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RELAZIONE ATTIVITA' ANNUALE DEI PERFEZIONANDI/DOTTORANDI – SECONDO ANNO
REPORT ON THE PHD ACTIVITY – SECOND YEAR

NOME E COGNOME **NAME AND SURNAME**	Nicola Melchioni
DISCIPLINA **PHD COURSE**	Nanoscienze

CORSI FREQUENTATI CON SOSTENIMENTO DI ESAME FINALE **ATTENDED COURSES (WITH FINAL EXAM)**	**VOTAZIONE RIPORTATA** **MARK**	**NUMERO DI ORE** **HOURS**

CORSI FREQUENTATI SENZA SOSTENIMENTO DI ESAME FINALE **ATTENDED COURSES (ATTENDANCE ONLY)**	**NUMERO DI ORE** **HOURS**

ALTRE ATTIVITÀ FORMATIVE (SEMINARI, WORKSHOP, SCUOLE ESTIVE, ECC.) – DESCRIZIONE **OTHER PHD ORIENTED ACTIVITIES (SEMINARS, WORKSHOPS, SUMMER SCHOOLS, ETC) – DESCRIPTION**	**NUMERO DI ORE** **HOURS**
International Quantum Cascade Laser School & Workshop	32
Photonics Online Meet-up (POM)	5
MID Infrared Discussion	30
Carbonhagen 2020	5
Visit ICFO – 4 days	32
Data Analysis School	32

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ATTIVITÀ DI RICERCA SVOLTA (MAX. 8.000 CARATTERI)* RESEARCH ACTIVITY (MAX. 8000 CHARACTERS)

Surface polaritons are quasiparticles resulting from the coupling of electromagnetic waves with an electric or magnetic dipole in matter. Many examples can be given: surface plasmons, where light is coupled with electronic oscillations; phonon polaritons, where light is coupled with oscillations of atoms in the lattice, and many more [1]. All these excitations share two main properties: since they are coupled light-matter modes, polaritons carry much more momentum with respect to free-space photons at the same energy and, due to their nature of surface excitation, polaritons have an out-of-plane component of the electric field which is exponentially decaying with a characteristic length of the order of the polaritonic wavelength. This leads to a strong confinement of the electromagnetic energy in a volume up to few hundred times smaller than the free-space wave. Interesting effects can occur when surface polaritons are brought into contact with other out-of-plane excitations such as intersubband (ISB) transitions in shallow quantum wells. Such a high energy density can lead to strong or even ultra-strong coupling regimes. Moreover, the non-negligible momentum of the polariton leads to the breakdown of the dipole approximation for polariton-mediated ISB transitions, allowing non-vertical optical transitions and thus opening a new field of study for photonics. In this framework, we are currently studying four different systems and coupled excitations:

1) **Local measurement of intersubband (ISB) transitions in a InAs Quantum Well and coupling with Phonon Polaritons in hBN with s-SNOM**: intersubband transitions in a QW are usually measured with far-field light, the focalization of which is limited by diffraction. In such measurements, the spot dimension is much larger than the spatial extent of thickness fluctuations in the QW, thus yielding an averaged measurement of the optical transition influenced by those fluctuations [2]. On the opposite, near field spots like the field at the apex of an oscillating tip (s-SNOM) is not limited by diffraction [3] and can thus be used to locally measure the ISB transition. To isolate the absorption of the QW from spurious absorption in the system, a modulation of the doping can be used [4]. Thus, we made different attempts at insulating the 2DEG of the shallow InAs quantum well from the substrate of the sample to allow for electrical gating. Even if we had no success yet, in a visit at ICFO(Casteldefells, Barcelona) in the group of Frank Koppens, we performed the dry transfer of hBN crystals on top of the shallow InAs QW and measured the Phonon Polaritons dispersion in hBN crystals of different thicknesses [5] to detect any sign of strong coupling between the two excitations. We reconstructed the polaritonic dispersions with no sign of Strong Coupling;
2) **Critical coupling driven by Graphene surface plasmons:** optimisation of a method for fabricating large area nano-pattern of squares both on a bare substrate and on CVD grown Graphene followed by spectral measurements in a FTIR. Comsol simulations of the system pointed out that the best situation to allow for Critical Coupling in such a cavity is reached

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with a pattern of 800nm-large gold squares with a pitch of 1 micron. Since the final measurements are performed in a FTIR, a large area of at least 1 mm is needed for reaching the best contrast of the resonance. This requirement yields two strong challenges: finding the right EBL parameters to allow for the quickest and most precise lithography possible and developing a successful and reproducible lift-off procedure to remove the mask from the chip while preserving both the pattern and Graphene below. We fabricated 1 reference sample of the pattern without graphene and 2 samples with large area patterns of 1.5 and 2 mm^2. We measured the first two and highlighted the effect of the gold nano-pattern. We are currently fabricating contacts on one of the patterns on graphene to allow for electrical gating and observe the dependency of the resonance on the doping of graphene;

3) **Whispering Gallery Modes(WGM) in a graphene nanodisk:** Comsol simulations of the interaction of a metallic tip (s-SNOM) with a nanodisk of graphene with the addition of various defects that break the rotational symmetry of the disk to confirm the experimental observability of WGMs in the disks. WGMs are electromagnetic modes which live at the edge of disk cavities [6]. No direct evidence of WGMs in Graphene has ever been observed with a near field measurement, also because of the rotational symmetry of the system. Due to this symmetry, WGMs are degenerate in phase, which means that if locally excited with a near field light at a fixed phase (like a s-SNOM tip), the WGM will inherit the phase of light independently of the position of the excitation along the disk [7]. A measurement of the oscillation of the mode is therefore impossible in a symmetric system. Breaking the rotational symmetry for the EM field can be done in many ways, for example by putting gold bars on the disk or by adding a perturbation to the disk border. We simulated systems in which the rotational symmetry is broken and shown that a non-symmetric disk yields a lifting of the phase degeneracy of WGMs;
4) **Nonlocal intersubband (ISB) transitions:** theoretical study of ISB transitions in a Metal-Insulator-Graphene cavity to explore both the change in the transition when mediated by graphene plasmons instead of free-space photons and the (Ultra) Strong Coupling of the two excitations. ISB transitions mediated by plasmons have been theoretically demonstrated to break the dipole approximation, thus showing a frequency shift, different selection rules and an increased transition rate with respect to the free-photon-mediated ISB transition [8]. Recently, the effect of surface plasmons on interband transitions in a InAs QW in a Metal-Insulator-Graphene cavity has been studied to show a bandgap renormalization and non-local effects [9]. We therefore aim to extend the calculations to the ISB transitions.

[1] D. Basov et al, *Polaritons in van der Waals materials*, Science, 2016
[2] B. Stuart, *Infrared spectroscopy: fundamentals and applications,* John Wiley and Sons, 2004
[3] R. Hillenbrand et al, *Pure optical contrast in scattering-type scanning near-field microscopy,* J. of Microscopy, 2001
[4] P. Schmidt et al, *Nano-imaging of intersubband transitions in van der Waals quantum wells*, Nat. Nanotech., 2018

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[5] S. Dai et al, *Tunable Phonon Polaritons in Atomically Thin van der Waals Crystals of Boron Nitride*, Science, 2014

[6] V. Braginsky, *Quality-factor and nonlinear properties of optical whispering-gallery modes*, Phys. Lett. A, 1989

[7] A. Nikitin et al, *Real-space mapping of tailored sheet and edge plasmons in graphene nanoresonators*, Nat. Phot. 2016

[8] Y. Kurman et al, *Control of semiconductor emitter frequency by increasing polariton momenta*, Nat. Phot. 2018

[9] Y. Kurman et al, *Tunable bandgap renormalization by nonlocal ultra-strong coupling in nanophotonics*, Nat. Phys. 2020

*se si intende sottoporre una relazione di ricerca più estesa, utilizzare il campo per una descrizione sintetica e allegare il documento in formato .pdf

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EVENTUALI PUBBLICAZIONI
PUBLICATIONS (IF AVAILABLE)

NOME DEL RELATORE
THESIS ADVISOR

Alessandro Tredicucci

DATA DATE	18/10/2020	FIRMA SIGNATURE	