

BOOK OF ABSTRACTS

XVII Iberian Meeting on Computational Electromagnetics

Elgorriaga, Navarre, Spain | 27–30 October 2026

29 scientific contributions | 7 sessions

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WEDNESDAY 28 OCTOBER | 09:30-10:30
Chair: Miguel Beruete

Francisco Medina Mena

University of Seville, Spain

Bridging Maxwell and Circuit Theory: Physical Insight in Periodic Surface Design

BIOGRAPHY



Francisco Medina Mena was born in Puerto Real (Cádiz, Spain) in November 1960. He received the degree in Physics, specializing in Electronics, from the University of Seville in 1982, graduating with the Extraordinary Degree Award. In 1987, he obtained his Ph.D. in Physics from the same university under the supervision of Prof. Manuel Horno, with a dissertation devoted to the modelling of planar transmission structures. His doctoral thesis received the City of Seville Award for the best dissertation in the field of Engineering and Architecture, as well as the Rogelio Segovia Torres Award granted by the Spanish Section of the IEEE.

Following a postdoctoral stay at the Laboratoire de Microondes of ENSEEIHT (N7), Institut National Polytechnique de Toulouse, France, he returned to the University of Seville, where he became Associate Professor in 1990 in the Department of Electronics and Electromagnetism. Since October 1998, following the passing of its founder, Prof. M. Horno, Francisco Medina has led the Microwave Group of the University of Seville (GMUS), which brings together researchers from the aforementioned department and from the three Departments of Applied Physics at the same institution. He became Full Professor in 2009. At the beginning of this period, he also carried out a research stay at Queen Mary University of London.

His research activity has focused mainly on the solution of electromagnetic problems involving the transmission, radiation and scattering of electromagnetic waves in the microwave frequency range. He has also worked on the design of passive microwave devices and antennas and, over the last two decades, on the modelling of periodic electromagnetic structures and metamaterials.

His scientific output includes approximately a dozen book chapters, more than 180 JCR-indexed journal papers and more than 350 contributions to national and international conferences. He has also co-edited a book on balanced microwave filters together with F. Martín, J. Hong and L. Zhu. His work has received significant recognition, with more than 6,700 citations and an h-index of 38 in Web of Science, and more than 11,400 citations and an h-index of 49 in Google Scholar. He has been a Fellow of the MIT Electromagnetics Academy since 2005 and an IEEE Fellow since 2010, the latter distinction being awarded for his contributions to the modelling of planar structures, anisotropic media and metamaterials. Several of his journal and conference papers have received Best Paper Awards and related distinctions.

PLENARY LECTURE

Francisco Medina Mena

Bridging Maxwell and Circuit Theory: Physical Insight in Periodic Surface Design

Wednesday 28 October | 09:30-10:30 | Chair: Miguel Beruete

BIOGRAPHY / CONTINUED

Francisco Medina has also been actively involved in the organization of scientific conferences in different roles. He served as Co-Chair of IEEE NEMO 2017 in Seville and was a member of the Technical Programme Committee of the European Microwave Conference (EuMC) for many years. He has also acted as a reviewer for numerous conferences in the field of applied electromagnetics.

He has served as an editor of the International Journal of Microwave and Wireless Technologies, where he has also been, and continues to serve as, an Associate Editor. He has reviewed hundreds of manuscripts for more than 70 journals in the fields of electrical engineering and applied physics and has prepared numerous evaluation reports for research projects and academic appointments in Spain and in several countries across Europe, Africa and the Americas.

ABSTRACT

The interaction of electromagnetic waves with periodic structures has fascinated scientists since early observations of optical diffraction gratings. In modern microwave, millimeter-wave, and optical engineering, metallo-dielectric periodic arrays—such as Frequency-Selective Surfaces (FSSs), metasurfaces, and absorbers—are essential for controlling wave filtering, absorption, and polarization. While modern Computational Electromagnetics (CEM) relies heavily on full-wave numerical solvers, these tools often function as "black boxes" that obscure underlying physical mechanisms.

This talk provides a unified perspective on the modeling of periodic electromagnetic structures, balancing historical foundations with modern analytical advances. We first review the evolution of Equivalent Circuit Models (ECMs), tracing their origins from early quasi-static approximations and waveguide discontinuity theories to their modern implementations. We then highlight our contributions to rigorous multimode network formulations for 1D strip/slit arrays and 2D planar periodic scatterers embedded in multilayered media. By mapping Floquet modes to equivalent transmission lines and lumped reactances, our approach separates the infinite modal spectrum into a few dynamically tracked low-order harmonics and a frequency-independent reactive remainder. This yields closed-form, minimal-order circuit topologies derived directly from Maxwell’s equations without requiring empirical curve-fitting. Finally, we demonstrate how these equivalent networks provide intuitive physical explanations for complex electromagnetic anomalies, including extraordinary optical transmission (EOT) and phase resonances in compound gratings.

WEDNESDAY 28 OCTOBER

SESSION 1

Integral Equation Methods and Advanced Computational Techniques

11:00-12:40 | Chair: Francisco Mesa

E27 Novel Approach for the Efficient Determination of Matrix Entries in the Method of Moments Analysis of Multilayered Periodic Structures with RWG Basis Functions

E05 About the Efficient Computation of Monostatic RCS Using Fast Iterative Solvers

E18 Fast Direct Solvers for the EFIE at High Frequencies

E23 AI-Driven Algorithms for Electromagnetic Computation Using MoM and MLFMA

E25 High-Order Kernel-Regularized Quadratures for Augmented Maxwell Boundary Integral Formulations

Novel approach for the efficient determination of matrix entries in the Method of Moments analysis of multilayered periodic structures with RWG basis functions.

Topic: Integral Equation Methods in time or frequency domains.

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The Method of Moments (MoM) has been extensively used for the electromagnetic analysis of 3-D scatterers and antennas in free space by solving surface integral equations with Rao-Wilton-Glisson (RWG) basis functions (S. Rao et al., *IEEE Transactions on Antennas and Propagation*, vol. 30, no. 3, pp. 409-418, May 1982). These basis functions are versatile and enable the study of a large variety of geometries. When applying MoM with RWGs to structures in free space, the matrix entries are 4-D integrals involving the Green's functions and the basis functions. Since free space Green's functions are available in closed-form, great efforts have been made to use both analytical and numerical strategies in order to determine these 4-D integrals in an efficient and accurate way (see D. Tihon et al., *IEEE Transactions on Antennas and Propagation*, vol. 66, no.4, pp. 1925-1936, April 2018, and references therein). RWG basis functions are also useful in the spatial domain MoM analysis of multilayered periodic structures, which has an interest in the design of frequency selective surfaces and LP-to-CP polarization converters, and in the characterization of unit cells for reflectarray antennas and metasurface antennas. In the periodic multilayered case, MoM matrix entries are again 4-D integrals, but the efficient determination of these integrals is not that simple since periodic multilayered Green's functions cannot be obtained in closed-form.

In this paper we introduce a novel concept for the efficient and accurate determination of the 4-D integrals appearing in the spatial domain MoM matrix entries of periodic multilayered problems when RWG basis functions are used. In particular, these 4-D integrals are expressed as 2-D integrals involving the multilayered Green's functions and the cross-correlation between the RWG basis functions. These cross-correlations between RWG basis functions turn out to be different from zero in polygonal domains known as Minkowski sums, and they consist of 2-D fourth degree polynomials. The cross-correlations between RWG basis functions have been obtained in closed-form in the cases of RWGs defined in a standard periodic mesh with a two-triangle unit cell, in a Tetrakis periodic mesh with a four-triangle unit cell, and in a combination of periodic meshes with different periods involving multibranch RWGs (S. Huang et al., *IEEE Transactions on Antennas and Propagation*, vol. 69, no.10, pp. 6624-6634, October 2021). In all these cases, the remaining 2-D integrals involving the Green's functions and the cross-correlations are expressed as linear combinations of 2-D integrals in triangular domains belonging to the Minkowski sums, and these latter integrals can be numerically computed in an efficient way. On the one hand, the integrals in triangles containing the Green's functions singularities at the origin of coordinates are transformed into polar coordinates to cancel the singularities, and the remaining integrals in the radial and angular directions are obtained by means of low-order gaussian quadratures. On the other hand, the integrals in triangles not containing the Green's functions singularities are simply computed by means of low-order numerical cubatures. By applying all these strategies, we have implemented a spatial domain MoM code for periodic multilayered structures with RWG basis functions which is around two orders of magnitude faster than the brute force spectral domain MoM when an accuracy of two significant figures is enforced, and which is around one order of magnitude faster than CST for the same degree of accuracy.

ABOUT THE EFFICIENT COMPUTATION OF MONOSTATIC RCS USING FAST ITERATIVE SOLVERS

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The Method of Moments (MoM) discretization of electromagnetic scattering problems modeled with Integral Equations results in systems of equations with a vast number of unknowns, demanding significant computational resources. Over the past three decades, substantial research has produced highly efficient algorithms [1], termed "Fast Solvers", with reduced storage requirements and computational complexity, enabling iterative solutions on personal computers with millions of unknowns and even billions on supercomputers.

When using these iterative fast solvers for monostatic RCS computation, the bottleneck becomes the linear system solution for multiple RHS, since the matrix compression and the solution for a single RHS are very fast.

If the sampling of the incident directions is fine enough for a proper plot of the monostatic RCS, the RHS matrix is rank-deficient. Thus, the number of RHS vectors can be reduced to the minimum necessary if the RHS matrix is compressed using low-rank compression algorithms like ACA [2], minimum squared residual interpolation [3], or interpolation with the MLFMA aggregation coefficients [4], among other techniques.

To decrease the number of iteration steps for each incident angle, without RHS matrix compression and with very fine direction sampling, [5] employed the previously computed surface current as an initial guess for the next incident angle, which is currently the usual practice. We propose an extrapolation scheme based on the previous solutions to obtain an initial guess accurate enough to allow convergence of GMRES to a 10^{-3} relative error in one iteration, on average. However, when using this strategy, the total computation time is still larger than when using RHS compression.

When the RHS matrix is compressed, the prediction of a good initial guess is not straight forward. If the resulting RHS vectors do not correspond to incident plane waves, as with ACA, there is no relation between consecutive previous solutions that can be used to predict the initial guess for the next one. If the compressed RHS vectors are plane waves, as in [3], the angular difference between consecutive directions is too large for an accurate prediction of the initial guess, and only a modest reduction in the number of iterations is achieved. Our presentation will address this issue.

[1] W. Chew, J. Jin, C. Lu, E. Michielssen, and J. Song, “Fast solution methods in electromagnetics”, IEEE Trans. Antennas Propag., vol. 45, no. 3, pp. 533–543, Mar. 1997.

[2] Zhi-Qing Lü, Xiang An, “Fast monostatic radar cross-section computation for perfectly electric conducting targets using low-rank compression and adaptive integral method”, IET Microw. Antennas Propag., 2014, Vol. 8, Iss. 1, pp. 46–51.

[3] A. Gomez-Rodriguez, L. Landesa, V. F. Martin, J. M. Taboada, F. Obelleiro, “Self-Correcting Interpolation Technique for Multi-Source Electromagnetic Scattering Problems”, 2025 19th European Conference on Antennas and Propagation (EuCAP), Stockholm, Sweden, 2025.

[4] E. García, C. Delgado, F. Catedra, “Efficient Interpolation Technique for the Analysis of RCS Problems”, IEEE Trans. on Antennas and Propag., vol. 72, no. 8, August 2024.

[5] Song, J., Lu, C.-C., Chew, W.C.: ‘Multilevel fast multipole algorithm for electromagnetic scattering by large complex objects’, IEEE Trans. Antennas Propag., 1997, 45, (10), pp. 1488–1493

Fast Direct Solvers for the EFIE at High Frequencies

A. Heldring, E. Ubeda and J.M. Rius

Fast Direct Solvers for CEM problems have been a subject of research gaining popularity in recent years due to their capacity to solve for many different excitations at once and their relative immunity to poorly conditioned systems compared with iterative solvers. In [1] we published the first such solver that achieves pseudolinear complexity for high-frequency problems. However, the demonstration of this complexity, both theoretically and through numerical examples, did not account for the possible ill-conditioning of the impedance matrix. The numerical examples used the CFIE formulation, which is known to yield well-conditioned systems.

The EFIE formulation is considered to be more accurate than the CFIE, especially for non-smooth geometries. Furthermore, while the CFIE is only applicable to closed surface targets, the EFIE is valid for open surfaces as well. However, the EFIE impedance matrix is often poorly conditioned. In consequence, iterative solvers need computationally expensive preconditioners to drastically improve the convergence rate. For direct methods, the situation is very different. The ill-conditioning does not affect the computational effort directly, since this is fixed for a given problem. However, the accuracy of the solution is compromised. The accuracy depends on the combined effect of the impedance matrix condition and the accuracy of the approximation inherent to any fast method. Improving the latter implies less compression and therefore a larger computational burden. The impedance matrix condition of the EFIE is well known to degrade with the size of the matrix and hence with the frequency, while the computational complexity implies a fixed accuracy. Therefore, the solver in [1] is not of pseudolinear complexity for the EFIE without further intervention. Such an intervention will clearly be similar to the preconditioners used with iterative methods but with some essential differences.

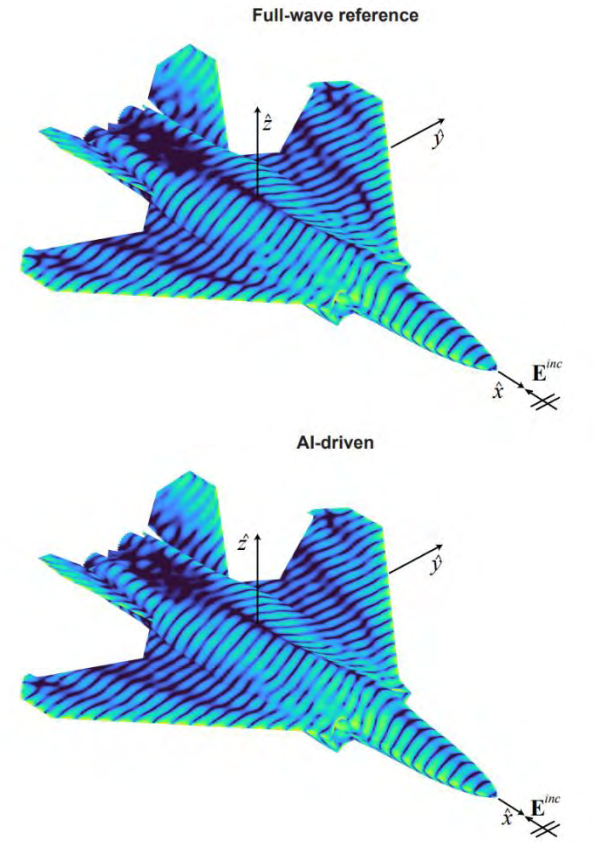
This contribution presents and discusses the difference between iterative and direct preconditioners, the particular requirements for a direct preconditioner for the EFIE, and promising approaches to meet those requirements and ultimately regain pseudolinear complexity.

[1] A. Heldring, E. Ubeda and J. M. Rius, "Fast Direct High-Frequency MoM Solver Using Butterfly Algebra," in IEEE Transactions on Antennas and Propagation, vol. 74, no. 1, pp. 703-712, Jan. 2026, doi: 10.1109/TAP.2025.3627867

AI-Driven Algorithms for Electromagnetic Computation using MoM and MLFMA

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This contribution presents recent advances in the application of surrogate AI-driven models to the Method of Moments (MoM) and the Multilevel Fast Multipole Algorithm (MLFMA). These developments enable the efficient electromagnetic analysis of electrically large and highly complex platforms using GPU-accelerated computing infrastructures.

The proposed approach focuses on the incorporation of AI-driven techniques directly into the electromagnetic operators involved in MoM and MLFMA formulations. This strategy differs from conventional end-to-end deep learning approaches, which typically attempt to predict the electromagnetic response directly from the geometry.

Additional developments related to the use of artificial intelligence tools for electromagnetic design and analysis will also be presented during the conference.

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High-Order Kernel-Regularized Quadratures for Augmented Maxwell Boundary Integral Formulations

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High-order Nyström discretizations of boundary integral equations for electromagnetic scattering require accurate and robust quadrature for self and near-surface interactions on curved geometries. These local quadrature corrections are often among the most delicate parts of a solver: the relevant kernels are singular or principal-value, the geometry is curved, and the desired accuracy must be compatible with high-order surface discretizations.

This talk will discuss a kernel-regularization approach to this problem, inspired by the recent high-order regularization framework of Faria, Pérez-Arancibia, and Tlupova for Helmholtz boundary integral operators [1]. In that framework, a broad class of singular surface operators is written locally in the form

$$B[\phi](x) = \mathrm{p.f.} \int_\Gamma \frac{\Phi(k|x-y|)}{|x-y|^{2p+1}} \, \Psi(x,y)\phi(y) \, \mathrm{d}s(y),$$

and replaced by a regularized operator

$$B_\delta[\phi](x) = \int_\Gamma \frac{\Phi(k|x-y|)}{|x-y|^{2p+1}} \, \sigma_p(|x-y|/\delta)\Psi(x,y)\phi(y) \, \mathrm{d}s(y).$$

The functions σ_p are built from error functions together with polynomial corrections. Their coefficients are chosen by moment conditions so that the singular kernel is replaced by a smooth high-order approximation, after which standard smooth surface quadrature rules can be used.

We will present an extension of this idea to Maxwell problems formulated through augmented charge-current integral equations [2]. The regularized kernels are designed so that the local regularization error can reach seventh order, $O(\delta^7)$, while the remaining numerical integration is performed with standard high-order smooth quadrature rules on curved surface patches.

The talk will include numerical solutions of electromagnetic scattering problems involving complex geometries. These examples will illustrate how kernel-level regularization can simplify the treatment of singular and principal-value self interactions in high-order Maxwell boundary integral solvers.

Keywords: boundary integral equations, Maxwell equations, high-order quadrature, kernel regularization, Nyström methods.

References

1. L. M. Faria, C. Pérez-Arancibia, and S. Tlupova, "High-order kernel regularization of singular and hypersingular Helmholtz boundary integral operators," arXiv preprint arXiv:2604.14797, 2026.
2. F. Vico, L. Greengard, M. O'Neil, and M. Rachh, "Fast adaptive high-order integral equation methods for electromagnetic scattering from smooth perfect electric conductors," *IEEE Open Journal of Antennas and Propagation*, 2025.

WEDNESDAY 28 OCTOBER

SESSION 2

Model Reduction, Differentiable Solvers and Inverse Problems

14:10-15:30 | Chair: Mario Fernández Pantoja

E19 Model Order Reduction for Full-Wave EM Design: Are We There Yet?

E14 Reduced Basis Method in Numerical Modeling of Induction Heating Systems

E26 Recent Updates on Autodifferentiable Solvers for Electromagnetics

E29 Updates on Inverse Problems for 1D Multilayer Electromagnetic Structures

Model Order Reduction for Full-Wave EM Design: Are We There Yet?

Noelia Naranjo, Pablo Biurrun, Pinki Gourish Chandra Das, Carlos J. Ramos-Salas, Ziqing Guo, Luis D. Angulo and Valentín de la Rubia

Abstract

Computational electromagnetics (CEM) tools are now essential for RF and microwave engineering. Accurately predicting the EM behavior of a device before prototyping is critical. However, reliability alone is not enough—simulation speed is equally important. Faster simulations accelerate optimization cycles in computer-aided design (CAD) and enable real-time prediction of EM circuit behavior. Traditional numerical methods such as finite elements (FEM) and the method of moments (MoM) provide reliable results but suffer from high computational cost. Trading reliability for speed is possible, but often at an unacceptable price. Modern industrial demands require advanced EM design tools that meet tight electrical specifications, especially as EM devices evolve into complex multifunctional systems.

In our group, we develop FEM-based solvers for both frequency- and time-domain analyses. These full-wave approaches are accurate but computationally intensive, limiting them mainly to analysis tasks. To address this, we have invested significant effort in model order reduction (MOR) techniques tailored to full-wave design of microwave circuits and antennas [1], [2]. Our work covers both frequency- and time-domain MOR, with a strong emphasis on certifying the reliability of the reduced-order models [3], [4]. This allows us to achieve not only high computational efficiency but also guaranteed accuracy in EM results—thus eliminating the classic trade-off between speed and reliability.

Following the beat of a different drum, we have also developed a data-driven system identification methodology that constructs consistent ROMs solely from input-output data, without requiring full state-space access. Validation across different electromagnetic scenarios with varying signal richness demonstrates high accuracy in temporal extrapolation and robustness under nonpersistent excitation conditions. Once identified, the resulting model accurately predicts responses to new excitations whose spectral content lies within the training subspace, avoiding further full-wave simulations. This framework offers straightforward implementation and high computational efficiency, providing a robust alternative for large-scale EM systems where traditional simulations face significant bottlenecks.

In a parallel effort, we have tackled uncertainty quantification (UQ) in microwave filters, a critical need as materials approach fatigue limits under electromagnetic and thermal stress. Traditional Monte Carlo methods relying on full FEM simulations become computationally prohibitive near fatigue thresholds, requiring thousands of high-dimensional solves. To address this, we have developed a reduced-basis method (RBM) that constructs a low-dimensional basis capturing parametric electromagnetic dynamics. This approach accelerates repeated simulations by orders of magnitude while maintaining accuracy. We have applied this approach to a dielectric resonator filter, treating permittivities as random parameters with distributions that reflect material degradation near fatigue limits. This work shows that MOR can make UQ feasible in reliability-critical EM design scenarios.

We have also extended our MOR framework to radar cross section (RCS) applications. Full-wave monostatic RCS computation over fine angular samplings is computationally prohibitive with conventional MoM solvers. To overcome this, we combine RBM with Discrete Empirical Interpolation (DEIM) to compress the $n \times n$ MoM system to size $r \ll n$, typically $r \approx 10$–20. The resulting ROM captures all essential scattering physics, enabling rapid angular sweeps with controlled residual error. Validation on several perfectly electrically conducting targets demonstrates significant speedups while maintaining full-wave accuracy.

So, are we there yet? Not completely—challenges remain in nonlinear, multiscale, and fully automated scenarios. There is still plenty of work that needs to be done. However, with certified reduction, data-driven identification, uncertainty quantification, and accelerated RCS computations now demonstrated in our group, we have firmly crossed the threshold where MOR transforms full-wave EM design from a slow necessity into a practical, high-speed engineering reality.

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Reduced Basis Method in Numerical Modeling of Induction Heating Systems

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***Abstract*—Induction heating (IH) systems are typically modeled using frequency-domain numerical methods under simplifying assumptions. To reduce computational costs, the conductive load—often requiring fine discretization—is replaced by an Impedance Boundary Condition (IBC) within the Magnetic Vector Potential (MVP) formulation. This work demonstrates the implementation of the Reduced Basis Method (RBM) combined with Proper Orthogonal Decomposition (POD) to construct a mapping of the normalized impedance Z/ω against the corrected penetration depth δ_c. This approach enables rapid, accurate solutions for IH configurations across a wide parameter space with significant computational savings.**

***Index Terms*—Induction heating, eddy currents, Reduced Order Model.**

I. Goals of the work

Numerical modeling of induction heating (IH) systems—comprising a planar coil, conductive load, flux concentrator, and shielding—requires an efficient representation of electromagnetic coupling. To avoid the high computational cost of fine-meshing the load, it is modeled via an Impedance Boundary Condition (IBC). This replaces the explicit conductor mesh by enforcing a relationship between the tangential electric and magnetic fields at the interface, effectively treating the load as a surface impedance.

Under the Magnetic Vector Potential (MVP) formulation, the IBC is expressed as a Robin boundary condition. This acts as a dimension-reduction strategy by collapsing the complex dependencies of frequency (ω), electrical conductivity (σ), and complex magnetic permeability (μ_r) into a single, complex-valued corrected penetration depth (δ_c), [1]. Consequently, the normalized characteristic impedance (Z/ω) is primarily a function of δ_c, thereby streamlining subsequent parametric studies.

To accelerate the evaluation of this mapping, the Reduced Basis Method (RBM) is integrated with Proper Orthogonal Decomposition (POD). The process begins with an offline sampling phase, in which 20 to 50 high-fidelity, full-order simulations are performed over the operational range of δ_c. These snapshots span conductivities from μS/m to TS/m and include random variations in the phase of the complex permeability to ensure broad generalization of the model.

Next, a Singular Value Decomposition (SVD) is applied to the snapshot matrix to construct the POD-SVD basis. Analyzing the resulting singular value energy spectrum allows the dominant system modes to be isolated. The basis is then truncated to retain only these essential modes, minimizing the size of the projection matrix while capturing the necessary physical behavior.

A Galerkin projection is then used to project the high-dimensional governing equations onto this lower-dimensional POD subspace. This mathematical transformation drastically reduces the active degrees of freedom, converting the massive global system into a compact, dense matrix equation while fully preserving the structural and physical accuracy of the full-order model.

Finally, the online extraction phase utilizes this pre-computed reduced basis to evaluate arbitrary configurations within the trained parameter space. The online solver computes the normalized impedance $Z/\omega(\delta_c)$ in milliseconds, bypassing time-consuming finite element simulations and enabling real-time optimization and iterative design workflows.

II. Results and Conclusion

The RBM significantly reduces the computational overhead of modeling IH systems. The model demonstrates high accuracy for standard industrial configurations, with divergence observed only at extreme parametric limits (e.g., ultra-high conductivity or low permeability). This methodology provides a robust, efficient framework for the design and optimization of IH devices, offering a balance between computational speed and physical fidelity.

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Recent Updates on Autodifferentiable Solvers for Electromagnetics

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This communication presents an exploratory and reproducible benchmark of autodifferentiable solvers for electromagnetics. The motivation is that a solver should provide not only fields, scattering parameters, or derived observables, but also their sensitivities with respect to material and geometrical parameters. These sensitivities enable gradient-based inverse design, parameter identification, uncertainty-aware workflows and neural-network training loops. Automatic Differentiation (AD) computes them by applying the chain rule at the level of program operations, avoiding both finite-difference step-size compromises and manual adjoint implementations [1]. Since these applications often reduce many design variables to a scalar loss, reverse-mode AD is the main regime of interest: its gradient cost is largely independent of the number of inputs, although it must store and traverse the computational trace.

The benchmark comprises two analytical solvers for plane-wave propagation in multilayer media, one-dimensional finite-element solver and a mode-matching solver. In Julia, they are evaluated with *FiniteDiff*, *ForwardDiff*, *Zygote*, and *Enzyme*; the differentiated quantities are reflection coefficients, field amplitudes, and electric-field distributions with respect to material parameters. Analytical tests show machine-precision errors for the AD backends, while finite differences remain limited by truncation and round-off. They also expose the main implementation constraints: consistent representation of complex-valued outputs, backend-dependent treatment of array mutation, and the need for domain-specific adjoints for linear solves.

Particular attention is paid to *Zygote* and *Enzyme*. *Zygote* performs source-to-source reverse-mode AD at the Julia level, whereas *Enzyme* differentiates optimized compiler intermediate representation and targets existing scientific codes [2]. Both are correct to machine precision when provided with the same mathematical information. *Enzyme* shows lower per-call overhead for small functions, which is relevant in long optimization loops, but its first-call compilation cost is significant. These measurements are compared with *ForwardDiff* and finite-difference baselines to separate AD-mode, backend, and adjoint-rule effects.

In parallel, the multilayer solvers are implemented in *JAX*, a Python framework with NumPy-like syntax, just-in-time compilation, vectorization and composable AD transformations. The study of `jax.jacfwd`, `jax.jacrev`, and `jax.grad` reproduces the Julia picture: forward mode is simple and competitive for few inputs, whereas reverse mode is the natural option for scalar losses depending on many material or pixel parameters. The presentation will therefore combine accuracy, performance and implementation results, identifying which solver components can be differentiated as written, which require domain-specific adjoints, and which trade-offs dominate beyond small demonstrators. Results will cover multilayer propagation, field and scattering-parameter sensitivities, scaling with parameter count and linear-system size, and first solver-in-the-loop inverse-design experiments.

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Updates on Inverse Problems for 1D Multilayer Electromagnetic Structures

Fernando F. Moya-Rangel, Juan Fernández López, Izan Rodríguez Cuerdo, Eduardo Gómez-González, Adrián Amor-Martin, Luis E. Garcia-Castillo and Sergio Llorente Romano

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This communication presents an exploratory study of inverse problems in one-dimensional multilayer electromagnetics. Beyond gradients, the key question is the information carried by the observable when the forward map is non-injective [1]. A normally incident plane wave illuminates a homogeneous stack of layers with different electric permittivities; the unknowns are the material parameters and thicknesses, whereas the observables are fields, single- or multi-frequency S_{11}, or time-domain reflected pulse trains. The problem is non-convex even in 1D: e.g., a lossless slab is transparent at half-wavelength resonances, so single-frequency S_{11} cannot distinguish different permittivity branches.

The first set of results use auto-differentiable solvers in Julia. A one-dimensional finite-element solver is embedded in gradient-based inversion workflows where simulated and target observables are compared and the material profile is described by few degrees of freedom. The loss landscapes exhibit multiple minima for two unknown permittivities; complex losses smooth them, but do not remove non-uniqueness. In practice, AD is combined with Sobol multistart initialization and local BFGS or conjugate-gradient optimization, which reach the target loss rapidly once a suitable initial guess is found. Derivative-free methods provide useful baselines, but do not change the role of observable information.

In parallel, analytical multilayer solvers are implemented in *JAX*. Recursive-reflection and interface-matrix formulations are adapted to `jax.jit`, `jax.vmap`, and forward- and reverse-mode AD, and used to train neural inverse models with and without a solver-in-the-loop loss. A cautionary result is that reconstruction in observation space is not necessarily a good inverse loss: if two parameters produce almost identical S_{11}, minimizing $\|F(\hat{\varepsilon}) - F(\varepsilon^*)\|^2$ can select the wrong branch. This motivates Mixture Density Networks (MDNs) [2], where several permittivity candidates are represented and the differentiable solver acts as physical regularizer or selector. For a single slab, moving from one to three frequencies reduces the selected MDN mean absolute error from the order of 10^{-1} to the order of 10^{-3}.

The study is extended to a stack of five layers with three unknown interior permittivities and fixed thicknesses. The ambiguity is no longer a set of separated branches: the central layer can be electrically thin ($0.0625\lambda_0$ in the reference case), and Jacobian/SVD diagnostics show that its S_{11} sensitivity is about twenty times smaller than that of the most visible layer. Multi-frequency data improves over monofrequency observations, but a physical selector may be nearly random when many parameter combinations reconstruct the measurement with similar accuracy. In the reported tests, a deep ensemble of supervised residual networks outperforms MDN and tandem-style models, with test mean absolute errors of approximately 0.85, 1.58, and 0.67 for the three unknown permittivities.

A complementary time-domain line uses physics-informed and domain-decomposed models with pulsed reflectometry data. The differentiable forward model includes reflection paths, Fresnel coefficients and propagation delays, while the inverse network combines supervised, reconstruction and regularization terms to exploit separated echoes and off-resonance content. The presentation will report loss landscapes, multistart optimization, JAX details, MDN and ensemble predictions, and Jacobian/SVD diagnostics. The main conclusion is that differentiable solvers must be paired with informative observables and ambiguity-aware models.

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WEDNESDAY 28 OCTOBER

SESSION 3

Electromagnetic Power Transfer, Absorption and High-Power Effects

16:00-17:20 | Chair: António L. Topa

E20 Comparative Characterization of Two 13.56 MHz Resonant Inductive Wireless Power Transfer Coil Systems for Implantable Cardiac Applications

E11 Multilayer Semisolid Phantom for SAR Evaluation in On-Body Antennas: Development and Characterization

E24 Rigorous Calculation of the Electromagnetic Fields in Gap Waveguide Technology with Corrugated Surface Profiles for Reduction of Multipactor Effect

E10 Increasing Corona Discharge Breakdown Thresholds in ESIW Bandpass Filters

Comparative Characterization of Two 13.56MHz Resonant Inductive Wireless Power Transfer Coil Systems for Implantable Cardiac Applications

I. M. Fernandes, P. Pinho
University of Aveiro, Instituto de Telecomunicações, Aveiro, Portugal

Implantable cardiac support devices require continuous power delivery, while transcutaneous drivelines remain a major limitation due to infection risk and restrictions to full implantability [1]. Resonant inductive wireless power transfer (WPT) has been investigated as a promising alternative for implantable medical devices [2,3]. However, receiver miniaturization, required for cardiac implantable applications, may affect magnetic coupling and transmission performance. This work compares two 13.56 MHz resonant inductive WPT coil systems. System 1 used identical planar transmitter and receiver coils, whereas System 2 used the same transmitter with a miniaturized receiver. Both systems were simulated in CST, fabricated, and characterized through VNA S-parameter measurements under unloaded conditions and with three agar-based tissue-like phantoms. Without phantom loading, CST simulations showed similar transmission for both systems at 13.56 MHz, with S21 = -0.27 dB for System 1 and S21 = -0.23 dB for System 2, indicating that receiver miniaturization did not compromise the unloaded link. With phantom loading, both systems showed detuning and S-parameter degradation; however, System 2 remained closer to the target frequency, with simulated S21 around -4.2 dB compared with approximately -7.3 dB for System 1. Experimental measurements supported this trend: System 2 retained higher S21-based transmission under phantom loading, particularly for Phantoms 1 and 3, while System 1 remained around -10 dB. These results suggest that miniaturized-receiver WPT links can remain compatible with 13.56 MHz operation, provided that matching is further optimized under tissue-loaded conditions.

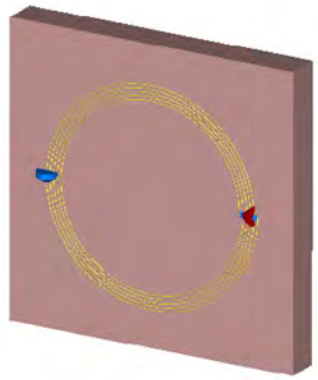
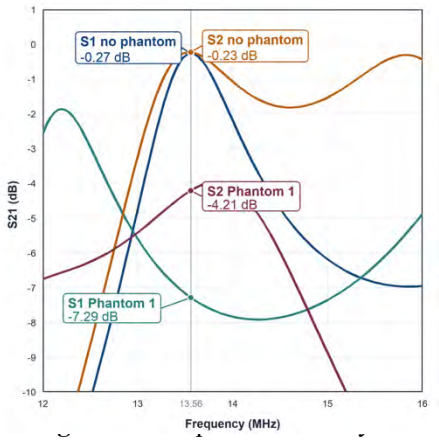


Fig.1 – CST phantom-loaded model of System 1



under unloaded and phantom-loaded conditions

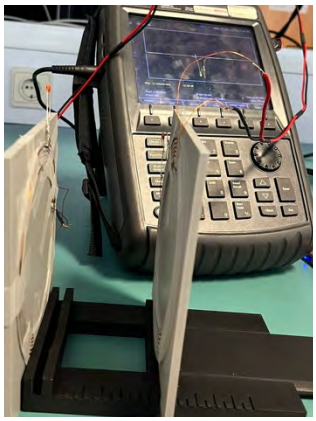


Fig.3 – VNA setup with controlled coil positioning

References

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Multilayer Semisolid Phantom for SAR Evaluation in On-Body Antennas: Development and Characterization

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Abstract

On-body and in-body antennas have been emerging as an essential and important technology for biomedical applications. These antennas allow wireless communication between the body-centric device and external transceivers, enabling bidirectional data transfer for monitoring and diagnostics. However, electromagnetic energy transmission through human tissue requires an evaluation of its potential harmful effects and the monitoring of its limits [1], [2].

This paper presents the development of a semisolid phantom that simulates conditions similar to those of biological tissues, serving as an alternative to conducting radiation tests directly on the body. To make the model more realistic, the phantom consists of three distinct tissue layers: skin, fat and muscle. For its development, the dielectric properties were determined at a frequency of 2.45 GHz. This frequency was chosen because it is well suited for biomedical detection applications and falls within the Industrial, Scientific and Medical (ISM) band [3].

Furthermore, the electric field was measured for different compositions of the phantom layers using an electric field probe. Based on these measurements and calculations of tissue density and conductivity, it was possible to estimate the Specific Absorption Rate (SAR) values.

The final phantoms obtained for muscle and skin tissues revealed a good proximity between the measured properties and the target values. For fat tissue, the results fell short of expectations, so lard was used as an alternative approach [4], [5]. Analysis of the electric field and SAR revealed a proportional relationship with transmitted power, as well as the influence of the phantom's composition and its dielectric properties on signal transmission through the tissues. The results also indicate that both tissue density and thickness significantly influence the resulting SAR values [6].

The complete experimental workflow, including the dielectric characterization, the fabricated multilayer structure, and the final measurement setup, is illustrated in Fig. 1.



Fig. 1. Experimental stages of the phantom development and validation: (a) measurement of the dielectric properties of the muscle-emulating phantom layer, (b) fabricated multilayer phantom prototype showing the distinct skin, fat, and muscle layers, and (c) experimental setup for electric field measurements inside the anechoic chamber.

Acknowledgment

This work is funded by national funds through FCT – Fundação para a Ciência e a Tecnologia, I.P., and, when eligible, co-funded by EU funds under project/support UID/50008/2025 – Instituto de Telecomunicações, with DOI identifier - https://doi.org/10.54499/UID/50008/2025

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Rigorous Calculation of the Electromagnetic Fields in Gap Waveguide Technology with Corrugated Surface Profiles for reduction of Multipactor Effect

Sarah M. Bonte[1], **Ángela Coves**[1], **Ángel A. San Blas**[1], **José J. Vague**[2] **and Vicente E. Boria**[2]
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Abstract- Multipactor is a major limitation in high-power microwave and millimeter-wave components operating under vacuum conditions. This work investigates the use of corrugated surface profiles as a passive technique for increasing the multipactor threshold in gap waveguide (GW) technology. Two Ka-band devices —a ridge gap waveguide (RGW) transformer and a groove gap waveguide (GGW) bandpass filter— are considered. Corrugations are introduced in regions of maximum electric-field intensity, and their impact is analyzed through a comprehensive simulation campaign combining full-wave electromagnetic solvers and electron-tracking tools. Parametric studies are carried out to evaluate the influence of the corrugation geometry and number of corrugations on both the RF performance and the multipactor behavior. The results show that corrugated surfaces effectively disrupt resonant electron trajectories, significantly increasing the predicted levels of multipactor threshold power while preserving the RF response of the original designs. Selected configurations have been manufactured using standard CNC milling techniques, and experimentally validated through high-power testing under vacuum conditions. The measurements confirm the trends observed in simulation and demonstrate the effectiveness of the proposed approach. The presented technique provides a simple, passive, and manufacturable solution for multipactor mitigation in GW components, that can be readily extended to other waveguide technologies and frequency bands.



(a) (b) (c)

Fig. 1. (a) Corrugations geometry on the gap waveguide walls (b) of the RGW transformer and (c) of the GGW filter under study for reducing the multipactor effect.

Topic: 1. Electromagnetic Simulation for Advanced Application

Increasing Corona Discharge Breakdown Thresholds in ESIW Bandpass Filters

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In this work, corona discharge breakdown thresholds in empty substrate integrated waveguide (ESIW) bandpass filters are investigated and experimentally validated for the first time. The objectives are the analysis, and subsequent enhancement, of the peak power handling capability of inductive ESIW filters operating in low-pressure environments, where gas breakdown may limit the maximum admissible RF power level. First, the critical regions where the electric field reaches its maximum amplitude are identified by full-wave electromagnetic (EM) simulations. Then, an enhancement strategy based on the introduction of drilled apertures in the ESIW covers is applied to reshape the field distribution in the most critical zones without compromising the in-band response. Next, based on the EM field distribution obtained, a diffusion problem has been solved to determine the evolution of the electron density and the breakdown level of corona effect. Simulated and measured results show a consistent increase of the corona discharge threshold at low pressure, between 2 and 3.1 dB, with respect to a reference ESIW bandpass filter of the same electrical specifications [1].

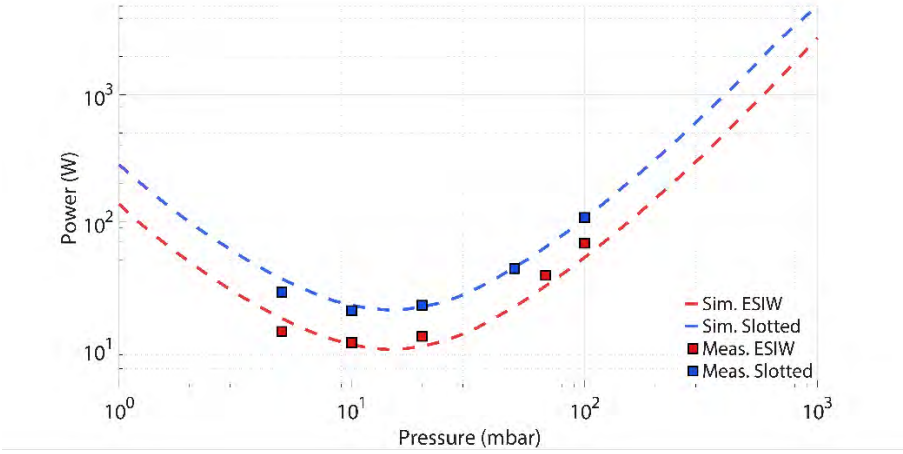


Fig.1. Comparison of simulated (dotted lines) and measured (points) corona breakdown thresholds as a function of pressure for the reference and slotted ESIW filters.

ACKNOWLEDGEMENTS
This work is funded by MCIN/AEI/10.13039/501100011033 and by “FEDER, a way of making Europe,” through Subprojects C44, C43, and C41 of the Coordinated Projects PID2022-136590OB, and has been developed thanks to the European Social Fund (ESF+).

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THURSDAY 29 OCTOBER

SESSION 4

RF Circuit Models and Engineered Electromagnetic Surfaces

09:30-10:50 | Chair: Ángela Coves

E01 On the Extension of the Eigenstate Lattice Network to an Arbitrary Number of Ports

E12 On the Circuital Properties of Matching Networks and Their Practical Implementations in Radiofrequency Engineering

E06 Recommendations for the Design of External Devices

E13 Chiral Metasurfaces for Electromagnetic Wave Control in Unguided Media

ON THE EXTENSION OF THE EIGENSTATE LATTICE NETWORK TO AN ARBITRARY NUMBER OF PORTS

Alberto Hernández-Escobar[1], Elena Abdo-Sánchez[1], Jaime Esteban[2], Teresa M. Martín-Guerrero[1], Carlos Camacho-Peñalosa[1]

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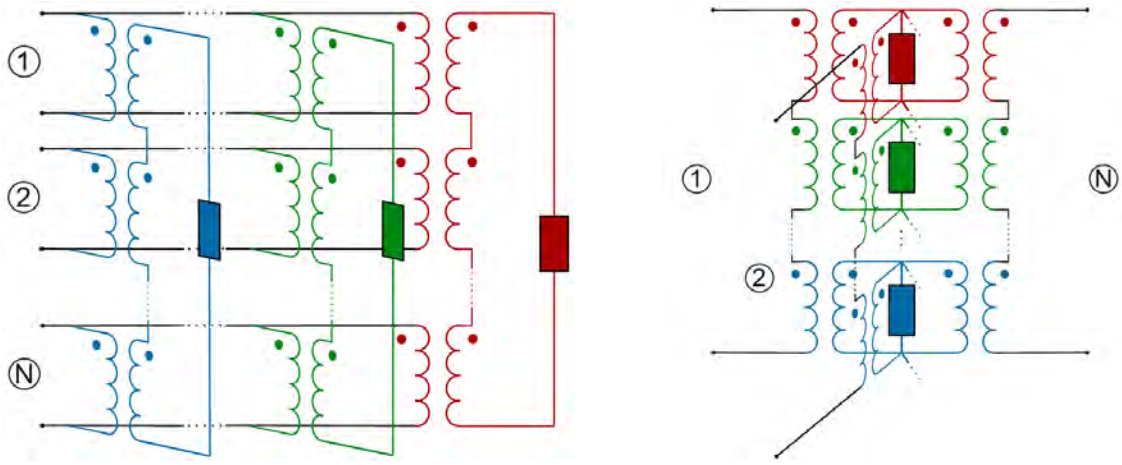
[2] Information Processing and Telecommunications Center, E.T.S. Ingenieros de Telecomunicación, Universidad Politécnica de Madrid, 28040 Madrid, Spain

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ABSTRACT

Equivalent circuits remain a fundamental tool for the analysis and synthesis of electromagnetic structures, since they provide compact models with a clear physical interpretation. In this context, the well-known lattice network has long been a natural representation for symmetric two-port structures, because it captures the even and odd modes and uses only realizable circuit elements. More recently, a generalized lattice equivalent circuit for asymmetric reciprocal two-port networks was proposed by the authors [1], extending this idea while keeping realizable elements and an analogous modal interpretation by eigenstates.

In this work, the concept is extended to reciprocal networks with an arbitrary number of ports. The proposed formulation is based on the eigendecomposition of the network parameter matrices, which allows the admittance, impedance, and scattering matrices to be written as a sum of eigenstate contributions. Each contribution is then mapped onto a simple subcircuit formed by an immittance element and ideal transformers, leading to a generalized lattice-type equivalent circuit for N-port networks in both admittance and impedance forms. Fig. 1 shows the topology of the circuits in both forms, with the subcircuits highlighted in different colors.



(a) (b)

Fig. 1. Topology of the N-port eigenstate lattice network. (a) Admittance form. (b) Impedance form.

The method can be used to standard multiports, such as three-port power dividers and directional couplers, in order to yield compact equivalent circuits that preserve the modal structure of the devices and provide an intuitive framework for analysis and synthesis.

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On the circuital properties of matching networks and their practical implementations in radiofrequency engineering

Jesús Mª Rebollar*, José Ramón Montejo-Garai and Jorge A. Ruiz-Cruz

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Designing single-input, multi-output (N-output) circuits with high matching performance remains a well-known challenge in radiofrequency (RF) engineering. These networks are particularly relevant in applications such as power dividers and combiners, as well as microwave heating systems. In this work, a review of the electrical properties of the scattering matrix associated with these matching networks is presented.

The motivation for this work stems from our group's research on dual-polarization communication antennas and on antennas and probes for microwave heating applications [1]–[2]. Within this context, a device known as the quasi-lossless reciprocal isolator (QARSP) was developed, along with several practical implementations [3].

This paper investigates the properties of scattering matrices associated with lossless and reciprocal networks featuring one input and N outputs. It is demonstrated how these matrices can be leveraged to achieve practically useful matching levels in engineering applications, and their key numerical properties are derived. In addition, the feasibility of such configurations is discussed, and potential implementation strategies are outlined.

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This work was supported by Spanish Government through MCIU/AEI/10.13039/501100011033, FEDER, UE (Ministerio de Ciencia, Innovación y Universidades, Agencia Estatal de Investigación and Fondo Europeo de Desarrollo Regional de la Unión Europea) under Grant PID2023-146246OB-C31 (ANT4IT), in part by Comunidad de Madrid under Grant TEC-2024/TEC-22 (RAFTEC-CM)

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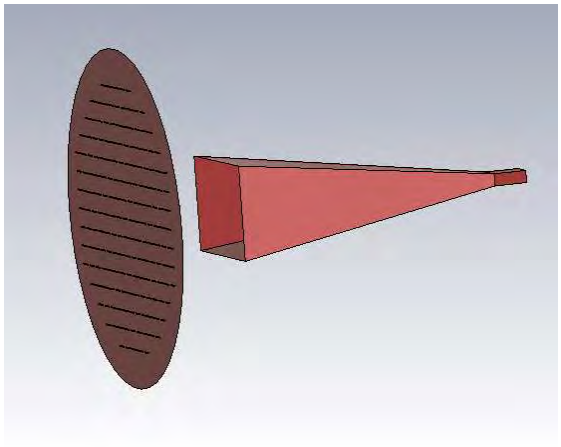
RECOMMENDATIONS FOR THE DESIGN OF EXTERNAL DEVICES

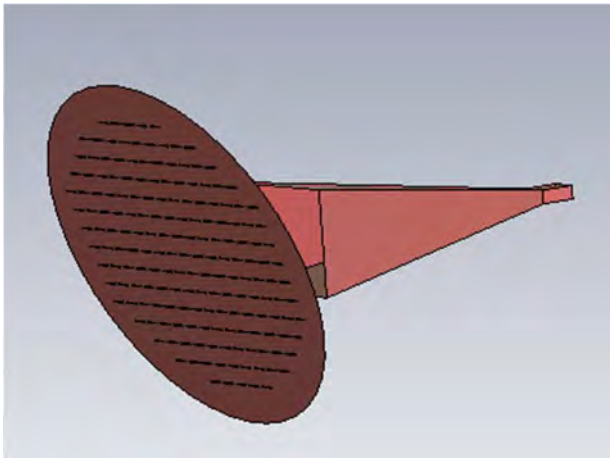
Juan E. Page. Catedrático Jubilado de la Universidad Politécnica de Madrid

The design of external devices, i.e., elements (filters, polarizers, etc.) that operate under illumination by the electromagnetic field of a radiating system, can be simplified through the use of equivalent circuits and the application of well-established microwave circuit synthesis techniques. As in the design of reflectarrays and transmitarrays, the local periodicity approximation and the model of an infinite periodic surface illuminated by a plane wave are employed. This approach provides a preliminary design that can subsequently serve as a seed for full-wave electromagnetic optimization.

Let us consider a typical case. Figure 1 illustrates a simple first-order external band-pass filter configured by means of slots etched on a circular conducting plate. As a first approximation, the filter is assumed to be homogeneous; that is, the period is constant, all the slots have identical dimensions, and they are uniformly illuminated by a plane wave incident normal to the disk, with the electric field linearly polarized in a direction perpendicular to the longer side of the slots. Under this approximation, the slots can be represented by an equivalent circuit consisting of an anti-resonant L-C circuit connected in shunt to a transmission line, whose parameters can be straightforwardly obtained through electromagnetic simulation. These parameters can be calculated for a reasonable set of slot dimensions, allowing the required geometry to be determined by interpolation in order to achieve a specified center frequency and bandwidth.

However, in practice, neither is the periodic surface infinite nor is it illuminated under the assumed conditions. On the contrary, the surface is truncated to the size of the disk, the illumination is not a plane wave, and the incidence is not normal to the filter. This leads to several key questions: What should the disk size be? At what distance from the horn aperture should it be placed? How can the approximation be improved? Addressing these issues becomes even more critical when the horn axis is not aligned with the normal to the filter surface, as shown in Figure 2.





This communication proposes simple answers to these questions based on readily available data and summarizes the results obtained for these illustrative examples.

Chiral Metasurfaces for Electromagnetic Wave Control in Unguided Media

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Chiral metamaterials and metasurfaces have become well-established tools for the manipulation of electromagnetic waves, enabling a high degree of control over polarization, phase, and propagation direction. In this context, the Electromagnetism Group at the University of Cantabria has carried out a sustained research activity on planar implementations of these structures using printed circuit technologies. The work has explored both intrinsic and extrinsic chirality as mechanisms to enhance electromagnetic responses, particularly in terms of circular birefringence and circular dichroism.

One of the main research lines has focused on **polarization control**. Through the design of different chiral unit cells, such as conjugated omega or gammadion-like particles, various polarization transformation functionalities have been investigated. Representative examples include linear polarization rotation, linear-to-circular conversion, and circular polarization transformation, typically achieved with subwavelength thickness and relatively high efficiency. These effects are associated with differences in phase delay and absorption between circularly polarized eigenwaves, which allows tailoring the transmitted field.

Another relevant aspect addressed in these works is **wavefront control** based on engineered phase discontinuities. By introducing spatial phase gradients along the metasurface, it is possible to steer or refract electromagnetic waves and to shape radiation patterns in accordance with the generalized Snell's law. This approach provides a practical route to implement compact and lightweight alternatives to conventional devices, such as lenses, while maintaining the additional capability of polarization transformation due to the chiral response of the structures.

ACKNOWLEDGMENT

This work was supported by the Spanish Ministry of Science and the European Union: MCIN/AEI /10.13039/501100011033 / FEDER, UE under Project PID2022-137619NB-I00.

THURSDAY 29 OCTOBER

SESSION 5

Electromagnetic Modelling and Scattering Techniques

11:20-12:40 | Chair: Juan Manuel Rius

E17 Rethinking Ray Tracing and Physical Optics for Electromagnetic Simulation

E21 Image Theory for the Analysis of Scatterers Inserted into a Metallic Plane

E16 Computationally Efficient Full-Wave Analysis of Metallic Reflectarrays for Satellite Communications Based on Spherical Mode Domain Decomposition

E07 Optimization in the Evaluation of the Rectangular Cavity Green's Functions and Their Spatial Derivatives

Rethinking Ray Tracing and Physical Optics for Electromagnetic Simulation

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Asymptotic methods rooted in Geometrical Optics (GO) have long been employed for the analysis of lens antennas. When the GO framework, particularly its ray-tracing (RT) formulation, is combined with the inherent approximations of Physical Optics (PO), the result is a computationally efficient methodology that has proven to be highly adaptable in a wide range of engineering problems. Nevertheless, the combined RT-PO technique is often considered too approximate to accurately predict the radiation characteristics of lens antennas and radomes and is therefore presumed to be suitable only for a restricted range of scenarios. Contrary to this common assumption, our experience with RT-PO has demonstrated that its practical applicability is far broader than that generally acknowledged.

Our first use of RT-PO focused on the study of geodesic lenses. In this application, the computed radiation patterns, gain, and directivity showed excellent agreement with results obtained from full-wave electromagnetic solvers, to the point that the differences were negligible. In addition to its accuracy, the low computational burden of RT-PO (achieved without relying on specialized hardware or optimized software) made it particularly attractive for antenna design tasks. This enabled the development of unconventional structures such as half Maxwell fish-eye lenses, Luneburg-type lenses with non-spherical geometries, and geodesic horn array antennas. Motivated by these results, we extended the RT-PO methodology to leaky-wave antennas, where it provided a simple but effective means of incorporating lensing effects. (Related publications can be found at http://ant.eecs.kth.se/oscarqt/)

RT-PO was subsequently applied to the study of radome-induced effects in phased array antennas. Even in configurations that involve strong element-radome coupling and radomes placed at distances as small as three to four wavelengths from the array, the method retained a satisfactory level of precision. Its simplicity allowed efficient investigations of more elaborate radome arrangements, including multilayer designs and structures based on metamaterials.

Beyond these applications, RT-PO has been used in the synthesis of broadband, quasi non-diffracting radial GRIN lenses capable of beam steering. More recently, this method has been applied to the study of reverberation chambers, specifically for assessing the early-time response, a task that is computationally intensive for full-wave solvers, yet easily handled using RT-PO. Finally, when combined with the reaction theorem, RT-PO also enables a direct evaluation of mutual coupling between radiating elements in parallel-plate lens antenna configurations.

Taken together, these examples highlight an important point in an era dominated by highly optimized commercial solvers and GPU-accelerated computation: whenever feasible, low-cost approximate methods should be preferred. The central issue is not whether such approaches are approximate, but rather identifying the problem classes for which their accuracy is sufficient. Based on our experience, these classes are significantly more numerous than is often assumed.

Image theory for the analysis of scatterers inserted into a metallic plane

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Image theory, in conjunction with spherical mode expansion and addition theorems, is a well-established technique that has been applied for over 30 years for the efficient analysis of scatterers located above or resting on a metallic plane illuminated by a plane wave [1,2]. This technique is based on generating the image scatterer and then applying translation theorems to couple the real scatterer with its physical image. In the case of scatterers resting on the metallic plane, the solution is to create a composite scatterer consisting of the original scatterer and its physical image. This is the case, for example, with hemispheres on a metallic plane, which are studied by analyzing complete spheres illuminated simultaneously by the original plane wave and their image [3].

In this work, the above method is extended to the analysis of scatterers inserted in the metallic plane and excited by an arbitrary antenna (Fig. 1). It is based on the creation of a virtual scatterer from hemispherical mode expansions. Moreover, it is shown that the image antenna can be analytically characterized from the original antenna. As an example, the method will be used to approach a reflectarray on an infinite ground plane.

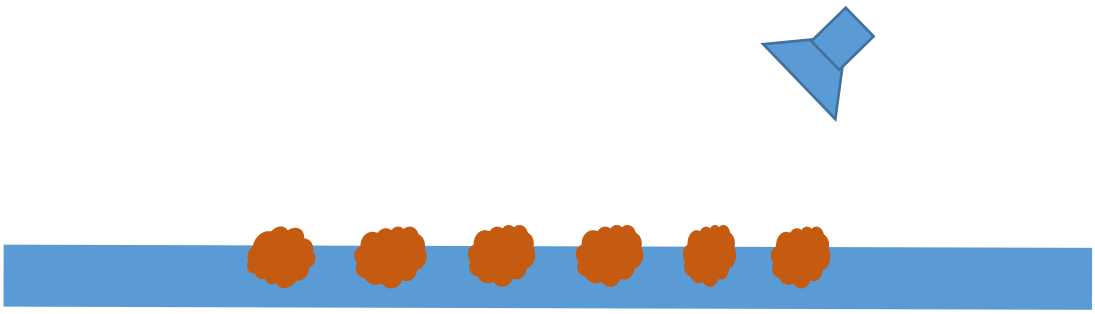


Fig. 1. Scatterers inserted in a metallic plane, excited by an arbitrary antenna

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Computationally Efficient Full-Wave Analysis of Metallic Reflectarrays for Satellite Communications based on Spherical Mode Domain Decomposition

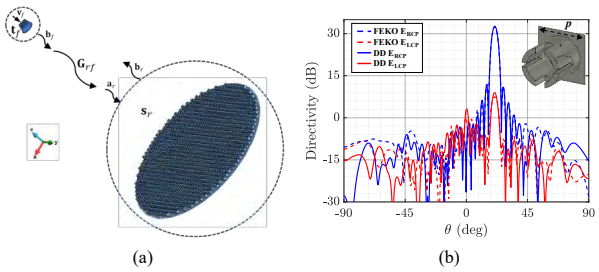
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This work presents an efficient full-wave analysis method for electrically large metallic reflectarrays (RAs), based on domain decomposition (DD) using spherical modes (SM) and translation addition theorems. Reflectarrays combine the advantages of conventional reflectors and phased arrays, offering high gain, reduced weight, compact design, and simplified manufacturing. Their ability to locally control the phase of reflected waves enables advanced functionalities such as beam steering and polarization control, making them well suited for satellite communications. However, their design and analysis remain computationally demanding.

To overcome these limitations, the authors propose a direct domain decomposition method. The approach models the entire system by separating the feeder and the reflectarray into independent domains expressed in terms of spherical modes, see Fig.1(a). The feeder is characterized by a transmission matrix relating waveguide excitations to radiated spherical modes, while the reflectarray is described by its scattering matrix. The interaction between both domains is established through translation matrices that map spherical modes between coordinate systems. A critical contribution of this work lies in the efficient computation of the reflectarray scattering matrix. First, the response of each individual element is obtained using the finite element method. For arrays composed of rotated identical elements, only one simulation is required, since other configurations can be derived analytically. Then, the global reflectarray response is constructed by coupling individual elements using translation addition theorems. An important advantage of the proposed framework is its suitability for optimization processes. Once the initial matrices and domains are computed, subsequent iterations only require analytical updates, such as rotations of elements, avoiding repeated full-wave simulations and eliminating convergence issues typical of iterative methods. The method is validated through the analysis of a fully metallic reflectarray operating at 29 GHz with an aperture of 18λ. The structure employs Pancharatnam–Berry phase elements to achieve circular polarization and beam steering. The results show excellent agreement with the commercial simulator FEKO, accurately reproducing radiation patterns and achieving polarization discrimination leve

The proposed method provides an efficient and accurate full-wave analysis of large metallic reflectarrays, enabling fast evaluation of the far-field response. Its high computational efficiency—requiring only 109 seconds per analysis after initialization—highlights its strong potential for optimization and design applications.



(a) (b)

Figure 1: (a) Description of the analysis method based on DD and SM. (b) Simulated radiation pattern of the RA antenna at 29.0 GHz pointing to 21 deg at the output direction.

This work was partially supported by Grant GR24070, 85% co-financed by the EU, FEDER, and Junta de Extremadura, managing Authority: Ministerio de Hacienda; by Grant PID2024-158542NB-I00, funded by MICIU/AEI/10.13039/501100011033/FEDER, EU; by Project No. PID2022-137845NB-C21, funded by MCIN/AEI/10.13039/501100011033;
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Optimization in the evaluation of the Rectangular Cavity Green's Functions and their spatial derivatives

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***Index Terms* — Ewald method, Green's functions, integral equation (IE), Method of Moments (MoM), passive devices.**

ABSTRACT

In this paper, an efficient method for evaluating the Green's functions of a rectangular cavity and their spatial derivatives is proposed. To achieve this, the well-known Ewald method is employed. Building on previous work, the complex-argument complementary error functions present in the Ewald formulation are evaluated using rapidly converging infinite series, thereby significantly improving computational efficiency. In addition, an optimal splitting parameter is introduced to ensure the proper convergence of both the spectral and spatial series. This highly efficient evaluation approach is of great interest for analyzing electromagnetic fields within microwave circuits, as well as for analyzing waveguide structures or cavity-backed antennas through integral equation techniques.

I. INTRODUCTION

In the microwave industry, waveguide components [1] play a fundamental role in communication systems, offering unique properties such as low loss and excellent high-power handling capabilities. The widespread adoption of these devices has driven the development of different numerical methods for their efficient analysis. Among these, integral equation (IE) techniques [2] are particularly efficient, primarily because they make use of Green's functions, which inherently satisfy the boundary conditions of the cavities and waveguide segments. Consequently, numerical solutions are exclusively required for the internal discontinuities introduced by conducting or dielectric objects, which are typically modeled using the surface equivalence principle [3]. Comprehensive analysis of these components, alongside the characterization of their internal electromagnetic fields, strictly necessitates the efficient evaluation of these Green's functions and their corresponding spatial derivatives.

To address this need, this work focuses primarily on the efficient evaluation of rectangular cavity Green's functions and their spatial derivatives, which are conventionally expressed as slowly converging series in both the spectral and spatial domains. To accelerate this evaluation, the Ewald method is employed, following the approach outlined in [4]. However, the application of this technique results in complementary error functions with complex arguments that are computationally expensive to compute. To solve this problem, the methodology established in [5] and [6] for rectangular waveguide geometries is extended here to the cavity case. This approach expresses the complementary error functions of complex argument as rapidly converging infinite series, thereby significantly reducing the overall computational overhead. Furthermore, to optimize the performance of the Ewald method, several formulations are proposed to determine the optimal splitting parameter (E) as a function of frequency, waveguide dimensions, and other numerical parameters.

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THURSDAY 29 OCTOBER

SESSION 6

Time-Varying and Reconfigurable Electromagnetic Structures

14:10-15:30 | Chair: Rafael R. Boix

E03 Equivalent Circuit for Strip-Like Spatiotemporal Periodic Structures

E28 Contributions to Time-Varying Computational Electromagnetics

E22 Temporal Glide Symmetry in Scalar Bulk Photonic Time Crystals: A Parity-Sideband Selection Rule

E15 Reconfigurable Wideband Linear-to-Circular Polarization Converters

Equivalent Circuit for Strip-Like Spatiotemporal Periodic Structures

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***Index Terms* — Circuit Model, Periodic Structure, Space-Time, Time-Modulation, Spatiotemporal Transmission Line.**

ABSTRACT

This work provides key remarks to derive equivalent circuits under spatiotemporal modulations. The approach is applied to a two-dimensional array periodic array of strips controlled by diodes, which induce the temporal variation of the structure. The circuit model is applied to exploit the tuning capability associated with space-time modulation.

I. INTRODUCTION

The study and development of space-time structures have gained significant momentum from the past decade due to their remarkable properties, including nonreciprocal responses, multi-frequency operation, and net parametric amplification [1]. Although many of these exotic behaviors were theoretically anticipated in the 60s and 70s of the last century [2], the technological limitations at that period hindered their practical realization. The concept was later revisited in pursuit of magnetless nonreciprocal devices vie space-time periodic metasurfaces [3]. Time modulation is typically introduced through diodes, varactors, or other externally biased switching elements. Applying periodic control signals to these devices imposes a temporal periodicity on the unit cells, generating space-time harmonics [4]. One of the current limitations in the field is the scarcity of commercial electromagnetic solvers capable of accurately modelling such time-varying structures. This paper offers a focused perspective on the problem by providing analytical circuit-based models to emulate the behavior of split-patch-type periodic arrays subject to space-time modulation

II. THEORETICAL REMARKS AND PRELIMINARY RESULTS

The unit cell of the structure to analyze is presented in Fig. 1(a), formed by a two strips connected through a diode and illuminated by a vertically-polarized plane wave. The structure has narrow thickness and is inmersed in free-space. The circuit derivation is inspired in that in [5], realized for passive arrangements. The introduction of time modulation keeps the same topology in [5], shown in Fig. 1(b). Three main periodicities appear in the problem: two spatials, p_x and p_y; one temporal T_m. This situation direcly leads to the definition of space-temporal transmission lines in the circuit, governed by the indexes, *n,m,i,* and defined through their impedance Z_{nmi}, propagation constant β_{nmi}, and transformer N_{nmi}. Analytical results are plotted in Fig. 1(c), representing the reflection coefficient as a function of the duty cycle α, which is defined as the time, inside a time periodic cycle, in which the diode is ON ($0 \le t < \alpha T_m$), in contrast to the rest of the cycle in which the diode is in OFF ($\alpha T_m \le t < T_m$).

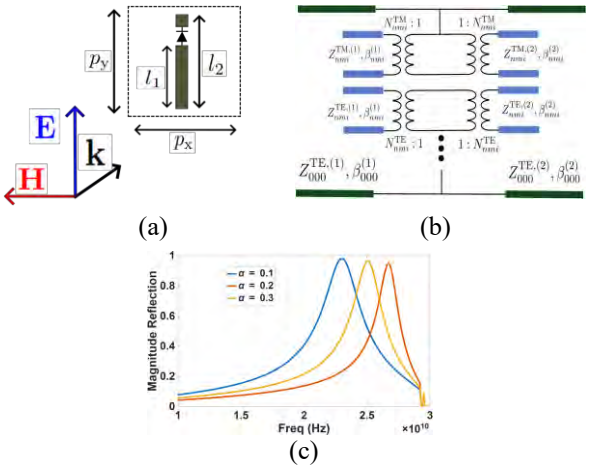


Fig. 1. (a) Unit cell formed by 2 metallic strips (grey color) connected by a diode. (b) Equivalent circuit. (c) Reflection coefficient vs frequency for 3 values of α. Structure parameters: $p_x = p_y = 10$mm, $l_1 = 4$ mm, $l_2 = 8$mm, $T_m = 1$GHz.

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Contributions to time-varying computational electromagnetics

TIME-VARYING structures, such as discrete loads in antennas/scatterers, are used to introduce remarkable electromagnetic properties in comparison to their static counterparts. This communication further explores these capabilities, for instance by means of an efficient numerical procedure to include time-varying passive loads for thin-wire structures modeled by means of an electric-field time-domain integral-equation (EFIE-TD). Numerical results illustrate remarkable effects of these structures, such as a non-linear frequency redistribution of source energy which effectively integrates mixer and antenna properties in a single device (Figure 1).

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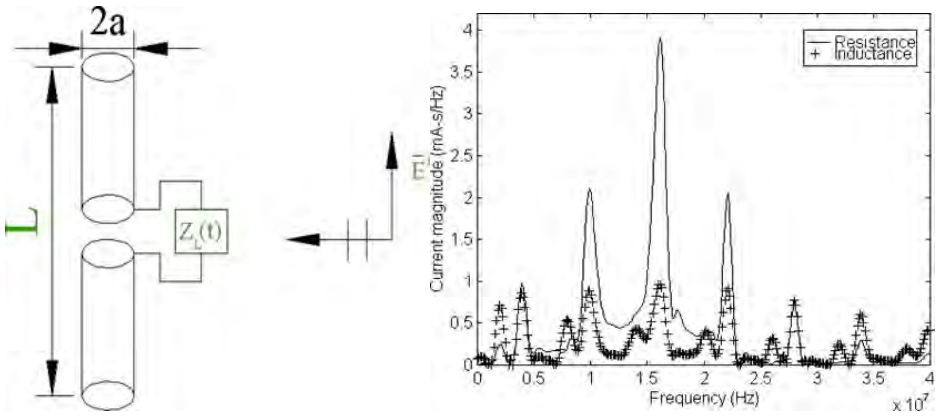


Fig. 1 Non-linear currents in a time-varying loaded dipole.

Temporal glide symmetry in scalar bulk photonic time crystals: a parity–sideband selection rule

Topic: Metasurfaces, Metamaterials and Periodic Structures.

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Spatial glide symmetry gives a practical route for controlling photonic mode families: protected band contacts, suppressed stop bands and modified dispersion. In a photonic time crystal, the analogous protocol is temporal glide, a spatial reflection combined with a half-period shift of the modulation. The visual analogy, however, has to be used with care in scalar bulk media (an isotropic permittivity modulated throughout the volume, rather than a bianisotropic medium or a thin space-time metasurface). The relevant signature is not a zone-edge degeneracy but field content: how the modulation redistributes static transverse parity across Floquet sidebands.

At the level of the one-period map, the glide eigenvalue is fixed by the Floquet multiplier and does not supply an additional zone-edge label. The symmetry is seen instead in the eigenvectors themselves. In scalar bulk media, the robust effect is static-parity hybridization along the sideband ladder.

We illustrate this with a perfectly conducting trilayer waveguide whose two outer regions are time modulated. In the synchronous protocol, both regions are driven in phase; the perturbation is even under transverse reflection and shifts both parity sectors separately. In the time-glide protocol, the two regions are driven with a half-period delay, turning on a reflection-odd drive that couples opposite static parities in neighboring Floquet sidebands. Temporal glide forces the transverse parity to alternate along the sideband ladder; at the output of a finite section this becomes an exact channel rule.

The bulk calculation uses a spatiotemporal mode-matching scheme. Each half period is treated as a static guide: the transverse-electric field is expanded in the sine modes of the conducting reference guide, propagated through the dielectric profile of that stage, and connected to the next stage by the temporal jump conditions. In practice we work in displacement form, so that the electric displacement is continuous through the permittivity switch while the electric field is rebuilt from the instantaneous material profile. Composing the stage maps gives the Floquet spectrum; sampling the periodic eigenvectors over one period gives their sideband amplitudes and static-parity content.

We verify the rule with this modal solver and with a finite-difference time-domain calculation. The modal solver resolves the Floquet eigenvectors into their static-parity components and shows order-unity hybridization under time glide, while the synchronous protocol remains parity pure down to numerical precision; forbidden parity components sit about ten orders of magnitude below the residuals associated with accidental suppression alone. The time-domain simulation then converts an odd TE_2 mode into the even TE_3 mode at the first upper sideband, while the same channel remains at the numerical floor under synchronous modulation. In the designed window, time glide places approximately ninety percent of the generated propagating power in the selected channel.

Experimentally, the stable observable is the static-parity content resolved by output sideband. A phase-delay sweep between the two driven regions interpolates between two exact patterns: constant parity for synchronous modulation and alternating parity for temporal glide. The allowed output-channel pattern is set by the timing of the modulation banks rather than by tuning each modal coupling separately—a selection rule enforced by symmetry, confirmed by both the modal solver and the time-domain simulation.

Reconfigurable Wideband Linear-to-Circular Polarization Converters

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We present two reconfigurable metasurfaces that convert normally incident linear polarization into RHCP or LHCP through a 90° mechanical rotation.

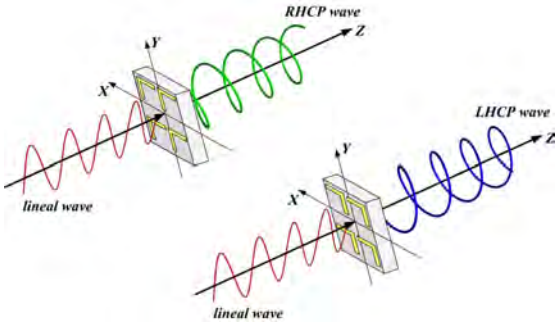


Fig. 1. Metasurfaces in transmission to convert a linearly polarized wave into either right- or left-handed circular polarization through a simple 90º mechanical rotation.

Our first proposal (Fig. 2) comprises two arrays of L-shaped metallic resonators placed on the opposite faces of a low-permittivity substrate.

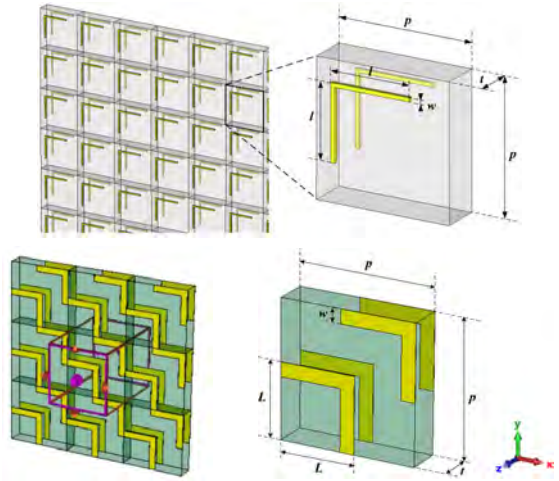


Fig. 2. First proposal (up): L-shaped resonator. Second proposal (down): staircase distribution.

The second design is a staircase-shaped transmissive metasurface. Unlike the resonator-based design, this structure employs continuous meander-line conductors, enabling distributed currents and broader bandwidth.

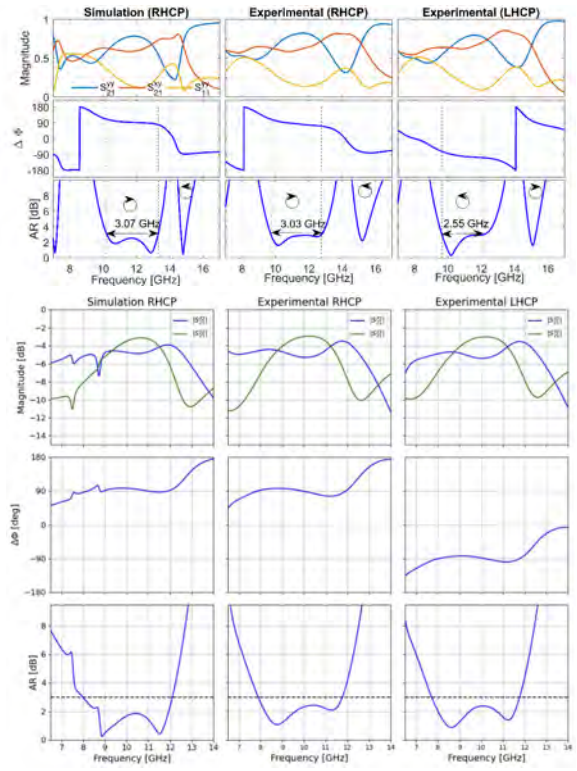


Fig. 3. Simulated and measured responses: L-shaped resonator (up) and staircase distribution (down). From top to bottom: magnitudes of the transmission ($|S_{21}^{yy}|$ and $|S_{21}^{xy}|$) coefficients; phase difference ΔΦ; and axial ratio.

The first design achieves 26% bandwidth and 65% conversion efficiency, while the second reaches 41% bandwidth covering the entire X-band (8–12 GHz). Scaled prototypes were fabricated and validated the model. These results suggest that mechanical rotation could provide a simple and reliable alternative to electronic tuning in reconfigurable circular polarizers.

ACKNOWLEDGEMENTS

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THURSDAY 29 OCTOBER

SESSION 7

Radar, Sensing and Wireless Communications

16:00-17:20 | Chair: Jesús Rubio

E02 Spherical Wavefront Synthesis for Near-Field Focusing and Spatial Modulation with Physical Layer Security

E04 Active FMCW Prototype and Dataset for Target Identification with ISAR

E09 Electromagnetic Origin of Dead Zones in Short-Range Bio-Radar and Bistatic Geometry as a Structural Solution

E08 Experimental Performance Evaluation of BPSK Communication through Multilayer Biomedical Phantoms Using a SDR

Spherical Wavefront Synthesis for Near-Field Focusing and Spatial Modulation with Physical Layer Security

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The deployment of large-scale antenna arrays operating at higher frequency bands has significantly expanded the scenarios where targets are located within the radiative near-field (Fresnel) region. In this regime, the curvature of spherical wavefronts introduces unique spatial degrees of freedom (DoF) for the advanced control of electromagnetic propagation. Unlike far-field propagation, the Fresnel region allows for Near-Field Focusing (NFF) [1]. By selecting adequate phase shifts of the radiating elements, NFF exploits spherical wavefronts to concentrate the radiated electromagnetic energy on specific 3D spatial coordinates rather than angular directions [2, 3]. To extend these techniques, this work proposes an electromagnetic wavefront synthesis framework to generate secure NFF patterns combined with spatial QAM modulation, but using strictly uniform amplitude symbols at the array. This ensures a 0 dB Peak-to-Average Power Ratio (PAPR) while effectively treating the propagation medium as an active analog spatial modulator able to recreate a QAM modulation at the receiver, and only at its location (Fig. 1).

Practical implementation of NFF in arrays typically demands complex amplitude tapering, which severely reduces power amplifier efficiency due to a high PAPR. To resolve this hardware bottleneck and maintain maximum RF efficiency, the proposed synthesis enforces a strict constant-envelope constraint where each antenna transmits with identical power. Instead of conventional linear weights, the optimal discrete phase profile is computed via projected gradient descent so that it forces the spherical waves to interfere constructively with precise amplitude and phase only at the intended spatial targets, establishing proper QAM modulation, pure energy focusing spots, or a combination of both. The nonlinear nature of this uniform-amplitude synthesis ensures that the electromagnetic field collapses at any other location, making it impossible to decode the information, guaranteeing physical layer security (PLS) through the physics of propagation.

Numerical evaluations show that the intended electromagnetic focus and signal modulation is reconstructed flawlessly exclusively at the assigned coordinates. Due to the rapid variation of the spherical phase fronts, any spatial deviation—even by just a few electrical wavelengths—disrupts the constructive interference. This spatial decorrelation triggers a massive stochastic phase collapse, scattering the received complex field chaotically and rendering the signal fundamentally undecodable to any unauthorized nearby observer, thus acting as a native electromagnetic shield. Fig. 1 whows the results of a numerical simulation using a 16×16 element array at 28GHz, where simultaneous energy focusing and a perfect 64-QAM modulation are achieved at the legitimate user's coordinates, while an eavesdropper located very closely, just a few wavelengths away, receives a collapsed signal that cannot be decoded.

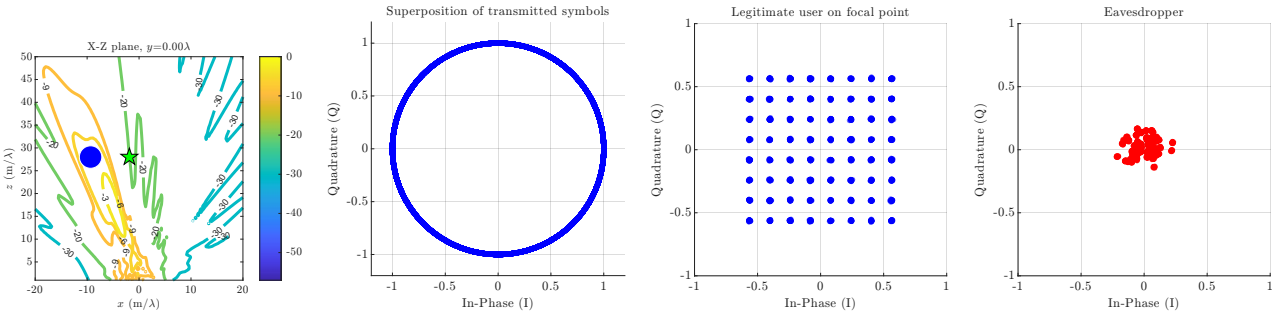
The array system can be designed to focus pure, unmodulated continuous wave power on a designated coordinate for wireless power transfer (WPT) while simultaneously projecting a modulated data field on a secondary, independent focal point (for information transfer, WIT), or both objectives can be combined on the same location (Simultaneous Wireless Information and Power Transfer, SWIPT), bridging the gap between rigorous antenna theory and advanced wireless system deployment.

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(a) X-Z plane NFF (b) Transmitted symbols (c) Synthesized focus (d) Stochastic collapse

Figure 1: Example of results: (a) Normalized received power density in the X-Z plane, highlighting the legitimate focus (blue circle) and the eavesdropper location (green star). (b) Transmitted symbol distribution, (c) reconstruction of a 64-QAM constellation at the intended coordinate, and (d) complete phase collapse observed at the unauthorized observer plane.

Active FMCW Prototype and Dataset for Target Identification with ISAR

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The increasing relevance of Unmanned Aerial Vehicles leads to an equal increase of need for that type of aircraft to be detected and classified. This work presents the design, implementation, and validation of a prototype Frequency Modulated Continuous Wave (FMCW) active radar system operating in the Ultra High Frequency (UHF) band (400 MHz to 900 MHz). With the use of a commercial transceiver, the LimeSDR Mini 2.0 software-defined radio (SDR), the developed system is tailored for Inverse Synthetic Aperture Radar (ISAR) imaging within a controlled benchtop environment.

Through the motion of a target drone, which manifests as a sum of translations, rotations, and oscillations, the radar system captures the complex electromagnetic scattering characteristics on which a detailed image can be reconstructed, and hence, the drone can be identified.

Another aspect explored is the implementation of signal processing pipelines aimed at multi-drone detection and isolation. To aid in the development of future algorithms for drone classification and target recognition, an architecture was established to compile a comprehensive radar data set through acquisition of I/Q data.

The purpose of the prototype and the data set is to provide a basis for future research on drone targeting and classification algorithms.

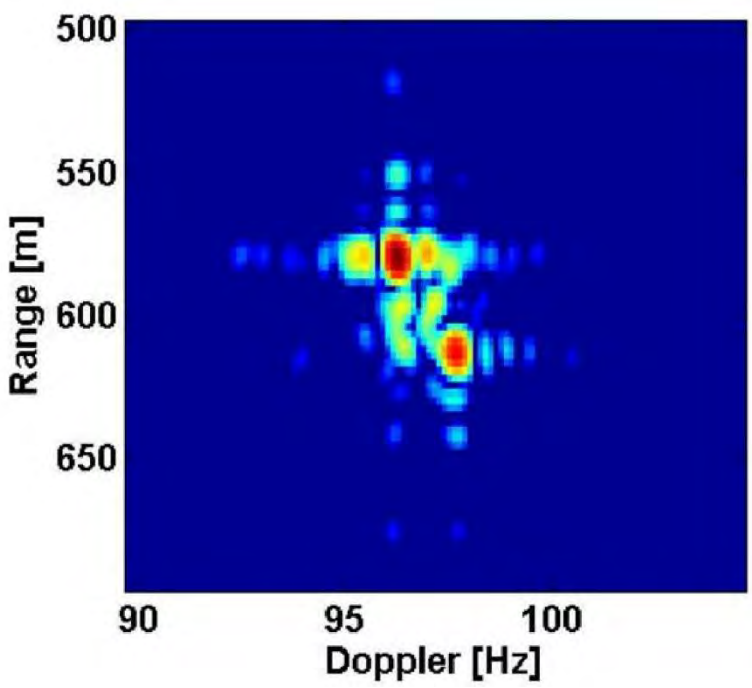


Figure 1: Example of an ISAR image of an Airbus 321 (source: https://www.ucy.ac.cy/enalab/wp-content/uploads/sites/285/2024/01/apis.pdf)

Electromagnetic Origin of Dead Zones in Short-Range Bio-Radar and Bistatic Geometry as a Structural Solution

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Abstract

Non-contact vital sign monitoring using Continuous-Wave (CW) Bio-Radar systems has attracted significant research interest due to its potential in healthcare [1], assisted living [2], and emergency response applications [3]. These systems exploit the micro-Doppler effect to detect chest-wall displacements caused by respiratory and cardiac activity, without requiring any physical contact with the subject. Despite their advantages, CW Bio-Radar systems operating at short ranges face a fundamental limitation: the received signal quality is highly dependent on the Radar Cross Section (RCS) of the human body, which exhibits an oscillatory behavior with distance in near-field conditions. At specific subject-radar distances, the RCS reaches pronounced minima, where vital sign extraction is severely compromised or entirely impossible.

Previous experimental work conducted in an anechoic chamber at $5.8\,\mathrm{GHz}$ demonstrated that these dead zones are a consistent phenomenon across subjects with different body characteristics, with the critical distance range falling approximately between 0.8 and $1.2\,\mathrm{m}$ for a monostatic CW radar configuration. To mitigate this limitation, a multi-frequency and spatial diversity approach was investigated, showing that fusing measurements at $2.4\,\mathrm{GHz}$, $5.8\,\mathrm{GHz}$, and $24\,\mathrm{GHz}$ reduces respiratory rate estimation error by up to 19%, exploiting the fact that dead zones occur at different distances for different frequencies. While effective, this approach requires multi-band hardware and does not eliminate the fundamental scattering problem.

To understand and address the root cause of dead zones, electromagnetic simulations are conducted with realistic human body models at $5.8\,\mathrm{GHz}$. The simulation methodology is first validated against the analytical near-field RCS formulation for a perfectly conducting circular disk [4]. The validated approach is then applied to digitized human body models, confirming the existence of dead zones in simulation and revealing their physical origin: destructive interference between the scattered fields of the arms and the trunk, whose phases become approximately opposed at specific distances. This geometric phase effect is shown to be consistent across models of different gender and morphology, confirming that dead zones are an inherent electromagnetic property of the near-field scattering problem rather than a subject-specific artifact.

Building on this understanding, bistatic radar geometries are explored as a structural solution to the dead zone problem. By separating the transmit and receive antennas, the bistatic configuration modifies the scattering geometry, potentially avoiding the destructive interference conditions that arise in the monostatic configuration [5]. Preliminary simulation results suggest that bistatic configurations can significantly improve RCS levels at distances where monostatic systems fail, offering a promising path toward robust vital sign monitoring across the full operational range of Bio-Radar systems.

ACKNOWLEDGMENT

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Experimental Performance Evaluation of BPSK Communication through Multilayer Biomedical Phantoms Using a SDR

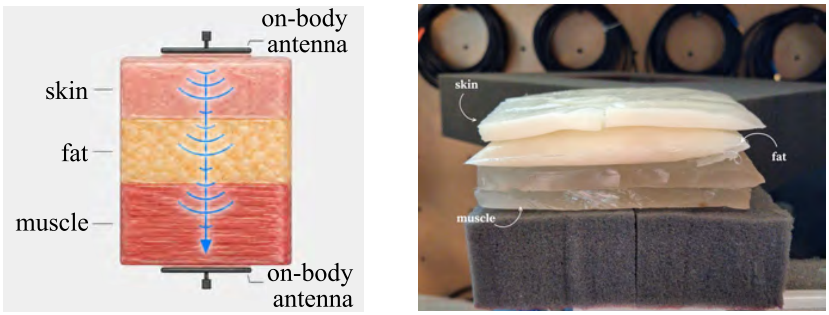
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Abstract

The rapid growth of on-body and in-body biomedical technologies demands reliable wireless data transmission through complex biological media. However, the human body introduces severe signal attenuation and impedance mismatch due to the high permittivity and conductivity of its tissues, posing a major challenge for telemetry and continuous monitoring applications [1], [2], [3]. To address this without direct human testing, this work presents an experimental evaluation of a BPSK (Binary Phase Shift Keying) digital communication link in on-body to on-body scenarios, with coupling through in-body tissues, using representative biomedical phantoms [4], [5], [6].

A wireless communication system was implemented using GNU Radio, an SDR USRP B210 platform, and on-body antennas operating in the 2.45 GHz ISM band [5], [6], [7], [8]. Individual phantoms representing skin, muscle, and fat, as well as multilayer stack-ups, were analyzed. The experimental evaluation was based on received power, attenuation, power transfer efficiency (PTE), and bit error rate (BER).

The results show that BPSK communication through biomedical phantoms is feasible, although strongly influenced by tissue composition and thickness. Individual phantoms presented lower attenuation and higher PTE, while multilayer stack-ups introduced greater losses. For transmitted powers equal to or above -40 dBm, the BER was zero in all tested configurations, whereas at -60 dBm some stack-ups showed significant degradation. Overall, BPSK modulation proved to be a robust solution for data transmission through emulated biomedical media, provided that the received power remains above a minimum reception threshold. The conceptual communication scenario along with the developed multilayer phantom prototype structure are illustrated in Fig. 1.



(a) (b)

Fig. 1. Overview of the evaluation environment: (a) conceptual representation of RF signal transmission by on-body antennas through the biological medium (AI-generated for illustrative purposes), and (b) prototype of the fabricated multilayer phantom showing the distinct skin, fat, and muscle layers used during the bench tests.

Acknowledgment

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