Metamaterials: Designing Wave Propagation with a Focus on Electrodynamics

760. WE-Heraeus-Seminar

07 Feb - 11 Feb 2022
Hybrid
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 760. WE-Heraeus-Seminar:

Metamaterials are artificial materials and media of designed properties governing propagation phenomena with a wide range of realizations in, e.g., electrodynamics, fluid mechanics, acoustics, heat and diffusion, quantum physics and atom optics, as well as seismology. Their influence on the propagation of physical fields is based on artificially tuned macroscopic constitutive relations beyond the natural regime, leading to new effects such as cloaking and negative refraction. One common method for the design of metamaterials is to use (periodic) sub-wavelength structures. Despite the manifold applications ranging from medical imaging over the absorption of sound or protection of buildings against earth quakes to analog gravity, the underlying mathematical description is universal. This seminar aims to bring together scientists from many different fields related to theoretical and experimental research as well as applications of metamaterials. We want to stimulate the cross-disciplinary exchange of ideas and solution methods and bridge the theoretical fundamental research with experiments and applications.

Scientific Organizers:

Prof. Dr. Matthias Günther	Fraunhofer MEVIS; Bremen, Germany E-mail: matthias.guenther@mevis.fraunhofer.de
Dr. Dennis Philipp	ZARM, University of Bremen and Fraunhofer MEVIS, Bremen, Germany E-mail: dennis.philipp@zarm.uni-bremen.de
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Prof. Dr. Claus Lämmerzahl	ZARM, University of Bremen, Germany E-mail: claus.laemmerzahl@zarm.uni-bremen.de

Introduction

Administrative Organization:

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Registration:

at the Physikzentrum, reception office
Sunday (17:00 h – 20:00 h) and Monday morning

Program

Program

Sunday, 6 February 2022

17:00 – 20:00	Registration	
from 18:00	BUFFET SUPPER / Informal get together	

Monday, 7 February 2022

08:00 – 08:45	*BREAKFAST*	
08:45 – 09:00	Scientific organizers	**Welcome and opening**
09:00 – 10:00	John Pendry (online)	**Luminal gratings enable: photon localisation, Bloch symmetry breaking, and a novel amplification mechanism**
10:00 – 11:00	Ralf Schuetzhold	**Optical Analogues for Fundamental Physics**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Silke Weinfurtner (online)	**Quantum simulators for fundamental physics**
12:30	*LUNCH*	
14:30 – 15:30	Michèle Heurs (online)	**Potential and prospects for meta-mirrors in precision metrology**
15:30 – 16:30	Stefanie Kroker (online)	**Metamaterials for Measurements at Ultimate Precision**
16:30 – 17:00	*COFFEE BREAK*	
17:00 – 18:00	Martin Wegener	**3D Metamaterials: Chirality and Non-Locality**
18:00 – 18:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
18:15 – 19:00	**Open Discussion**	
19:00	*HERAEUS DINNER* at the Physikzentrum (cold & warm buffet, with complimentary drinks)	

Program

Tuesday, 8 February 2022

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Andrew Webb (online)	**Novel materials in magnetic resonance imaging: high permittivity ceramics, metamaterials, metasurfaces and artificial dielectrics**
10:00 – 11:00	Rita Schmidt (online)	**Tailoring the RF field at ultra-high field MRI with artificial materials**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Friedrich Hehl	**Electrodynamics with a local and linear anisotropic constitutive law: metamaterials, Cr_2O_3, optics, and Fresnel-Kummer surfaces**
12:30	*LUNCH*	
14:30 – 15:30	Yuri Obukhov (online)	**General structure of electromagnetism: covariant formulation**
15:30 – 16:30	Jonathan Gratus (online)	**Corrugated Structures and Mathieu's equation for EM generation and particle acceleration**
16:30 – 17:00	*COFFEE BREAK*	
17:00 – 18:00	**Poster Flash**	
18:00 – 19:00	**Poster Session**	
19:30	*DINNER*	

Program

Wednesday, 9 February 2022

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Robin Tucker (online)	**Applications of an analysis of classical Plasmon-Polariton-Brewster Modes in Homogeneous Media with an anisotropic planar interfacial surface admittance tensor.**
10:00 – 11:00	Christian Pfeifer	**General Linear Electrodynamics: Causal Structure, Propagators, Quantization and quantum energy inequalities**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Christian Bär (online)	**Wave equations on curved backgrounds**
12:30	*LUNCH*	
14:30 – 15:30	Philippe Roux (online)	**Locally resonant metamaterials : from wave physics to geophysics**
15:30 – 16:30	Irina Khromova	**NFC wireless charging for multiple devices**
16:30 – 17:00	*COFFEE BREAK*	
17:00 – 18:00	Alena Shchelokova (online)	**Metamaterial inspired wireless coils and pads for clinical MRI**
18:00 – 18:45	**Open discussion**	
18:45	*DINNER*	
20:00	Evening lecture Philipp Klais	**tba**

Program

Thursday, 10 February 2022

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Walter Fuscaldo	**Microwave Generation of Localized Waves Through Leaky-Wave Antennas Based on Metasurfaces**
10:00 – 11:00	Vahid Sandoghdar (online)	**Quantum Metamaterials with Magnetic Response at Optical Frequencies**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Igor Tsukerman	**Homogenization of Metamaterials: Symmetry Breaking and "Bulk Transition"**
12:30	*LUNCH*	
14:30	**Excursion**	
18:45	*DINNER*	

Program

Friday, 11 February 2022

08:00 – 09:00	*BREAKFAST*	
09:00 – 10:00	Yakov Itin	**Finsler's metric as a novel tool for wave propagation analysis**
10:00 – 11:00	Agostino Monorchio (online)	**Multifunctional metasurfaces with absorbing, reflecting and high impedance properties for ICT and Biomedical applications**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Rebecca Seviour (online)	**Metamaterial Mediated EM Wave Generation and Amplification**
12:30	*LUNCH*	
14:30 – 15:30	Sophia Sklan	**Nonlinearity, Nonlocality, and Nonreciprocity: New Directions for Metamaterials**
15:30 – 16:30	Thomas Bertuch (online)	**A Review of RF Metamaterial Applications at Fraunhofer FHR**
16:30 – 16:45	Scientific organizers	**Conclusion / Poster Award**

End of seminar and departure

Posters

Posters

Danilo Brizi	**Metasurfaces Design for Magnetic Resonance Imaging and Wireless Power Transfer Applications**
Ruth Cardinaels	**Designing multi-layer polymeric nanocomposites for electromagnetic shielding**
Andrey Iljin	**Light-induced dynamic subwavelength structures in liquid crystals for wave control**
Sharmetha Kannan	**Optical non-linear effects in metasurface using finite model**
Sascha Lang	**Quantum vacuum physics in dispersive and dissipative dielectrics**
Marius Lippke	**Investigation of Digitally-Reconfigurable Metasurfaces for MRI Applications**
Parthasarathi Majumdar	**Effective General Relativistic Description of Jamming in Granular Matter**
Mariia Matiushechkina	**High-reflective Si metasurface on a sapphire substrate for 1550 nm**
Aniqa Mehboob	**Detailed Analysis of the Temperature Dependent Goos-Hänchen Shift**
Edoardo Negri	**Analysis of Resonant Bessel-Beam Launchers based on Isotropic Metasurfaces**
Hervé Ngremale	**Metamaterials: Designing Wave Propagation with a Focus on Electrodynamics**
Marco Tannino	**A heuristic model to evaluate dielectric properties of human tissues at microwave band based on water and solid content**
Robert Thompson	**Dielectric analog space-times, transformation optics, and manifold maps**

Abstracts of Lectures

(in alphabetical order)

Wave equations on curved backgrounds

C. Bär

Institute for Mathematics, University of Potsdam, Germany

This will be a survey on the theory of linear wave equations on curved backgrounds. We will discuss the characteristic and non-characteristic Cauchy problems, fundamental solutions, the Hadamard expansion and more.

References

[1] C. Bär, F. Pfäffle and N. Ginoux, Wave equations on Lorentzian manifolds and quantization, EMS 2007

[2] C. Bär and R. Tagne Wafo, Math. Phys. Anal. Geom. **18**, 7 (2015)

[3] C. Bär, Commun. Math. Phys. **333**, 1585 (2015)

[4] C. Bär and A. Strohmaier, arXiv:2012.01364, 2020

A Review of RF Metamaterial Applications at Fraunhofer FHR

D. Betancourt[1], E. Stoja[1], T. Badawy[1], C. Löcker[1],

A. Konforta[1], T. Bertuch[1]

[1] *Fraunhofer Institute for High Frequency Physics and Radar Techniques FHR, Wachtberg, Germany*

Electromagnetic Metamaterials (MTM) have been in the focus of engineering research for more than 20 years with applications in various fields like communication and remote sensing but also medical engineering or wireless power transfer. The Fraunhofer Institute for High Frequency Physics and Radar Techniques FHR in Wachtberg, Germany has a long history of application-driven research and development in the field. Most of the applications deal with the suppression of parasitic, i.e. undesired waves resorting to electromagnetic bandgap (EBG) surfaces, which, in some cases, are also used as artificial magnetic conductors. Inspired by the typical EBG surface geometry, a surface-integrated leaky-wave antenna was developed along with a comprehensive equivalent circuit model that facilitates rapid design optimization. Transmission line metamaterials are of interest for dispersion engineered, compact delay lines and power splitters with large splitting ratios. The miniaturization of Antennas has been addressed as well. Array antennas with electronic scanning capabilities are crucial components of modern radar systems and 5G base stations. At FHR the application of electronically tunable metasurfaces has been investigated to improve the electronic scanning capabilities of these antennas. Finally, FHR has considered MTMs also for medical applications in the field of magnetic resonance imaging (MRI). Here, at FHR-untypical frequencies, again the suppression of undesired fields was considered. Induced RF currents on the shields of cables inside an MRI scanner where suppressed by an EBG-inspired coating. Furthermore, the scanner's RF magnetic field was focused with the help of MTM resonators. The talk will cover all of these applications and give some details on the design concepts and the achieved performance.

Microwave Generation of Localized Waves Through Leaky-Wave Antennas Based on Metasurfaces

W. Fuscaldo[1]

[1]*Institute for Microelectronics and Microsystems, National Research Council of Italy (CNR-IMM), Rome, Italy*

In recent years, microwave and millimeter-wave applications such as medical and security imaging, wireless power transfer, and high data-rate wireless communications, just to mention but a few, have gained much attention in the area of Information and Communication Technology (ICT) due to their potentially high social impact. In this context, it is of paramount importance to focus energy in the near-field region, and thus the generation of limited-diffraction, limited-dispersion waves in the microwave and millimeter-wave regime is a topic of recent increasing interest.

In this Seminar, I will show part of my research activity in the field of localized waves trying to emphasize the intrinsic versatility of the leaky-wave approach to design metasurface-based devices capable to focus energy in the near-field region at microwave frequencies [1]. I will first cover general theoretical aspects related to the main properties of two important classes of localized waves: Bessel beams and X-waves [2]. After a brief historical review of the early generations of such kinds of solutions in the optical regime, I will describe the latest realizations in the microwave frequency range. Specific emphasis will be given to those realizations based on metasurfaces and leaky waves showing both theoretical and experimental results.

I will conclude the Seminar commenting on the advantages and limitations of these solutions and opening to the main challenges and future perspectives in this field.

References

[1] W. Fuscaldo, D. Comite, A. Boesso, P. Baccarelli, P. Burghignoli, and A. Galli, "Focusing leaky waves: A class of electromagnetic localized waves with complex spectra," Phys. Rev. Appl., 9(5), 054005, 2017.

[2] H. E. Hernández-Figueroa, M. Zamboni-Rached, and E. Recami, "Localized Waves," Hoboken, NJ, USA: John Wiley & Sons, 2007.

Corrugated Structures and Mathieu's equation for EM generation and particle acceleration.

J. Gratus[1,2], **T. Boyd**[1,2], **S. Jamison**[1,2], **R. Seviour**[3], **P. Kinsler**[1,2,4] **and R. Letizia**[1,2]

[1] *Lancaster University, Physics department, Lancaster LA1 4YB, UK*
[2] *The Cockcroft Institute, Sci-Tech Daresbury, Daresbury WA4 4AD, UK*
[3] *University of Huddersfield, Huddersfield HD1 1JB, UK*
[4] *Imperial College, London SW7 2AZ, UK*

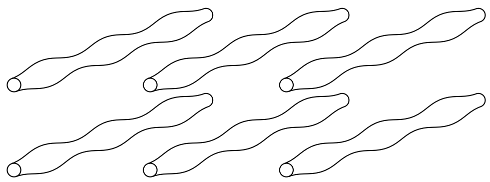

Fig. 1. Corrugated Wire Medium

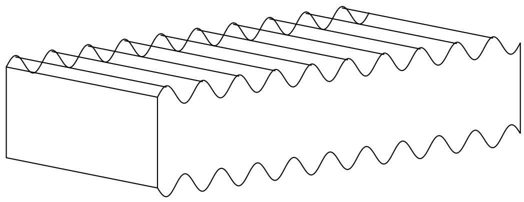

Fig 2. Corrugated Wave Guide

Both a wire medium and a waveguide can be considered as a 1–dimensional metamaterial with spatial dispersion. We consider the case where the parameters of these structures vary sinusoidal along the structure with a gentle gradient. We can find approximate solutions for the electromagnetic field in terms of Mathieu functions. In the case of a corrugated wire medium, the parameters of this

In the wire medium, Fig. 1, we can find approximate solutions for the longitudinal component of the electric field along a line in the centre of four wires [1,2]. By contrast for the corrugated waveguide, Fig. 2, a closed expression for the approximate electromagnetic field for the full structure is given [3]. These solutions have been compared with full numerical 3–dimensional simulations with very good results. Having an analytic solution enables one to predict the dispersion relation and quickly run though the parameter space without numerical simulations. As such we can easily find parameters where the group and phases velocities match, Fig. 3. A pulse in such a waveguide will propagate with low dispersion which has also been confirmed numerically, Fig. 4. A co-moving bunch of electrons will be able to interact over a long distance to enhance EM-particle interactions. We propose that this can be used for either EM generation or for particle acceleration.

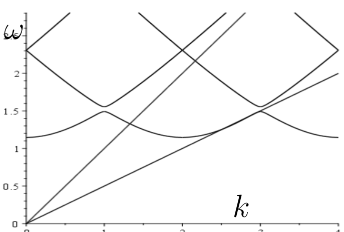

Fig. 3. Dispersion relation

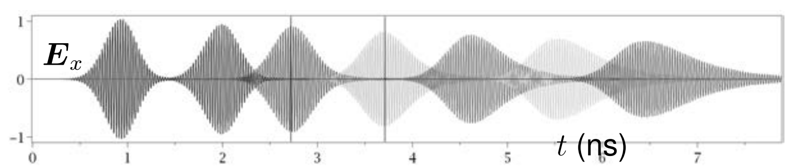

Fig. 4. Pulse Propagation

References

[1] T. Boyd, J. Gratus, P. Kinsler, R. Letizia Optics express **26** (3), 2478-2494 (2018)
[2] T. Boyd, J. Gratus, P. Kinsler, R. Letizia, R. Seviour, *Applied Sciences* **8** (8), 1276 (2018)
[3] J. Gratus, T. Boyd, R. Seviour, S. Jamison. In preparation (2022)

Electrodynamics with a local and linear anisotropic constitutive law: metamaterials, Cr_2O_3, optics, and Fresnel-Kummer surfaces

by Friedrich W. Hehl

Abstract:

We start from a premetric form of the classical Maxwell equations and assume a specific constitutive law with a constitutive tensor χ of fourth rank. In this framework, which includes metamaterials, we discuss the magnetoelectric effect in chromium sesquioxide Cr_2O_3. Moreover, we investigate the propagation of light and construct the Tamm-Rubilar tensor G, which is *cubic* in χ: $\mathrm{G} \sim \chi\chi\chi$. The ray surfaces, described by the fourth rank tensor G, turn out to be Kummer surfaces, which play an important role in algebraic geometry and in string theory. Literature: Hehl and Obukhov, "Foundations of Classical Electrodynamics," Birkhäuser, Boston (2003). C. Lämmerzahl et al., "Riemannian light cone from vanishing birefringence in premetric vacuum electrodynamics," Phys. Rev. D **70**, 105022 (2004). Baekler, Favaro, Itin, et al., "The Kummer tensor density in electrodynamics and in gravity," Annals of Physics (NY) **349**, 297-324 (2014).

Potential and prospects for meta-mirrors in precision metrology

Mariia Matiushechkina1,2 , Andrey B. Evlyukhin3, Johannes Dickmann4,5,6, Boris N. Chichkov3, Stefanie Kroker4,5,6, Michèle Heurs1,2

1 Institute for Gravitational Physics, Leibniz Universität Hannover, Germany
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4 LENA - Laboratory for Emerging Nanometrology, TU Braunschweig, Germany
5 Institut für Halbleitertechnik, TU Braunschweig, Braunschweig, Germany
6 Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Metasurfaces are structures in which the (here: optical) properties of the surface are intentionally designed, their properties depending on the choice of materials and topology. The design process allows for metasurfaces with very specific optical and mechanical properties. As an example, designed two-dimensional arrangements of nanoparticles of defined sizes (e.g. silicon nanospheres) can form new types of metasurfaces [1]. In these metasurfaces abrupt changes in the amplitude, phase, and polarisation of an incoming electromagnetic wave can be induced. With achievable layer thicknesses in the ~nm range extremely light structures can be produced. [2] They have potential as superlight mirrors (e.g. in the Starshot Lightsail project [3]) or as novel mirror coatings for ultra-low-noise applications (e.g. in nextgeneration
gravitational wave detectors [4]). Other periodic nanostructures show
promise as „coating-free mirrors“ or as tailored input-output couplers for effective negative mass quantum noise cancellation schemes [5, 6].
This contribution will highlight some recent developments in the field of metasurfaces with a focus on potential applications in fundamental physics, such as nextgeneration interferometric gravitational wave detection.

References

[1] Zywietz, U. et al. „Laser Printing of Nanoparticles“, chapter 11 of „Laser Printing of Functional Materials – 3D Microfabrication, Electronics and Biomedicine“, edited by Alberto Piqué and Pere Serra, Wiley-VCH (2018).
[2] Zywietz, U. et al. „Laser printing of silicon nanoparticles with resonant optical electric and magnetic responses“, Nat. Commun. 5:3402 (2014).
[3] Atwater, H.A., Davoyan, A.R., Ilic, O. et al. “Materials challenges for the Starshot lightsail”, Nature Mater. 17, 861–867 (2018).
[4] GWIC 3G Committee, the GWIC 3G Science Case Team and the International 3G Science Team Consortium, “ R&D for the Next Generation of Ground-Based Gravitational Wave Detectors” (2021).
[5] M. Tsang and C. M. Caves, „Coherent Quantum-Noise Cancellation for Optomechanical Sensors“, Phys. Rev. Lett. 105, 123601 (2010).
[6] M. H. Wimmer, D. Steinmeyer, K. Hammerer, and M. Heurs, „Coherent cancellation of backaction noise in optomechanical force measurements“, Phys. Rev. A. 89, 053836 (2014).

Title: Finsler's metric as a novel tool for wave propagation analysis

Speaker: Yakov Itin (Jerusalem College of Technology)

Abstract:

An extension of Riemmann's geometry into a direction dependent geometric structure is usually described by Finsler's geometry. Historically, this construction was motivated by the well-known Riemann's quartic length element example. Quite surprisingly, the same quartic expression emerges in solid-state electrodynamics as a basic dispersion relation---covariant Fresnel equation. Consequently, Riemann's quartic length expression can be interpreted as a mathematical model of a well-established physics phenomena. In this talk, we present various examples of Riemann's quartic that demonstrate that Finsler's geometry is too restrictive for many applications even in the case of a positive definite Euclidean signature space. In the case of the spaces endowed with an indefinite (Minkowski) signature, there are much more singular hypersurfaces where the strong axioms of Finsler's geometry are broken down. We propose a weaker definition of Finsler's structure that is required to be satisfied only on open subsets of the tangent bundle of a manifold. Finsler's metric are calculated for axion and skewon extensions electromagnetism. A more viable example of a uniaxial crystal is aimed to give a physical meaning to the formal structure definition.

NFC wireless charging for multiple devices

Irina Khromova[1]

[1]*Metaboards, Oxford, United Kingdom*

We will soon need a charger that can service several devices at the same time. As we embrace new technologies, we delegate more and more of our daily tasks to electronic devices. Wearables, IoT and other small, low-power devices are on the rise [1] and keeping them charged will soon become a challenge. Plug-in charging is not sustainable as the number of devices grows. Wireless charging of today, with its 1:1 charger to receiver ratio and strict alignment requirements is not a solution.

Metaboards wireless charging technology allows for charging multiple receiver devices at the same time everywhere on a large transmitter surface. It is compatible with the emerging NFC wireless charging standard – a technology boasting a huge infrastructure and promising to service billions of small electronic devices.

Our multi-coil wireless charging platform [2] uses Metaboards' patented metamaterial-based technologies to automatically detect and locate receivers on its surface and provide targeted power delivery to all of them from a single power input source. We configure the elements of the transmitter dynamically from a central controller to ensure precise and balanced power routing across the wireless charging platform. This technology exploits magneto-inductive waves supported by a multi-resonator medium – a metamaterial – to carry both power and communication signals enabling power solutions compatible with the NFC charging standard.

Metaboards NFC wireless charging solution will significantly boost the user experience and accelerate the adoption of wireless charging for personal and professional use. We aspire to contribute to the power solutions for smarter education and healthcare environments.

References

[1] IoT and NFC: Better Together, NFC forum (2021) https://nfc-forum.org/wp-content/uploads/2021/08/NFC_and_IoT_Infographic_Final-2.pdf

[2] I. Khromova, Charging matters, Cambridge Wireless Journal 2 (3), 27-31 (2019)

Metamaterials for Measurements at Ultimate Precision

Johannes Dickmann[1,2,3], Steffen Sauer[1,2], Liam Shelling Neto[1,2] and Stefanie Kroker[1,2,3]

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Optical metamaterials provide a fascinating platform to tailor light fields in virtually arbitrary manner. Particularly in the field of high-precision optical metrology and quantum technology metamaterials and metasurfaces give promise to overcome the limitations of conventional bulk optics. On the one hand, they allow the integration of even complex optical functionalities into compact and robust devices enabling scalable systems e.g. for chip-based quantum computing. On the other hand, the spatial control of optical near fields by metamaterials enables the control of light-matter interaction. This capability is particularly important for optical atomic clocks and gravitational wave detectors, which are the most precise experiments ever developed by mankind [2,3]. These systems are crucially limited in their performance by the optomechanical interaction of light fields with optical components. Metasurfaces with dedicated near-field distributions can elevate their sensitivity to the next level and thereby giving access to fundamental phenomena such as the change of fundamental constants, dark matter or the big bang [2-5].

In this contribution, we give an overview on the development and possibilities of metamaterials for applications in precision optical experiments. We explain important physical phenomena of light-matter interaction and illustrate the role of material properties in these experiments.

References

[1] A. S. Solntsev, G. S. Agarwal, Y. S. Kivshar, Nature Photonics 15 (2021)
[2] B. Sathyaprakash et al., Class. Quantum Grav. 124013 (2012)
[3] D. G. Matei et al., Phys. Rev. Lett. 118 (2017)
[4] J. Dickmann, S. Kroker, Physical Review D 98 (2018)
[5] S. Kroker, J. Dickmann, C. B. Rojas Hurtado, D. Heinert, R. Nawrodt, Y. Levin, S. P. Vyatchanin, Physical Review D 96 (2017)

Multifunctional metasurfaces with absorbing, reflecting and high impedance properties for ICT and Biomedical applications

Danilo Brizi and Agostino Monorchio

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Recently, the increased popularity of multiservice and flexible telecommunication systems fostered the development of Multifunctional Frequency Selective Surfaces (MFSSs) which employs specifically designed FSS, able to perform different behaviour at different bands (reflecting and/or absorbing, and/or polarizing or even high surface impedance or bandgap). By making proper use of active devices, such as PIN diodes and varactor diodes, we are also able to realize electrically controlled Active FSSs due to their features of low cost, high integration level and fast switching speed.
In this presentation, the use of MFSSs for obtaining tunable metasurfaces with multifunctional behavior (absorbing and reflecting and so on) will be discussed with particular reference to the bandwidth of such devices. Some solutions will be presented to show their applications to ICT and biomedical devices.

References

[1] Li, H.; Costa, F.; Wang, Y.; Cao, Q.; Monorchio, A.; A wideband multifunctional absorber/reflector with polarization-insensitive performance, *IEEE Transactions on Antennas and Propagation*, 68, 6, 5033-5038, (2019).

[2] Brizi, D.; Stang, J. P.; Monorchio, A.; Lazzi, G.; A compact magnetically dispersive surface for low-frequency wireless power transfer applications, *IEEE Transactions on Antennas and Propagation*, 68, 3,1887-1895, (2020).

[3] Brizi, D.; Fontana, N.; Costa, F.; Tiberi, G.; Galante, A.; Alecci, M.; Monorchio, A.; Design of distributed spiral resonators for the decoupling of MRI double-tuned RF coils, *IEEE Transactions on Biomedical Engineering*, 67,10,2806-2816, (2020).

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General structure of electromagnetism: covariant formulation

Yuri N. Obukhov

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We present an overview of the classical electrodynamics formulated as a generally covariant theory. This approach is based on the fundamental premetric ideas originally put forward by Kottler, Cartan and van Dantzig. The generally covariant formulation has become quite popular recently among engineers, physicists, and mathematicians. It is equally useful for understanding of the fundamental structure of electrodynamics and for the development of advanced engineering solutions as well, being perfectly suited for applying it to complex (anisotropic, inhomogeneous, moving) media with an arbitrary response behavior. The crucial advantage of this approach is the general covariance, inherent in the exterior calculus, of the field equations that have the same form independently of the choice of the local coordinates or frames. The structure of Maxwell's theory is derived from first principles on the well established experimental basis of electric charge and magnetic flux conservation. The premetric field equations are expressed in terms of the electric and magnetic excitations and the field strengths, and the general constitutive relation is encoded in the 36 independent components of a 4th rank constitutive tensor, characterizing polarizational, magnetizational and also magnetoelectric properties (a restriction to the reciprocal case leaves 21 components). The light propagation in such a metamaterial is described by quartic Fresnel surfaces, determined by a 4th rank Tamm-Rubilar tensor that is cubic in the constitutive tensor. The electromagnetic wave propagation exhibits the phenomenon of birefringence, in general. Among the physically most interesting issues, we discuss the axion electrodynamics, the transformation optics, and the electrodynamics in noninertial frames.

Luminal gratings enable: photon localisation, Bloch symmetry breaking, and a novel amplification mechanism

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In gratings travelling at nearly the velocity of light a symmetry breaking transition is observed between free-flowing fluid-like Bloch waves observed at lower grating velocities and, at luminal velocities, localised states of light captured in each period of the grating and locked to its velocity. The localised states are amplified by the previously unidentified mechanism which will be elucidated in this talk.

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General Linear Electrodynamics: Causal Structure, Propagators, Quantization and quantum energy inequalities

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From an axiomatic point of view, the fundamental input for a theory of electrodynamics are Maxwell's equations dF=0 (or F=dA) and dH=J, and a constitutive law H=# F, which relates the field strength 2-form F and the excitation 2-form H. In this talk we consider general linear Electrodynamics, the theory of Electrodynamics which is defined through a local and linear constitutive law. The best known application of this theory is the effective description of Electrodynamics inside (linear) media including for example birefringence. We will analyze the classical theory of the electromagnetic potential A thoroughly before we use methods familiar from mathematical quantum field theory in curved spacetimes to quantize it.

As a specific application of this theory of quantum premetric electrodynamics I will present the derivation of a quantum energy inequality, that is satsified by the energy density of the electromagnetic field averaged along observer wordlines inside a uniaxial crystal. The later is geometrically described by a constitutive law that depends not only on a metric, but in addition on two vector fields describing the crystal's optical axis and rest frame.

The talk is based on the articles [1,2].

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Quantum Metamaterials with Magnetic Response at Optical Frequencies

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Laboratory manipulation of single quantum emitters and single photons has matured to a routine procedure over the past two decades. These activities have paved the way to a new emerging field, involving coherent cooperative interactions among several quantum emitters. By designing the positions and frequencies of individual emitters, one can hope to realize man-made quantum materials with different (quantum) optical functionalities. In our laboratories, we have embarked on the challenge to extend our expertise in single-molecule spectroscopy to the coupling of a handful of molecules and photons on a chip. In addition, we have theoretically explored novel arrangements of atoms and molecules to achieve magnetic response at optical frequencies in a much analogous fashion as in classical metamaterials using elementary units such as split ring resonators. In this presentation, I discuss these topics from the experimental and theoretical points of view.

Tailoring the RF field at ultra-high field MRI with artificial materials

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Ultra-high field human MRI offers increased signal-to-noise (SNR) and sensitivity, which can be translated into increased resolution of the acquired images. Inspired by the metamaterials design in optics, but driven by MRI requirements and constrains, we aspired to develop and optimize a new platform for generating MRI-viable artificial materials, thus extending the MR hardware beyond state-of-the-art RF coils. Among new directions are utilization of high permittivity dielectric materials and new hybrid metamaterial-based structures. The design of metamaterial-based structures becomes especially relevant, since it can offer compact design, improving patient comfort. Our work includes several designs of dielectric resonators as well as hybrid metamaterial-based structures toward improving patient positioning as well as improving imaging sensitivity. Our study showed a feasibility of artificial material to improve local sensitivity at ultra-high-field (7T) human brain MRI[1]. We examined and characterized set of structure properties to control the RF field distribution, bearing in mind the power deposition constraints. Another topic of interest for MRI is a dual-nuclei design. We designed a dual-nuclei metamaterial-based structure for calf imaging, for phosphorous and proton imaging[2].

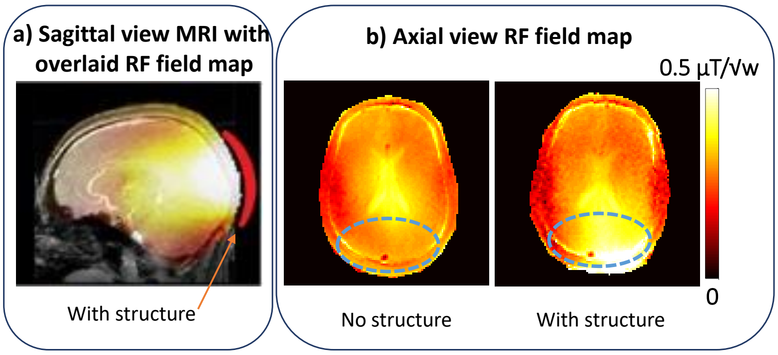

Fig.1: Feasibility results with artificial materials. (a) RF field local increase in Sagittal view shown as an overlay on anatomical MRI image, b) Axial view RF field map without and with the metamaterial-based structure.

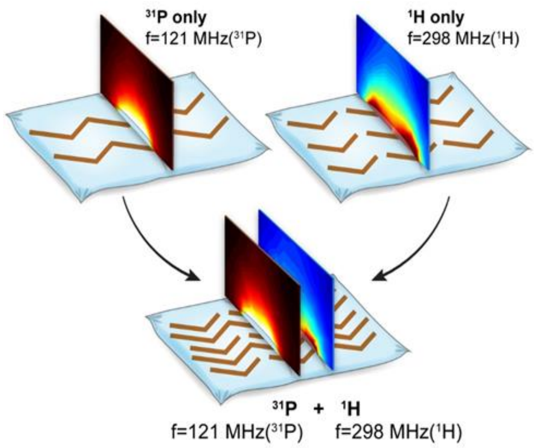

Fig. 2: *Schematic view of the metamaterial combined from sub-setups: top-left) phosphorous nucleus band, tuned to 121 MHz; top-right) proton nucleus band tuned to 298 MHz. On top of the structure, a central cross-section of the magnetic field |H| is shown (for the combined structure, two maps for two bands are shown).*

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Optical Analogues for Fundamental Physics

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There are fascinating analogies between the propagation of phonons in flowing fluids or photons in dynamical media on the one hand and fundamental phenomena such as cosmological particle creation or Hawking radiation (i.e., black-hole evaporation) on the other hand. After a brief introduction into these analogies, which can help us to better understand both sides of the medal, this talk will be devoted to a discussion of the impact of dispersion and dissipation.

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Metamaterial Mediated EM Wave Generation and Amplification

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In this paper we examine the ability of metamaterials to generate and amplify EM waves. Metamaterials offer two key advantages for EM wave generation. First, they offer the possibility of exploiting new forms of wave interactions, and they offer a path to reduce the dimensions of standard EM sources.

Firstly, we consider the interaction between a charged particle beam and a propagating electromagnetic wave in the presence of a metamaterial. We show that a metamaterials novel dispersion relation can give rise to unique particle – wave interactions, using a modified form of Madey's theory to describe energy transfer between wave and particle beam [1]. We show that the metamaterial mediated interaction between wave and beam can either lead to an amplification of energy in the EM wave or to the acceleration of the particle beam, depending upon the characteristics of the beam. Secondly, we present our results of using the interaction between a charged particle beam and a metamaterial to generate an EM wave. Utilising a low loss, dispersion engineered, metamaterial as an oscillator for the generation of EM wave.

We also examine the exploitation of metamaterials whose constitutive relationships vary with time to amplify a propagating wave in the media. Most models for these materials assume a constant permittivity and permeability, which work when both the quantities are real. Issues arise when material losses are taken into account, we show that these models predict nonphysical amplification of a wave. We show that deriving the correct the boundary conditions necessary for wave propagation in a time dependent media produces physical results [2].

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Metamaterial inspired wireless coils and pads for clinical MRI

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The impact of magnetic resonance imaging (MRI) in the medical world continues steadily to grow. The non-invasiveness, absence of ionizing radiation, and a broad range of functional information that can be gathered in vivo constantly open new horizons for applying magnetic resonance (MR) in clinics. As a result, human MR examinations become highly specialized with a well-defined and often relatively small target in the body. While being very valuable for boosting the MRI specificity, the latter often implies an intensive usage of the high peak radiofrequency (RF) powers since existing clinical MR equipment was initially designed to be universal, compromising its' efficiency for a small target. Thus, advanced, and valuable MR methods often cannot be (or only with a suboptimal performance) routinely applied in clinical MR studies.

This talk aims to overview the results in metamaterial-inspired wireless coils and artificial pads for clinical MRI applications [1-5]. Wireless coils are electromagnetically coupled to the body birdcage coil and can redistribute an electromagnetic field, focusing it on the region of interest. It improves local transmit efficiency and receive sensitivity of the body coil, making it comparable with local receive arrays. The main advantages of such resonators are simplicity of the design (hence, robustness and ease of maintenance), absence of RF cables, and consequently, low cost. Moreover, these devices can be directly integrated and applied within any clinical MR scanner with no modifications to the scanner hardware.

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Nonlinearity, Nonlocality, and Nonreciprocity: New Directions for Metamaterials

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The success of metamaterial devices has been deeply tied an intuitive theory of transformation optics for application design [1,2]. This approach, which linked physical optics to differential geometry, is both powerful and limiting. It is powerful because it gives direct prescriptions for a wide range of devices, including previously fantastic ones like cloaks, but it is limited because the focus on differential geometry has constrained the possible functions of metamaterials to mimicking a particular geometry. But real materials have a wider range of properties than can be captured by a local coordinate transformation. Starting with inspirations in nonlinear optics and general relativity, we shall extend transformation optics to incorporate nonlinearity and present some applications of this new design approach [3]. We shall further demonstrate the connection between nonlinearity and nonlocality [4] and explore some potential implications of this additional property for metamaterial applications [5,6]. Significantly, nonlocality also reveals the limitations of a local coordinate transformation for describing metamaterials, and so we shall examine transformations to non-metric (non-Riemann) geometries in chiral materials [7], which will lead to an analysis of nonreciprocal metamaterials and one-way devices [8].

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Homogenization of Metamaterials: Symmetry Breaking and "Bulk Transition"

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Two somewhat counterintuitive topics in homogenization of metamaterials are addressed.

- If a metamaterial sample lacks mirror symmetry, whereas its homogenized version is perforce geometrically symmetric, these symmetries are at first glance incompatible. We show, however, that homogenization can still be accurate if the effective tensor incorporates a particular form of magnetoelectric coupling [1].
- It is common to assume that the effective parameters of a metamaterial sample converge to their bulk values as the number of layers in the sample increases and exceeds a certain threshold. However, we prove that this picture is flawed: in a sense, one layer is already "bulk" [2].

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Applications of an analysis of classical Plasmon-Polariton-Brewster Modes in Homogeneous Media with an anisotropic planar interfacial surface admittance tensor

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In my talk I outline a formulation for the analysis of certain solutions to the classical macroscopic Maxwell equations in bulk homogeneous anisotropic materials, separated by a planar interface, that may sustain field-dependent electric currents induced by a surface admittance tensor. Based on Clemmow's description of complex inhomogeneous plane time-harmonic waves, a systematic procedure is given that yields particular global field solutions in terms of solutions to a system of bivariate polynomial and linear eigenvalue equations for a set of six complex dimensionless scalars. From the resulting solutions, analytic formulae for the electromagnetic fields can be expressed in terms of values for these six scalars and the electromagnetic phenomenological properties of the bulk media and their interface. General properties of Surface Plasmon–Polariton (SPP) and Brewster modes follow from this unified viewpoint without appeal to any Fresnel reflection criteria. In particular, endowing the material interface with (in general) anisotropic admittance properties can lead to new global electromagnetic field characteristics that offer new possibilities for the control of surface characteristics by using recent advances in the fabrication of meta-materials. The results indicate how a mono-layer of graphene in a surface-normal magneto-static field can be used to construct a tunable meta-surface for surface plasmon-polariton generation and how a simple conducting Ohmic interface can be used to excite both transverse electric and transverse magnetic Brewster modes as a function of the interface admittance.

Novel materials in magnetic resonance imaging: high permittivity ceramics, metamaterials, metasurfaces and artificial dielectrics

A.G.Webb

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This talk will review recent developments in designing and testing new types of materials which can be: (i) placed around the body for in vivo imaging, (ii) be integrated into a conventional RF coil, or (iii) form the resonator itself. These materials can improve the quality of MRI scans for both in vivo and magnetic resonance microscopy applications. The methodological section covers the basic operation and design of two different types of materials, namely high permittivity materials constructed from solid ceramics and artificial dielectrics/metasurfaces formed by coupled conductive subunits either alone or surrounded by dielectric material. Applications of high permittivity materials and metasurfaces placed next to the body to neuroimaging and extremity imaging at 7T, body and neuroimaging at 3T, and extremity imaging at 1.5T are shown. Results using solid ceramic resonators for both high field in vivo imaging and magnetic resonance microscopy are also shown.

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3D Metamaterials: Chirality and Non-Locality

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3D metamaterials have been discussed for many areas of physics, including electromagnetism, optics, acoustics, elasticity, diffusion, electrical transport, and thermal transport [1]. Here, we focus on 1) chirality and 2) non-locality as mechanisms to achieve unusual wave propagation behavior.

1) By exploiting the analogy between electromagnetisms and elasticity [2], the phenomenon of optical activity can be translated to acoustical activity [3]. While the underlying chiral metamaterial phonons are generally highly anisotropic in metamaterial crystals [4], isotropic chiral phonons as well as isotropic acoustical activity can be achieved in three dimensions [5,6].

2) Using tailored beyond-nearest-neighbor interactions in metamaterials leads to non-local responses and can be used to achieve roton-like dispersion relations, which were previously restricted to correlated quantum systems at low temperatures (e.g., superfluid helium), in 3D elastic and acoustic metamaterials [7,8], and perhaps also for electromagnetic waves.

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Quantum simulators for fundamental physics

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The dynamics of the early universe and black holes are fundamental reflections of the interplay between general relativity and quantum fields. The essential physical processes occur in situations that are difficult to observe and impossible to experiment with: when gravitational interactions are strong, quantum effects are important, and theoretical predictions for these regimes are based on major extrapolations of laboratory-tested physics.

We will discuss the possibility to study these processes in experiments by employing analogue quantum simulators. Their high degree of tunability, in terms of dynamics, effective geometry, and field theoretical description, allows one to emulate a wide range of elusive physical phenomena in a controlled laboratory setting. We will discuss recent developments in this area of research.

Abstracts of Posters

(in alphabetical order)

Metasurfaces Design for Magnetic Resonance Imaging and Wireless Power Transfer Applications

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In this work, an overview on our activity on magnetic metasurfaces for Magnetic Resonance Imaging and resonant inductive Wireless Power Transfer applications is provided. In particular, the use of miniaturized spiral resonators to decouple MRI RF coils is presented. Attention is firstly directed to the spiral resonators electromagnetic characterization and then specific MRI test-cases are considered, from the basic theoretical aspects up to preliminary experimental validations carried out on fabricated prototypes. Then, bi-dimensional metasurfaces for resonant inductive Wireless Power Transfer are examined. Metasurfaces can produce an excellent WPT performance enhancement, as well as a reduced exposure in terms of Specific Absorption Rate which make them good candidates for biomedical applications and rechargeable devices. Finally, an overview on possible technological outcomes for MRI and WPT applications deriving from metasurfaces' response control is discussed.

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Designing multi-layer polymeric nanocomposites for electromagnetic shielding

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The ever-growing number of radiative, inter-communicative electronic devices in the GHz regime has exacerbated the modern day issue of electromagnetic pollution, rendering a range of challenges for the new smart age: preserving signal fidelity (smart automotive), reducing emission levels and ensuring efficient shielding to secure environments (defense, medical facilities). This research focuses on the experimental analysis and modelling of multi-layered electromagnetic (EM) polymer nanocomposites, operational in the X-band with an efficient modular approach thereby demonstrating that the spatial order inherent in 2D systems can be well exploited to generate reflective and absorptive functionalities. In the first part of the work, the nanocomposites consist of a polymer matrix (polymethylmethacrylate) filled with conductive carbon nanotubes. Different multi-layered polymeric nanocomposites, consisting of stacks of nanocomposite slabs with different compositions are prepared via extrusion followed by compression moulding. Their electromagnetic characteristics are measured inside a waveguide using a vector network analyzer. An analytical model and numerical finite element simulations are used to optimize the stacking order and nanocomposite composition. In the second part of the work, the focus will shift towards 3D systems prepared via additive manufacturing. The latter technique opens up several unexplored regions of the design space in terms of possible structures to incorporate electromagnetic metamaterial behaviour.

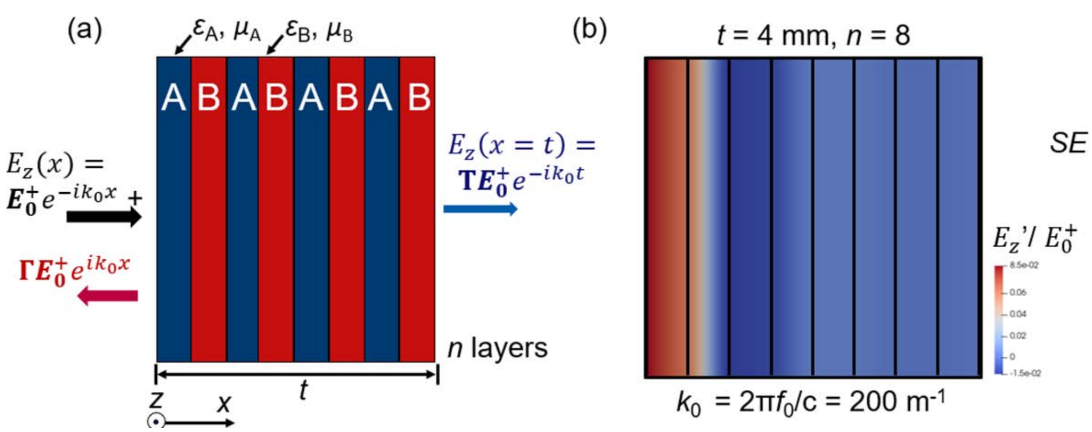

Figure 1: a) Example of a simple multi-layer structure consisting of alternating ABAB layers, b) Amplitude of the electromagnetic wave inside the material

Light-induced dynamic subwavelength structures in liquid crystals for wave control

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Light-induced changes of the LC order parameter, or light-induced order modification (LIOM), result in substantial and fast modulation of the LC refractive indices [1, 2]. An important feature of LIOM-mechanisms is a completely local and reversible response essential for photonic applications. Fine resolution (<1μm) and quite a high diffraction efficiency could be achieved with response times being within 1-10 ms range under moderate intensities of the pumping light [3]. Good resolution and locality should allow for the recording of different light-induced dynamic patterns in an LC cell, dimensions of which would be much less of the wavelength being in the THz-range.

Subwavelength patterns (SWP) has been attracting much attention for their special diffractive properties that may realize many functions such as control of polarization or reflection, wave filtering and so on. The form birefringence of one-dimensional subwavelength dielectric periodic gratings is well-known for quite a long resulting in creation of effective phase retarders. Moreover, a new class of artificial materials – planar chiral metamaterials (PCM, e.g. arrays of gammadion-shaped nanoparticles), have invoked much interest due to their peculiar polarizing properties: large optical activity and polarization conversion can be achieved in a PCM structure with a thickness of only a fraction of a wavelength [4].

Feasibility of dynamic optically controlled and tuneable metamaterials based on SWP for manipulation of THz-range radiation by means of LIOM-type mechanisms are discussed and parameter optimization by proper structural design is considered.

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Optical non-linear effects in metasurface using finite model

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Control and enhancement of nonlinear optical phenomena at the nanoscale with all-dielectric metasurfaces is a booming research area based on the principles explored with the plasmonic counterparts, this new approach brings advantages such as reduced dissipative losses, large resonant enhancement of both electric and magnetic near-fields, larger mode volumes and the presence of strong bulk light-matter interaction which enables higher conversion efficiencies.
With recently developed software called "Smuthi", a linear space-limited model is constructed in an all-dielectric metasurface made of AlGaAs nanocylinders on aluminium oxide substrate, this structure has been demonstrated to support very strong nonlinear optical effects such as second-harmonic generation (SHG) with efficiency around 10^{-4} at magnetic dipole resonance wavelength (around 1600nm). This model includes border effects, the contribution of lateral walls representing the finite structure same as the experimental phase.
The results are promising, with simplified parameters I have been able to simulate a 100x100 structure and to calculate how both the reflection and transmission coefficients varies with the wavelength. The consistency of the developed structure is also validated at different number of scatterers.

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Quantum vacuum physics in dispersive and dissipative dielectrics

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Effective field theories for electrodynamics in condensed matter systems are often based on an empirically given dielectric permittivity $\varepsilon(\omega)$. Existing studies of quantum vacuum phenomena in space-time dependent media (relevant, e.g., for experiments on optical analogs of the Hawking effect) typically assume a real dielectric permittivity $\varepsilon(\omega)$ and hence include dispersion but neglect dissipation.

In frequency regimes far from the medium's resonances, this approximation is reasonable but realistic materials also involve "slow" quantum fluctuations close to resonance, which can have observable consequences. Based on an effective field theory, we present a straightforward and intuitive model for quantum electrodynamics in dissipative dielectrics [1].

As an application, we discuss spontaneous excitations of inertial atoms moving through a vacuum-state dielectric (a.k.a. the Ginzburg effect) [2]. Triggering Ginzburg excitations with quantum fluctuations far from resonance would require strongly relativistic atom velocities but the speeds required are significantly lowered due to "slow" (near-resonance) fluctuations, which might allow for an experimental verification.

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Investigation of Digitally-Reconfigurable Metasurfaces for MRI Applications

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Reconfigurable metamaterials offer the potential to innovate medical imaging in manifold aspects as they allow to establish new imaging paradigms in the field of Magnetic Resonance Imaging (MRI). A one-dimensional, reconfigurable, smart metasurface intended for use in MRI is shown to yield a signal-to-noise-ratio (SNR) enhancement. The device's digital interface offers a wirelessly controlled, dynamically adjustable spatial sensitivity profile. The structure's design, numerical simulations, an analytical treatment of the reconfigurability, and on-bench measurements for characterization are presented.

Effective General Relativistic Description of Jamming in Granular Matter

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We propose here that certain observational features of granular matter in the infrared limit, exhibiting the phenomenon of jamming, arise from an underlying effective general relativistic de-scription. The proposal stems from the assumption (which we justify on physical grounds) that grains in granular matter move freely in an effective curved Riemannian space. The termination of their trajectories at the onset of jamming is obtained from the focussing of a converging congruence of geodesics in such a space, as a solution of the Raychaudhuri equation for such congruences. This may happen irrespective of whether or not the curvature is sourced by external stresses (via an effective Einstein equation), although the properties of the resultant jammed state solution do differ in the two cases. A definite prediction of this geometrical approach is the negative role played by those trajectories which twist about each other, in reaching the jammed state. The local symmetries of granular interaction, translational and rotational invariance (corresponding to 'force balance' and 'torque balance' in standard force-based approaches to jamming) are inherent in the effective general relativity framework. A recently-proposed effective elasticity model of the jammed state, based on a tensorial variant of standard electrostatics (Vector Charge Theory), is seen to be entirely subsumed within a linearized version of the effective general relativistic description.

Reference :

This contribution is based on the paper with the same title, by Soumendra Kishore Roy, Pratyusava Baral, Ratna Koley and Parthasarathi Majumdar, E-Print ArXiv : 2011.01194v2.

High-reflective Si metasurface on a sapphire substrate for 1550 nm

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A huge variety of metasurfaces are being developed with the purpose to manipulate light behavior in order to achieve precision in quantum measurements. In our project we are focused on developing high-reflective metasurfaces at the wavelength 1550 nm with low optical and mechanical losses as a possible coating for mirrors in future gravitational waves detectors. The designed metamaterial surface consists of periodically arranged silicon nano-spheres that are placed on a sapphire substrate. Due to electric or magnetic dipole resonant responses of nanoparticles [1], the light is fully reflected in the absence of material losses at the wavelength 1550 nm. We theoretically and numerically investigate the functionality of such metasurfaces and study the influence of structural and dimensional imperfections on the optical properties.

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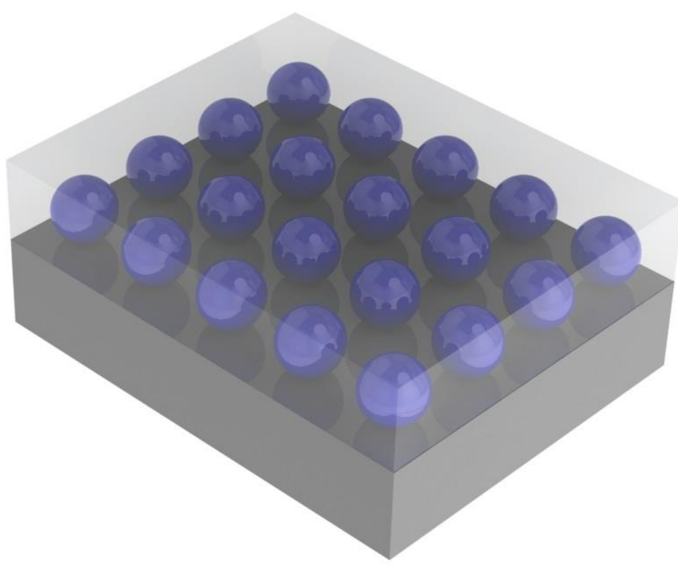

Detailed Analysis of the Temperature Dependent Goos-Hänchen Shift

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Theoretical study of the temperature-dependent Goos-Hänchen shift for the air-metal interface is discussed, starting with the observation of negative Goos-Hänchen shift and then analyzing the impact of temperature on it [1]. Temperature-dependent Goos-Hänchen shift is explored through a well-known Drude model as this directly connects the plasma and scattering frequency of the metal as a function of temperature to the complex dielectric function of metal [2]. We have considered both parallel and perpendicularly polarized incidence in this regard. We have dug deeply into optical parameters of metal which affect the thermal properties of metal [3]. This theoretical model leads to the close possibility of designing an optical sensor for temperature monitoring Goos-Hänchen shift [2, 4].

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Analysis of Resonant Bessel-Beam Launchers based on Isotropic Metasurfaces

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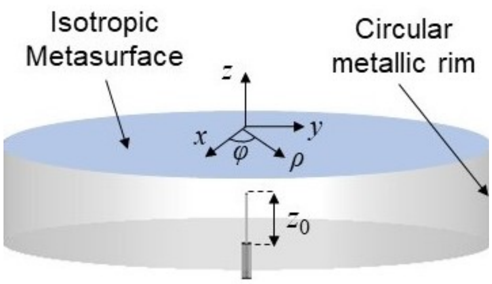

Figure 1: Pictorial representation of a Bessel-beam launcher

Various modern applications call for radiating devices capable of focusing the electromagnetic energy in a narrow spatial region at millimeter waves. In this regard, in the last decade, several planar structures have been proposed at microwaves and millimeter-wave frequencies (see, e.g., [1] and refs. therein). Among these structures, Bessel-beam launchers play an important role thanks to the limited-diffractive and self-healing properties of such beams [2]. Resonant Bessel-beam launchers are azimuthally invariant structures characterized by a circular grounded dielectric slab with an isotropic metasurface on top. Previous works analyzed the launchers performance for some specific cases, assuming TE or TM polarizations, inductive or capacitive metasurfaces, cavities with sub-wavelength or half-wavelength height. We will show, with both theoretical and full-wave results, that the inductive or capacitive nature of the metasurface has a fundamental role in the radiating behavior. Results will be reported for the relevant TM-polarized case, considering air-filled, half-wavelength-thick cavities. In particular, we will show that the presence of a homogenized inductive or capacitive metasurface on top of the cavity may induce the excitation of a TM surface plasmonic wave or a fundamental leaky mode, respectively. This kind of waves can drastically reduce radiation properties and performance of the device. This is why we will also show how these waves can be suppressed or mitigated through a correct choice of the metasurface, feeder or cavity parameters of the Bessel-beam launcher.

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Metamaterials: wave propagation control

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Abstract

The problem of wave propagation control in one-dimensional systems, including electrical charges and dipole magnetic moments is investigated. The waveguide is characterized by long-range and nonlinear interaction forces of Coulomb and Lorentz nature. Wave propagation properties are derived by a method based on an equivalent partial differential equation that replaces the discrete equation of motion of the chain. The paper shows how the waves propagating in these special systems have characteristics, such as phase and group velocity, that are function of the electrical and magnetic property distribution along the chain. Of interest are also possible wave-stopping phenomena. The paper presents an outline of some basic principles developed by some of the authors in recent theoretical papers and shows also numerical experiments illustrating wave propagation in metamaterials characterized by long-range elastic-electromagnetic interactions.

A heuristic model to evaluate dielectric properties of human tissues at microwave band based on water and solid content

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Abstract

In silico models of the human body are increasingly used in dosimetry studies as well as in medical applications of electromagnetic fields. However, up to now, human body models are mostly derived from Magnetic Resonance Imaging (MRI) through the segmentation of the different anatomical elements by expert teams of biologists and physicians [Christ et al., 2010]. Moreover, dielectric properties of tissues, to be used in combination with the geometrical models, are mostly obtained through ex vivo measurements [Gabriel et al. 1996 I, II and III; Peyman et al 2015]. Accordingly, this procedure limits the availability of human models, particularly useful in medical applications where the exact knowledge of the patient anatomy and related electromagnetic properties would be of great benefit for the success of the treatment. As an example, in Hyperthermia Treatment Planning (HTP) [Kok et al., 2015] simulations are carried out on the patients' anatomy to obtain the optimum hyperthermia protocol. However, the same should be performed in microwave thermal ablation, or microwave-based diagnostic applications, as e.g. microwave tomography.

The aim of this work is to propose a heuristic method, effective and easy to adopt, to estimate the complex dielectric permittivity of human tissues in the frequency range of microwaves and, in particular, at 2.45 GHz only on the base of their solid and water content. In this way it could be possible to realize an *ad hoc* dielectric mapping useful for presurgical and SAR simulations.

The correlation between water content and dielectric permittivity of human tissues is well known [J. L. Schepps and K. R. Foster, 1980; S. R. Smith and K.R. Foster, 1985; P. Bernardi, M. Cavagnaro and S. Pisa, 1997; R. Pethig and D. B. Kell, 1987], however, even if a dielectric model of the human body was derived based on this assumption [M. Mazzurana et al., 2003], an automatic tool was never devised. Several works were performed in the past to link dielectric properties of the human body tissues with their water content [J. L. Schepps and K. R. Foster, 1980; S.R. Smith and K.R. Foster, 1985]. In these works, the dielectric properties of biological tissues were measured from audio frequencies to microwaves, and some mathematical models were proposed to predict their values as a function of the frequency in order to understand the dielectric relaxation phenomena in tissues. In these works, it is assumed that tissue's total water content belongs to two pools: 70 % can be considered 'free water' while 30% is the hydration water considered to be bound to the tissue's solid content and supposed to have the same dielectric properties of the dry protein.

Our idea

Because at microwave frequencies the major contribution to the dielectric properties in human tissues is due to the water content and collagen is the major component of many organs, we propose to use it to model a generic human tissue [N. Shinyashiki et al. 1990] as a mixture of hydrated proteins and adipose cells. This is possible because the collagen protein has a diameter of about 1.6 nm and a length of around 300 nm, and the shorter field wavelength into the human body, related to 10 GHz, the maximum frequency of this study, is $\lambda = [c/(f_{max}\sqrt{\varepsilon_r})] \sim 4\text{x}10^{-3}$ m ($\varepsilon_r \sim 50$ for collagen) is many orders of magnitude of the size of the inclusions of the 'mixture' and the homogenization theory can be applied.

Dielectric analog space-times, transformation optics, and manifold maps

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The concept of analog space-times in dielectrics is made rigorous by demanding that solutions to Maxwell's equations in a curved vacuum space-time be mapped to solutions in a medium that lives in Minkowski space-time. Transformation optics is a similar picture, but with the goal of transforming an initial seed solution, e.g. in vacuum Minkowski space-time, into some other solution inside a medium also in Minkowski space-time, where the medium, where the medium is what physically enacts the transformation. Both dielectric analog space-times and transformation optics are therefore two special cases of a general picture of mapping solutions of Maxwell's equations in medium χ_1 on manifold M_1 to solutions of Maxwell's equations in medium χ_2 on manifold M_2. However, the interpretation of electric and magnetic fields, as well as permeability and permittivity, etc, are entirely observer dependent quantities. In general, there is no natural identification between observers on different manifolds and so the "analogy" of analog space-times is entirely dependent on the choice of mapping. It is shown that the Plebanski equations are recovered by choosing a trivial mapping that preserves the sense of observer orthogonality. Meanwhile, since the transformation optics mapping is an automorphism it is physically meaningful to simply demand the observer remain fixed. The TO equations end up looking similar to the Plebanski equations, but with subtle differences and distinctions in interpretation.