Scientific Report

April 30, 2013

1 Summary

The workshop "Graphene Nanophotonics", held in the Centre for Science (Benasque, Spain), during 4-8, March (2013) gathered 101 researchers to discuss the latest results in the new and fast growing field of electromagnetism in graphene nanostructures. In fact this workshop has been, up to our knowledge, the first one devoted monographically to the topic of Graphene Nanophotonics.

Although the workshop covered many different aspects, as will be discussed later on in the section devoted to the scientific content of the meeting, the main focus was on the properties of electromagnetic modes bound to the graphene structure. These modes, known as graphene plasmons, present a strong field confinement in the direction perpendicular to sheet. The reduced modal volume, with the associated strong plasmon-molecule interaction, makes graphene plasmons very interesting candidates for playing a role in applications in biosensing.

The workshop was a great success, both from the point of view of the science discussed as from the scientific contact and collaboration, point this which was evident in the large number of questions after each talk, discussions at coffee breaks and poster sessions and, in general, the buzzing scientific atmosphere permeating the centre during that week.

Given the interest that the workshop has originated, a forthcoming special issue on Graphene Nanophotonics will appear in the Journal of Optics. Although this special issue can not be considered as the conference proceedings, all speakers at the workshop have been offered the possibility to contribute with an invited paper. The seminal role played by workshop and, of course, the sponsorship of the ESF to the workshop will be highlighted in the special issue.

2 Scientific Content

In this section we will highlight some of the more relevant contributions presented in the workshop.

The workshop contained several general talks on different aspects of the interaction between electromagnetic fields and graphene structures, as "Graphene plasmonics: hybrid devices", "The interaction of light and graphene: physics and applications" and "Graphene plasmons and electrons: nano and fast". These talks covered the basic facts and were specially valuable for the younger researchers in the audience.

A very important line of research on graphene is on how to grow the material, both alone and in combination with other materials. This aspect was covered in the workshop by the presentations entitled "Chemically functionalized graphene: a platform for plasmonics and photodetectors", and ""Interfacial engineering of graphene nanostructures". It was apparent that the great versatility in, for instance, creating heterostructures containing graphene sheets is very proposing for designs of new metamaterials with desired functionalities.

Graphene multilayers and metamaterials were discussed in a number of presentations, as "Plasmonics in double-layer graphene structures", "Optical properties of non-symmetrical hyperbolic media, based on graphene multilayers", "Novel hyperbolic metamaterials based on multilayer graphene structures" and "Tunable metamaterials on graphene". In particular, layered graphene metamaterials are excellent candidates for tunable hyperbolic media (materials characterized by a tensorial dielectric constant, with some diagonal elements being larger than zero and some negative ones), with the corresponding large Purcell factors and modes with very small volume.

As previously mentioned, the main topic in the conference was the properties of graphene plasmons. Many different talks were devoted to: (i) the effect of geometry and nano-structuring in these electromagnetic modes, as "Diffraction, absorption and scattering in structures with graphene plasmons", "Strongly Confined Gap Plasmon Modes in a Graphene Sandwich", "Graphene Micro and Nano Plasmonics: Experiments and Theory", and "Excitation of surface polaritons in graphene and other accompanying phenomena". (ii) dispersion and effect losses, discussed in "Momentum dependence and losses of graphene plasmons", "Plasmon damping in graphene", "Spatial Dispersion and the Tensor Intraband Conductivity of Graphene", (iii) visualization of plasmons in real space, presented in "Real-space map-

ping of graphene plasmons by near-field microscopy" and "Near-field study of graphene plasmons: theory and experiment".

These studies showed that graphene plasmonics is a field that is developing very rapidly and that, after the initial phase of theoretical proposals and first experimental demonstrations, combined studies (involving both experiments and theory) are appearing with the idea of having a quantitative description of the systems involved.

The effect of lattice vibrations (phonons) both as a characterization tool of graphene nanostructures was discussed in "Phonon and exciton localization in graphene and carbon nanotubes" and "Raman characterization of graphene-based systems", as well as the possibility of using them as a means for measuring field enhancement in plasmonic structures ("Polarized plasmonic enhancement by Au nano structures probed through Raman scattering of suspended graphene").

The issue of new ways for enhancing the absorption of graphene in the optical regime (beyond its well know 2.3% broad-band absorption per graphene sheet) was presented in "Coherent and broadband enhanced optical absorption in graphene" and "A coherent perfect absorber made from graphene".

The workshop also addressed the non-linear electromagnetic properties of graphene ("Nonlinear electrodynamic phenomena in graphene", "Optical solitons in graphene"), and there was a large number of talks devoted to applications. Here we can highlight those devoted to amplification and lasing ("Challenges to create graphene-based terahertz and infrared lasers", "Superradiance, amplification, and lasing of terahertz radiation in an array of graphene plasmonic nanocavities"), and to resonators and photo- and THz detectors ("Broadband graphene room temperature photodetectors", "THz detection in graphene nanotransistors", "Graphene nanophotonics methods and devices: what can we learn from the microwave field?").

Importantly, there were ample discussions on the relation between the electromagnetic properties of graphene and those of other two-dimensional electron gases, such as those created in semiconductor heterojunctions. Also, the workshop covered other new layered systems (""Light emission and detection in single layer MoS_2" and "Plasmonic Excitations in a Topological Insulator"). Clearly research on these new low-dimensional gases in atomically thin films will expand quickly in the near future.

3 Assessment of results and future direction of the field.

Both as organizers and as scientists benefiting from the workshop, the results have far exceeded even our most optimistic expectancies. The quality of the work presented and the collaborative atmosphere in the meeting has been extremely high. We believe that everybody left the workshop with a invigorated sense of the potential scientific relevance and plethora of applications in the field of graphene nanophotonics, and with plenty of new ideas to work on.

As for the future of the field, based on what was presented at the workshop, we expect great activity in the characterization, visualization and understanding of graphene plasmons (in deep collaboration between experiment and theory), and their application to sensing in general and biosensing in particular. Another very active and promising area (not totally unrelated to the previous one) is the development of ultra-compact THz antennas and resonators. Lastly, graphene may be only the tip of the iceberg, with many different *classes* of atomically-thin materials (both isolated and in a superlattice arrangement) being only starting to be explored. Specially interesting seems the combination of conducting graphene with insulating systems as MoS_2.

To summarize, we strongly believe that such a monographic workshop on Graphene Nanophotonics was both timely and needed. It has allowed the close interaction between researchers coming from different fields, which were in many cases unknown to each other before the workshop. The workshop has been extremely successful in the presentation of recent scientific results and the creation of new collaborative links between the participants. We can only hope that such a workshop has a follow up, ideally in two years time.

4 Appendix: Program and Participants

CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

SCIENTIFIC ACTIVITY
PRESENT
2013
2014
2015
PREVIOUS

ORGANIZERS
YOUR SESSION
MAKE A PROPOSAL

VISITORS
VENUE
BENASQUE
FEEDBACK

OTHER ACTIVITIES
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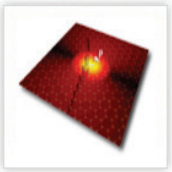

Graphene Nanophotonics

2013, Mar 03 -- Mar 08

Organizers:
L. Martín Moreno (ICMA, CSIC - U. Zaragoza)
Stefan Maier (Imperial College)

Monday, March 04

14:45h **Welcome**

15:00h **Graphene plasmonics: hybrid devices.**
A. Grigorenko

15:35h **The interaction of light and graphene: physics and applications**
F. Xia

16:10h **Magneto-plasmonic effects in epitaxial graphene**
A. Kuzmenko

16:45h **Broadband graphene room temperature photodetectors**
X. Cai

17:40h **THz detection in graphene nanotransistors**
A. Tredicucci

18:15h **Chemically functionalized graphene: a platform for plasmonics and photodetectors**
M. Craciun

18:50h **Diffraction, absorption and scattering in structures with graphene plasmons**
A. Nikitin

19:25h **Role of phonons on the optoelectronic and plasmonic response in graphene**
T. Low

20:00h **Strongly Confined Gap Plasmon Modes in a Graphene Sandwich**
Y. Francescato

Tuesday, March 05

15:00h **Phonon and exciton localization in graphene and carbon nanotubes**
L. Novotny

15:35h **Raman characterization of graphene-based systems.**
L. G. Cancado

16:10h **Optomechanics of Raman active Graphene optical cavities**
V. Bouchiat

16:45h **Enhanced Raman Scattering of Graphene using Arrays of Split Ring Resonators**
G. Sarau

17:05h **Polarized plasmonic enhancement by Au nano structures probed through Raman scattering of suspended graphene**
S. Heeg

17:45h **Near-field study of graphene plasmons: theory and experiment**
M. Fogler

18:20h **Real-space mapping of graphene plasmons by near-field microscopy**
R. Hillenbrandt

18:55h **Terahertz plasmon nanofocusing in graphene taper**
A. Davoyan

19:30h **Plasmonics in double-layer graphene structures**
T. Stauber

20:05h **Optical properties of non-symmetrical hyperbolic media, based on graphene multilayers**
I. Nefedov

20:25h **Novel hyperbolic metamaterials based on multilayer graphene structures.**
I. V. Iorsh

Wednesday, March 06

09:00h **Nonlinear electrodynamic phenomena in graphene**
S. Mikhailov

09:35h **Optical solitons in graphene**
F. J. Garcia-Vidal

10:10h **Terahertz Mixers Based on Two-dimensional Electron Gas Transistors**
M. Ortolani

11:05h **Momentum dependence and losses of graphene plasmons.**
F. Guinea

11:40h **Plasmon damping in graphene**
M. Jablan

12:15h **Spatial Dispersion and the Tensor Intraband Conductivity of Graphene**
G. Hanson

12:50h **Lunch**

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CONFERENCE DATA
LIST OF PARTICIPANTS
PROGRAM
PICTURES

LINKS

OUR BUILDING

15:00h **Graphene Micro and Nano Plasmonics: Experiments and Theory**
F. Rana

15:35h **Challenges to create graphene-based terahertz and infrared lasers**
T. Otsuji

16:10h **Effect of strong radiation on conduction in graphene**
S. Syzranov

16:30h **Superradiance, amplification, and lasing of terahertz radiation in an array of graphene plasmonic nanocavities**
V. V. Popov

17:15h **Poster Session**

Fabry-Perot enhanced Faraday rotation in graphene
N. Ubrig, I. Crassee, J. Levallois, L. Nedoliuk, F. Fromm, M. Kaiser, T. Seyller, A. B. Kuzmenko

Domains in zero resistance states
I. Dmitriev, M. Khodas, A. Mirlin, D. Polyakov

Dispersion Forces on Graphene Systems
S. Ribeiro and S. Scheel

Drude weight, cyclotron resonance and the Dicke model of graphene cavity QED
L. Chirolli, M. Polini, V. Giovannetti, A. H. MacDo

A new green, ascorbic acid-assisted method for versatile synthesis of Au-graphene hybrids as efficient surface-enhanced Raman scattering platformsAcknowledgements
M. Iliut, C. Leordean, V. Canpean and S. Astilean

Strong optical dichroism in graphene nano-ribbons
F. Hipólito, V. M. Pereira and N. M. R. Peres

Optical characterization of graphene layers using spectroscopic ellipsometry CORES CMYK
P. S. André, R. A. S. Ferreira, M. K. Singh, R. Correia, D. Karpinsky

Graphene supports the propagation of subwavelength optical solitons
M. L. Nesterov, J. Bravo-Abad, A. Yu. Nikitin , F. J. García-Vidal, L. Martín-Moreno

Near-field heat transfer controlled by plasmons in graphene and applications in thermophotovoltaics
M. Jablan, O. Ilic, M. Soljacic and H. Buljan

A microwave dielectric resonator for quality assessment of large area graphene
O. Shaforost, K. Wang, Z. Guo, L. Hao, J. Gallop, N. Klein

Thursday, March 07

15:00h **Graphene plasmons and electrons: nano and fast**
F. Koppens

15:35h **Interfacial engineering of graphene nanostructures**
C. Mattevi

16:10h **Plasmon-mediated wideband Far-infared Absorption in Graphene**
D. Han

16:30h **Guided-Mode Resonances of Graphene Plasmonic Waves**
Q. Xu

16:50h **Ultrafast Electron-Electron Dynamics**
D. Brida

17:30h **Classical and quantum effects in graphene plasmonics**
F. J. Garcia de Abajo

18:05h **Light emission and detection in sigle layer MoS2**
R. S. Sanduram

18:40h **Plasmonic excitations in a Topological Insulator**
M. Ortolani

19:15h **Coherent and broadband enhanced optical absorption in graphene**
G. Piruccio

19:50h **A coherent perfect absorber made from graphene**
R. Alaee

Friday, March 08

08:45h **Excitation of surface polaritons in graphene and other accompanying phenomena**
Y. Bludov

09:20h **Graphene nanophotonics methods and devices: what can we learn from the microwave field?**
J. Perruisseau-Carrier

09:55h **Many-Body effects in the Near-Field Optics of Graphene**
J.P.F. LeBlanc

10:50h **Tunable metamaterials on graphene**
S. Cakmakyapan

11:25h **Sample size effects on performance of subwavelength bolometers**
P. Renoux

11:45h **Coupling light into graphene plasmons with the help of surface acoustic waves**
J. Schiefele

12:05h **Enhanced Optical Dichroism of Graphene Nanoribbons**
F. Hipolito

Graphene Nanophotonic

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