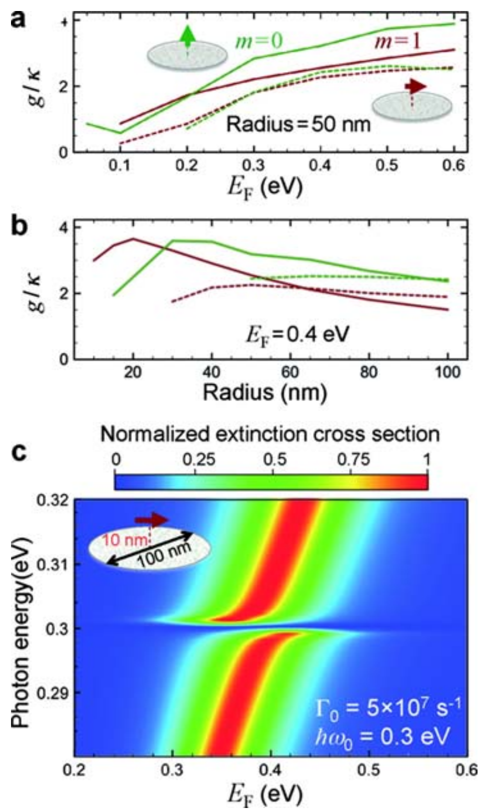

Fig. 4. (a-b) Fermi-energy and disk-radius dependence of the strong-coupling parameter g/κ for an emitter placed 10 nm above the center of a doped graphene disk. (c) Fermi- and photon-energy dependence of the extinction cross section of a combined emitter–nanodisk system showing anti-crossing behavior characteristic of Rabi splitting. Further details can be found in [8].

An experimentalist's perspective

Graphene is a unique 2D material platform where range of exciting physical phenomena has been studied. If indeed the ideas described in the previous sections

could be realized it would be a major breakthrough. Some observations from my perspective as an experimentalist are:

- Mid-IR Operation: The ideas discussed above would work at mid-IR frequencies due to the fact that graphene plasmons suffer significant losses above optical phonon frequency of 0.2 eV (Raman G-mode: 1580 cm^{-1}, 6.4 μm). To my knowledge there are no emitters in IR spectrum. Another interesting (and perhaps simpler) system for observing strong coupling would be to fabricate graphene disks on quantum wells exhibiting intersubband transitions. It has been recently shown that plasmonic antenna resonance on top of quantum wells shows anti-crossing behavior characteristic of strong coupling[9].

- Saturation: Nonlinear effects in graphene are expected to saturate very quickly with increasing carrier concentration[10]. This is because the change in conductivity quickly saturates because of linear dependence of density of states on Fermi wavevector. Therefore, Graphene is good choice for study of quantum optics in mid-IR frequencies.

- Losses in graphene: The papers discussed consider the mainly the scattering which is a little optimistic. When graphene is patterned in 20-50 nm regime there would be significant edge scattering. This could be detrimental to observation of any quantum effects.

- Signal to Noise: Currently high quality graphene is obtained by exfoliation where the size of samples is limited to few ums. In general, quantum optics experiments are performed when there are many atoms since it is difficult to experimentally observe single atom interaction. Current large area techniques like CVD do not produce homogenous high quality graphene needed for sensitive measurements.

References

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