June 30th – July 5th, 2024
Costa Dorada - Spain

2nd International Workshop on Microwave Research and Applications

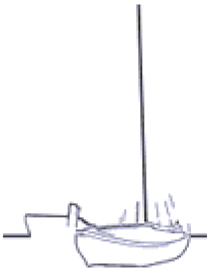
BOOK OF ABSTRACTS

COMARUGA
2024

http://www.ub.edu/gmag/comaruga
comaruga.workshop@gmail.com

INTERNACIONAL WORKSHOP ON MICROWAVES RESEARCH AND APPLICATIONS

BOOK OF ABSTRACTS



COMA-RUGA (EL VENDRELL)

June 30th – July 5th, 2024

Organizing committee:
E. M. Chudnovsky
J. Tejada
J. M. Lopez-Villegas
M. P. Marín
J. M. Hernàndez
J. Calvo-de la Rosa

Edited by
J. Calvo-de la Rosa

Welcome to

Bienvenidos a

Benvinguts a

Добро пожаловать в

Willkommen bei

Benvenuti

Сардэчна запрашаем у

Vítejte na

स्वागत

Bienvenue

Witamy w

Welkom op

欢迎来到

Fáilte go dtí

Coma-ruga 2024

ברוכים הבאים

へようこそ

에 오신 것을 환영합니다

GENERAL PROGRAMM

COMA-RUGA 2024 | International Workshop on Microwave Research and Applications

Hotel Balneario Playa de Comarruga | Avinguda Balneari, 4, 6, 43880 Coma-ruga, Tarragona | *Penedès* room

Schedule

	Sunday, June 30th	Monday, July 1st	Tuesday, July 2nd	Wednesday, July 3rd	Thursday, July 4th	Friday, July 5th	
9:30 - 10:00		**O1.1** *KEYNOTE SPEAKER* **Gerrit Bauer** Magnonics and ferronics	**O2.1** *KEYNOTE SPEAKER* **Mathias Weiler** Magnetoacoustics	**O3.1** *KEYNOTE SPEAKER* **Enrique del Barco** Coherent sub-terahertz spin pumping from an insulating antiferromagnet	**O4.1** *KEYNOTE SPEAKER* **Willie Padilla** Fundamental Bounds and Experimental Demonstration of Microwave and Terahertz Absorption from Metasurfaces	**O5.1** *KEYNOTE SPEAKER* **Valentine Novosad** On-chip microwave photon-mediated coupling and energy exchange in hybrid magnonic systems	9:30 - 10:00
10:00 - 10:25		**O1.2** **David Citrin** Microwave Scattering and the Properties of a New Quasi-Periodic Lattice: The Gauss Chain	**O2.2** **Madeleine Msall** Acoustic Anisotropy and Vortex Generation	**O3.2** **Norio Kumada** Ultrafast Carrier Dynamics in Graphene Investigated Using THz Electronics	**O4.2** **Mark Lee** Millimeter Wave Spectroscopy of Dielectrics for the 6G Telecom Spectrum	**O5.2** **Alexander Tselev** Near-field scanning microwave microscope with optical confocal distance control	10:00 - 10:25
10:25 - 10:50		**O1.3** **Manuel Vazquez** Cylindrical micro and nanowires: From advanced fabrication to microwave magnetic properties	**O2.3** **Alexander Poshakinskiy** Optically detected magnetic and spin-acoustic resonances in the excited state of silicon vacancies in SiC	**O3.3** **Iwona Swiderska** Molecular mechanism behind the interaction of microwaves with living neurons	**O4.3** **Eugene M. Chudnovsky** Scaling Theory of Microwave Absorption in Random Magnets	**O5.3** **Germán Álvarez-Botero** Integration of Microwave Resonant Sensors and Machine Learning Modeling for Advanced Characterization of Magnetodielectric Composites	10:25 - 10:50
10:50 - 11:20		**COFFEE BREAK**					10:50 - 11:20
11:20 - 11:45		**O1.4** **Andrey Chabanov** Designing a non-reciprocal metasurface with zero net magnetization for large-aperture microwave applications	**O2.4** **Alberto Hernández-Mínguez** Identification of acoustically driven spin resonances of silicon vacancies in 4H-SiC	**POSTER SESSION** (extended coffee break)	**O4.4** **Antoni García-Santiago** Barium hexaferrite-based nanocomposites as random magnets for microwave absorption	**O5.4** **Pablo Cerrato Serrano** Strong spin-photon coupling in van der Waals magnets	11:20 - 11:45
11:45 - 12:10		**O1.5** **Qiannan Xue** Microwave Toxin Discrimination Based on Simulated Cellular Membrane	**O2.5** **Alexey Scherbakov** Driving magnons by optically generated acoustic phonons: coherent control and reservoir computing	**O3.5** **Thomas Metzger** Terahertz magnetism of antiferromagnets	**O4.5** **Alberto Castellano-Soria** Particle Size Effects on Tuning Microwave Absorbing Properties: Fe3C@ Core@Shell Nanoparticles for Double-Peak Wideband Absorber	**O5.5** **Giovanni Finocchio** New opportunities for spintronic technology from Internet of Things to co-processors	11:45 - 12:10
12:10 - 12:35		**O1.6** **Ander Centeno-Pedrazo** Plastic waste valorization to clean H2 and decarbonized chemicals through its catalytic deconstruction by novel ionic liquid-based catalytic systems (WASTE2H2)	**O2.6** **Alessandro Pitanti** Geometrical control of symmetry and chirality of GHz acoustic waves	**O3.6** **Vanya Darakchieva** Terahertz optical Hall effect in microwave III-nitride HEMT structures	**O4.6** **Jaume Calvo-de la Rosa** Design of new multilayered systems and characterization methods for microwave absorption applications	**O5.6** **Yee Sin Ang** Physics of Electron Emission from 2D Materials: Analytical modelling of Thermal, Field, Optical-Field and Photoemission in the 2D Flatland	12:10 - 12:35
12:35 - 16:00		**LUNCH**				**Closing remarks**	12:35 - 12:45
							12:45 - 16:00
16:00 - 16:30		**O1.7** *KEYNOTE SPEAKER* **Daniel Navarro Urrios** Nonlinear dynamics on individual and interacting pairs of optomechanical crystal oscillators	**O2.7** *KEYNOTE SPEAKER* **Mathias Kläui** Microwave studies of spin-orbitronics and orbitronics	**O3.7** *KEYNOTE SPEAKER* **David Citrin** Terahertz Nondestructive Evaluation of Microelectronics Packaging	**O4.7** *KEYNOTE SPEAKER* **Vincent Laur** Study of resonant and broadband microwave absorbers based on multi-materials 3D printing		16:00 - 16:30
16:30 - 16:55		**O1.8** **Alexander Kuznetsov** Bridging microwave and optical domains with hybrid polariton phonon microcavities	**O2.8** **Ferran Macià** Surface acoustic wave induced spin waves	**O3.8** **Pilar Marín** Reinforcing Microwave absorbing properties of magnetic microwires based composites by combination with ball-milled magnetic and/or carbon-based nanostructures	**O4.8** **Javier Rodríguez** Microwave absorber integration in typical composite sandwich structures used in aeronautical construction		16:30 - 16:55
16:55 - 17:25		**COFFEE BREAK**					16:55 - 17:25
17:25 - 17:50		**O1.9** **Ignacio Carraro Haddad** GHz mechanical coherent control of an exciton-polariton condensate	**O2.9** **Del Atkinson** Ferromagnetic damping and spin transport behavior in thin-films and multilayers for spintronic applications	**O3.9** **Jonathan Bird** Using Transient Electrical Measurement to Reveal The Details of Hot-Carrier Dynamics in Semiconductor Devices	**O4.9** **Guido Luzi** A simple low-cost active reflector to assist spaceborne SAR interferometry		17:25 - 17:50
17:50 - 18:15		**O1.10** **Snezana Lazic Knezevic** Dynamic sound tuning of quantum light emission from GaN/InGaN nanowire quantum dots	**O2.10** **Alexander Buzdin** ac Hall Effect and Radiation Drag of Superconducting Condensates	**O3.10** **Jose Verdu** Trapped electrons for quantum microwave technology applications	**O4.10** **Dario Arena** Microwave and Optically Excited Studies of Ferromagnetic Resonance in Magnetic Multilayers		17:50 - 18:15
18:15 - 18:40		**O1.11** **Israel Arnedo** Terahertz NDT technology for radar coatings: radomes and stealth	**O2.11** **Dirk Hammer** Colosal acoustic waves	**O3.11** **Krishna C Balram** Towards efficient microwave interfaces to nanoscale systems: light, sound and spins	**O4.11** **María Guijarro Maortua** Analysis of Planar Metasurfaces for Monostatic and Bistatic RCS Reduction		18:15 - 18:40
	Welcome party (19:30 at *Penedès* room, Hotel Balneario Playa de Comarruga)			**Conference dinner** (20:30 at Cara al Mar restaurant)			

EVENT SCHEDULE

COMA-RUGA 2024

International Workshop on Microwave Research and Applications

JULY, 1st

01.1. Gerrit Bauer 09:30 – 10:00

Magnonics and ferronics

01.2. David Citrin 10:00 – 10:25

Microwave Scattering and the Properties of a New Quasi-Periodic Lattice: The Gauss Chain

01.3. Manuel Vázquez 10:25– 10:50

Cylindrical micro and nanowires: From advanced fabrication to microwave magnetic properties

COFFE BREAK (10:50 – 11:20)

01.4. Andrey Chabanov 11:20 – 11:45

Designing a non-reciprocal metasurface with zero net magnetization for large-aperture microwave applications

01.5. Qiannan Xue 11:45 – 12:10

Microwave Toxin Discrimination Based on Simulated Cellular Membrane

01.6. Ander Centeno-Pedrazo 12:10 – 12:35

Plastic waste valorization to clean H2 and decarbonized chemicals through its catalytic deconstruction by novel ionic liquid-based catalytic systems (WASTE2H2)

LUNCH (12:35 – 16:00)

01.7. Daniel Navarro Urrios 16:00 – 16:30

Nonlinear dynamics on individual and interacting pairs of optomechanical crystal oscillators

01.8. Alexander Kuznetsov 16:30 – 16:55

Bridging microwave and optical domains with hybrid polariton phonon microcavities

COFFE BREAK (16:55 – 17:25)

01.9. Ignacio Carraro Haddad 17:25 – 17:50

GHz mechanical coherent control of an excitonpolariton condensate

01.10. Snezana Lazic Knezevic 17:50 – 18:15

Dynamic sound tuning of quantum light emission
from GaN/InGaN nanowire quantum dots

01.11. Israel Arnedo 18:15 – 18:40

Terahertz NDT technology for radar coatings: radomes and stealth

JULY, 2nd

02.1. Mathias Weiler *09:30 – 10:00*

Magnetoacoustics

02.2. Madeleine Msall *10:00 – 10:25*

Acoustic Anisotropy and Vortex Generation

02.3. Alexander Poshakinskiy *10:25– 10:50*

Optically detected magnetic and spin-acoustic resonances in the excited state of silicon vacancies in SiC

COFFE BREAK (10:50 – 11:20)

02.4. Alberto Hernández-Mínguez *11:20 – 11:45*

Identification of acoustically driven spin resonances of silicon vacancies in 4H-SiC

02.5. Alexey Scherbakov *11:45 – 12:10*

Driving magnons by optically generated acoustic phonons: coherent control and reservoir computing

02.6. Alessandro Pitanti *12:10 – 12:35*

Geometrical control of symmetry and chirality of GHz acoustic waves

LUNCH (12:35 – 16:00)

02.7. Mathias Kläui *16:00 – 16:30*

Microwave studies of spin-orbitronics and orbitronics

02.8. Ferran Macià *16:30 – 16:55*

Surface acoustic wave induced spin wave

COFFE BREAK (16:55 – 17:25)

02.9. Del Atkinson *17:25 – 17:50*

Ferromagnetic damping and spin transport behavior in thin-films and multilayers for spintronic application

02.10. Alexander Buzdin *17:50 – 18:15*

ac Hall Effect and Radiation Drag of Superconducting Condensates

02.11. Dirk Hammer *18:15 – 18:40*

Colosal acoustic waves

EVENT SCHEDULE

COMA-RUGA 2024

International Workshop on Microwave Research and Applications

JULY, 3rd

03.1. Enrique del Barco 09:30 – 10:00

Coherent sub-terahertz spin pumping from an insulating antiferromagnet

03.2. Norio Kumada 10:00 – 10:25

Ultrafast Carrier Dynamics in Graphene Investigated Using THz Electronics

03.3. Iwona Swiderska 10:25– 10:50

Molecular mechanism behind the interaction of microwaves with living neurons

COFFE BREAK (10:50 – 11:20)

POSTER SESSION 11:20 – 11:45

Extended coffee break

03.5. Thomas Metzge 11:45 – 12:10

Terahertz magnetism of antiferromagnets

03.6. Vanya Darakchieva 12:10 – 12:35

Terahertz optical Hall effect in microwave III-nitride HEMT structure

LUNCH (12:35 – 16:00)

03.7. David Citrin 16:00 – 16:30

Terahertz Nondestructive Evaluation of Microelectronics Packaging

03.8. Pilar Marín 16:30 – 16:55

Reinforcing Microwave absorbing properties of magnetic microwires based composites by combination with ball-milled magnetic and/or carbon-based nanostructures

COFFE BREAK (16:55 – 17:25)

03.9. Jonathan Bird 17:25 – 17:50

Using Transient Electrical Measurement to Reveal The Details of Hot-Carrier Dynamics in Semiconductor Devices

03.10. Jose Verdu 17:50 – 18:15

Trapped electrons for quantum microwave technology applications

03.11. Krishna C Balram 18:15 – 18:40

Towards efficient microwave interfaces to nanoscale systems: light, sound and spins

CONFERENCE DINNER | 20:30 at Cara al Mar restaurant

EVENT SCHEDULE

COMA-RUGA 2024

International Workshop on Microwave Research and Applications

JULY, 4th

04.1. Willie Padilla *09:30 – 10:00*

Fundamental Bounds and Experimental Demonstration of Microwave and Terahertz Absorption from Metasurfaces

04.2. Mark Lee *10:00 – 10:25*

Millimeter Wave Spectroscopy of Dielectrics for the 6G Telecom Spectrum

04.3. Eugene M. Chudnovsky *10:25– 10:50*

Scaling Theory of Microwave Absorption in Random Magnets

COFFE BREAK (10:50 – 11:20)

04.4. Antoni García-Santiago *11:20 – 11:45*

Barium hexaferrite-based nanocomposites as random magnets for microwave absorption

04.5. Alberto Castellano-Soria *11:45 – 12:10*

Particle Size Effects on Tuning Microwave Absorbing Properties: Fe3C@ Core@Shell Nanoparticles for Double-Peak Wideband

04.6. Jaume Calvo-de la Rosa *12:10 – 12:35*

Design of new multilayered systems and characterization methods for microwave absorption applications

LUNCH (12:35 – 16:00)

04.7. Vincent Laur *16:00 – 16:30*

Study of resonant and broadband microwave absorbers based on multi-materials 3D printing

04.8. Javier Rodríguez *16:30 – 16:55*

Microwave absorber integration in typical composite sandwich structures used in aeronautical construction

COFFE BREAK (16:55 – 17:25)

04.9. Guido Luzi *17:25 – 17:50*

A simple low-cost active reflector to assist spaceborne SAR interferometry

04.10. Dario Arena *17:50 – 18:15*

Microwave and Optically Excited Studies of Ferromagnetic Resonance in Magnetic Multilayers

04.11. María Guijarro Maortua *18:15 – 18:40*

Analysis of Planar Metasurfaces for Monostatic and Bistatic RCS Reduction

COMA-RUGA 2024

International Workshop on Microwave Research and Applications

EVENT SCHEDULE

JULY, 5th

05.1. Valentine Novosad *09:30 – 10:00*

On-chip microwave photon-mediated coupling and energy exchange in hybrid magnonic systems

05.2. Alexander Tselev *10:00 – 10:25*

Near-field scanning microwave microscope with optical confocal distance control

05.3. Germán Álvarez-Botero *10:25– 10:50*

Integration of Microwave Resonant Sensors and Machine Learning Modeling for Advanced Characterization of Magnetodielectric Composites

COFFE BREAK (10:50 – 11:20)

05.4. Pablo Cerrato Serrano *11:20 – 11:45*

Strong spin-photon coupling in van der Waals magnets

05.5. Giovanni Finocchio *11:45 – 12:10*

New opportunities for spintronic technology from Internet of Things to co-processors

05.6. Yee Sin Ang *12:10 – 12:35*

Physics of Electron Emission from 2D Materials: Analytical modelling of Thermal, Field, Optical-Field and Photoemission in the 2D Flatland

CLOSING REMARKS (12:35 – 12:45)

Magnonics and Ferronics

Gerrit Bauer[a,b]

[a]Kavli Institute for Theoretical Sciences, UCAS, Beijing, China
[b]WPI-AIMR, Tohoku University, Sendai, Japan

The duality between electric and magnetic dipoles in electromagnetism only partly applies to condensed matter. In particular, the elementary excitations of the magnetic and ferroelectric orders, namely magnons and ferrons, differ in many respects. I will compare the basic physics underlying the advanced field of “magnonics” with that of the emerging field of “ferronics” [1] and share recent insights.

[1] G.E.W. Bauer, P. Tang, R. Iguchi, J. Xiao, K. Shen, Z. Zhong, T. Yu, S.M. Rezende, J.P. Heremans, and K. Uchida, Perspective: Polarization transport in ferroelectrics, Phys. Rev. Appl. **20**, 050501 (2023).

Microwave Scattering and the Properties of a New Quasi-Periodic Lattice: The Gauss Chain

D.S. Citrin

Georgia Tech-CNRS IRL2958, Georgia Tech-Europe, 2 Rue Marconi, 57070 Metz, France
and
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta,
Georgia 30332-0250 USA

Since the discovery of quasicrystals, interest in one-dimensional quasiperiodic chains has taken off. Perhaps, the most studied are the Fibonacci and Thue-Morse chains [1,2], but many others have attracted interest. Quasiperiodic chains are one-dimensional nonperiodic lattices that exhibit some properties similar to periodic systems and well as novel properties not encountered in crystals. The scattering properties of quasiperiodic systems show frequency or angular dependence that is singular-continuous or exhibit self-similar properties. In addition, solving for the electronic structure of such chains may show a mix of localized, extended, and critical states.

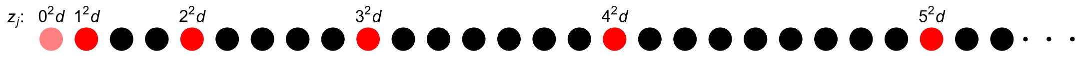


Fig.1: Schematic diagram of the Gauss chain. $z_j = j^2d$ labels positions of lattice sites (pink for $j = 0$, red for $j \in \mathbb{N}$). The atomic form factor of the sites in black is zero. The Fourier transform of this chain is the Jacobi theta function $\theta_3(q)$ with $q = \exp[i(k + i\alpha)d]$ the nome and $\alpha \rightarrow 0$ a convergence factor leading to a highly complex structure factor despite the chain's simplicity.

We have recently introduced the Gauss chain (see Fig. 1) in which scattering or lattice sites are located at j^2d where j is an integer and d is a length [3-9]. The scattering properties of the Gauss chain show highly complex behavior qualitatively distinct from that shown by periodic or random lattices as frequency or angle is varied. This chain, though manifestly nonperiodic, may exhibit a set of extended states with a singular-continuous spectrum. These extend states can be found in closed form and their existence is due to a hidden symmetry of the Gauss chain. The Gauss chain also is related to functions of number-theoretic importance.

In this talk I review the basic properties of Gauss chains and discuss possible applications relying on their scattering behavior.

[1] R Merlin, "Structural and electronic properties of nonperiodic superlattices," IEEE J Quantum Electron **24**, 1791 (1988).
[2] A Jagannathan, "The Fibonacci quasicrystal: Case study of hidden dimensions and multifracticality," Rev Mod Phys **93**, 045001 (2021).
[3] DS Citrin, "Quadratic superlattices: A type of nonperiodic lattice with extended states," Phys Rev B **107**, 125150 (2023).
[4] DS Citrin, "Structure factor and the electronic structure in quadratic Gauss chains: A hidden symmetry revealed," Phys Lett A, 128978 (2023).
[5] DS Citrin, "Continuum approach to the quadratic chain: Exact closed-form classification of extended states," Phys Rev B **107**, 235144 (2023).
[6] DS Citrin, "Gauss chains: Quadratic to quintic," J Appl Phys **134** (2023).
[7] DS Citrin, "Real-space renormalization-group treatment of quadratic chains," Phys. Scr. **98**, 115016 (2023).

Cylindrical micro and nanowires: From advanced fabrication to microwave magnetic properties

Manuel Vazquez

Instituto de Ciencia de Materiales de Madrid, CSIC

There is currently growing interest in the effects of curvature on the magnetic response of curved nanostructures, as they offer novel alternatives to planar systems. In particular, the cylindrical geometry introduces significant singularities in the magnetic properties of ferromagnetic wires just from their curvature [1]. In this presentation we will revisit some of the most outstanding magnetic responses of magnetic wires and their arrays with diameter in the range from 20 μm down to 20 nm as a function of the excitation frequency in the range from 0.1 up to 20GHz frequency. Two families of magnetic wires will be considered: i) microwires fabricated ultrarapid solidification techniques, and ii) nanowires electrochemically synthesized.

Microwires are fabricated by in-rotating-water and by quenching and drawing ultrarapid solidification techniques. The ultrasoft microwires with CoFe-based alloy compositions show nearly vanishing magnetostriction and exhibit Giant Magneto-Impedance, GMI, effect originated by classical skin effect. By this phenomenon, real and imaginary components of impedance change drastically at the presence of static magnetic field or applied mechanical stress. It requires a small amplitude high-frequency AC current flowing through the microwire. The ferromagnetic resonance frequency phenomenon is in addition analyzed in those microwires as well as in bimagnetic multilayer microwires where an external shell is also grown where multipeak absorption is observed [2]. These microwires are currently employed in very sensitive field and stress sensors based on the GMI.

Arrays of magnetic (Fe, Ni, Co and their alloys) nanowires embedded in self-assembled porous templates are synthesized by electrochemical route. After a brief overview on the fabrication and static magnetic characterization of individual nanowires, we will concentrate on the ferromagnetic resonance phenomena [3]. This is a powerful tool to determine fundamental dynamics parameters as damping or gyromagnetic factor, as well as magnetic anisotropy constant or saturation magnetization, but also to serve as the base for microwave applications mostly in the communications sector [4]. Here, we will first review the dependence of microwave absorption on the orientation of applied field, a useful tool to determine the magnetic anisotropy parameters and the significance of magnetostatic interactions of nanowire arrays with different composition. The magnetization easy axis can be switched from the nanowires direction to the plane of the template membrane as the nanowire filling factor increases or at a compensation temperature. In both cases it derives from the energy balance of anisotropy and magnetostatic interactions among nanowires. Final comments will be devoted to the spin waves resonance spectra, and the perspectives of applications making use of microwave properties.

[1] R. Streubel et al., J. Phys. D Appl. Phys. 49, 363001 (2016).
[2] J. Torrejon et al., J. Phys. D Appl. Phys. 43, 145001 (2010).
[3] M. Darques et al., J. Magn. Magn. Mater. 321, 2055 (2009).
[4] M. Vazquez, J. Magn. Magn. Mater., 543, 168634 (2022).

Designing a non-reciprocal metasurface with zero net magnetization for large-aperture microwave applications

Sadi Ayhan,[a] Nazar Pyvovar,[a] Carl Preiffer,[b] Igor Anisimov,[b] Ilya Vitebskiy,[b] Andrey A Chabanov[a]

[a]*Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, TX, 78249, USA*
[b]*Sensors Directorate, Air Force Research Laboratory, Wright-Patterson AFB, OH, 45433, USA*

The key element of most nonreciprocal devices, such as microwave and optical isolators, circulators, and nonreciprocal phase shifters, is a magnetic material, self-biased or placed in an external magnetic field. However, a magnetized material creates its own demagnetization field, which may be nonuniform and thereby seriously degrade the performance of a nonreciprocal device. Another common problem is the magnetic field outside the magnetic component. There are important applications, such as quantum navigation and sensing, that cannot tolerate even a tiny magnetic field. Using single-phased compensated ferrites can also be problematic because they maintain zero net magnetization only at a certain temperature. Here, we introduce a self-biased composite structure of magnetically hard neodymium cylinders incorporated into a flat, magnetically soft matrix of yttrium iron garnet (YIG). The array of neodymium cylinders provides a uniform magnetic bias for the YIG matrix, while YIG itself is responsible for the Faraday rotation. This structure provides a strong and temperature-independent Faraday rotation while maintaining zero net magnetization within a wide temperature range. The aperture of such a Faraday rotator is virtually unlimited. We demonstrate a highly uniform 45-degree Faraday rotation for an X-band microwave beam.

Microwave Toxin Discrimination Based on Simulated Cellular Membrane

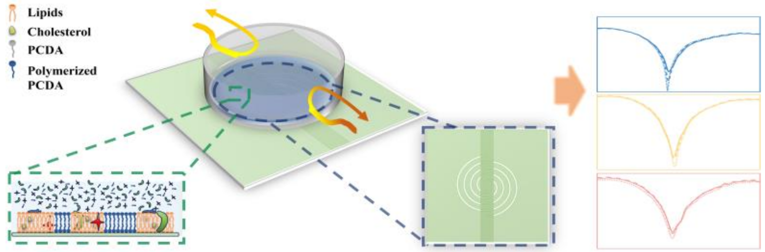
Qiannan Xue,[a]* Jiaxu Wang,[a] Zhou Shen,[a] Rongheng Wang,[a] Xuexin Duan[a]

*[a] State Key Laboratory of Precision Measurement Technology and Instruments, School of Precision Instruments and Optoelectronics Engineering, Tianjin University, Tianjin 300072, China. * qiannanxue@tju.edu.cn*

Biological organisms possess unique responsiveness to biochemical targets. As the primary biological interface for cells and organelles, lipid membranes are garnering increasing attention and are widely employed as models for studying interactions between cell surfaces and external compounds. While preserving membrane conformation, lipid membranes can be utilized to construct biosensors organized at the molecular level. Furthermore, by doping with organic functional molecules, lipid membrane interfaces capable of stable operation in air can be prepared. Biological and polymeric materials can be doped into ultrathin films for use as biosensor platforms, mimicking the fundamental physiological processes extensively engaged by lipid polymers and fully exploiting their unique ability to recognize biochemical molecules.

Based on the variations in electromagnetic properties of sensing materials at ultra-high frequencies, microwave bio-sensors have emerged. Microwave biosensors typically offer non-invasive or non-destructive functionalities, allowing for the preservation of sample integrity without the need for handling or damaging the sample, enabling real-time monitoring of biological sample changes and facilitating continuous monitoring and tracking of biological processes. Microwave sensing methods have previously been demonstrated to be effective for monitoring temperature and humidity, and in recent years, applications have been reported for detecting ethanol mixtures [3], milk adulteration [4], cell growth [5], among others.

This paper presents a novel method for microwave-based discrimination of biological toxins, utilizing different interactions between toxins and simulated cell membranes, coupled with microwave signals for discernment and readout. The employed microwave sensor consists of Archimedean spiral resonators, demonstrating high responsiveness to microwave sensing signals within characteristic frequency bands of simulated cell membranes. This enables the sensitive identification and extraction of physiological process variations associated with the interaction between simulated cell membranes and toxins. The higher robustness and signal-to-noise ratio of this microwave biosensor, along with its good integration capabilities with backend circuits and potential for wireless transmission, open up a new avenue for the development of high-precision discrimination of biological targets.



[1] Gulsu Mustafa Suphi; Bagci Fulya; Can Sultan; Yilmaz Asim Egemen; Akaoglu Baris, Sensors and Actuators A: Physical, 330: 112841(2021).

[2] Abdulkarim Yadgar I.; Bakır Mehmet; Yaşar İbrahim; Ulutaş Hasan; Karaaslan Muharrem; Alkurt Fatih Özkan; Sabah Cumali; Dong Jian, Applied Optics, 61: 1972-1981(2022).

[3] Longo Matthieu; Rioual Stéphane; Talbot Philippe; Faÿ Fabienne; Hellio Claire; Lescop Benoît, Sensing and Bio-Sensing Research, 36: 100493(2022).

Plastic waste valorization to clean H_2 and decarbonized chemicals through its catalytic deconstruction by novel ionic liquid-based catalytic systems (WASTE2H2)

Ander Centeno-Pedrazo,[a] **Jonatan Pérez-Arce**,[a] **Eduardo J. Garcia-Suarez**,[a,b]

[a] *Center for Cooperative Research on Alternative Energies (CIC energiGUNE), Basque Research and Technology Alliance (BRTA), Alava Technology Park, Albert Einstein 48, 01510 Vitoria-Gasteiz, Spain.*
[b] *IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain.*

Daily basis used plastics cause a huge amount of waste having an enormous impact on the environment and living species at the end-of-life of plastics disposal. In fact, around 300 million tons of plastic are produced annually in the world and only small percentage, less than 9 % according to UNEP, of this plastic is recycled, 12 % is incinerated and the 79% left generates big contamination problems.[1] There are already different ways, not all of them economically viable, to valorize plastic waste (PW) e.g., chemical recycling to feedstocks and energy.[2] Furthermore, the decarbonization of all sectors of activity becomes of paramount importance and hydrogen is set to play a key role in decarbonizing hard-to-electrify sectors, as well as represent a zero-carbon feedstock for chemicals and fuel production but for H_2 to play the desired role in the energy transition, the scientific community must face the big challenge of decarbonizing H_2 production at a competitive cost. In this world context, the IEC-funded project WASTE2H2 is proposing a novel method where innovative Ionic Liquid-based catalytic systems are combined with microwave (MW) irradiation to selectively produce highly pure clean H_2 and valuable decarbonized chemicals (solid carbon) from PW, addressing simultaneously PW remediation and global climate change.

The IEC-funded project WASTE2H2 add to novelty significant progress compared to other routes for PW mitigation and H_2 production: i) plastic waste deconstruction by single-step method powered by renewable electricity and working under mild conditions; ii) fast production of highly pure H_2; iii) valuable solid carbon production as sole decarbonized co-product, with easy recovery for its commercialization; iv) expected long lifespan of catalytic system, easy recovery and reuse; v) reducing significantly the energy consumption due to MWs; and vi) high potential to reduce H_2 production cost.

[1] S. Devasahayam, G.B. Raju, C.M. Hussain, Materials Science for Energy Technologies, 2 (3), 634 (2019).
[2] P.S. Roy, G. Garnier, F. Allais, K. Saito, ChemSusChem, 14 (19), 4007 (2021).

Nonlinear dynamics on individual and interacting pairs of optomechanical crystal oscillators

Daniel Navarro-Urrios[a]

[a] *MIND –IN2UB, Electronics and Biomedical Engineering Department at University of Barcelona*

The advances of fabrication techniques have made available the successful demonstration of a wide variety of high-quality nanoscaled optomechanical devices, i.e., high-Q mechanical resonators that are efficiently coupled to high-Q optical cavities [1]. Of particular importance are the so-called optomechanical crystal cavities, where the optical cavity is created as a defect within a photonic crystal operating in the near-infrared region.

Under specific conditions, radiation pressure forces within the optical cavity become effective enough to trigger a self-sustained mechanical, giving rise to the concept of optomechanical crystal oscillators (OMO). In this work, I will review our recent studies using one-dimensional OMOs consisting of Silicon nanobeams or nanopillars, giving rise to coherent mechanical oscillations with frequencies up to few GHz. I will cover our recent studies on individual OMOs [2], spontaneous synchronization of pairs of OMOs [3], cascaded injection locking of several OMOs to an external signal [4] and multimode phonon lasers [5].

References:

[1] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, Rev. Mod. Phys. **86**, 1391 (2014).

[2] D. Navarro-Urrios, N. Capuj, M. Colombano, P. D. Garcia, M. Sledzinska, F. Alzina, A. Griol, A. Martinez, C. Sotomayor-Torres, Nature Communications, **8**, 14965 (2017).

[3] D. Alonso-Tomás, N. E. Capuj, L. Mercadé, A. Griol, A. Martínez, and D. Navarro-Urrios, ACS Photonics, **11**, 1, 7-12 (2024)

[4] D. Alonso-Tomás, N. E. Capuj, L. Mercadé, A. Griol, A. Martínez, and D. Navarro-Urrios, under review

[5] R. C. Ng, P. Nizet, D. Navarro-Urrios, G. Arregui, M. Albrechtsen, P. D. García, S. Stobbe, C. M. Sotomayor-Torres, and G. Madiot, Phys. Rev. Research **5**, L032028 (2023).

Bridging microwave and optical domains with hybrid polariton-phonon microcavities

Alexander S. Kuznetsov,[a] Klaus Biermann,[a] Paulo V. Santos[a]

[a]Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e. V., Hausvogteiplatz 5-7, 10117 Berlin, Germany

Superconducting qubits operate at a few GHz, while the long-distance information transfer relies on optical photons of a few 100^{ds} THz. Therefore, distributed quantum networks require efficient interconversion between microwave and optical photons. One attractive approach is to use optomechanical (OM) interactions, which involve resonant conversion of a microwave quantum into a phonon and the up-conversion of the latter to the optical photon [1]. Typical OM systems rely on the surface acoustic waves and the radiation-pressure-like coupling of the latter to photons in micro-resonators with sub-MHz coupling rates. It has been suggested that the conversion efficiency can be enhanced by utilizing GHz bulk acoustic waves (BAW phonons) and excitonic light-matter polariton quasi-particles in semiconductor microcavities (MCs). Polaritons enable exciton-enhanced deformation potential coupling of BAWs to photons with coupling rates reaching 20 MHz [2]. We use hybrid patterned AlGaAs MCs, which co-localize BAWs and optical fields and enhance coupling to excitons in quantum wells to realize compact on-chip cells for the conversion between microwaves and light. In the experiment, we convert 7 GHz microwave to BAWs using bulk acoustic transducers. The BAW strain couples efficiently to the energy of the polariton laser-like resonances (non-equilibrium bosonic condensates) with sub-GHz linewidth excited optically at 10 K. The coherent conversion is then evidenced in the emission of polaritons as well-resolved sidebands (frequency comb) with the spacing equal to the frequency of the microwave signal [3]. The number of phonon sidebands can be tuned by the microwave power. Further challenges lie in reducing the optical linewidth below the BAW frequency in the few-polariton regime for the quantum transduction.

[1] X. Han, W. Fu, C-L Zou, L. Jiang, H. X. Tang, Optica, 8 (8), 1050 (2021)
[2] P. Sesin, A. S. Kuznetsov, G. Rozas, S. Anguiano, A. E. Bruchhausen, A. Lemaître, K. Biermann, P. V. Santos, A. Fainstein, Phys. Rev. Research 5, L042035 (2023)
[3] A. S. Kuznetsov, K. Biermann, A. A. Reynoso, A. Fainstein, P. V. Santos, Nat. Commun., 14, 5470 (2023)

GHz mechanical coherent control of an exciton-polariton condensate

Ignacio Carraro-Haddad,[1] Dimitri L. Chafatinos,[1] Alexander K. Kuznetsov,[2] Ignacio A. Papuccio-Fernández,[1] Andrés A. Reynoso,[1] Axel Bruchhausen,[1] Klaus Biermann,[2] Paulo V. Santos,[2] Gonzalo Usaj,[1, 3, 4] and Alejandro Fainstein[1]

[1]*Centro Atómico Bariloche and Instituto Balseiro, Bariloche, Argentina.*
[2]*Paul-Drude-Institut für Festkörperelektronik, Berlin, Germany.*
[3]*TQC, Universiteit Antwerpen, Antwerpen, Belgium*
[4]*CENOLI, Université Libre de Bruxelles, Brussels, Belgium*

Semiconductor Ga(Al)As microcavities offer a unique platform for investigating the strong coupling between excitons and photons, as well as their interaction with GHz cavity phonons (bulk acoustic waves, BAWs). This strong coupling leads to the emergence of exciton-polaritons, composite quasi-particles inheriting both the low effective mass and propagation properties of cavity photons and the strong non-linear interactions of excitons. Additionally, polaritons in these structures exhibit a highly efficient coupling to confined cavity phonons, characterized by frequencies in the range 20-100 GHz [1,2].

Under non-resonant continuous-wave laser excitation, polaritons transition into a Bose-Einstein condensate state at sufficiently high pump power [3]. In our investigation, we illustrate that these condensates in fully confined microstructured traps, spontaneously break continuous time translation symmetry, leading to the formation of a periodic temporal structure known as a continuous time crystal (TC). The observed temporal structure involves the spinor degree of freedom of the condensate, which is shown to display Larmor-like limit cycle orbits. Moreover, these time crystalline states synchronize their frequency with that of the cavity phonon, thereby stabilizing the TC. Interestingly, at higher laser powers, the TC exhibits more intricate dynamics such as period doubling relative to the mechanical vibrational frequency. This secondary disruption of an internal discrete time translation symmetry is identified as a discrete TC. We show that the dynamics of the system can be mapped to Bloch equations similar to those used to describe spins in nuclear magnetic resonance, where radiofrequency vibrations play the role of time-dependent synthetic magnetic fields, thus opening the path for the use of BAWs for swapping between polariton states. As an illustration, we propose a theoretical implementation of an optical switch utilizing a $\pi/2$ mechanical pulse protocol. The observed temporally stable periodic states pave the way for a mechanically controlled optical system operating in the GHz range, with potential applications in classical and quantum computing [4].

[1] A. Fainstein, N. D. Lanzillotti-Kimura, B. Jusserand, and B. Perrin, Phys. Rev. Lett., **110**, 037403 (2013).
[2] P. Sesin, A. S. Kuznetsov, G. Rozas, S. Anguiano, A. E. Bruchhausen, A. Lemaître, K. Biermann, P. V. Santos, and A. Fainstein, Phys. Rev. R., **5**, L042035 (2023).
[3] J. Kasprzak, M. Richard, S. Kundermann, A. Baas, P. Jeambrun, J. M. J. Keeling, F. M. Marchetti, M. H. Szymańska, R. André, J. L. Staehli, V. Savona, P. B. Littlewood, B. Deveaud and Le Si Dang, Nature, **443,** 409–414 (2006).
[4] I. Carraro-Haddad, D. L. Chafatinos, A. S. Kuznetsov, I. A. Papuccio-Fernández, A. A. Reynoso, A. E. Bruchhausen, K. Biermann, P. V. Santos, G. Usaj and A. Fainstein, arXiv:2401.06246 [cond-mat.other] (2024)

Dynamic sound tuning of quantum light emission from GaN/InGaN nanowire quantum dots

Snežana Lazić[a]

[a]*Departamento de Física de Materiales, Instituto 'Nicolás Cabrera' and Instituto de Física de Materia Condensada (IFIMAC),*
Universidad Autónoma de Madrid, 28049 Madrid, Spain

Efficient production and manipulation of single-photons are crucial prerequisites for quantum light applications. Future on-chip quantum photonics requires controllable quantum emitters that can be operated on-demand and with the possibility of in situ control of the photon emission wavelength and its polarization state. Among various non-classical light sources available, quantum dots (QDs) outdo with their integrability into existing semiconductor technologies. Here, we report the first proof-of-principle demonstration of the dynamic real-time control, using radio frequency surface acoustic waves (SAWs), of the optical emission from QDs embedded in epitaxially grown core-shell GaN/InGaN nanowire (NW) heterostructures [1]. The SAWs are excited on the surface of a piezoelectric $LiNbO_3$ crystal equipped with an acoustic delay line onto which the NWs were mechanically transferred [2,3]. Luminescent QD-like exciton localization centers, induced by indium content fluctuations within the InGaN nanoshell, are identified using spatially, polarization- and time-resolved stroboscopic micro-photoluminescence (µ-PL) spectroscopy. They exhibit narrow and highly linearly polarized emission lines in the µ-PL spectra and a pronounced antibunching signature of single-photon emission in the photon correlation experiments [2,3]. Depending on their location within the InGaN nanoshell, nonpolar (m-), semipolar (r-) or polar (c-facet) QDs are discerned, thereby making these NWs the first single nanostructures able to host non-classical light emitters with both high- as well as low-polarity crystallographic orientations [1]. Owing to their shorter radiative lifetimes resulting from weak built-in electric field values along the growth axis, the III-nitride QDs grown on alternative low-polarity crystallographic planes are greatly beneficial for future high-speed quantum information technologies. When such NWs are perturbed by the propagating SAW, the embedded QDs are periodically strained and their excitonic transitions are dynamically modulated by the acousto-mechanical coupling, giving rise to a spectral fine-tuning within a ~2 meV bandwidth at the acoustic frequency of ~330 MHz [2,3]. This outcome is further combined with spectral detection filtering for temporal control of the emitted photons [2]. In this way, both spectral tunability and on demand emission of single photons is achieved simultaneously. Moreover, the SAW-triggered acousto-electric effect inflicts changes in the QD charge population and its optical polarization [3]. Reduction (up to 30%) in the initially high linear polarization degree is observed (unpublished result). This is an important advance since, to date, the photon polarization state of III-nitride QDs has been either probabilistic or pre-determined by electronic properties of the system. Altogether, this study opens the door to the use of sound for scalable integration of III-nitride-based quantum emitters in nanophotonic and quantum information technologies. The advantage of the acousto-optoelectric over other control schemes is that it allows in-situ manipulation of the optical emission properties over a wide frequency range (up to GHz frequencies).

[1] Ž. Gačević et al., ACS Photon. 4, 657 (2017).
[2] S. Lazić et al., Semicond. Sci. Technol. 32, 084002 (2017).
[3] S. Lazić et al., J. Phys. D: Appl. Phys. 51, 104001 (2018).

Terahertz NDT technology for radar coatings: radomes and stealth

Israel Arnedo, PhD,[a,b]

[a]*Public University of Navarra (UPNA)*
[b]*das-Nano*

Radar coatings are crucial for both the optimal performance of radomes and ensuring stealth capabilities. The thickness of these coatings must be meticulously measured and controlled within specific parameters. Currently, monitoring the thickness of radome coatings is an indirect process. After painting and curing, radar wave transmission is measured to evaluate the coating thickness. If the thickness falls outside the acceptable range, the paint must be removed and reapplied, leading to significant economic losses. Terahertz technology offers a solution by enabling contactless, rapid measurements of wet paint during the painting process to predict the final dry thickness. This allows real-time control of the painting process, ensuring zero-defects production.

Measuring the thickness of stealth coatings on composite substrates is a complex task. Terahertz technology effectively addresses this challenge.

Magnetoacoustics

Mathias Weiler

Department of Physics and State Research Center OPTIMAS,
RPTU Kaiserslautern-Landau, Germany

Spin waves form the basis for the field of magnonics, where they are used for information transport and processing [1]. Acoustic waves, in particular surface acoustic waves (SAWs), are widely employed as frequency filters in mobile communication technology. SAWs have group velocities comparable to that of spin waves and consequently can be generated with magnon-compatible wavelengths and at microwave frequencies. In magnetic media, spin waves can interact with SAWs which defines the field of magnetoacoustics. Magneto-acoustic devices can be used to excite and detect magnetization dynamics acoustically and control SAW propagation magnetically. Because of the ellipticity of the magneto-acoustic driving fields, as well as the spin-wave non-reciprocity due to dipolar coupling and the Dzyaloshinskii-Moriya interactions [2,3], magneto-acoustic waves are thereby generally chiral and non-reciprocal [4,5].

I will discuss the chirality and non-reciprocity of magneto-acoustic waves in magnetically ordered thin films and heterostructures. The magnon-phonon coupling is driven not only by magneto-elastic interactions [6] but also by magneto-rotation [7,8]. The coupling of SAWs and spin waves is coherent [9] and can drive non-linear magneto-acoustic dynamics [10]. Non-linear and non-reciprocal coherent magneto-acoustic waves may be useful for the implementation of miniaturized on-chip microwave components.

[1] P. Pirro et al., Nat. Rev. Mater. 6, 1114 (2021).
[2] J.-H. Moon et al., Phys. Rev. B 88, (2013).
[3] H. T. Nembach et al., Nat. Phys. 11, 825 (2015).
[4] M. Küß et al., Frontiers in Physics 10, (2022).
[5] M. Küß et al., ACS Appl. Electron. Mater. 5, 5103 (2023).
[6] M. Weiler et al., Phys. Rev. Lett. 106, 117601 (2011).
[7] M. Küß et al., Phys. Rev. Lett., 125, 217203 (2020).
[8] M. Xu et al., Sci. Adv. 6, eabb1724 (2020).
[9] Y. Kunz et al., Apl. Phys. Lett. 124, 152403 (2024).
[10] P. J. Shah et al., Adv. Elect. Mat. 9, 2300524 (2023).

Acoustic Anisotropy and Vortex Generation

M.E. Msall[a,b]

[a]Department of Physics and Astronomy, Bowdoin College, Brunswick, ME 04011
[b]Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, 10117 Berlin

Helical acoustic waves can be coupled to magnetic systems or used to transfer angular momentum to opto-electronic states. Though magnetoacoustic waves have intrinsic chirality, such couplings may be enhanced by the generation of acoustic vortices using interdigital transducers (IDTs). MHz frequency acoustic vortices, along with strong helical pressure waves, have been successfully created in liquids using spiral IDTs. [1] In crystalline systems, phonon propagation and coupling is often highly anisotropic. The creation of a localized surface acoustic wave (SAW) vortex requires IDT structures tailored to conform to the anisotropic group velocity surface along with spiraling offsets that introduce appropriate phase shifts in the converging acoustic beams. This talk will present COMSOL finite element models of spiral IDTs on GaAs and on ZnO and propose new designs for SAW vortex generation in the GHz range.

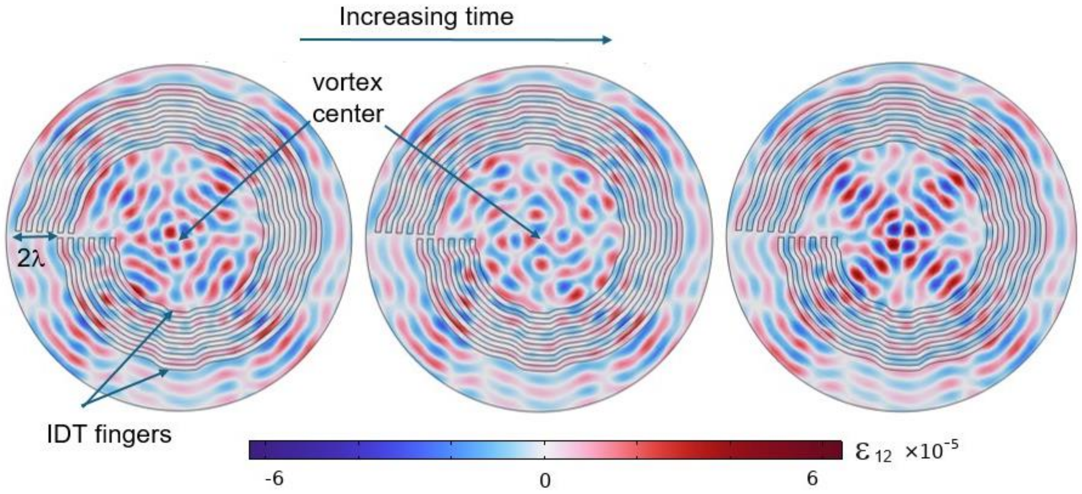


Fig. 1 Strain vortex on [001] GaAs surface. The IDT finger outlines are shown in black. A 2.6 GHz RF voltage applied across neighboring metal finger pairs launches SAW along the surface. The color indicates the value of the xy-component of the strain tensor, ε_{12}, which describes an in-plane shear strain of the acoustic wave. Due to the spiraling increase in the finger distance from the center, which increases by 2λ around the circle, a stable zero strain point forms at the IDT center. As time advances, from left to right, the strain maxima are seen to rotate around this point. The IDT wavelength is $\lambda = 1$ μm. The vortex is rotating CCW.

[1] Baudoin, Michael, et al. "Spatially selective manipulation of cells with single-beam acoustical tweezers." *Nature communications* 11.1 (2020): 4244.

Optically detected magnetic and spin-acoustic resonances in the excited state of silicon vacancies in SiC

A.V. Poshakinskiy,[a] A. Hernández-Mínguez,[b] M. Hollenbach,[c] P.V. Santos,[b] G.V. Astakhov[c]

[a]ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology,
08860 Castelldefels, Barcelona, Spain
[b]Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V.,
Hausvogteiplatz 5-7, 10117 Berlin, Germany
[c]Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials
Research, Bautzner Landstrasse 400, 01328 Dresden, Germany

Silicon vacancies in silicon carbide have optically addressable spin states that are promising for quantum applications. Their spin can be manipulated by radio-frequency fields and lives up to several seconds at low temperature and tens of milliseconds at room temperature. The ground state of the negatively charged vacancy is described by five electrons with the total orbital momentum $L = 0$ and total spin $S = 3/2$. The optical properties of the vacancy are governed by the excited states with $L = 1$ and $S = 3/2$. While the spin properties of the ground state are rather well known, those of the excited states remain largely unexplored [1].

Here, we study the excited states of the silicon vacancies by means of optically detected magnetic and spin-acoustic resonance, that is, by monitoring the change of the photoluminescence intensity under application of RF electromagnetic or acoustic wave. The spin-acoustic resonance technique offers additional sensitivity and flexibility for the study of excited states, as compared to the conventional magnetic resonance. While the RF magnetic field couples to the ground and excited states with the same strength, the spin-acoustic interaction constant in the excited state is about two orders of magnitude larger. Also, in contrast to RF magnetic field, that can induce transitions with the spin projection change by $\Delta S_z = \pm 1$ only, the acoustic wave can also induce transitions with $\Delta S_z = \pm 2$ [2].

We show that the interference of the spin transitions in the ground and excited states induced by the same acoustic wave leads to the trapping of the spin along a certain direction. The coherence of the spin-trapped states becomes limited by intrinsic relaxation processes only [3]. A weak magnetic field applied perpendicular to the symmetry axis reorients spin multipoles in the ground state and leads to the inversion of the net spin quadrupole polarization and appearance of the dipole spin polarization, that is much higher than the thermal one [4]. All our experimental findings are well explained in the framework of the rate equations for spin-density matrices of the ground and excited states of the vacancy.

[1] I. D. Breev, Z. Shang, A.V. Poshakinskiy, H. Singh, Y. Berencén, M. Hollenbach, S.S. Nagalyuk, E.N. Mokhov, R.A. Babunts, P.G. Baranov, D. Suter, S.A. Tarasenko, G.V. Astakhov, A. N. Anisimov, npj Quantum Information, 8, 23 (2022).
[2] A. Hernández-Mínguez, A.V. Poshakinskiy, M. Hollenbach, P.V. Santos, G.V. Astakhov, Phys. Rev. Lett., 125, 107702 (2020).
[3] A. Hernández-Mínguez, A.V. Poshakinskiy, M. Hollenbach, P.V. Santos, G.V. Astakhov, Science Advances, 7, eabj5030 (2021).
[4] A. Hernández-Mínguez, A.V. Poshakinskiy, M. Hollenbach, P.V. Santos, G.V. Astakhov, arXiv:2404.07915 (2024).

Identification of acoustically driven spin resonances of silicon vacancies in 4H-SiC

A. Hernández-Mínguez,[a] T. Vasselon,[b] M. Hollenbach,[c,d] G.V. Astakhov,[d] Paulo V. Santos[a]

[a] *Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., Germany*
[b] *Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France*
[c] *Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, Germany*
[d] *Technische Universität Dresden, Germany*

Spin centers in solids are attractive systems for applications in quantum technologies. One such center is the negatively charged silicon vacancy (V_{Si}) in 4H-SiC. This center emits in the near infrared, where optical glass fibers have low absorption, and its long-living spin states can be optically addressed and controlled by microwave (MW) magnetic fields [1]. V_{Si} centers can occur at two non-equivalent sites in the 4H-SiC polytype, with hexagonal (V1) and cubic (V2) local crystallographic environments, see inset in Fig. 1(a). Both V1 and V2 centers share the same half-integer spin S = 3/2, but their orbital and spin states have different energies due to the non-common local environments. The V2 center has been intensively studied because its MW-driven spin transitions can be efficiently addressed even at room temperature. In contrast, room-temperature spin manipulation of the V1 center has remained elusive [2].

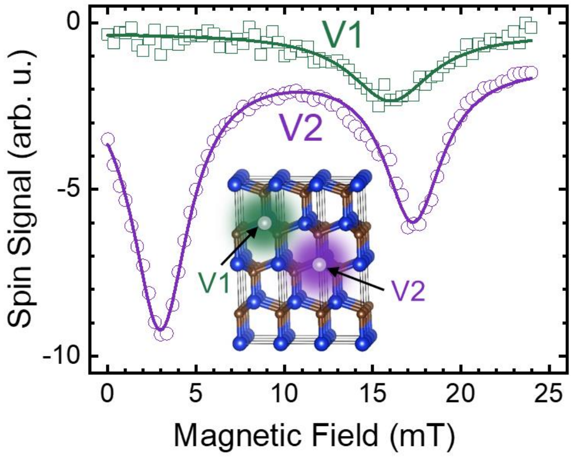


Figure 1. Spin resonances for the V1 (green squares) and V2 (purple circles) centers, driven by a 920 MHz SAW. The different energies of the spin states for the V1 and V2 centers determine the magnetic fields at which the spin resonances appear. The inset shows the crystallographic structure of the V1 and V2 centers in the 4H-SiC polytype.

Recently, we have shown that acoustic vibrations in the form of surface acoustic waves (SAWs), similar to MW magnetic fields, can drive spin transitions in the V2 center at room temperature [3]. In this contribution, we show that SAW strain fields can also manipulate the spin states of the V1 center [4], see Fig. 1. In contrast to MW-driven spin resonances, SAW-driven resonances are observed for both the V1 and V2 centers at all temperatures studied, even at room temperature, thus suggesting that both types of centers have similar sensitivity to the dynamic strain of the SAW. Based on the width and temperature dependence of the spin resonances, we attribute them to transitions between spin sublevels in the optically excited state. The dynamic acoustic control of both V1 and V2 spin centers in their excited states opens possibilities for the implementation of efficient quantum sensing protocols using spin optomechanics in the GHz frequency range.

[1] E. Sörman *et al.*, “Silicon vacancy related defect in 4H and 6H SiC”, Phys. Rev. B **61**, 2613 (2000).

[2] R. Nagy *et al.*, “Quantum Properties of Dichroic Silicon Vacancies in Silicon Carbide”, Phys. Rev. Appl. **9**, 034022 (2018).

[3] A. Hernández-Mínguez *et al.*, “Anisotropic Spin-Acoustic Resonance in Silicon Carbide at Room Temperature”, Phys. Rev. Lett. **125**, 107702 (2020).

[4] T. Vasselon *et al.*,” Acoustically Induced Spin Resonances of Silicon-Vacancy Centers in 4H -SiC”, Phys. Rev. Appl. **20**, 034017 (2023).

Driving magnons by optically generated acoustic phonons: coherent control and reservoir computing

Alexey V. Scherbakov

Experimentelle Physik 2, Technische Universität Dortmund, 44227 Dortmund, Germany

Magnons and phonons are prospective information carriers for quantum and neuromorphic computing. Their functionality becomes significantly enriched by their interaction, which is present in all magnetically ordered materials [1]. The magnon-phonon interaction is most pronounced at resonance conditions when the frequencies and wave vectors of the interacting quasiparticles coincide. In ferromagnets, it can be fulfilled in the frequency range of ~10-100 GHz and wavelengths of ~10-100 nm. Accordingly, the magnon and phonon eigenmodes of a ferromagnetic structure with such characteristic dimensions are also spectrally matched. Thus, by exploiting the possibility of controlling the dispersion, spatial profile, and lifetime of the phonon and magnon modes by the structural design and observing their interaction in the time domain, we can explore the manifold manifestations of magnon-phonon interaction.

The talk overviews the two experiments [2,3] with magnetic nanostructures based on Galfenol – a metallic ferromagnet with enhanced magnetoelastic coupling. The studied structures are lateral ferromagnetic nanogratings with a period of ~100 nm deposited on a GaAs substrate. In the pump-probe experiments, we monitor the coherent elastic and magnetic response on ultrafast optical excitation. The transient reflectivity and Kerr rotation signals measured in the scheme of asynchronous optical sampling (ASOPS) reflect the phonon and magnon dynamics, respectively. An external magnetic field controls the magnon frequencies and, thus, spectral detuning of the interacting phonon and magnon modes.

In the first experiment [2], the structural design was adjusted to form the long-living ground magnon and phonon modes, which are well spectrally separated from their counterparts. In this case, the coherent magnetic response is determined by two processes: a broadband direct optical excitation of the magnon mode and its quasi-harmonic driving by the phonon mode. The interference of these two excitations, whose phase relation was controlled by the external magnetic field and the pump laser fluence, allowed us to realize coherent control of the magnon dynamics.

In the second experiment [3], a magnetic nanograting was deposited on a multimode phonon waveguide [4] and, opposite to the first experiment, contained a bunch of spectrally close magnon modes. Their interaction with the optically generated multimode phonon wavepacket propagating in the phonon waveguide resulted in a complex spatiotemporal evolution of the coherent magnetic response. Its waveform demonstrated continuous transformation with superior volatility. We show that such a system can be used for physical reservoir computing – a framework for solving neuromorphic tasks at the hardware level [5]. We proved the neuromorphic potential of our invention by recognition of visual symbols “drawn” by the pulsed laser on the nanograting surface in an area of the size of a single photo pixel.

[1] Y. Li, C. Zhao, W. Zhang, A. Hoffmann, and V. Novosad., APL Mater. **9**, 060902 (2021).
[2] A. V. Scherbakov et al., Phys. Rev. Research **6**, L012019 (2024).
[3] D. D. Yaremkevich et al., Nat. Commun. **14**, 8296 (2023).
[4] D. D. Yaremkevich et al., ACS Nano **15**, 4802 (2021).
[5] D. Marković, A. Mizrahi, D. Querlioz, and J. Grollier, Nat. Rev. Phys. **2**, 499 (2020).

Geometrical control of symmetry and chirality of GHz acoustic waves

Alessandro Pitanti[a,b,c]

[a]*University of Pisa, largo B. Pontecorvo 3, 56127 Pisa - Italy*
[b]*Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, 10117 Berlin - Germany*
[c]*CNR – Istituto Nanoscienze, piazza San Silvestro 12, 56127 Pisa - Italy*

High frequency acoustic waves are gaining momentum as a key element in hybrid systems, where the pervasive nature of mechanical coupling, the low dissipation and device footprint favor their combination with classical and quantum excitations. A strong requirement for optimal connection is the ability to exert full control over acoustic symmetries, enabling effects such as wavefront manipulation, wave routing as well as more complex behavior, including topologically protected transport. Among the different approaches for acoustic wave control, we focus on the use of appropriate geometrical designs to sculpt the wave phase and achieved desired outcomes.

In a first investigation, we combined acoustic metasurfaces with surface acoustic waves in a GaAs-based material platform, demonstrating tailorable wave transmission and refraction and in particular realizing effects not available in natural materials such as symmetric and asymmetric negative refraction [1,2]. The same technological platform has already shown interesting effects of optomechanical manipulation of near-infrared light at MHz frequencies, offering interesting perspectives for GHz acoustic-optic interaction in delocalized structures [3].

In another approach, we employed bulk acoustic wave resonators featuring spiral-shaped contacts to generate acoustic vortex beams, propagating into a sapphire substrate [4]. Exhibiting a broad excitation band around 4 GHz and tunable topological charge, the acoustic vortices can unveil interesting effects in combination with magnetic materials, spins as well as light, in the latter case enabling dynamical control of spin and orbital angular momentum.

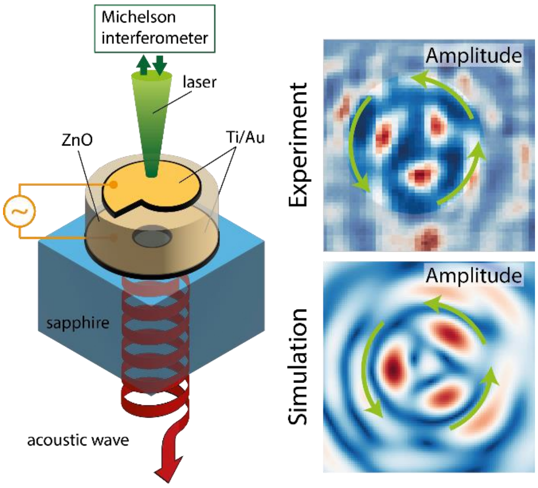


Figure 1: Sketch of the bulk acoustic wave resonator generating acoustic vortices and experimental and simulated vertical displacement map at 1.135 GHz at the device top surface showing a typical acoustic vortex

[1] S. Zanotto, G. Biasiol, P. V. Santos, A. Pitanti, Nat. Comm., 13, 5939 (2022).
[2] A. Pitanti, M. Yuan, S. Zanotto. P. V. Santos, Phys. Rev. Appl., 20, 054054 (2023)
[3] A. Pitanti, G. Da Prato, A. Tredicucci, S. Zanotto, *submitted*
[4] A. Pitanti, N. Ashurbekov, M. Msall, I. de Pedro-Embid, P. V. Santos, *in preparation*

Microwave studies of spin-orbitronics and orbitronics

Mathias Kläui[a,b]

[a] Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany
[b] Centre for Quantum Spintronics, NTNU, 7491 Trondheim, Norway

Novel spintronic devices can play a role in the quest for GreenIT if they are stable and can transport and manipulate spin with low power. Devices have been proposed, where switching by energy-efficient approaches is used to manipulate topological spin structures [1,2].

We combine ultimate stability of topological states due to chiral interactions [3,4] with ultra-efficient manipulation using novel spin torques [3-5]. In particular orbital torques [6] increase the switching efficiency by more than a factor 10. Using microwave dynamics, we ascertain the strengths of the spin-orbit torques and in particular identify orbital torques.

We use microwave-induced skyrmion dynamics for non-conventional stochastic computing applications, where we developed skyrmion reshuffler devices [7] based on skyrmion diffusion, which also reveals the origin of skyrmion pinning [7]. Such diffusion can furthermore be used for Token-based Brownian Computing and Reservoir Computing [8].

We go beyond simple ferromagnets and study multilayers with antiferromagnetic coupling termed synthetic antiferromagnets. We find that the diffusion dynamics is drastically enhanced due to the topology and efficient microwave dynamics can be induced by spin torques [9]. Finally, we find novel topological spin structures, such as bi-merons that are stabilized in synthetic antiferromagnets that exhibit higher frequency eigenmode dynamics [10].

[1] G. Finocchio et al., J. Phys. D: Appl. Phys., vol. 49, no. 42, 423001, 2016.
[2] K. Everschor-Sitte et al., J. Appl. Phys., vol. 124, no. 24, 240901, 2018.
[3] S. Woo et al., Nature Mater., vol. 15, no. 5, pp. 501–506, 2016.
[4] K. Litzius et al., Nature Phys., vol. 13, no. 2, pp. 170–175, 2017.
[5] K. Litzius et al., Nature Electron., vol. 3, no. 1, pp. 30–36, 2020.
[6] S. Ding et al. Phys. Rev. Lett. 125, 177201, 2020; Phys. Rev. Lett. 128, 067201, 2022.
[7] J. Zázvorka et al., Nature Nanotechnol., vol. 14, no. 7, pp. 658–661, 2019;
R. Gruber et al., Nature Commun. vol. 13, pp. 3144, 2022.
[8] K. Raab et al., Nature Commun. vol. 13, pp. 6982, 2022;
M. Brems et al., Appl. Phys. Lett. 119, 132405, 2021.
[9] T. Dohi et al., Nature Commun. vol. 14, pp. 5424, 2023.
[10] M. Bhukta et al., Nature Commun. vol. 15, pp. 1641 2024.

Surface acoustic wave induced spin waves

Marc Rovirola[1, 2], M. Waqas Khaliq[1, 3], Travis Gustafson[4], Blai Casals[2, 5], Joan Manel Hernàndez[1, 2], Sandra Ruiz-Gómez[6], Miguel Angel Niño[3], Lucía Aballe[3], Alberto Hernández-Mínguez[7], Michael Foerster[3] , A. Begué[8], N. Cotón[8], N. Biskup[8], R. Ranchal[8] and ***Ferran Macià[1, 2]***,
[1]*Dept. of Condensed Matter Physics, University of Barcelona, 08028 Barcelona, Spain*
[2]*Institute of Nanoscience and Nanotechnology (IN2UB),University of Barcelona, 08028 Barcelona, Spain*
[3]*ALBA Synchrotron Light Source, 08290 Cerdanyola del Vallès, Spain*
[4]*Department of Physics, Norwegian University of Science and Technology (NTNU), 7034 Trondheim, Norway*
[5]*Dept. of Applied Physics, University of Barcelona, 08028 Barcelona, Spain*
[6]*Max Planck Institute for Chemical Physics of Solids, 01187-Dresden, Germany*
[7]*Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., 10117 Berlin, German*
[8]*Departamento de Física de Materiales, Facultad de Ciencias Físicas (UCM), Avenida Complutense, s/n 28040-Madrid, Spain*

Magnetoacoustic waves (MAWs) are joint magnetization and acoustic excitations in ferromagnetic thin films. The subject is gaining interest because acoustic generation of magnetization waves is energy efficient and uses well-established fabrication processes. Surface acoustic waves (SAWs) provide an efficient coupling between strain and magnetization, which makes it an attractive option to generate and manipulate MAWs. The transformation of strain into magnetization is done through the magnetoelastic effect, which needs a magnetostrictive ferromagnetic material.

Direct imaging using X-ray Photoemission electron microscopy (XPEEM) together with X-ray magnetic circular dichroism (XMCD) allow for a complete picture of the behavior of MAWs compared to indirect measurements such as, acoustic ferromagnetic resonance. These techniques not only provide qualitative information but can also be used to quantifying MAWs and SAWs. Here we present the findings from experiments involving different materials (nickel, cobalt [1], FeSi [2], and FeGa [3]) subjected to high-frequency SAWs ranging from 500 MHz up-to 3 GHz. The experimental set-up, shown on the bottom part of Fig. 1 (a), consists of a piezoelectric and a ferromagnetic thin film. SAWs are generated using Interdigital transducers which in turn interact with the ferromagnetic material, resulting in the generation of MAWs. A representative XMCD image is shown in the top part of Fig. 1 (a), where MAWs are shown on Nickel at two different frequencies. These experimental techniques, together with micromagnetic simulations, allow the quantification of the magnetoelastic constants, which is an indication of the coupling strength between strain and magnetization. Moreover, we have also explored through micromagnetic simulations the effects of SAWs and MAWs on magnetic domain walls (DW), revealing that DW dynamics can be altered depending on the DW characteristics.

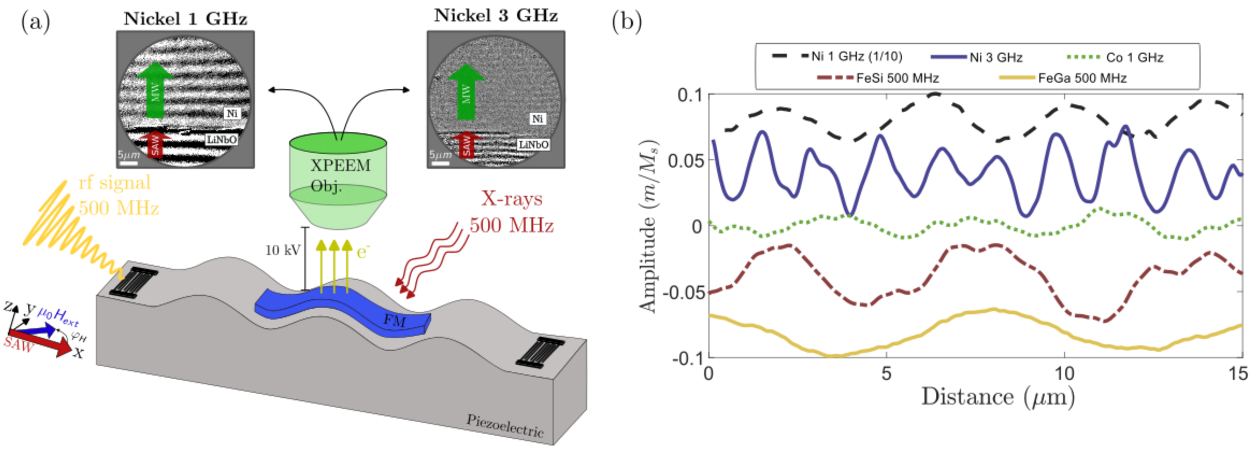


Fig. 1. (a) Bottom part illustrates the hybrid set-up, comprising of a piezoelectric and a ferromagnetic material. Interdigital transducers (IDTs) are used to generate SAWs and X-rays are used to excite electrons from the sample to capture XMCD images as showcased on the top part, for Nickel at 1 and 3 GHz. (b) Displays the normalized MAW amplitude for different ferromagnetic materials. The Nickel profile of 1 GHz has been scaled down 1/10 to be compared with the rest.

[1] M. Rovirola et al. arXiv:2312.15269v1 (2023)
[2] M. Rovirola et al. Phys. Rev. Applied 20, 034052 (2023)
[3] Manuscript in preparation

Ferromagnetic damping and spin transport behavior in thin-films and multilayers for spintronic applications

Del Atkinson[a]

[a] *Department of Physics, Condensed Matter Physics, Durham University, Durham, UK*

Interfacial interactions in thin-film multilayers mediate phenomena that are significant for spintronics applications, such as spin transport, interfacial anisotropy, Dzyaloshinskii-Moriya interactions (iDMI) and the proximity-induced-magnetization (PIM) of heavy metals (HM) layers.

The focus in this overview is on thin-film ferromagnetic damping. The first part discusses developments in understanding of the widely studied enhancement of damping in ferromagnetic (FM) / non-magnetic (NM) spintronic multilayers that occurs via interfacial effects and the pumping of spin-current into NM layers, see recent reviews [1, 2]. Via Onsager reciprocity, knowledge from such spin-pumping FMR also directly impacts our understanding of spin-orbit torque (SOT) switching by spin-current injection from a HM layer into a FM layer.

The role of interfaces and the linkage between different interfacial phenomena has been the subject of debate [3], including the role of proximity induced magnetisation (PIM) in damping and spin transport across FM/HM interfaces. Debate has also surrounded the values for spin-diffusion length obtained from FMR spin-pumping analysis [4] and spin-pumping through insulating layers [5]. The spin-diffusion length is an important parameter in spintronics and here a fuller physical description of the analysis of spin-transport from spin-pumping in FM/NM is presented that shows that both the NM and FM layer thicknesses should be systematically studied and also shows the need to incorporate a thickness dependence for the spin-diffusion length in the NM layer [5]. Next, the effects on FM damping and spin-transport across the interface in relation to induced magnetization, PIM, in non-magnetic heavy metal layers [6] and the role of additional interfaces on damping ferromagnetic multi-layered systems [7] are discussed. This work demonstrates a strong relationship between Pt PIM and enhancement of the ferromagnetic damping and furthermore shows the role of additional interfaces to be important and dependent on the materials involved.

The final part considers the need for ultralow damping materials for applications such as magnonics. Newly published results are presented that demonstrates that deliberate, controlled localised compositional doping within a metallic ferromagnetic layer can effectively reduce the fundamental precessional damping in the layer by localised electronic engineering. In this case Cr was doped into the upper and lower few monolayers of a Co thin-film layer during film growth to create a ‘synthetic’ thin-film material with lower damping [8]. Results shows a huge reduction of the measured damping and good agreement with tight binding theory, for doping up to 30% only within the upper and lower few monolayers. Above 30% the damping falls further, but structural changes cannot be ruled out at these levels of doping.

[1] S. Azzawi, A.T. Hindmarch & D. Atkinson *J Phys D: Appl. Phys.* 50, 473001 (2017)
[2] C. Swindells & D.Atkinson *J. Appl. Phys.* 131,170902 (2022)
[3] R. Rowan-Robinson *et al.* D. Atkinson *Sci Reps* 7: 16835 (2017)
[4] C. Swindells A.T. Hindmarch A.J. Gallant. & D. Atkinson *Phys. Rev. B* 99, 064406 (2019)
[5] C. Swindells A.T. Hindmarch A.J. Gallant & D. Atkinson *Appl. Phys. Letts* 116, 042403 (2020)
[6] C. Swindells *et al.* D. Atkinson *Appl. Phys. Letts.* 119, 152401 (2021)
[7] C. Swindells *et al.* D. Atkinson *Phys Rev B* 105, 094433 (2022)
[8] S. Azzawi *et al.* D. Atkinson *APL Mater.* 11, 081108 (2023)

ac Hall Effect and Radiation Drag of Superconducting Condensates

A. Buzdin,[a] **S. Mironov,**[b] **A. Melnikov** [b]

[a] *University of Bordeaux, LOMA UMR-CNRS 5798, F-33405, France*
[b]*Institute for Physics of Microstructures, RAS, 603950 Nizhny Novgorod, Russia*

We suggest a theoretical description of phenomena arising in superconducting condensates in the field of electromagnetic wave [1]. The ac Hall effect and EM drag are related with the second-order nonlinear response of superconducting carriers caused by the modulation of their concentration due to the combined influence of the electron-hole asymmetry and charge imbalance generated by the incident electromagnetic wave. Starting from the time-dependent Ginzburg-Landau theory with the complex relaxation constant, we develop a phenomenological description of these phenomena and investigate the resulting behavior of the dc supercurrent and second harmonic induced by microwave radiation incident on a superconductor surface

[1] S. V. Mironov, A.S. Melnikov, and A.I. Buzdin, Phys. Rev. Lett., **132**, 096001 (2024).

Coherent sub-terahertz spin pumping from an insulating antiferromagnet

Enrique del Barco[a], Priyanka Vaidya[a], Sophie A. Morley[b], Johan van Tol[c], Yan Liu[d], Ran Cheng[e], Arne Brataas[f], and David Lederman[b]

[a]*Department of Physics, University of Central Florida, Orlando, FL 32765, USA.*
[b]*Department of Physics, University of California Santa Cruz, Santa Cruz, CA 95064, USA.*
[c]*National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310, USA.*
[d]*Northeastern University, Shenyang, Liaoning, China*
[e]*Department of Electrical and Computer Engineering, and Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA.*
[f]*Department of Physics, Center for Quantum Spintronics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*

Emerging phenomena, such as the spin-Hall effect (SHE), spin pumping, and spin-transfer torque (STT), allow for interconversion between charge and spin currents and the generation of magnetization dynamics that could potentially lead to faster, denser, and more energy efficient, non-volatile memory and logic devices. Present STT-based devices rely on ferromagnetic (FM) materials as their active constituents. However, the flexibility offered by the intrinsic net magnetization and anisotropy for detecting and manipulating the magnetic state of ferromagnets also translates into limitations in terms of density (neighboring elements can couple through stray fields), speed (frequencies are limited to the GHz range), and frequency tunability (external magnetic fields needed). A new direction in the field of spintronics is to employ antiferromagnetic (AF) materials. In contrast to ferromagnets, where magnetic anisotropy dominates spin dynamics, in antiferromagnets spin dynamics are governed by the interatomic exchange interaction energies, which are orders of magnitude larger than the magnetic anisotropy energy, leading to the potential for ultrafast information processing and communication in the THz frequency range, with broadband frequency tunability without the need of external magnetic fields.

I will present the first evidence of sub-terahertz coherent spin pumping at the interface of a uniaxial insulating antiferromagnet MnF2 and platinum thin films, measured by the ISHE voltage signal arising from spin-charge conversion in the platinum layer. The ISHE signal depends on the chirality of the dynamical modes of the antiferromagnet, which is selectively excited and modulated by the handedness of the circularly polarized sub-THz irradiation (see figure). Contrary to the case of ferromagnets, antiferromagnetic spin pumping exhibits a sign dependence on the chirality of dynamical modes, allowing for the unambiguous distinction between coherent spin pumping and the thermally-driven, chirality-independent spin Seebeck effect. Our results open the door to the controlled generation of coherent pure spin currents with antiferromagnets at unprecedented high frequencies.

This work has been primarily supported by the Air Force Office of Scientific Research under Grant FA9550-19-1-0307.

[1] Priyanka Vaidya, Sophie A. Morley, Johan van Tol, Yan Liu, Ran Cheng, Arne Brataas, David Lederman, and Enrique del Barco, “Subterahertz spin pumping from an insulating antiferromagnet” Science 368, 160-165 (2020) / Work highlighted in the Journal by a perspective article: Spin pumping gathers speed, by Axel Hoffman, Science 368, 135-136 (2020)).

Ultrafast Carrier Dynamics in Graphene Investigated Using THz Electronics

**Katsumasa Yoshioka,[a] Guillaume Bernard,[a] Taro Wakamura,[a] Masayuki Hashisaka,[a]
Kenichi Sasaki,[a] Satoshi Sasaki,[a] Kenju Watanabe,[b] Takashi Taniguchi,[c] Norio Kumada[a]**

*[a]NTT Basic Research Laboratories, NTT Corporation, Atsugi 243-0198, Japan
[b]Research Center for Electronic and Optical Materials, National Institute for Materials Science, Tsukuba 305-0044, Japan
[c]Research Center for Materials Nanoarchitectonics, National Institute for Materials Science, Tsukuba 305-0044, Japan*

High-frequency electrical measurements are essential for time-resolved studies of charge propagation in two-dimensional electron systems. However, conventional high-frequency measurement techniques are limited to time resolutions on the order of tens of picoseconds, making it challenging to investigate charge dynamics in small-scale two-dimensional materials, such as those fabricated by exfoliation. To address this issue, we have developed terahertz (THz) electronics to achieve sub-picosecond time resolution.

Our THz electronics is based on excitation of ultrashort electrical pulse and its time domain detection by laser pulses on photo-conductive switches. In this presentation, we report two results. First, we demonstrate the operation of a graphene photodetector with a bandwidth of 220 GHz by performing time-resolved measurements of graphene photocurrent [Figs. 1(a) and (b)]. Optical-to-electrical conversion processes in graphene will be discussed [1]. Second, we present the propagation of 1-ps-wide wavepackets of graphene plasmons [Figs. 2(a) and (b)]. We demonstrate that the velocity of the wavepacket changes with the carrier density $v \propto n^{1/4}$ as expected for acoustic graphene plasmons [2]. Our results not only provide insights into ultrafast charge dynamics in graphene but also open new possibilities for developing high-speed optoelectronic devices based on two-dimensional materials. This work was supported by JSPS KAKENHI Grant No. JP22H00112.

[1] K. Yoshioka et al., Nat. Photon. **16**, 718 (2022).
[2] K. Yoshioka et al., arXiv:2311.02821

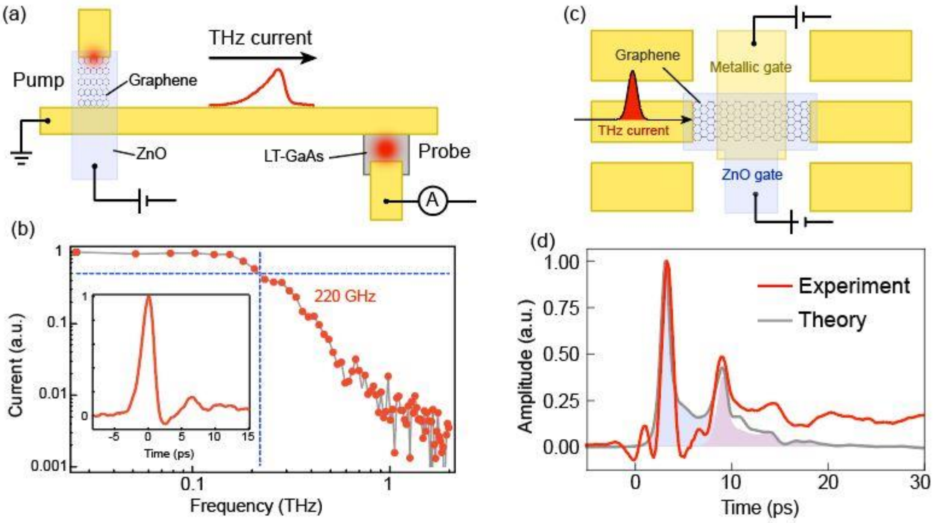


Fig. 1: (a) Schematic of the device structure for graphene photodetector measurement. (b) Temporal profile of the photocurrent (inset) and the Fourier-transformed spectrum. (c) Schematic of the device structure for graphene plasmon measurement. (d) Time-domain waveform of the plasmon wavepacket. Current peak time corresponds to the time-of-flight of the wavepacket across graphene micro ribbon.

Molecular mechanism behind the interaction of microwaves with living neurons

Iwona Swiderska,[a] Sylvie Roke,[a]

[a]*Laboratory for fundamental BioPhotonics (LBP), Institute of Bio-engineering (IBI), and Institute of Materials Science (IMX), School of Engineering (STI), and Lausanne Centre for Ultrafast Science (LACUS), École Polytechnique Fédérale de Lausanne (EPFL), CH-1015, Lausanne, Switzerland*

Microwave (MW) neurostimulation with MWs well below IEEE limits has recently shown promising medical applications of microwaves hinting at non-thermal interaction pathways [1]. These results warrant a thorough investigation into the molecular-level mechanism of MW-cell interactions. We aim to investigate the molecular fundamentals behind the non-thermal interaction of microwaves with living neurons, using the building blocks of life in a sequential manner. Since all living matter is for ~60 % composed of water, we start by investigating liquid water-MW interactions, and increase the complexity towards membrane-water interfaces and finally neuron-MW interactions. We use high-throughput nonlinear light scattering [2] and imaging [3] tools to do so. These methods (Fig. 1) are uniquely suited to understand the molecular structure of water in bulk solution [4] and at interfaces. In our preliminary results we observe instantaneous changes to the molecular structure of bulk and interfacial water upon microwave exposure, which cannot be explained by induced temperature variations, and hint towards changes in the electrostatic energy landscape.

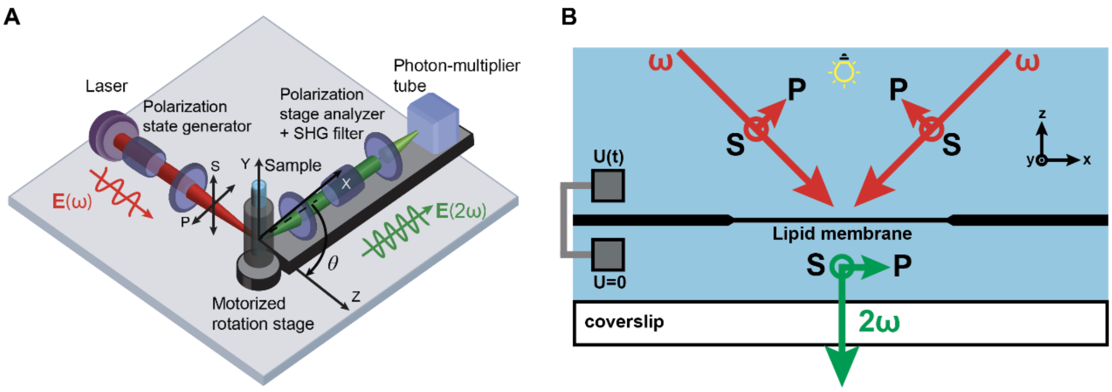


Figure 1: Methods: A: femtosecond elastic second harmonic scattering and B: wide field membrane-water imaging

[1] Carolyn, M., et al., Wireless Neuromodulation at Submillimeter Precision via a Microwave Split-Ring Resonator. bioRxiv, 2022.07.22.501150 (2022).

[2] Okur, H.I., et al., Chemistry of Lipid Membranes from Models to Living Systems: A Perspective of Hydration, Surface Potential, Curvature, Confinement and Heterogeneity. Journal of the American Chemical Society, 141, 12168-12181 (2019).

[3] Macias-Romero, C., et al., Optical imaging of surface chemistry and dynamics in confinement. Science, 357, 784-787 (2017).

[4] Schonfeldova, T., et al., Charge Gradients around Dendritic Voids Cause Nanoscale Inhomogeneities in Liquid Water. J Phys Chem Lett, 13, 7462-7468 (2022).

Terahertz magnetism of antiferromagnets

Thomas Metzger [a], **Alexey Kimel** [a]

[a]*Institute for Molecules and Materials, Radboud University, Nijmegen, Netherlands*

Antiferromagnets are considered to be promising candidates for next generation data storage. That is in particular due to their ultrafast dynamics in the terahertz frequency range governed by the exchange energy of collinearly aligned spins. This is in strong contrast to their ferromagnetic counterparts which are limited to the gigahertz frequency range.

The booming fields of antiferromagnetic spintronics and terahertz magnonics urge to understand ultrafast dynamics triggered in antiferromagnets by ultrashort stimuli, which has led to new and vastly counter-intuitive findings in experimental and theoretical research [1-2]. However, the majority of the studies was dedicated to antiferromagnets in their collinear ground state.

Here, we report on the ultrafast dynamics in the poorly explored, non-collinear phase of antiferromagnets where sublattice symmetry is broken by spin canting. Particularly, we coherently address spin dynamics in bulk and thin film antiferromagnets utilizing novel terahertz spectroscopy techniques while tuning the spin canting by high external magnetic fields up to 7 T. Utilizing this approach, we demonstrate a nonlinear channel of energy transfer and show that our findings nourish new ways for the coherent control of antiferromagnetic spin dynamics in general.

[1] P. Němec, M. Fiebig, T. Kampfrath et al., Nature Phys 14, 229–241 (2018)
[2] A. Kimel, B. Ivanov, R. Pisarev et al., Nature Phys 5, 727–731 (2009)

TERAHERTZ OPTICAL HALL EFFECT IN MICROWAVE III-NITRIDE HEMT STRUCTURES

Stanishev V.,[a] Kühne P.,[a] Armakavicius N.,[a] Papamichail A.,[a] Kim M.,[a] Streicher I.,[b] Leone S.,[b] Darakchieva V.[a,c]

[a]Center for III-Nitride Technology, C3NiT-Janzén, Linköping University, SE-58183 Linköping, Sweden
[b]Fraunhofer Institute for Applied Solid State Physics IAF, 79108 Freiburg, Germany
[c]NanoLund, Center for III-Nitride Technology, C3NiT-Janzén, Terahertz Materials Analysis Center (THeMAC), Lund University, 22100 Lund, Sweden

AlGaN/GaN high-electron-mobility transistors (HEMT) have enabled breakthroughs in high-power and high-frequency electronics. AlScN and AlYN provide a higher polarization gradient than AlGaN and hence increased sheet charge carrier density (n_s) of the two-dimensional electron gas (2DEG) if employed as barrier layers. Optimization of 2DEG properties is critical for improved device performance and requires reliable methods to assess them. In this work, we review the application of THz Optical Hall effect [1] (OHE) for the contactless determination of 2DEG properties of GaN HEMT structures with different barrier layers: AlGaN, AlScN and AlYN [2,3]. The OHE represents the magnetic-field induced birefringence by free or confined charge carrier excitations upon interaction with electromagnetic waves, which can be measured by generalized spectroscopic ellipsometry. Room temperature (RT) THz OHE measurements were performed at magnetic field of B=0.55T using a permanent magnet and up to 8T employing a superconducting magnet and temperatures of 10-370K.

The RT OHE results reveal record high mobility of 2300 – 2400 V(s.cm)$^{-1}$ for AlGaN/GaN HEMT structures with Al content ~20% and n_s of ~5x10^{12} cm^{-2}. We show that a graded AlGaN channel, which leads to improved device linearity [2] is associated with significant reduction in mobility to 750 – 050 V(s.cm)$^{-1}$ depending on the Al grading profile. High n_s of 3-3.5x10^{13} cm^{-2} for all Sc contents and mobility parameters of 520-600 V(s.cm)$^{-1}$ are determined from the THz OHE. For the AlYN HEMT structures the mobility was found to be slightly higher, but for a lower n_s in the range 2-3x10^{13} cm^{-2}. All results are corroborated by eddy-current sheet resistance and contactless Hall measurements. The 2DEG electron effective mass parameters (m^*) was determined at RT to be m^*=0.34 m_0 for the AlScN/GaN HEMT structures, in agreement with results for AlGaN/GaN HEMTs [1,2,4]. For AlYN barrier structures, the RT 2DEG effective mass was determined to be significantly higher - 0.47m_0. The analysis of the low temperatures (10-130K) OHE yielded 2DEG effective mass m^* = 0.23-0.27m_0, much closer to the typically accepted value of 0.23 for bulk GaN [5]. The causes for the peculiar behavior of the 2DEG effective mass are discussed in detail and possible explanation, associated with deviation from the classical Drude model is proposed.

References

[1] P. Kühne, N. Armakavicius, V. Stanishev, C. M. Herzinger, M. Schubert, and V. Darakchieva, IEEE Trans. Terahertz Sci. Technol. 8, 257 (2018).

[2] A. Papamichail, A. R. Persson, S. Richter, P. Kühne V. Stanishev, R. Ferrand-Drake del Castillo, M. Thorsell, H. Hjelmgren, P.P. Paskov, N. Rorsman and V. Darakchieva, Appl. Phys. Lett. 122, 153501 (2023).

[3] I. Streicher, S. Leone, C. Manz, L. Kirste, M. Prescher, P. Waltereit, M. Mikulla, R. Quay and O. Ambacher, Cryst. Growth Des. 23, 782 (2023).

[4] S. Knight, S. Richter, A. Papamichail, P. Kühne, N. Armakavicius, A.R. Persson, V. Stanishev, V. Rindert, P. O. A. Persson, P.P. Paskov, M. Schubert and V. Darakchieva, J. Appl. Phys. 134, 185701 (2023).

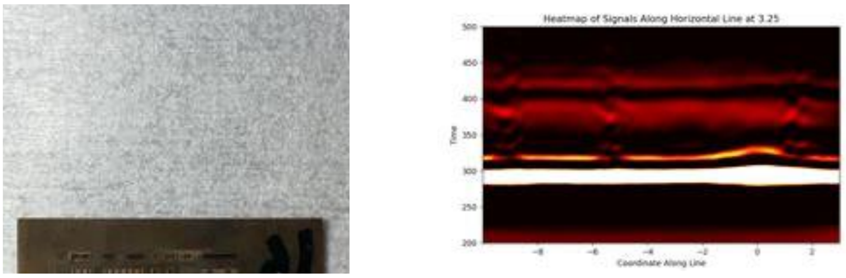
[5] N. Armakavicius, S. Knight, P. Kühne, V. Stanishev, D.Q. Tran, S. Richter, A. Papamichail, M. Stokey, M. Schubert, P. P. Paskov, V. Darakchieva, *APL Mater.* 12, 021114 (2024).

Terahertz Nondestructive Evaluation of Microelectronics Packaging

Haolian Shi, Alexandre Locquet, and D.S. Citrin

Georgia Tech-CNRS IRL2958, Georgia Tech-Europe, 2 Rue Marconi, 57070 Metz, France
and
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta,
Georgia 30332-0250 USA

With the approaching limits to Moore's law, new packaging microelectronics architectures are being implemented with an increased emphasis on vertical integration. These new architectures bring on new challenges to insure that packaged microelectronics are free of flaws that could lead to degradation and failure over time due to incorporation of defect in manufacture or development over time. At the same time, as higher frequencies are pursued for wireless communications with the advent of 6G, it becomes increasingly urgent to identify low-loss materials above 100 GHz and to characterize their dielectric properties.



Left: Micrograph top view of 8-layer interposer consisting of 300 micron thick glass core and four polymer-film layers top and bottom with Cu metalization. Right: Terahertz B-scan through daisy chain (rectangular blocks near middle of left panel). Buckling on right due to incorporation of burried air bubble preventing propert lamination of polymer films.

In this talk I discuss our group's work in the frequency range 100 GHz-3 THz addressing aspects of microelectronics packaging that are facing challenges with few adequate solutions at present, namely the nondestructive evaluation of structures and subassemblies used and produced for heterogeneous microelectronics packaging and the dielectric characterization of candidate packaging materials for the 6G band. Examples of the former include mapping conformal coating thickness [1] over large areas, detecting defects in polymer/glass stackups, and moisture detection. For the latter, we discuss a number of materials used in the 5G band and their prospects for the 6G band [2,3].

[1] H. Shi, S. Calvelli, M. Zhai, M. Ricci, S. Laureti, P. Singh, H. Fu, A. Locquet, and D.S. Citrin, "Terahertz Nondestructive Characterization of Conformal Coatings for Microelectronics Packaging," IEEE Transactions on Components, Packaging and Manufacturing Technology, in press.

[2] M Zhai, P Bhaskar, H Shi, M Swaminathan, A Locquet, DS Citrin, "Terahertz Characterization of Glass-Based Materials and Stackups for 6 G Microelectronics Packaging," Journal of Infrared, Millimeter, and Terahertz Waves **44**, 841-857 (2023).

[3] D.S. Citrin, "Identification of Next-Generation Dielectric Materials and Testing Needs," NIST Advanced Manufacturing Technology (MfgTech) Roadmap, 5G/6G mmWave Materials and Electrical Test Technology Roadmap (5G/6G MAESTRO), available at www.inemi.org/maestro

Reinforcing Microwave absorbing properties of magnetic microwires based composites by combination with ball-milled magnetic and/or carbon-based nanostructures

P. Marín[a,b], A. Peña[a], A. Castellano[a], J. López-Sanchez[c], D. Matatagui[a,b]

[a] Instituto de Magnetismo Aplicado. Universidad Complutense de Madrid – ADIF, AV km 22,5 28230 Las Rozas, Spain
[b] Departamento de Física de Materiales. Universidad Complutense de Madrid. Pza de las Ciencias 1, 28040 Madrid, Spain
[c] Instituto de Cerámica y Vidrio, CSIC, Kelsen 5, 28049, Madrid, Spain

The present work discusses the production and application of two types of materials for microwave absorption purposes: Defective few-layered graphene mesostructures (DFLGMs) and amorphous $Fe_{73.5}Si_{13.5}B_9Cu_1Nb$ microwires (MWs).

DFLGMs are produced from graphite flakes via high-energy milling, allowing precise control over their structure and defect formation. When combined with MWs in paint, they achieve significant improvements in microwave absorption properties, with a reduction in minimum reflection loss coefficient (RLmin) by 47% and an enhancement in effective absorption bandwidth (EAB) by 137%. This combination demonstrates tunable absorption behavior and validates the Maxwell-Garnet standard model for microwave attenuation [1].

The second material, MWs, undergo a refining process to control their length, resulting in homogeneous microstructures. These MWs exhibit both soft magnetic properties and microwave absorption capabilities. Coatings of commercial paints with MWs deposited on metallic sheets achieve high attenuation values around -40 dB in specific frequency ranges. By varying MW lengths, precise control over the minimum reflection loss (RL) is achieved in the GHz range, making them suitable for frequency-selective microwave absorbers. Experimental and theoretical results align, supporting the feasibility of these composites for tailored microwave absorption applications with low filling percentages and high absorption intensity values [2].

[1] J. López-Sánchez, A. Peña, A. Serrano, A. del Campo, O. Rodríguez de la Fuente, N. Carmona, D. Matatagui, M. C. Horrillo, J. Rubio-Zuazo, E. Navarro, P. Marín, ACS Appl. Mater. Interfaces 2023, 15, 2, 3507–3521 (2023)
[2] P. G. Birame Gueye, J. López-Sánchez, E. Navarro, A. Serrano, P. Marín. ACS Appl. Mater. Interfaces 2020, 12, 13, 15644–15656 (2020)

Using Transient Electrical Measurement to Reveal The Details of Hot-Carrier Dynamics in Semiconductor Devices

Jonathan P. Bird,[a]

[a]*Department of Electrical Engineering, University at Buffalo, Buffalo, NY 14260, USA*

A common feature of semiconductor devices – ranging from field-effect transistors to photovoltaic junctions – is that their electrical response is typically governed by the action of their hot-carriers, generated when these devices are biased by what can be very large electric fields (>10^4 V/cm). With their carriers driven strongly out of thermal equilibrium, a whole host of new phenomena may be observed that are absent from linear transport. Notable examples include the inter-valley scattering that gives rise to the Gunn effect, enabling the use of semiconductors is high-power microwave sources, and the Bloch oscillations that can be generated at even higher (terahertz) frequencies in semiconductor superlattices. Observing such effects in practice is not trivial, however, as Joule heating (or self-heating) of the system can obscure the more rich phenomena of interest. It has therefore long been understood that fast transient electrical measurement, performed using pulses as short as nanoseconds, provides a means to subject systems to high electric fields while alleviating the impact of this heating.

In the past few years, we have employed fast electrical pulsing, on time scales down to the nanosecond range and with resolution of tens of picoseconds, to investigate a variety of hot-carrier behavior in emergent two-dimensional semiconductors. This has included studies of; inherent drift-velocity saturation in graphene [1] and MoS_2 [2]; the interplay of thermal and field-driven dynamics in 2D charge-density wave conductors [3,4]; and re-entrant metallic and semiconducting states in moiré graphene (graphene/h-BN heterostructures) [5]. In my presentation, I will review these different works, highlighting the use of transient electrical measurement as a powerful tool to reveal the underlying details of hot-carrier dynamics in semiconductors driven far from equilibrium.

[1] H. Ramamoorthy, R. Somphonsane, J. Radice, G. He, C.-P. Kwan, and J. P. Bird, Nano Letters **16**, 399 (2016).

[2] J. Nathawat, K. K. H. Smithe, C. D. English, S. Yin, R. Dixit, M. Randle, N. Arabchigavkani, B. Barut, K. He, E. Pop, and J. P. Bird, Physical Review Materials **4**, 014002 (2020).

[3] A. Mohammadzadeh, S. Baraghani, S. Yin, F. Kargar, J. P. Bird, and A. A. Balandin, Applied Physics Letters **118**, 093102 (2021).

[4] S. Yin et al., Advanced Physics Research, *revision submitted*.

[5] J. Nathawat, I. Mansaray, K. Sakanashi, N. Wada, M. D. Randle, S. Yin, K. He, N. Arabchigavkani, R. Dixit, B. Barut, M. Zhao, H. Ramamoorthy, R. Somphonsane, G.-H. Kim, K. Watanabe, T. Taniguchi, N. Aoki, J. E. Han, and J. P. Bird, Nature Communications **14**, 1507 (2023).

Trapped electrons for quantum microwave technology applications

Raquel Alvarez García,[a] Anna Migó i Lluis,[a] Antonín Líndner,[a] Alex Ridley,[a] Ryan Willetts,[a] and José Verdú,[a]

[a] *Department of Physics and Astronomy, University of Sussex, Falmer BN1 9QH, UK*

A practical and efficient detector of single or few microwave (MW) photons is a fundamental tool for many quantum technology applications. Such detectors are essential for determining the quantum state of the radiation fields, and hence they are vital for quantum communication, information and sensing applications with microwaves. While several alternatives based upon super- and semiconductor technologies have been proposed and are being developed, the first observations of single microwave photons employed a trapped electron as transducer[1]. At the University of Sussex we are developing a novel chip-based Penning trap technology which will enable trapped electrons as practical transducers (sensors and emitters) of quantum microwave radiation[2]. A single electron in a Penning trap is also known as a *geonium atom*. Conventional Penning trap systems invariably employ a big, "room-size", superconducting solenoid as magnetic source. We are radically changing that concept: we are implementing the trap electrodes and the magnetic field source in a scalable *geonium chip*[3]. In this talk I will present the status of the development of the *geonium chip*. I will also discuss the use of the trapped electron for quantum technology applications. Specifically, I will show how the trapped electron can be used to implement efficiently the "quantum microwave illumination" protocol. This is essential for the development of a future quantum radar. I will also very briefly discuss the potential use of the trapped electron as a microwave sensor for fundamental physics applications, such as the neutrino mass measurement with cyclotron resonance spectroscopy.

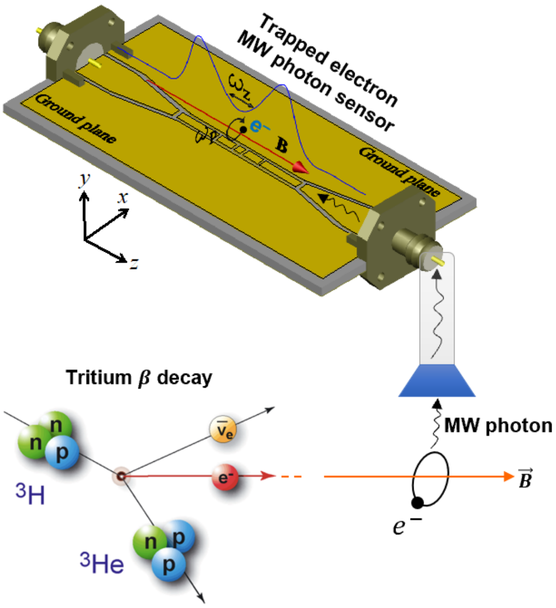


Figure 1: Example detection of beta particles from tritium decay with a trapped electron MW sensor.

[1] S. Peil *et al*, Phys. Rev. Lett. **83**, 1287 (1999).
[2] A. Cridland *et al,* Photonics, **3**, 54 (2016),
[3] J. Pinder *et al, Rev. Sci. Instrum.* 91, 103201 (2020)
[4] F. Crimin, I. Marzoli, and J Verdu, *Quantum Illumination using an ion trap,* w European Patent Application No. 22722337.7 (2023)

Towards efficient microwave interfaces to nanoscale systems: light, sound and spins

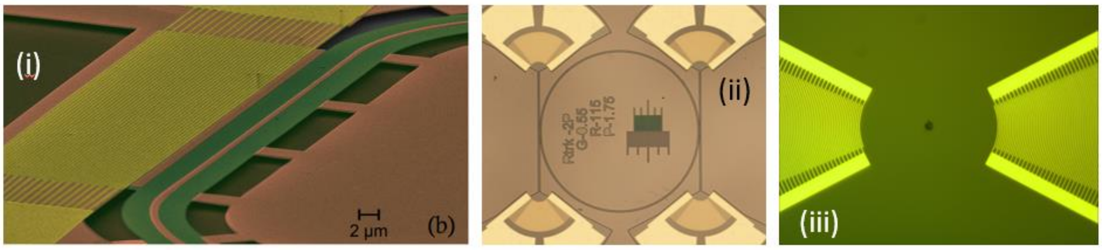
Krishna C Balram
Quantum Engineering Technology Labs and Department of Electrical and Electronic Engineering ,University of Bristol, UK

50+ years of Moore's law and related advances in nanofabrication have taught us how to make nanoscale objects routinely. But getting information (both classical and quantum) efficiently into and out of these (deeply sub-wavelength) nanoscale objects remains an unsolved problem in general. In this talk, we will discuss one instance of this '*nanoscale wiring*' problem: interfacing GHz microwave signals efficiently with nanoscale devices using acoustic waves as an intermediary. We show how the same efficiency challenges occur in three very different contexts (quantum, semi-classical and classical):

(a) building piezoelectric quantum microwave to optical signal transducers [1,2] for connecting remote superconducting qubit based quantum processors

(b) phononic integrated circuits for re-thinking RF front-ends [3], bringing ideas from silicon integrated photonics to microwave devices

(c) piezoelectric micro-resonators for electron spin resonance (ESR) experiments on single nanoparticles [4]. Going beyond quasistatic approximation in piezoelectric devices to engineer detection at the thermal noise limit and prospects for single spin readout at low T.



(i) Increasing efficiency of piezoelectric optomechanical quantum transducers by engineering mechanical supermodes [1,2] between a contour mode resonator and an optical microring resonator (ii) Acoustic microring resonators with record fQ products (beyond the AKE limit) in GaN [3], the waveguide geometry was also used to demonstrate spiral delay lines with delays > 2.5 μs with an on-chip footprint < 0.25 mm^2 (iii) YIG nanoparticles positioned at the focus of an acoustic confocal cavity [4]. At GHz frequencies, the surface currents on piezoelectric devices can be used to efficiently interface with nanoscale spin systems.

Acknowledgements: I would like to thank my current and former PhD students and postdocs who contributed to all this work, in particular, Ankur Khurana, Mahmut Bicer, Stefano Valle, Cecile Skoryna Kline and Jorge Monroy Ruz. I also gratefully acknowledge support from the European Research Council and the UK's Engineering and Physical Sciences Research Council that has funded all this work.

References:

[1] K.C. Balram and K. Srinivasan, K. *Advanced Quantum Technologies*, *5*(3), p.2100095, 2002
[2] A. Khurana, P. Jiang, P. and K.C. Balram, *Physical Review Applied*, *18*(5), p.054030, 2022
[3] M. Bicer and K.C. Balram, IEEE Trans. UFFC, 71(1), 172, 2023
[4] C.S. Kline, J.M-Ruz, and K.C. Balram, in preparation

Fundamental Bounds and Experimental Demonstration of Microwave and Terahertz Absorption from Metasurfaces

Willie J. Padilla,[a] Yang Deng,[a] Omar Khatib,[a] Vahid Tarokh,[a]

[a]*Pratt School of Engineering, Duke University, Durham, North Carolina, 27705, USA*

A well-known bound on absorption for any material backed by a perfect electric conductor was derived from the Kramers-Kronig relations. [1] The main result established a fundamental relationship for the minimal layer thickness to achieve a certain absorption bandwidth. We have established a similar fundamental bound for non-metal-backed layers and have validated our theory with transfer matrix calculations and full-wave numerical simulations of electromagnetic metamaterials. [2] We will show examples of metamaterial electromagnetic wave absorbers achieving near-perfect absorption across much of the spectrum from microwave [3] to terahertz [4] and infrared wavelengths [5].

An all-dielectric absorber permits the formation of a coherent perfect absorber (CPA) and may achieve either coherent or incoherent absorption. [6] Further, a so-called zero-rank absorber may be viewed as two CPAs with eigenmodes of opposite symmetry. CPAs may be fashioned form all-dielectric metasurfaces to absorb either in-phase or out-of-phase radiation, thereby establishing a path to realize a new class of absorbers useful for future novel applications, including hyperspectral imaging and energy harvesting.

This work demonstrates the optimization of absorption bandwidth and spectral complexity using deep learning for both forward and inverse problems. While metasurface inverse problems are typically ill-posed (meaning they have no unique solution or exhibit one-to-manyness), we present a deep learning-based inverse approach that can effectively identify excellent metasurface geometries to achieve a desired spectral response. The optimization process utilizes fundamental bounds as stopping criteria. We conclude by discussing the exciting future directions of this field.

[1] K.N. Rozanov, IEEE Trans. Antennas Propag., 48, 1230-1234 (2000).
[2] W.J. Padilla, Y. Deng, O. Khatib and V. Tarokh, Nanophotonics, 13, 1623–1629 (2024).
[3] W.J. Padilla, K. Fan, “Metamaterial Electromagnetic Wave Absorbers,” Springer International Publishing, 2022.
[4] K. Fan, J.Y. Suen, X. Liu, and W.J. Padilla, Optica, 4, 601 (2017).
[5] K. Fan, V. Stenger, and W.J. Padilla, Applied Physics Letters, 121, 021701 (2022).
[6] J.Y. Suen, K. Fan, and W.J. Padilla, Advanced Optical Materials, 7, 1801632 (2019).

Millimeter Wave Spectroscopy of Dielectrics for the 6G Telecom Spectrum

Mark Lee[a]

[a]*Department of Physics, University of Texas at Dallas, Richardson, TX, 75080, USA*

Telecommunications research now focuses on enabling 6G telecom. The US Federal Communications Commission has authorized spectrum from 95 to 300 GHz to explore 6G technologies. This approaches the “Terahertz technology gap” while also confronting rising atmospheric attenuation. Therefore, 6G systems must overcome stringent signal-to-noise requirements. 6G spectrum is also high enough that electromagnetic properties of commonly used materials have not been accurately measured and cannot be assumed retain their microwave values.

Semiconductor technology uses many dielectric materials to package high-frequency semiconductor chips. Packaging material should minimally interfere with or degrade high-frequency performance of the integrated circuit. To model and design a packaged circuit’s performance, it is critical that the packaging materials’ dielectric properties, permittivity, *Dk*, and dissipation factor, *Df*, be reliably known. There is use for materials having relatively low and high values of *Dk*, but it is desirable that *Dk* be non-dispersive. Minimizing loss is critical to performance of 6G circuits, so a smaller value of *Df* is always preferred.

I will present broadband measurements of *Dk* and *Df* on a variety of dielectric packaging materials from 90 to 325 GHz [1-3]. Materials include liquid crystal polymers, epoxy-oxide composites, and ceramic-fiberglass laminates. Measurements were made using a quasi-optical, phase-sensitive spectrometer capable of obtaining real and imaginary transmittance and reflectance with material at 23°C or 150°C. *Dk* values encountered ranged from 1.1 to 4.5 and mostly showed little difference between the two temperatures. *Df* values ranged from 0.01 to 0.04 at 23°C and in most cases increased by 2× to 3× at 150°C. Knowing these properties, it is possible to design packaging that reduces impedance mismatch between on-chip antennas and free-space, enhancing performance of a packaged circuit over an unpackaged one [4].

[1] M. P. McGarry, E. Tuncer, & M. Lee, J. Infrared Millim. THz Waves, 41, 1189 (2020).
[2] M. P. McGarry, M. K. Iyer, & M. Lee, IEEE Trans. Comp. Manuf. Packag. Tech., 12, 192 (2022).
[3] M. P. McGarry & M. Lee, IEEE Trans. Comp. Manuf. Packag. Tech., 12, 1575 (2022).
[4] H. S. Bakshi, P. R. Byreddy, K. K. O, A. Blanchard, M. Lee, E. Tuncer, W. Choi, IEEE Antenn. Wireless Propag. Lett., 2444 (2019).

Scaling Theory of Microwave Absorption in Random Magnets*

Eugene M. Chudnovsky
CUNY Lehman College and Graduate School

Magnetic order and microwave absorption in amorphous ferromagnets and materials sintered from nanoscale ferromagnetic grains have been investigated analytically and numerically within the random-anisotropy model. A scaling argument specific to static randomness allows one to make conclusions about the behavior of a large system with a weak disorder by studying a smaller system with a strong disorder. The breakdown of the scaling on increasing the strength of the magnetic anisotropy and/or the size of the grain separates two distinct regimes in magnetic ordering and frequency dependence of the absorbed microwave power. Analytical results are confirmed by numerical experiments on spin lattices containing up to ten million spins. The proposed scaling permits a drastic reduction of the computing time in simulating statics and dynamics of disordered systems. It should help design materials with desired magnetic and microwave properties. The method can be extended to other systems with quenched randomness, such as thin films on imperfect substrates, pinned charge density waves, flux lattices in superconductors, liquid crystals, and polymers.

*Research supported by the U.S. Air Force Office of Scientific Research

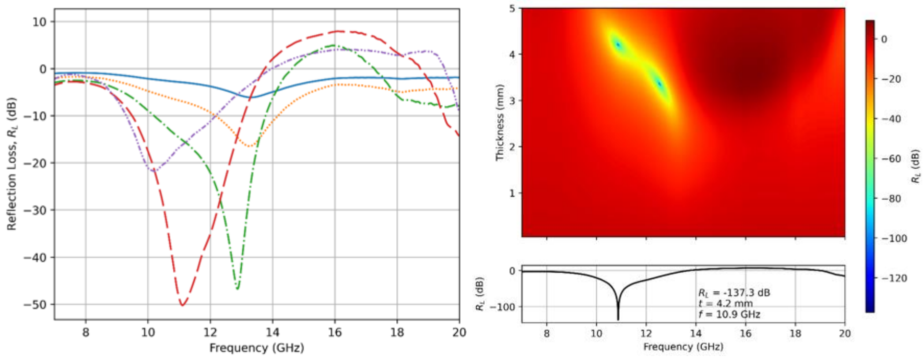
E. M. Chudnovsky and D. A. Garanin, *Scaling theory of magnetic order and microwave absorption in amorphous and granular ferromagnets*, Physical Review B **109**, 054429-(10) (2024).

Barium hexaferrite-based nanocomposites as random magnets for microwave absorption

Antoni García-Santiago,[a,b] Jaume Calvo-de la Rosa,[a,b] Joan Manel Hernàndez,[a,b] Marc Vazquez-Aige,[a] Jose Maria Lopez-Villegas,[c] Javier Tejada[a]

[a]Dept. de Física de la Matèria Condensada, Universitat de Barcelona, 08028 Barcelona, Spain
[b]Institut de Nanociència i Nanotecnologia (IN2UB), Universitat de Barcelona,
08028 Barcelona, Spain
[c]Dept. d'Enginyeria Electrònica i Biomèdica, Universitat de Barcelona, 08028 Barcelona, Spain

We present an experimental survey of modified barium hexaferrites as microwave (MW) absorbers in the GHz range. We prepared ceramic nanocomposites by adding either nickel, copper or manganese cations to common barium hexaferrites. We performed structural characterization and found that the modified samples consisted in micron-size particles that were made of a random mixture of nanocrystallites of both the original barium hexaferrite and the divalent cation ferrite. After performing magnetic measurements, we verified that the magnetization in approaching saturation of the modified materials fits well to the strong anisotropy case of random magnets, when the samples are formed by independent, non-interacting crystallites [1], in contrast to the original hexaferrites, which did not show any of the characteristics of such state. Recent theoretical models postulated random magnets as broadband MW absorbers [2]. To test such idea in our samples, we measured the two-port *S* parameters in the GHz range using a network analyzer with coaxial connectors. Then we deduced the complex dielectric permittivity and magnetic permeability using the Nicolson-Ross-Weir model. We therefore calculated the reflection loss coefficient (R_L) and found a remarkable enhancement of the power absorption in thin (less-than-2-mm thick) copper-modified samples. These findings strongly support the application of our ceramic nanocomposites as MW absorbing materials [3].



Left panel: R_L spectra for different thicknesses (t = 1-5 mm) of a copper-modified sample; right panel: R_L simulation for a wide and continuous range of thicknesses, for frequencies between 0.17 and 20 GHz.

This work was supported by the Air Force Office of Scientific Research.

[1] E. M. Chudnovsky, W. M. Saslow, and R. A. Serota, Phys. Rev. B 33, 251 (1986); E. M. Chudnovsky, J. Appl. Phys. 64, 5770 (1988).
[2] D. A. Garanin and E. M. Chudnovsky, Phys. Rev. B 103, 214414 (2021); Phys. Rev. B 105, 064402 (2022); E. M. Chudnovsky and D. A. Garanin, Phys. Rev. B 107, 224413 (2023).
[3] S. Bao *et. al.*, Nano Research 16, 11054 (2023); L. Jin *et al.*, Appl. Surf. Sci. Adv. 19, 100575 (2024).

Particle Size Effects on Tuning Microwave Absorbing Properties: Fe3C@ Core@Shell Nanoparticles for Double-Peak Wideband Absorber

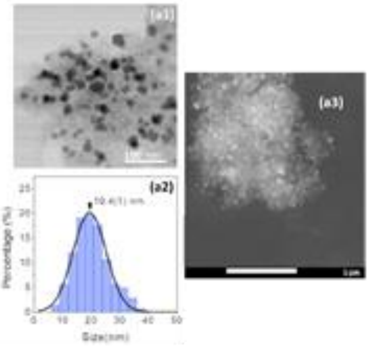
Alberto Castellano-Soria[a,b,c,d]*, Elena Navarro[a,b], Antonio Hernando Grande[a,c,d,e,f], Pilar Marin[a,b]

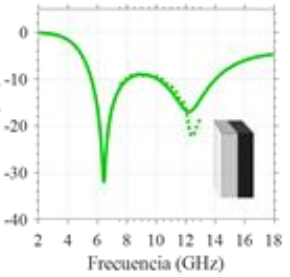
[a]Instituto de *Magnetismo Aplicado (IMA-UCM-ADIF), 28230 Madrid, Spain*
[b]Departamento de Física de Materiales, Facultad de Físicas, Universidad Complutense de Madrid (UCM), 28040 *Madrid, Spain.*
[c]Micromag 2000 SL, *Alcorcón, Madrid, Spain.*
[d]Universidad Antonio Nebrija, España.
[e]*Donostia International Physics Center, 20028 Donostia, Spain.*
[f]*IMDEA Nanociencia, 28049 Madrid, Spain.*

* *albcas04@ucm.es.*

At present, a plethora of proposals exist for fabricating shielding materials in the microwave radiofrequency domain, with micro or nanoscale material composites emerging as the most promising substrates for this purpose [1]. Powder-form materials are mixed with matrices allowing adjustment of their permittivity and dielectric permeability values to tailor absorbent properties. Conversely, another significant domain in absorbent material design relies on employing conductive patterns, endowing surfaces with absorbent capabilities, known as Frequency Selective Surfaces (FSS). Their high efficiency and versatility have garnered significant attention in recent years, achieving bandwidths of up to 10 GHz and attenuation levels of -20 dB. On the contrary, the thicknesses typically used in their fabrication are sometimes high.

The present study focuses on bilayer absorbers of powder-matrix type. Specifically, a material composed of core/shell Fe3C@C nanoparticles embedded in graphite flakes and amorphous carbon [2] is investigated. It is hypothesized that the high surface-to-volume ratio and free charges allow for obtaining elevated values of dielectric permittivity for the same concentrations as an absorber made of graphite. Additionally, the effects of particle size are evaluated, and it is concluded that the combination of layers generated with milled and not-milled material [3] enables the attainment and design of absorptive systems with a double-peaked attenuation structure overlapping. This results in bandwidths of up to 8.5 GHz with an attenuation level of at least -10 dB for total low thickness conditions of 5 mm.





References

[1] Green, M., & Chen, X. (2019). Journal of Materiomics, 5(4), 503–541.
[2] Castellano, A., et. al.. (2022). Journal of Alloys and Compounds, 902, 163662.
[3] Castellano-Soria, A., Navarro, E., & Marín, P. (2024d). Materials & Design, 238, 112641.

Design of new multilayered systems and characterization methods for microwave absorption applications

Jaume Calvo-de la Rosa,[a, b] Marc Vazquez-Aige,[a] Antoni García-Santiago, [a, b] Joan Manel Hernàndez, [a, b] Pilar Marín, [c, d] Jose Maria Lopez-Villegas,[e] Javier Tejada, [a]

[a]Departament de Física de la Matèria Condensada, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain
[b]Institut de Nanociència i Nanotecnologia (IN2UB), Universitat de Barcelona, 08028 Barcelona, Spain
[c]Instituto de Magnetismo Aplicado (IMA-UCM-ADIF), 28230 Madrid, Spain
[d]Departamento de Física de Materiales, Facultad de Físicas, Universidad Complutense de Madrid
(UCM), 28040 Madrid, Spain
[e]Departament d'Enginyeria Electrònica i Biomèdica, Universitat de Barcelona, 08028 Barcelona, Spain

The development of novel materials and systems is gaining momentum for stealth technology sector. Many are the works published in literature that report the potential that homogeneous materials have, typically in the form un bulk or single-layer samples. Heterogeneous materials and multilayered systems are, nonetheless, stemming as high-potential options. There is also a general lack in literature regarding reliable and realistic measurement methods. Most of references rely on measuring the complex *S*-parameters of a bulk sample (which, probably, will not be the final shape of the material when used) in a transmission line or coaxial probe. The absorbing capacities are, then, approximated by homogeneous impedance models.

In this presentation we report our recent advances on the field from two different perspectives: first, we show an experimental setup that we have developed for the measurement of the complex *S*-parameters and electromagnetic constants directly on sheet-type samples. Given that we oriented to stealth technology, characterizing the samples already deposited into a substrate gives us a real picture about its performance.

On the other hand, we also report the improved radar absorption capacities that we have achieved through the design of bi-layered systems [1]. We make use of an appropriate combination between paint or polymeric agents and functional powders (such as soft magnetic metallic alloys or modified hexaferrites with random magnetic properties [2]) to build-up the systems. The results clearly show how the microwave absorption can be tunned and intensified with a proper optimization of its functional and geometrical conditions. Meaningful broadband absorptions have been achieved as well.

[1] J. Calvo‐de la Rosa et al., “New Approach to Designing Functional Materials for Stealth Technology: Radar Experiment with Bilayer Absorbers and Optimization of the Reflection Loss,” Adv Funct Mater, p. 2308819, Oct. 2023, doi: 10.1002/adfm.202308819.

[2] J. Calvo-De La Rosa, J. Manel Hernàndez, A. García-Santiago, J. Maria Lopez-Villegas, and J. Tejada, “Barium Hexaferrite-based nanocomposites as random field magnets for microwave absorption.” doi: https://doi.org/10.48550/arXiv.2402.14324.

Study of resonant and broadband microwave absorbers based on multi-materials 3D printing

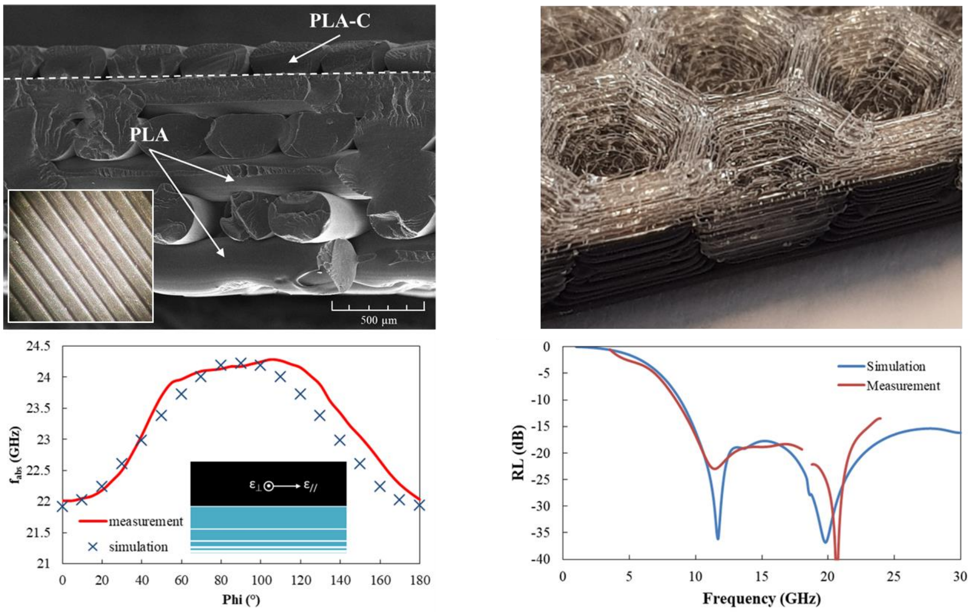
Vincent Laur[a], Azar Maalouf[a], Alexis Chevalier[a], Lana Damaj[a], Julien Ville[b]

[a]*Lab-STICC, University of Brest, Brest, France*
[b]*IRDL, University of Brest, Brest, France*

3D printing techniques, especially Fused Deposition Modeling (FDM), open up new possibilities to tune microwave absorbers performance. Indeed, FDM not only makes it possible to print polymers and composites together in a single step, but also to control the effective electromagnetic (EM) properties by structuring the materials. During the past years, we applied this possibility to the design of rectangular waveguide loads [1] or mono-materials free-space absorbers [2]. More recently, our interest was focused on the design and realization of multi-materials 3D printed EM absorbers.

This process was, as an example, applied to the co-printing of a low-loss dielectric (PLA) and a lossy dielectric composite (PLA-C). A pseudo-Salisbury absorber was designed and fabricated by using PLA as $\lambda_g/4$ spacer and a single layer of PLA-C (Fig. 1). We showed that 3D printing-induced planar anisotropy results in a phi dependence of absorption but that this phenomenon can be controlled. A bi-gradient index absorber was also designed. This broadband absorber is constituted of an impedance matching layer made of PLA on top of an absorptive layer made of a combination of PLA and PLA-C. The control of the evolution of effective permittivity and loss tangent along the absorber made it possible to achieve a -15dB-bandwidth of 82% in X-Ku band for a 5.2 mm-thick absorber.

In this presentation, we will discuss the opportunities offered by the multi-material printing process, but also the limitations linked to resolution, dependence on printing conditions and the anisotropy naturally induced by this process.



(a) (b)

Fig. 1. PLA/PLA-C multi-materials absorbers: (a) pseudo-Salisbury configuration: SEM image and evolution of absorption frequency as a function of phi angle and (b) bi-gradient broadband configuration: picture and return loss in the 1-30 GHz frequency band.

[1] Y. Arbaoui, V. Laur, A. Maalouf, P. Queffelec, D. Passerieux, A. Delias, P. Blondy, IEEE Trans. Micr. Th. & Techn., 64, 271-278 (2016)

[2] V. Laur, A. Maalouf, A. Chevalier, F. Comblet, IEEE Trans. Electromag. Comp., 63, 390-397 (2021)

Microwave absorber integration in typical composite sandwich structures used in aeronautical construction.

**Javier Rodríguez[a]*, Javier Calvo[a]*, Alberto Castellano [a]*, Susana Aberturas [a]*,
Pilar Marín[a,b] , Antonio Hernando[a,b]**

[a] Micromag 2000 S.L*, 28925 Madrid, Spain*
[b] Instituto de *Magnetismo Aplicado (IMA-UCM-ADIF), 28230 Madrid, Spain*
* jrodriguez@micromag.es

In the domain of aeronautics, the adoption of composite materials significantly enhances aircraft design and manufacturing. By combining reinforcing fibers embedded in polymeric matrices and incorporating lightweight cores into sandwich configurations, these composite structures not only deliver remarkable strength and stiffness with reduced weight but also present the potential to provide aircraft with stealth capabilities.

When subjected to an electromagnetic beam within the gigahertz spectrum, the configuration of rigid fiberglass on the external layers, coupled with a separated interior carbon fiber or metal exhibits a resultant reflected interference pattern. This phenomenon can be intentionally modulated at the design phase, for a deliberate compromise between the material's electromagnetic characteristics and its mechanical properties.

Additionally, the foam cores used in sandwich structures can be also loaded[1,2] to cause dielectric and magnetic loses resulting in the attenuation of energy as the beam traverses the material. In this work the balance between both phenomena is studied in the range of the microwaves from L band (1-2 GHz) to Ku Band (12-18 GHz). The shape, concentration and distribution of additives determine the optimal conditions for the absorber for each particular case of interest. Moreover, the nature of the foam core matrix (polyurethane, epoxy, PMI) and production conditions (temperature, foaming speed, density, viscosity…) do have an impact on additive local concentration which can be used to produce a gradient absorber, a constant loaded absorber, or a diffraction grating-like absorber.

This study highlights the critical balance between pure absorption and interference phenomena in standard aeronautical structures, featuring an outer fiber layer thickness of 1 to 3mm and a foam core thickness of 9 to 25mm. Each component has been individually characterized both locally and in the far field through a scattering matrix and modeled using its complex parameters, both individually and as a component of the entire structure. This approach allows for the prediction of the electromagnetic behavior across any incident wave polarization.

References

[1] US 3208013 (A) Walker. Electromagnetic wave absorber comprising inherently resonant filamentary fibers suspended in dielectric
[2] US 3599210 (A) Stander. Radar absorptive coating

A simple low-cost active reflector to assist spaceborne SAR interferometry

Guido Luzi[a*] , **Pedro F. Espín-López,** [a] **Qi Gao** [a]

a Centre Técnologic de Telecommunicacions de Catalunya(CTTC-CERCA), Geomatics Research Unit,
Av. Gauss 7, E-08860 Castelldefels, Barcelona, Spain

The installation of artificial reflectors, usually represented by Passive Corner Reflectors (PCR), is frequently used in spaceborne radar interferometry to assure that in the imaged areas the coherence is sufficient high and provide Persistent Scatterers (PS). One of the most used satellite SAR missions included in Copernicus by ESA is a C band sensor, Sentinel-1. At this frequency PCR capable of providing a high phase accuracy are cumbersome and heavy, and their installation in hard places can be difficult and costly. The use of Active Reflectors (AR), compact and smaller with respect to PCRs, can sometimes represent a valid alternative especially in mountain vegetated or snow-covered areas, or glaciers. These devices have often shown a high sensitivity over long interval to annual/seasonal temperature range of variation, reducing their reliability. This presentation, after a description of the Radio Frequency design, analyzes the performance of a low-cost AR designed to operate with C band spaceborne radars, tested in field campaign aiming at assessing the reliability of this device in deformation and landslides monitoring based on DInSAR . Although the concept of the proposed AR is not a novelty, the design and implementation of this device has been focused to the achievement of a rugged, low-cost device based on use of off-the-shelf (OTS) components and a low power consumption. The study tries to give a contribution to the understanding the main issue of use of active device for radiometric and phasimetric calibration, investigating the thermal drift of the transfer function of the device, strongly influencing the performance of the RF section. Experimental tests carried out in a real application case in field, confirm that the device is capable of providing a millimetric accuracy over a significant range of temperature.

Microwave and Optically Excited Studies of Ferromagnetic Resonance in Magnetic Multilayers

Darío Alejandro Arena
Department of Physics, University of South Florida, Tampa, FL, U.S.A.

We will present ferromagnetic resonance (FMR) studies of two classes of magnetic multilayers. The first are metallic trilayers consisting of Permalloy (Py, $Fe_{19}Ni_{81}$) and Permendur (Pmd, $Fe_{49}Co_{49}V_2$) magnetic active layers separated by a non-magnetic Ru spacer layer. The Ru layer is varied from 0.8 nm to 20 nm to modulate the FM to AF coupling of the Py and Py layers. These films are studied with a combination of x-ray detected FMR (X-FMR) and optically excited ferromagnetic resonance studied with time-resolved magneto-optic Kerr effect (tr-MOKE). The X-FMR studies permit high precision measurement of the precession orbit separately for the Py and Pmd layers, mapping out both the amplitude and phase of each layer's response as the samples are driven through the two collective excitation modes of the system. Comparison of the amplitude and phase data with an extended model of Landau-Lifshitz-Gilbert equation of motion that also accounts for spin pumping, we are able to identify that spin pumping in non-reciprocal in these dissimilar tri-layers [1]. The finite skin depth of optical probes in the tr-MOKE studies limits sensitivity to the topmost Pmd layer. However, we can clearly identify the collective excitations of the coupled systems. Shifts of the collective modes away from the response of isolated free layers quantify the exchange coupling. Most surprisingly, the damping of the Pmd is significantly reduced even in the case of the thickest Ru spacer layer where the coupling is negligible [2]. The second class of samples discussed is epitaxial Fe / MgO bilayers studied with broadband, temperature dependent FMR [3]. For MgO spacer layer thickness of 1.7 nm, along the in-plane easy axis the system exhibits two resonance modes termed acoustic and optical excitations; thinner MgO spacer layers (1.1 nm and thinner) display only a single resonance mode. For the 1.7 nm spacer thickness, the resonant response at reduced temperatures is characterized by a reduction of the optical mode intensity and a lessening of the field splitting between the two modes. Additional temperature-dependent FMR measurements along the hard-axis and out-of-plane will also be discussed.

[1] Y. Pogoryelo, D.A. Arena *et al.*, "Nonreciprocal spin pumping damping in asymmetric magnetic trilayers," *Phys. Rev. B*, vol. 101, no. 5, p. 054401, Feb. 2020.

[2] H. Liu, A. Ciuciulkaite, V. Kapaklis, D. Karaiskaj, and D. A. Arena, "Enhanced optical mode coherence in exchange coupled soft magnetic multilayers," *J. Appl. Phys.*, vol. 131, no. 21, p. 213902, Jun. 2022.

[3] Ayomipo Ojo, Anna Ravensburg, Leonardo Ramos-Aponte, V. Kapaklis, D.A. Arena, *in preparation.*

Analysis of Planar Metasurfaces for Monostatic and Bistatic RCS Reduction

María Guijarro Maortua[a], Francisco Luna Valero[b,c], José Manuel Fernández González[a], Pablo Sánchez Olivares[a], Adrián Tamayo Domínguez[a]

[a]*Grupo de Radiación, Dpto. de Señales, Sistemas y Radiocomunicaciones, ETSI Telecomunicación, Universidad Politécnica de Madrid. Madrid, España.*
[b]*Dpto. de Lenguajes y Ciencias de la Computación, Universidad de Málaga. Málaga, España.*
[c]*ITIS Software, Universidad de Málaga. Málaga, España.*

In recent years, stealth technologies have become a field of interest in both military and civil applications. To address this problem, the scenario must first be analysed from the radar's point of view in order to know exactly what requirements a target has to meet to avoid detection. Thus, reducing the distance at which a target can be detected means reducing its radar cross section (RCS). There are several methods of RCS reduction that can be generally classified in two categories: absorption and scattering; in addition to physically modify the target. This study focuses on reducing the RCS by scattering the incident waves on the target. For this purpose, metasurfaces are designed, which are artificial flat structures composed of arrays of conductive elements placed on a substrate and capable of manipulating the electromagnetic waves impinginng on them. The response of these structures is determined by the design of the unit cells of which they are composed, so in this contribution the analysis and optimization of them and, subsequently, of the complete structure have been carried out. To analyse and quantify the RCS, it has to be taken into account that it depends on the size of the target, the angle of incidence, the polarization and the frequency. Throughout this work, it has been designed in such a way that the metasurface response is independent of polarization and target size and works for an incidence range of [-60, 60]º. For both monostatic and bistatic, a RCS reduction below -12 dB is achieved, which means a reduction in distance of 50%, in a bandwidth of 22.22% (9.2 – 11.5 GHz) for the monostatic case and 19.72% (9.6 – 11.7 GHz) for the bistatic case.

ACKNOWLEDGEMENTS

This work was supported by the Spanish Government, Ministry of Economy, National Program of Research, Development and Innovation under the project "New Array Antenna Technologies and Digital Processing for the Future Integrated Terrestrial and Space-based Millimeter Wave Radio Systems - UPM-InTerSpaCE" (PID2020-112545RB-C51).
Project PID2020-112545RB-C51 funded by MCIN/ AEI /10.13039/501100011033

REFERENCES

[1] W. Chen, C. A. Balanis and C. R. Birtcher, "Checkerboard EBG Surfaces for Wideband Radar Cross Section Reduction," in IEEE Transactions on Antennas and Propagation, vol. 63, no. 6, pp. 2636-2645, June 2015, doi: 10.1109/TAP.2015.2414440.
[2] Y. Wang and Z. Li, "A Metasurface for Boardband RCS Reduction," 2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting, Montreal, QC, Canada, 2020, pp. 1217-1218, doi: 10.1109/IEEECONF35879.2020.9329663.
[3] M. Qu, C. Zhang, J. Su, J. Liu and Z. Li, "Extremely Wideband and Omnidirectional RCS Reduction for Wide-Angle Oblique Incidence," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 8, pp. 7288-7293, Aug. 2022, doi: 10.1109/TAP.2022.3161309.

On-chip microwave photon-mediated coupling and energy exchange in hybrid magnonic systems

Yi Li & Valentine Novosad

Materials Science Division, Argonne National Laboratory, Lemont, IL 60439, USA

Magnon–photon dynamic systems have recently attracted great attention due to their rich physics and ease of on-chip integration. Of particular interest are hybrid magnonic-superconducting platforms that operate at microwave frequencies [1]. In this presentation, we will review two examples of such systems.

First, we will describe an all-on-chip magnon-photon hybrid circuit with a Permalloy (Ni80Fe20, Py) thin-film devices directly fabricated on top of a coplanar superconducting resonator [2]. On the magnon side, Py is a classical metallic ferromagnet with well-known magnetic properties and industry-friendly deposition requirements. It exhibits high magnetization of saturation and allows large coupling strengths. On the photon side, a coplanar superconducting resonator has a much smaller mode volume and a higher quality factor than a macroscopic microwave cavity, which allows more concentrated and long-lived photons to couple with magnons. In this system, we achieved a strong magnon-photon coupling strength of $g/2\pi=0.152$ GHz and cooperativity of $C=68$ for a 30-nm-thick Py stripe, along with a high coupling efficiency of 26.7 Hz per Bohr magneton. Furthermore, the coupling strength can be further enhanced by driving the superconducting resonator into the nonlinear regime, which is attributed to the creation of dynamic magnetic flux vortices.

Next, we will consider magnon-magnon coupling in a compact superconducting-magnon hybrid circuit, using single-crystal YIG spheres that are mounted in lithographically defined holes on silicon substrates with superconducting resonators. The all-lithographic circuit design allows for arbitrary engineering of hybrid magnonic dynamics while achieving long magnon coherence. For a single 250-μm-diameter YIG sphere, we achieve a magnon-photon coupling strength of 130 MHz and a cooperativity of 13 000 with both the magnon and photon damping rates approaching 1 MHz at 1.6 K. For a two-sphere-one-resonator circuit, we achieve a resonator mediated magnon-magnon coupling strength from 10 to 40 MHz in the dispersive coupling regime. Furthermore, we also demonstrated the dissipative coupling of the magnon modes between the two YIG spheres mediated by propagating microwave photons.

Our results suggest the combination of superconducting resonators and ferromagnets can be a promising platform for investigating on-chip quantum magnonics and spintronics, and brings new potential for coherent manipulation and long-distance propagation of spin information.

This work was supported by the U.S. DOE, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division, under contract No.DE-SC0022060.

[1] Li, Y.; Zhang, W.; Tyberkevych, V.; Kwok, W. K.; Hoffmann, A.; Novosad, V., “Hybrid magnonics: physics, circuits, & applications for coherent information processing”, *J. Appl. Phys.,* **128** (2020).

[2] Li, Y.; Polakovic, T.; Wang, Y. L.; Xu, J.; Lendinez, S.; Zhang, Z. Z.; Ding, J. J.; Khaire, T.; Saglam, H.; Divan, R.; Pearson, J.; Kwok, W. K.; Xiao, Z. L.; Novosad, V.; Hoffmann, A.; Zhang, W., Strong coupling between magnons and microwave photons in on-chip ferromagnet-superconductor thin-film devices. *Phys. Rev. Lett.,* **123** (2019).

[3] Li, Y.; Yefremenko, V. G.; Lisovenko, M.; Trevillian, C.; Polakovic, T.; Cecil, T. W.; Barry, P. S.; Pearson, J.; Divan, R.; Tyberkevych, V.; Chang, C. L.; Welp, U.; Kwok, W. K.; Novosad, V., “Coherent coupling of two remote magnonic resonators mediated by superconducting circuits”, *Phys. Rev. Lett.,* **128** (2022).

Near-field scanning microwave microscope with optical confocal distance control

Nikolai Vyshatko and Alexander Tselev

CICECO-Aveiro Institute of Materials, University of Aveiro, Aveiro, Portugal

Numerous manufacturing processes at the micro- and nanometer scales demand tools capable of precise quality control to detect defects and flawed components. These processes span the fabrication of microfluidic components, micro-electro-mechanical systems (MEMS), and specific stages within the semiconductor and electronics fabrication. To address this need, we have developed a prototype hybrid scanning probe microscope. It employs an optical confocal distance sensor and near-fields of microwaves to examine and capture images of samples with sub-micrometer spatial resolution. Our microscope utilizes a near-field microwave probe, which remains at a distance from the sample surface during imaging to minimize probe damage and wear. Its primary function lies in inspecting parts with varying surface shapes and electrical properties, such as dielectric constant and conductivity, with a high spatial resolution. The lateral spatial resolution of our microwave near-field probing exceeds 1 µm, surpassing the approximately 2 µm resolution of current far-field optical systems in use in industry. This tool may serve both in-line and off-line inspection purposes, examining topographic features like channels and protrusions in microfluidic systems and MEMS. Furthermore, the ability to penetrate dielectric materials with microwaves enables imaging of buried structures like metal lines or voids in dielectric materials (see, e.g., the review [1]). This feature may be valuable for non-destructive failure analysis of semiconductor device packaging.

This work was supported by the European Commission under the HORIZON2020 Framework Programme Grant Agreement no. 760662. AT also acknowledges individual support by the 2021.03599.CEECIND through national funds provided by FCT – Fundação para a Ciência e a Tecnologia and project CICECO-Aveiro Institute of Materials, UIDB/50011/2020, UIDP/50011/2020 & LA/P/0006/2020, financed by national funds through the FCT/MCTES (PIDDAC).

[1] A. Tselev, “Near-field microwave microscopy: Subsurface imaging for in situ characterization”, IEEE Microw. Mag., **21**, 72 (2020).

Integration of Microwave Resonant Sensors and Machine Learning Modeling for Advanced Characterization of Magnetodielectric Composites

G. A. Álvarez-Botero(a), H. Lobato-Morales(b), K. Hui(c), N. Tarabay(c), J. Sanchez-Vargas(b), G. Méndez-Jerónimo(b), A. Pons-Abenza(a), I. Arregui(a), T. Lopetegi(a), M. A. G. Laso(a), C. Velez(c).

[a]Grupo de Microondas, Institute of Smart Cities (ISC), Departamento de Ingeniería Eléctrica, Electrónica y de Comunicación, Universidad Pública de Navarra (UPNA), Campus Arrosadia, 31006 Pamplona, España.
[b] Departamento de Electrónica y Telecomunicaciones, CICESE, Ensenada 22860, México.
[c] Mechanical and Aerospace Engineering Department, Magnetic Microsystems and Microrobotics Laboratory, University of California, Irvine, CA, 92697, USA.
germanandres.alvarez@unavarra.es

Additive manufacturing has created significant interest in the development of next-generation RF/microwave devices, including antennas, filters, and phase shifters, with a specific emphasis on innovative materials such as magneto-dielectrics (MD). Several methods, such as waveguides, microstrip transmission lines, and resonant structures like split-ring resonators (SRR), have been utilized to characterize MD materials and extract their permittivity (ε) and permeability (μ) values. However, these approaches encounter limitations in characterizing MD materials with non-zero complex permeability, often relying on separate polynomial expressions for ε and μ, thereby neglecting their intrinsic correlation.

In this study, we fabricated a series of MD composites with varying concentrations of Fe_3O_4 nanoparticles embedded in a PDMS matrix. To determine the ε and μ parameters, we propose a novel SRR sensor and a parameter extraction procedure utilizing Artificial Neural Networks (ANNs). This sensor is designed to stimulate two distinct regions that concentrate electric and magnetic fields differently, facilitating the excitation of these fields in a single measurement on a single sample. Consequently, the need to relocate the Sample Under Test (SUT) is eliminated, thereby mitigating the associated errors.

The obtained results demonstrate the effectiveness of the proposal in evaluating the manufacturing process of MD compounds. It is remarkable that the integration of SRRs and ANN modeling for characterizing MD material manufacturing suggests the potential extension of this technique to other nanoparticle compound formulations. Thus, this approach could guide manufacturing processes to align microwave properties more effectively with the resulting material characterization [1].

Acknowledgment: We acknowledge the support received from the Ministry of Science and Innovation – State Research Agency (MCIN/AEI/10.13039/501100011033), Spain, through project PID2020-112545RB-C53, as well as the support from Navarra Government through the Andia Fellowship. Additionally, we thank the Samueli School of Engineering, University of California, Irvine, USA, for their support.

[1] G. Álvarez-Botero et al., "Magneto-Dielectric Composites Characterization Using Resonant Sensor and Neural Network Modeling," in IEEE Microwave and Wireless Technology Letters, vol. 34, no. 4, pp. 447-450, April 2024, doi: 10.1109/LMWT.2024.3356418.

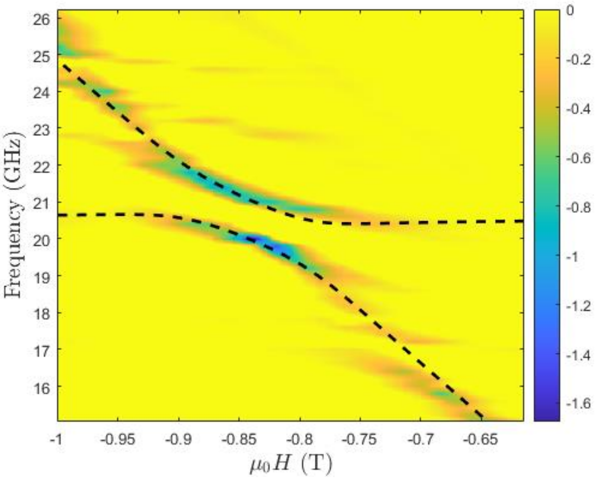
STRONG SPIN-PHOTON COUPLING IN VAN DER WAALS MAGNETS

Pablo Cerrato Serrano[a], Mihai I. Sturza[b], Marc Rovirola[a,b], Hilman Fikry[a], Ferran Macià[a,b], Antoni García-Santiago[a,b], Holger Kohlmann[b], Joan Manel Hernàndez[a,b], Marius V. Costache[a,b]
[a]*Departament de Física de la Matèria Condensada, Universitat de Barcelona*
[b]*Leipzig University, Faculty of Chemistry and Mineralogy*
Institute of inorganic chemistry and crystallography
[c]*Institut de Nanociència i Nanotecnologia (IN2UB)*
(Corresponding author: pabloces64@gmail.com)

Strong coupling between electromagnetic (EM) field and magnetization is emerging as powerful tool for pursuing coherent information processing owing to their rich quantum engineering functionalities. One prototypical example in hybrid systems is cavity magnonics, which consist of a magnetic material and a 2D/3D microwave cavity [1,2].

Here we report strong EM field - magnetization coupling in Cr2Ge2Te6 (CGT), a van der Waals magnet, and a nearly ideal 2D Heisenberg system, with highly correlated electronic and spin degrees of freedom [3]. The magnetocrystalline anisotropy energy required for long-range ferromagnetic order is generated by covalent bond between ligand Te-p and Cr-eg orbitals. We experimentally demonstrate the coherent coupling between magnons (collective spin excitations in CGT) and microwaves photons. The microwave absorption spectrum of the cavity shows anti-crossing features at each intersection between the cavity mode and magnetic resonance (figure below). Coupling strength values up to 1 GHz are obtained indicating a strong magnon-photon coupling in this system.

Our work introduces van der Waals magnets to the field of strong EM field-solid state physics and offers prospects for design and control of collective quantum phenomena such as magnetic phase transitions via cavity quantum electrodynamics.



[1] D. D. Awschalom *et al.,* IEEE Trans. Quantum Eng. 2, 5500836 (2021)
[2] D. Lachance-Quirion *et al.,* App. Phys. Express 12, 070101 (2019)
[3] C. Gong *et al.,* Nature, 546, 265–269 (2017)

New opportunities for spintronic technology from Internet of Things to co-processors

Giovanni Finocchio[a]

[a]*Department of Mathematical and Computer Sciences, Physical Sciences and Earth Sciences, University of Messina, Viale F. Stagno D'Alcontres 31, 98168 Messina, Italy*

The development of more efficient and high performance spintronic devices and the efforts to have co-integration of spintronics with CMOS technology is driving the development of hybrid CMOS-spintronic solutions for applications where one can take the advantages of both technologies while minimizing their disadvantages. In this talk, I will present our recent developments on new potential applications of magnetic tunnel junctions (MTJs) as compact sensors for IoT nodes and computing focusing on how MTJs can be used to develop compact and more effective accelerometers and physical unclonable functions for security applications. I will also discuss our recent results on spintronic microwave amplifiers which are based on the phenomenon of injection locking.

Finally, I will focus on probabilistic computing with probabilistic-bits (p-bits) which is emerging as a computational paradigm able to be competitive in solving NP-hard combinatorial problems. I will show how to map hard combinatorial optimization problems (Max-Sat, Max-Cut, Traveling Salesman problem) into probabilistic Ising machine by using the idea if invertible logic gates and more complex energy mapping approaches and how to implement those in spintronic and CMOS technology. We will investigate the potential of advanced annealing schemes comparing simulated annealing, parallel-tempering, and simulated-quantum-annealing and how it will be possible to implement an efficient probabilistic co-processor.

The author acknowledges the support of Petaspin team in implementing these research activities. This work was supported under the project number 101070287 — SWAN-on-chip — HORIZON-CL4-2021-DIGITAL-EMERGING-01, the project PRIN 2020LWPKH7 and PRIN 20225YF2S4 funded by the Italian Ministry of University and Research, and by the PETASPIN association (www.petaspin.com). This work has been also partially funded by European Union (NextGeneration EU), through the MUR-PNRR project SAMOTHRACE (ECS00000022).

Physics of Electron Emission from 2D Materials: Analytical modelling of Thermal, Field, Optical-Field and Photoemission in the 2D *Flatland*

Yee Sin Ang, L. K. Ang

Singapore University of Technology and Design, Singapore 487372

Electron sources play a key role in the generation of microwave and terahertz waves [1]. Two-dimensional (2D) materials offer an exciting platform to design electron sources due to their ultrathin body and atomically sharp edges, which are beneficial for device miniaturization and boosting the field enhancement effect. The physics of electron emission from 2D materials can no longer be described by the Richardson-Dushman (thermionic), Fowler-Nordheim (field) and Fowler-Dubridge (photoemission) models originally developed for bulk metals due to the reduced dimensionality, nonparabolic energy dispersion, and the presence of distinctive edge and surface emission geometry in 2D materials [2,3,4]. In this work, we reformulate the theory of thermionic [5,6,7], field [7], optical-field tunneling [8] and photoemission [9] in 2D materials. Intriguingly, we show that the electron emission from 2D materials can be captured by *universal scaling laws* that are valid for a large variety of 2D materials. Such scaling universality is a unique feature of 2D materials not found in bulk 3D electron emitters. Our models provide a theoretical foundation for understanding electron emission phenomena in 2D materials, thus paving important first steps towards the development novel ultracompact high-performance 2D material electron sources for microwave and terahertz waves generations.

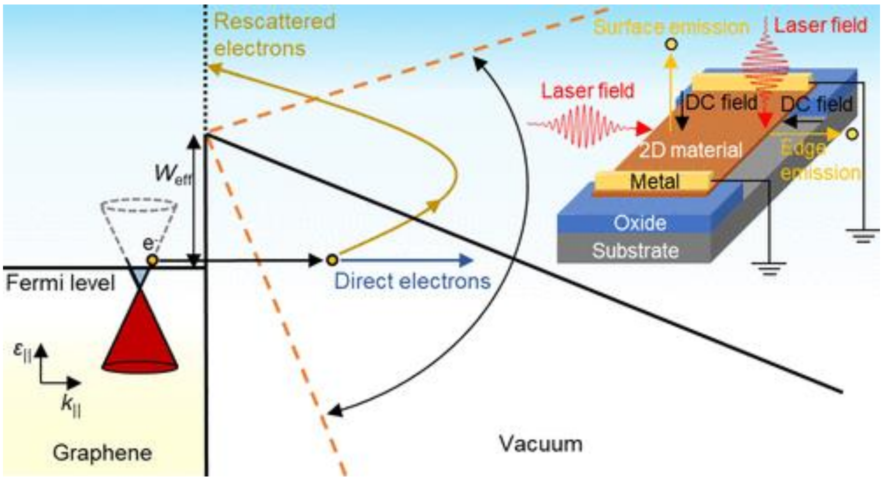


Figure 1. Schematics of optical-field tunneling from the surface and edge of 2D graphene.

[1] P. Zhang, Y. S. Ang, A. L. Garner, A. Valfells, J. W. Luginsland, L. K. Ang, J. Appl. Phys. **129**, 100902 (2021).
[2] Y. S. Ang, L. Cao, L. K. Ang, InfoMat, 3, 502 (2021).
[3] W. J. Chan, C. Chua, Y. S. Ang, L. K. Ang, IEEE Trans. Plasma Sci. **51**, 1656 (2022).
[4] Y. S. Ang, S.-J. Liang, L. K. Ang, MRS Bulletin 42, 505 (2017).
[5] Y. S. Ang, H. Y. Yang, L. K. Ang, Phys. Rev. Lett. **121**, 056802 (2018).
[6] Y. S. Ang, Y. Chen, C. Tan, L. K. Ang, Phys. Rev. Appl. **12**, 014057 (2019).
[7] Y. S. Ang, L. K. Ang, Front. Mater. **6**, 204 (2019).
[7] L. K. Ang, Y. S. Ang, C. H. Lee, Phys. Plasma **30**, 033103 (2023).
[8] Y. Luo, T. Su, H. Y. Yang, Y. S. Ang, L. K. Ang, Nano Lett. **24**, 3882 (2024).
[9] Y. Luo, C.-C. Er, Y. S. Ang, L. K. Ang, Appl. Phys. Lett. **124**, 101109 (2024).

Tuning on-chip integrated spin-wave transducers for improved efficiency and sensitivity

Felix Kohl,[a] Björn Heinz,[a] and Philipp Pirro[a]

[a] Fachbereich Physik and Landesforschungszentrum OPTIMAS,
Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau,
D-67663 Kaiserslautern, Germany

In recent years, magnonics has emerged as a promising candidate for integrated microwave devices. This research field, dedicated to manipulating and utilizing spin waves, the collective excitations of spins in magnetic material with wave characteristics, has shown promise for integrated microwave devices, providing inherent non-reciprocity and reconfigurability over several GHz spans. Ongoing research aims to bridge the gap between theoretical feasibility and practical implementation, with a particular focus on advancing on-chip integrated spin-wave devices. While dynamic Oersted-driven spin-wave transducers are commonly used in microstructured devices, their inefficiencies demand substantial enhancements to compete with established technology solutions. To address these challenges, a basic spin-wave transducer, composed of microstructured input and output antennas atop of Yttrium-Iron-Garnet (YIG) films with thickness ranging from 100nm to 800nm, serves as an exemplary testbed for integrated magnon-based RF devices with an active region significantly smaller than 0.1mm^2. In a comprehensive study, we assess insertion losses, bandwidths and their respective tuneability by external magnetic fields, considering various key parameters such as magnetic material properties and spin-wave dispersion relations. Leveraging propagating spin-wave spectroscopy, we measure spin-wave transmission and interpret results, providing valuable insights into the system's behavior and key parameters influencing device efficiency. Through reduction of reflection and dissipation losses, we achieve record transmission efficiency for integrated spin-wave devices. Notably, our achieved insertion losses are lower than 10 dB and exhibit stability across frequencies spanning from 3 GHz to 15 GHz, with the ability to be finely tuned by adjusting the external magnetic field. Additionally, we leverage inherent non-reciprocity to enhance isolation within the device, rendering it suitable for applications akin to a diode. This work represents a crucial step towards realizing the full potential of magnonics in practical applications. This research is funded by the European Union within HORIZON-CL4-2021-DIGITAL-EMERGING-01 (No. 101070536,MandMEMS)

High-Temperature Microwave-to-Optical Signal Conversion via Exciton-Polaritons in Optomechanical (Al, Ga) As Microcavities

Ismael dePedro-Embid, [a] **Alexander Kuznetsov,** [a] **Klaus Biermann,** [a] **Paulo V. Santos**[a]

[a]*Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im*
Forschungsverbund Berlin e.V., Hausvogteiplatz 5-7, 10117 Berlin, Germany

Classical and quantum communication networks depend on manipulating information using GHz electrical microwave signals while distributing this information as optical signals at THz frequencies. Achieving coherent microwave-to-optical conversion is essential for such networks but presents significant challenges due to the considerable difference in operating frequencies.

Recently, polaromechanical systems have emerged as good candidates to bridge this frequency gap using phonons to couple to both light and microwave fields [1]. In such systems, the photon is strongly coupled to an exciton giving rise to a quasiparticle called polariton. The quasiparticle nature allows for an enhanced coupling to vibration through the deformation potential mediated by the exciton component. In addition, the transition to a highly coherent polariton condensate – a Bose Einstein-like macroscopic coherent state- brings the system into the optomechanical sideband resolved regime allowing for coherent energy exchange between the phonons and the polaritons, as has been demonstrated at cryogenic temperatures (10 K) [2].

Our system consists of a hybrid (Al, Ga) As optomechanical microcavity confining both polaritons and phonons in a micro-sized trap. We use bulk acoustic wave resonators driven by a microwave electrical signal to inject GHz phonons into the polaromechanical cavity. To achieve high-temperature operation, we show that the sideband resolved modulation can be maintained by confining the polaritons in 0D structures (polariton dots). Confinement prevents the polariton lines from undergoing decoherence due to scattering with acoustic phonons, ensuring narrow linewidths up to temperatures as high as 200K and favoring the transition into a polariton condensate. With this approach, we have shown efficient modulation of polariton lines up to 80 K showing proof of concept coherent microwave-to-optical signal conversion above cryogenic temperatures.

[1] P. V. Santos and A. Fainstein. Optical Materials Express 13.7, 1974-1983 (2023).
[2] A.S. Kuznetsov, K. Biermann, A.A. Reynoso, A. Fainstein, P.V. Santos. Nat Commun 14, 5470 (2023).

Piezoelectric generation of GHz acoustic helical waves

Nazim Ashurbekov[a], Ismael de Pedro Embid[a], Alessandro Pitanti[b], Paulo V. Santos[a]

[a]Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im
Forschungsverbund Berlin e.V., Hausvogteiplatz 5-7, 10117 Berlin, Germany
[b]University of Pisa, largo B. Pontecorvo 3, 56127 Pisa, Italy,
CNR-Istituto Nanoscienze, Laboratorio NEST, Piazza San Silvestro 12, 56127 Pisa, Italy
and Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im
Forschungsverbund Berlin e.V., Hausvogteiplatz 5-7, 10117 Berlin, Germany

The dynamic control of the light circular polarization opened revolutionary new horizons in fundamental and applied research and technology. Such a modulation of light beams can be realized at GHz frequencies using helical surface (SAWs) and bulk acoustic waves (BAWs) in solids. Mechanical vibrations are also a convenient tool for coupling to electrons through the piezoelectric and deformation potential mechanisms as well as to control photons and magnetic excitation through the photoelastic effect or by a direct geometrical deformation of the material. In this work, we aim at a full opto-mechanical control of light that includes amplitude and polarization modulation. Possible applications cover optical wireless communication, microscopy and sensing of biological samples, and translation of chirality of light into mechanical elements.

Our strategy towards polarization control relies on the transfer of a helical mechanical polarization to the light field. A very important step is thus to achieve a fully tunable manipulation of the mechanical field. The technological challenges are thus related to the generation and detection helical acoustic waves.

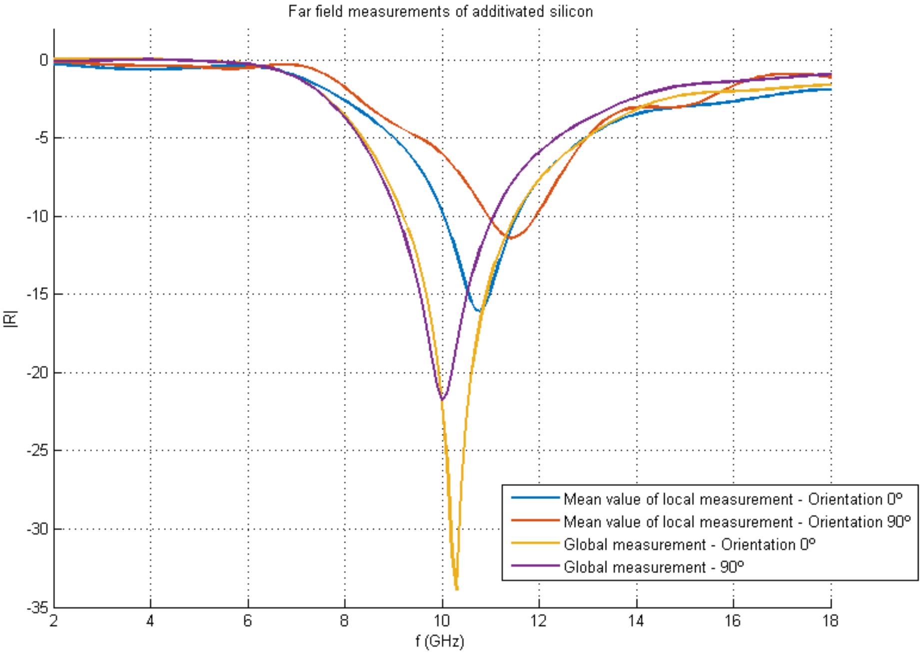
Here we present results of the generation and mapping of acoustic helical waves at GHz frequencies using atomic force microscopy (AFM) and optical interferometric technique. Our sample consist of a ring-shaped BAW resonator (BAWR) composed of three independent sectors that were fabricated using photolithographic technique. The ring-shaped BAWR has an inner and outer radius of 16 and 32 μm, respectively, and uses a ZnO film as the active piezoelectric layers. We show that transversal waves can be generated on the sample top surface, leading to different wavefronts according to the rf signals used, e. g. with equal phase (leading to focusing) or with phases differing by 120° deg to the three sectors (leading to rotational components). The generated acoustic fields were mapped by optical interferometry and AFM for a complete characterization of the field complex amplitude and intensity, respectively. The advantages and disadvantages of both mapping methods will be described in details. In addition, we provide results of Finite Elements Method (FEM) simulation to support the interpretation of the experiment data. Currently, experiments are being conducted on sapphire because of its relatively low transmission losses. The next generation of the device is planned to be fabricated on GaAs microcavities for experiments on light polarization modulation.

Development and measurement of radar absorbing material using different additives on a silicone matrix

Susana Aberturas[a*], Javier Calvo[a], Javier Rodríguez[a], Miguel Ángel García[c], Pilar Marín[b], Antonio Hernando[b,d,e,f]

[a] Micromag 2000 SL, Avenida de Arroyomolinos, 3 y 5, 28925 Alcorcón, Spain
[b] Instituto de Magnetismo Aplicado (IMA), Universidad Complutense de Madrid-Administrador de Infraestructuras Ferroviarias (UCM-ADIF), 28230 Las Rozas, Spain
[c] Instituto de Cerámica y Vidrio, Campus de Cantoblanco, Consejo Superior de Investigaciones Científicas (CSIC), 28049 Madrid, Spain
[d] Donostia International Physics Center, 20028 Donostia, Spain
[e] IMDEA Nanociencia, 28049 Madrid, Spain
[f] Engineering Department, Nebrija University, Sta. Cruz de Marcenado, 27, 28015 Madrid, Spain
**Author to whom correspondence should be addressed.*

Radar absorbing materials are nowadays widely used in different applications such as EMI isolation or to attenuate the reflected electromagnetic wave when illuminating an object with microwaves. For the development of radar absorbing materials, it is necessary to understand how the attenuation of the electromagnetic wave occurs, how it is possible to tune materials to specific frequencies, and select the adequate type and composition of additives. For this purpose, in this article the development of absorbing materials using silicon as the main base is studied, and samples have been manufactured. Samples have been characterized and measured by different methods, studying the global contribution of a larger sample measured under far-field conditions, but also the local contributions and possible orientations arising from the geometry of additives; and studying their characterization by waveguide measurements.



High-frequency surface-acoustic-wave generation and detection

Mingyun Yuan,[a] Duc Van Dinh,[a] Soumen Mandal,[b] Oliver A. Williams,[a] Oliver Brandt,[a] Paulo V. Santos[a]

[a]*Paul-Drude-Institut fuř Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., 10117 Berlin, Germany*
[b] *School of Physics and Astronomy, Cardiff University, Cardiff CF24 3AA, UK*

Devices based on surface acoustic waves (SAWs) operating in multi-gigahertz frequencies are highly desirable not only for their application in telecommunication of future generations, but also for the fast, dynamic acoustic manipulation of quantum nanostructures. To realize these functionalities, we need piezoelectric thin films that support high SAW velocities, have high electro-mechanical coupling coefficients, can be synthesized as thin-films, and ideally, are isotropic in the film plane. In this work, we explore the properties of SAW devices based on (Al,Sc)N thin film alloys grown on different substrates using molecular-beam epitaxy (MBE). We demonstrate the effective generation of SAWs with frequencies up to 8 GHz on substrates coated with (Al,Sc)N films [1]. The high contrast in acoustic impedance between the thin film and the substrate enables the excitation of multiple, wave-guiding overtones. Next, we will show a technique for the mapping of high-frequency SAW fields with high spatial resolution using atomic-force-microscopy (AFM) [2]. The spatial mapping of SAW profile facilitates the characterization of the SAW beam shape, the propagation losses, and moreover, the coupling of strain in hybrid SAW- nanostructures, which can be implemented on a large variety of substrates. We will also discuss the challenges and perspective related to the AlN based SAW technology.

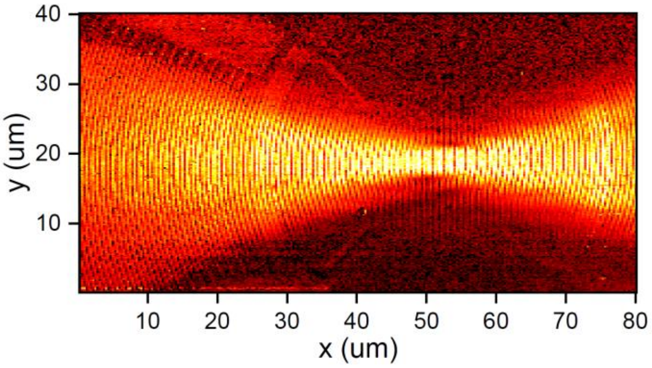


Figure 1. Surface-acoustic-wave profile in a focusing cavity on AlN/SiC, mapped by atomic-force microscopy

[1] M. Yuan, D. V. Dinh, S. Mandal et al., unpublished (2024).
[2] T. Hesjedal, Rep. Prog. Phys. 73, 016102 (2010).

Piezoelectric bulk acoustic transducers operating above 20 GHz for on-chip microwave-to-optical conversion

Meysam Saeedi,[a] K. Biermann,[a] Paulo V. Santos,[a] Alexander S. Kuznetsov[a]

[a] *Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e.V., Hausvogteiplatz 5–7, 10117 Berlin, Germany*

Over recent decades, the modulation of opto-electronic resonances with GHz-frequency acoustic waves (phonons) has attracted attention for the microwave-to-optical conversion, required for interconnection between superconducting qubits and optical photons[1,2]. Bulk acoustic wave resonators (BARs) can be used to convert microwave signals into acoustic phonons and integrated with optoelectronic chips [2]. There is also a considerable effort in pushing the operating frequencies of microwave qubits beyond 20 GHz to enhance their working temperatures [3]. This increase must therefore be accompanied by a corresponding increase in the operating frequency of BARs.

Our approach to the microwave-to-optical conversion relies on the coupling between GHz phonons and opto-electronic resonances in semiconductor GaAs-based microcavities with BARs fabricated on top . A BAR has a capacitor-like structure, Its resonance frequency (F_r) is determined by the thickness of the piezoelectric layer placed between top and bottom metal contacts [4]. Using such BARs we demonstrated acoustic modulation up to 20 GHz [5, 6]. The high F_r was achieved by reducing the thickness of the piezoelectric ZnO film down to 80 nm. The results highlighted several challenges for exceeding 20 GHz related to the poor crystallinity and presence of pinholes in ZnO thin films.

In this study, first, we aim to improve the fabrication of BARs capable of operating at 20 GHz on GaAs substrates. One studied approach was to progressively push F_r towards 20 GHz by systematically reducing the thickness of the ZnO film while ensuring that it remained pinhole free through controlled sputtering deposition conditions. Complementary, we considered optimizing the composition of top contacts, e.g.,Ti/Au, Ti/Al, and Ti/Pt. Techniques such as atomic force microscopy and electrical characterization of BARs were employed for analysis. In the future, to increase F_r beyond 20 GHz we will use other piezoelectric materials with higher acoustic velocities, e.g., AlN and ScAlN.

[1] L. Midolo, et al, *Nature nanotechnology, 13.1, 11 (2018).*
[2] X. Xu, et al. Micromachines, 15, 485 (2024).
[3] A. Anferov, et al. arXiv preprint arXiv:2402.03031 (2024).
[4] DHO. Machado, et al. Physical Review Applied, 12.4, 044013, (2019).
[5] A.S. Kuznetsov, et al. Nature Communications, 14.1, 5470 (2023).
[6] A. S.Kuznetsov, et al. *Physical Review X,* 11.2, 021020 (2021).

Acoustic control of magnetization in lattice-matched ferromagnetic thin films on GaAs (001)

Gomes, J. [a]**, Herfort, J.** [a]**, Hernández-Mínguez, A.** [a]

[a] *Paul-Drude-Institute für Festkörperelektronik, Hausvogteiplatz 5-7 10117 Berlin, Germany*

Surface acoustic waves (SAWs) are a very useful tool to probe elementary excitations and magnons are no exception [1]. SAW-driven magnetization precession [2] and switching [3] are achieved by driving the SAWs at the spin-wave resonant frequencies in magnetostrictive materials. This may be challenging due to (i) the high frequencies of spin-waves (several GHz) in typical ferromagnetic (FM) materials, and (ii) the high-quality piezoelectric substrates required for generation of large SAW amplitudes.

On the other hand, standing SAWs have been theoretically studied [4], and experimentally observed to acoustically control domain walls (DW) in magnetic structures under applied magnetic field pulses [5]. The standing SAW modifies the local magnetic energy landscape, thus inducing an array of energetically favorable pinning sites throughout the magnetostrictive material that accelerates the process of DW re-organization. Additionally, standing SAWs have been characterized in acoustic atomic force microscope (AAFM) setups, by probing the tip deflection caused by the SAW vertical displacement field and decoupling the contribution from the sample's topography by means of a lock-in demodulation scheme [6].

In this experiment, standing SAWs are excited in GaAs substrates to control DWs in microstructures patterned out of epitaxially grown highly crystalline Fe_3Si films. The local mapping of the SAW will be combined with magnetic force microscopy (MFM) to investigate the changes in domain configuration under the magnetoelastic perturbation. The goal is the tracking of the DW positions, as the phase of the standing SAW is shifted within the acoustic cavity, enabling a comprehensive study of acoustically driven DW motion.

[1] Yang, W. and Schmidt, H., Appl. Phys. Rev. 8, 021304 (2021);

[2] Weiler, M., Dreher, L., Heeg, C., Huebl, H., Gross, R., Brandt, M.S., and Goennenwein S.T.B., Physics Review Letters 106, 117601 (2011);

[3] Thevenard, L., Camara, I.S., Majrab, S., Bernard, M., Rovillain, P., Lemaître, A., Gourdon, C., Duquesne, J.-Y., Physical Review B 93, 134430 (2016);

[4] Dean, J., Bryan, M. T., Cooper, J. D., Virbule, A., Cunningham, J. E. and Hayward, T. J. , Applied Physics Letters, 107, 142405 (2015);

[5] Adhikari, A. and Adenwalla, S., AIP Advances, 11, 015234 (2021);

[6] Pitanti, A., Yuan, M., Zanotto, S. and Santos, P.V., Physical Review Applied, 20, 054054 (2023).

Ionic Liquids-Metal nanoparticles systems design for polyolefinic plastic waste chemical recycling to added value decarbonized products.

Maria Taeño[a], Jonatan Pérez-Arce[a], Ali Huerta[a], Stefania Doppiu[a], Elena Palomo del Barrio[a,b], and Eduardo J. García-Suárez[a,b]

[a]*Center for Cooperative Research on Alternative Energies (CIC energiGUNE), Basque Research and Technology Alliance (BRTA), Alava Technology Park, Albert Einstein 48, 01510, Vitoria-Gasteiz, Spain*
[b]*IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 480009 Bilbao, Spain*

Nowadays, two main challenges facing our society, future generations, and global sustainability can be found: firstly, the effective management of the vast quantities of plastic waste generated annually, and secondly, the generation of efficient, affordable, sustainable, and clean energy or decarbonized products. Recycling techniques are divided from primary to quaternary [1]. Tertiary recycling is of special interest and is a promising technique due to the possibility to convert plastic waste into high-added value products (H_2 or solid carbon). Moreover, catalytic, and non-catalytic thermal routes are usually employed for plastics recycling process, being the thermo-catalytic routes of major interest based on the presence of a proper catalyst which play a key role in the selectivity towards targeted products. Since conventional heating methods require higher temperatures, new non-conventional routes are necessary to overcome the limitations. In this context, microwave irradiation (MW) as a heating method presents a highly promising alternative. This is attributed to the effect of electromagnetic MW irradiation, which significantly reduces reaction times and enhances energy efficiency by minimizing energy loss.

The work shown here is part of the TWICE project, whose main objective is to employ non-easily recyclable plastic waste, such as LDPE (low density polyethylene) and PP (polypropylene) as a feedstock for generating decarbonized products, clean H_2, and valuable solid carbon materials. For this purpose, a system comprising ionic liquids (ILs) and metal nanoparticles (MNPs) has been prepared for the catalytic deconstruction of plastics under MW irradiation. First, different ionic liquids have been synthesized containing halogenated anions due to their expected high thermal stability and plastic solubility. On the other hand, different metal nanoparticles based on precious (Pd, Ru, Au) and non-precious (Mn, Fe, Cu) metals have been synthesized using well-established synthesis methods such as hydrothermal and microemulsion routes. Since the particle size of these materials directly affects conversion, selectivity, dispersion in the ILs and MW efficiency, special attention has been paid to the synthesis and characterization of them. Thorough TEM (transmission electron microscopy) studies have been carried out for the MNPs to know the size distribution and morphology of the particles. In the case of ILs, different analytical techniques, including Fourier-Transform Infrared Spectroscopy (FTIR), Nuclear Magnetic Resonance (NMR), and Thermogravimetric Analysis (TGA), have been employed for the final selection of the best IL.

[1] P. S. Roy, G. Garnier, F. Allais, K. Saito, ChemSusChem, 14(19), 4007 (2021)

New methodology for electromagnetic characterization of 2D materials with radar absorbing capabilities

Marc Vazquez Aige,[a] Jaume Calvo-de la Rosa,[a] Jose Maria Lopez-Villegas,[b] Javier Tejada,[a]

[a]*Dept. de Física de la Matèria Condensada, Universitat de Barcelona, 08028 Barcelona, Spain*
[b]*Dept. d'Enginyeria Electrònica I Biomèdica, Universitat de Barcelona, 08028 Barcelona, Spain*

We present a new methodology for electromagnetic characterization of thin film materials directly performing S-parameter Vector Network Analyzer (VNA) measurements onto the sheet. The whole process involves many calibrations and corrections to ensure the final signal can be attributed to the material exclusively so that the Nicolson-Ross-Weir equations can be applied properly. This is especially interesting considering the use of materials with magnetic properties, such as Zn-Mn ferrite powder dispersed in a paint/resin substrate and may open the door to more realistic experimentation for studying their radar absorbing capabilities. Once the reduced permittivity and permeability are calculated we can use the single layer impedance model to obtain the absorption and reflection loss.

$$Z = Z_0 \sqrt{\frac{\mu_r}{\varepsilon_r}} tanh\left[\left(j\frac{2\pi f d}{c}\right)\sqrt{\mu_r \varepsilon_r}\right]$$

The results are extremely promising as they adhere to theoretical predictions, adjust to our reference material with high accuracy and are comparable to reflection loss measurements performed in a different experimental setup for direct reflection loss measurements.

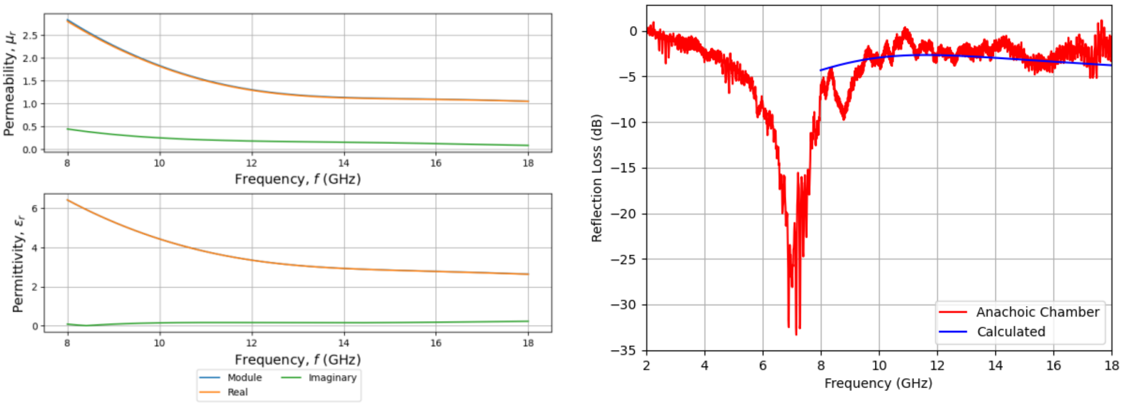


Figure. Left panel: reduced permittivity and permeability of PDMS charged with Mn-Zn ferrite in the 8-18 GHz frequency range; right panel: Comparison between direct reflection loss measurements with calculated ones using the reduced permittivity and permeability.

[1] Calvo-de la Rosa, J., Bou-Comas, A., Manel Hernàndez, J., Marín, P., Lopez-Villegas, J. M., Tejada, J., & Chudnovsky, E. M. Advanced Functional Materials, 34(6), 2308819 (2023)