Nanoscale Systems for Optical Quantum Technologies

Grant Agreement No: 712721
Start Date: 1st October 2016 - Duration: 36 months

D3.6 Schemes for hybrid systems

Deliverable:	D3.6 Schemes for hybrid systems
Work package:	WP3 Opto-electrical and opto-mechanical hybrid systems
Task:	3.5 Theoretical analyses, diagnostics and proposal for new experiments
Lead beneficiary:	AU
Type:	Report
Dissemination level:	Public
Due date:	30 September 2018
Actual submission date:	29 September 2018
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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 712721.

Version history

Version	Date	Author(s)	Description
V1	28/09/2018	K. Mølmer (AU)	First draft
V2	29/09/2018	K. Mølmer (AU) S. Seidelin (CNRS-IN) P. Goldner (CNRS-CP)	Submission to EC

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Deliverable description

This deliverable consists in a report on our proposal to use rare earth-ions to deterministically launch graphene plasmons with specific direction of propagation.

Introduction and context

In a previous article [1] we demonstrated that a collection of ions in the near vicinity of a graphene sheet may couple collectively to the continuum of graphene plasmon modes, and the entire system may display a normal phase, a spin-glass phase and a Dicke superradiant phase. The emitter density, and the plasmon density of states, controllable by a gate voltage, are the crucial parameters governing the phase transitions of the system.

In this report, we present a new analysis [2], where we propose to use a laser excited ensemble of ions to deterministically launch surface plasmon wave packets. The proposal aims to match the capabilities and goals of our experimental NanOQTech partner at ICFO, and the next step involves detailed discussions with the experimental team.

The main, original component in our proposal is the use of a sequence of laser pulses from different directions to provide a so-called *timed-Dicke state,* with spatial phases that are matched to the plasmon wave number. A main theoretical challenge addressed by our work is the non-Markovian character of the coupling to the plasmon and their rapid damping.

The proposal

Surface plasmons have shorter wavelengths than optical photons at the same energy, and therefore an optically excited ensemble of emitters will not obey the spatial phase matching condition for coherent emission into plasmon modes. We propose to remedy this difficulty by application of multiple excitation and de-excitation laser pulses from different directions, thus accumulating rapidly varying phase factors, see Fig 1. If the first laser pulse excites a superposition of states with only one excited emitter (e.g., by a heralded mechanism), the ion ensemble is optically thin for the subsequent in-plane lasers pulses, and when we reach the final phase-matched state, it experiences a collectively enhanced coupling to the plasmon mode with the desired in-plane wave vector.

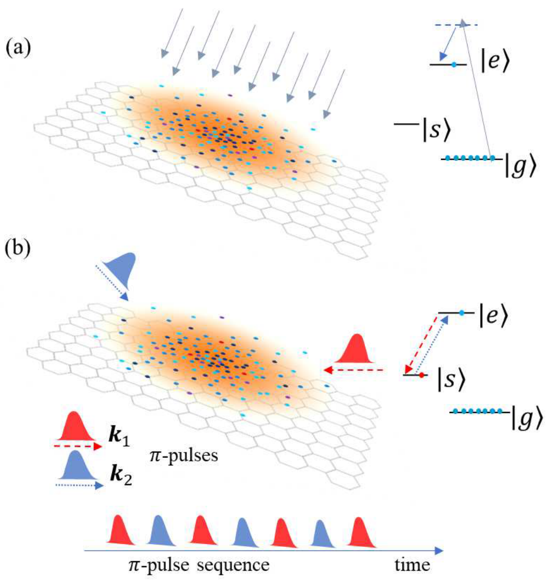

Figure 1 Scheme for preparation of a graphene surface plasmon phase matched timed-Dicke state. (a) Raman excitation of one of the emitters into the excited state |e>, using uniform optical illumination perpendicular to the surface. (b) Illumination by a train of π-pulses on the |s> ↔ |e> transition, driving the emitters to the target timed-Dicke state with spatially depending phase factors.

Analysis and results

Our analysis assumes a rather generic description of the plasmon field (solution of Maxwell equations in presence of a surface with specified conductivity properties), while our quantitative results are obtained with a Drude model matched to the graphene case. The presence of only a single quantum of excitation allows expansion of the full quantum state of the emitters and quantized fields on a basis of singly excited states.

The plasmon degrees of freedom can be formally eliminated leading to closed sets of equations for the emitter excited state amplitudes, and transforming to a wave number representation, the "spin wave" excitation amplitudes obey coupled equations,

$$-\partial_t \alpha_{\mathbf{k}_{\shortparallel}}(t) = N \int \frac{d^2\mathbf{q}_{\shortparallel}}{(2\pi)^2} \int_{\tilde{\omega}} \Im g_{z_{at}}(\tilde{\omega}, \mathbf{q}_{\shortparallel}) \zeta(\mathbf{k}_{\shortparallel}, \mathbf{q}_{\shortparallel}) \times \int_0^t d\tau \alpha_{\mathbf{q}_{\shortparallel}}(\tau) e^{-i(\tilde{\omega}-\omega_{sg})(t-\tau)}$$

The equation couples different spin-wave amplitudes in a non-Markovian manner, according to the propagation of the electric field among the emitters, and the overlap of wave number modes, ζ, evaluated over the finite volume occupied by the ions.

Depending on the parameters, the equation has damped oscillatory or exponentially damped solutions, and the subsequent evaluation of the field amplitudes yields the desired outcome: launching of a single plasmon in spatio-temporal mode with well-defined propagation vector.

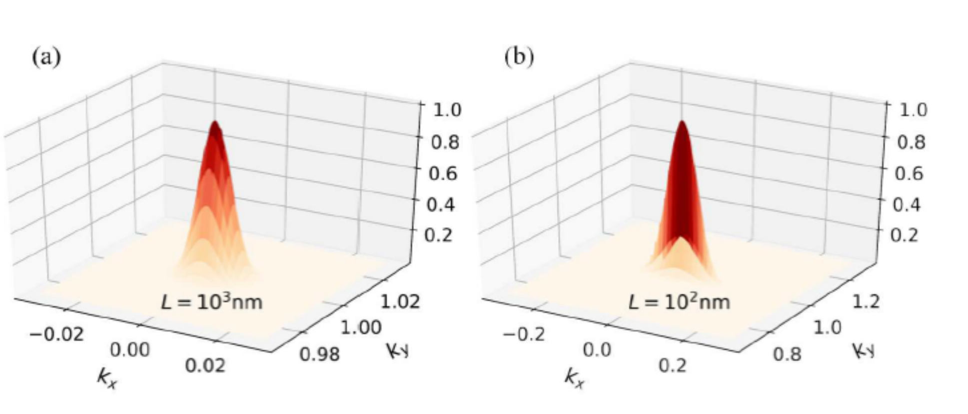

Figure 2. Wavenumber distribution for graphene surface plasmons, by an ensemble of ions located 10 nm from the graphene sheet. The ensemble size (a) L = 1000 nm; (b) L = 100 nm ensure the phase matching condition for the emitted plasmon with a wavelength of λsp = 36.2 nm.

Conclusion

We have in the framework of the NanOQTech project derived a formalism that accounts for the evolution of an excited ensemble of ions, interacting with the continuum of damped surface plasmon modes. We go beyond the usual quantum optics formalism to account for plasmon damping and for finite band-width effects, and we obtain an explicitly non-Markovian formalism, that we can study in different parameter regimes.

Our analysis shows that it is possible to observe the coherent interactions between the plasmon field and spin-wave like excitations in the ensemble and to induce a deterministic launching of plasmons.

In succession to the work reported here, we plan to

- develop and investigate the performance of the launching proposal in collaboration with the experimental partners.
- consider different kinds of plasmons
- extend the model to the launching of higher excited states (the equations are basically linear, and we expect that weak coherent, squeezed or number state excitations of the ensemble of ions will also be launched as similar states of plasmons.

Bibliography

[1] Yu-Xiang Zhang, Yuan Zhang, Klaus Mølmer, *Dicke Phase Transition in a Disordered Emitter-Graphene Plasmon System*; PhysRevA, 98 033821, (2018), NanOQTech publication.

[2] Yu-Xiang Zhang, Yuan Zhang, Klaus Mølmer, *Directional launching of surface plasmons by polariton superradiance*, http://xxx.lanl.gov/abs/1807.03682, NanOQTech publication, under review.