Graphene single-photon nonlinear optics

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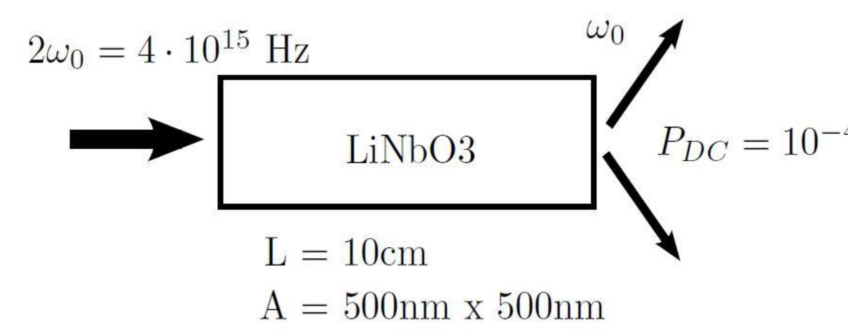
INTRODUCTION

Non linear optics is a tool of fundamental importance for future technologies, in particular for the implementation of quantum information and communication protocols. An ideal application of a strong optical nonlinearity would the realization of a **single-photon transistor**, a device in which a single-photon controls the propagation of a larger field. The biggest challenge to NLO is the **weak nonlinear response of conventional optical materials**. It is clear that in order to have large single-photon nonlinearities a material must satisfy three important requisites:

1) photons confined to a small space (small mode volume)
2) long lifetime of the photons in the material (low absorption, high Q factor)
3) large nonlinear susceptibility χ^2 and χ^3



BACKGROUND

Graphene plasmonics

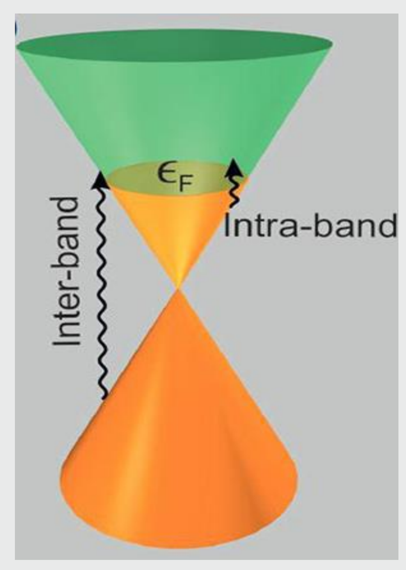
- Graphene is a **two-dimensional material** [1], which satisfies all three condition.
- It supports surface plasmon (SP) excitations [2], which have the ratio between the SP wavelength $\lambda_p = 2\pi/q_p$ and the corresponding wavelength in vacuum $\lambda_0 = 2\pi c/\omega_p$, equal to

$$\lambda_p/\lambda_0 = 2\alpha|E_F|/\hbar\omega_p,$$

where $\alpha \approx 1/137$ is the fine-structure constant).

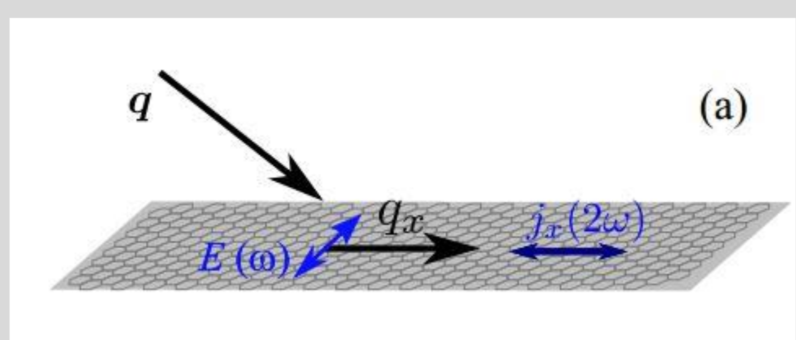
The **confinement** of the SPs is very strong (1).

- **Long lived SPs** have been observed (2), Q ~ 10^2.



Nonlinear properties of graphene

- Graphene is a centrosymmetric material, so its local second order conductivity vanish, but not the **nonlocal conductivity** proportional to *q*.



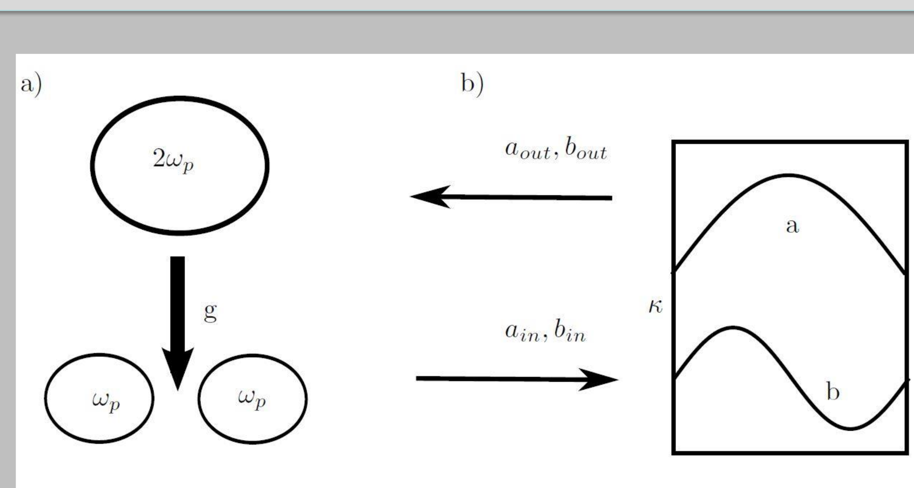
- We obtain the nonlinear conductivity by solving for the electron momentum distribution function $f_{\boldsymbol{k}}(\boldsymbol{r},t)$ with the **Boltzmann equation** [3].

$$\frac{\partial}{\partial t} f_{\boldsymbol{k}}(\boldsymbol{r},t) + v_F\hat{\boldsymbol{k}}\cdot\nabla_{\boldsymbol{r}} f_{\boldsymbol{k}}(\boldsymbol{r},t) = \frac{e}{\hbar}\nabla_{\boldsymbol{r}}\phi(\boldsymbol{r},t)\cdot\nabla_{\boldsymbol{r}} f_{\boldsymbol{k}}(\boldsymbol{r},t).$$

- The second order nonlocal conductivity is significant at $q_p \sim k_F$, a regime that can be reached in graphene (3), where $k_F^{-1} \sim 10\ nm$. In comparison in silver $k_F^{-1} \sim 0.1\ nm$.

Two-mode cavity

- A structure of graphene with two SPs at frequencies ω_p and $2\omega_p$ coupled by $\sigma^{(2)}$. We estimate $g \sim 0.1\omega_p \gg \gamma$.
- The internal Hamiltonian is



$$H = \hbar\left(\omega_p - \frac{i\gamma_a}{2}\right)a^\dagger a + \hbar\left(2\omega_p - \frac{i\gamma_b}{2}\right)b^\dagger b + \hbar g(a^2 b^\dagger + h.c.)$$

CONCLUSIONS

- Graphene is a unique NL material that can operate at the single-photon limit.
- Efficient single-photon down-conversion should be possible
- Broad impact for non linear optics and quantum information processing

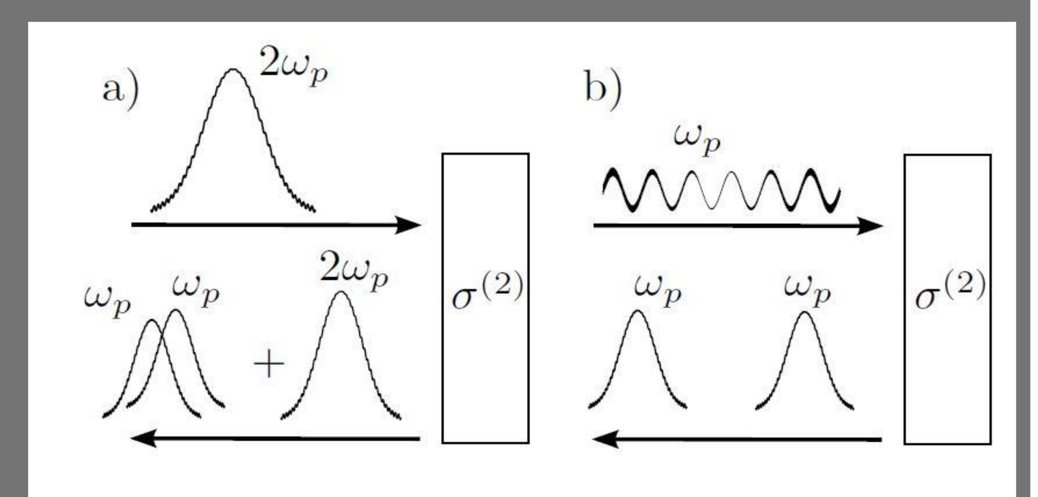
RESULTS

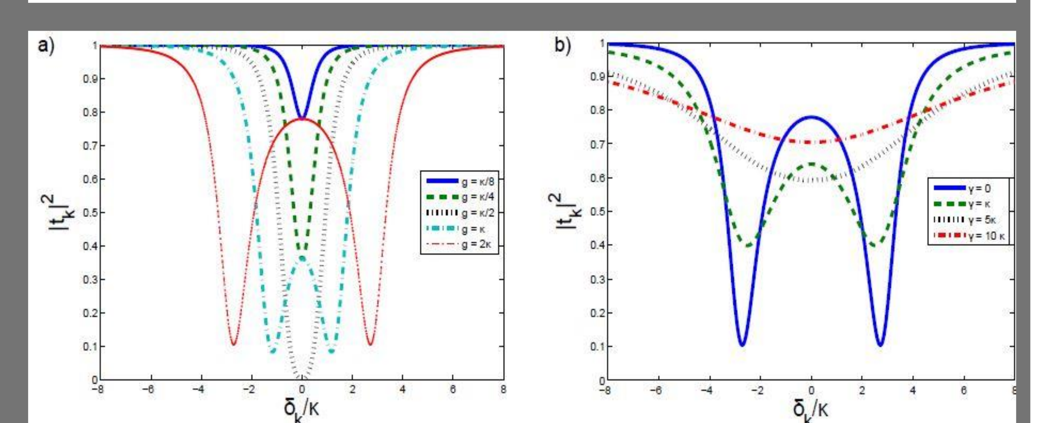
Signature of quantum strong coupling

- Since the coupling strength *g* can be comparable to or exceed the dissipation rates of graphene SPs, we expect that strong nonlinear effects at the single-photon level should be observable.

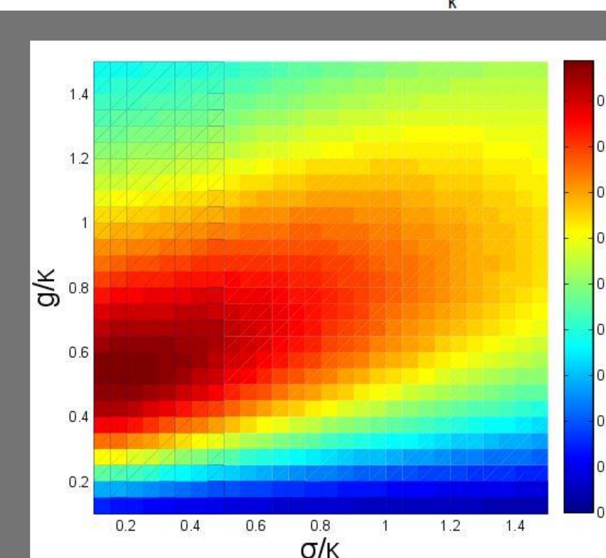
Down-conversion

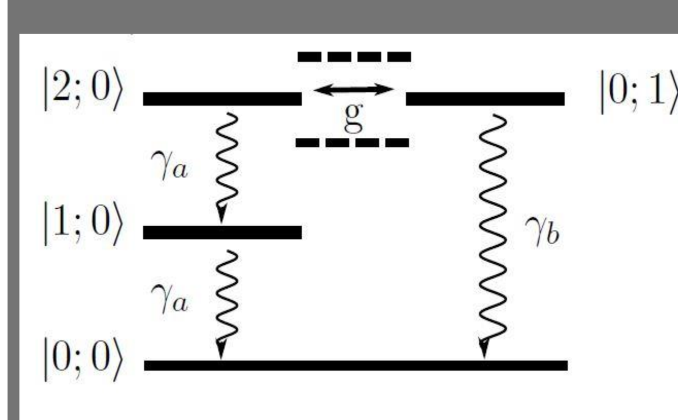
- When one photon is sent at $2\omega_p$, it can be down-converted into two photons with lower frequencies.
- For $g < \kappa/2$ the system behaves linearly, i.e. the transmission spectrum is Lorentian.
- For $g > \kappa/2$ the Lorentian peak splits up in two side peaks, signature of a quantum nonlinearity.





- For $g = \kappa/2$ we find a critical behaviour. For $\gamma = 0$ the transmission is zero, which means that <u>the input photon is down-converted with probability one</u>.
- In the Fig. beside is plotted the down-conversion probability versus coupling strength *g* and incoming pulse bandwidth σ.





Generation of nonclassical light

- If a weak laser at frequency ω_p drives the graphene cavity, it produces as output **nonclassical light**.
- The zero time second order coherence function is $g^{(2)}(0) = \frac{\Gamma^2(16g^2+3\Gamma^2)}{3(4g^2+\Gamma^2)^2}$, which tends to zero in the strong coupling regime.

REFERENCES

[1] Novoselov K. S. *et al.*, Science **306**, 666 (2004)

[2] Wunsch B. *et al.*, New. J. Phys. **8**, 318 (2006)

[3] Mikhailov S. A., and Ziegler K., J. Phys. Condens. Matter **20**, 384204 (2008)

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