



PULSE – Plasma reconfigURabLe metaSurface tEchnologies

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¹ **Type:** R = Report, P = Prototype, DEM = Demonstrator, DMP = Data Management Plan, O = Other

² **Dissemination Level:** PU = Public, SEN = Sensitive

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1. Purpose and scope of the deliverable

This document summarizes the main conclusions of the scientific discussion between the project participants carried out during the internal workshop held in hybrid form on September 10, 2023 (physical location: Crete, Greece). The main scope of the workshop has been to brainstorm and define – in a more systematic way - the scientific guidelines of the research to be carried out during the project.

2. Introduction to the project

PULSE is a European Project funded under the call *EIC Pathfinder Open 2022*, pursuing the ambitious goal of defining a **new technological horizon for implementing reconfigurable electromagnetic devices** by unifying the research domains of **METASURFACES** with **PLASMA** physics.

Indeed, the widespread proliferation of wireless systems and the emergence of exciting new wireless technologies (such as 5G and beyond-5G communication systems) are rapidly expanding their application fields (Internet of Things, autonomous vehicles, Industry 4.0, Smart Environments and Cities, Factories of the Future, e-Health, etc.), offering novel economic opportunities and bringing benefits to the society. In this framework, **electromagnetic (EM) reconfigurability** represents a *key enabling technology*, as it allows changing in real time the functionalities and the signature of a device, allowing to use it for different purposes and to react promptly against external attacks or to be adapted to different environmental constraints or conditions.

The main objective of the project is to exploit **plasmas-based metasurfaces** as a **radically new technological platform**, which allows to conceive and realize **cutting-edge devices exhibiting novel functionalities**. In particular, the proposed research program aims at revolutionizing the tuning strategies currently employed for artificial metasurfaces as well as introducing brand-new unprecedented functionalities for the next generation of wireless systems.

The ultimate goal of PULSE is to prove the **technological feasibility of different types of plasma-based reconfigurable metadevices** and their effectiveness for next-generation of wireless systems. For this purpose, four science-to-technology breakthroughs are proposed. In addition, the project aims at laying the **theoretical and technological foundations of a new family of metadevices**, in which the individual elements can change their shape in time.

Application areas	Technological lines	TRL-IN	TRL-OUT	Analysis	Demonstrator	Key performance indicators
Tunable lenses for antennas	Plasma meta-atoms in dielectric environments	2	4	Plasma simulation code combined with off the shelf simulation tools (Finite Element Method (FEM) & Finite Integration Technique (FIT))	Tunable beam steering using planar metalens for antennas (metagrating). <i>Target frequency:</i> 16-20 GHz (Ku band) with goal to Ka band	- Maximum deflection angle - Scan loss - Insertion loss - Side lobe level - Radiation efficiency - Tunability rate - Bandwidth
	Plasma based substrates with conventional meta-atoms	2	4	Plasma simulation code combined with off the shelf simulation tools (FEM & FIT)	Cylindrical metasurface surrounding a dipole / planar metasurface for horn or waveguide antenna. <i>Target frequency:</i> X band	- Pointing angle - Maximum directivity/gain - Scattering cross section - Absorption cross section - Tunability rate - Bandwidth
Non-reciprocal devices	Time-modulated plasma meta-atoms in dielectric environment	2	4	EM simulation codes for time-varying structure (Finite Difference Time Domain (FDTD) & FEMTD)	Magnet-less non-reciprocal isolator for waveguides. <i>Target frequency:</i> 1-2 GHz (L band)	- Isolation - Insertion loss - Power handling - Bandwidth
Four-dimensional (4D) devices	Single time-varying radiating meta-atom and a dielectric substrate with shape-variant plasma meta-atoms	1	3	EM simulation codes for shape-varying structures (FDTD & FEMTD)	Multiband/wideband metadevice <i>Target frequency:</i> UHF band	- Bandwidth - Tunability rate

Figure 1: The different science-to-technological breakthroughs involved in PULSE.

3. Summary of the scientific and technological methodologies

The scientific and technological approaches agreed during the workshop rely on the proper combination, integration and generalization of different methodologies belonging to the scientific and technological areas involved in the project. In the following, we summarize the different methodologies that have been discussed during the workshop and that are considered to be relevant to the project scopes. They are classified into several Sections, related with the different aspects that need to be addressed for achieving the ultimate goal of the project discussed above. The attachments to this document provide a more detailed explanation of the different techniques and how the different beneficiaries are planning to carry out the research activities.

1.1. Physical modelling and design

The physical modelling and design will be carried out by using relevant analytical and semi-analytical approaches commonly employed to describe the EM behavior of metadevices and plasma.

Regarding the **tunable lens for antennas**, we plan to explore the use of phase-gradient metasurfaces and meta-gratings. Both represent classes of engineered surfaces designed to control and manipulate electromagnetic waves beyond the conventional laws of electrodynamics. The formers are typically composed of an inhomogeneous arrangement of subwavelength elements, known as meta-atoms, aligned in a given direction and forming a desired phase distribution. Meta-gratings, instead, are sparser composite whose working principle combines the engineering of the meta-atom characteristics with the physics of the diffraction gratings. The tunability is achieved either by acting on the host material (i.e., plasma is used as the host medium for metallic meta-atoms) or by acting on the meta-atoms themselves (i.e., plasma is used to realize the meta-atom).

The physical modelling of all these scenarios requires to combine and integrate multiple approaches, as summarized below.

When plasma will be considered as a reconfigurable environment for metallic metasurfaces, the single unit cell of the metasurface structure can be implemented through a cascade configuration of metallic layers deposited onto plasma substrates. The structure can be simplified to a cascade configuration of ideal electric impedance sheets separated by (reconfigurable) substrates. The configuration can be conveniently modeled by exploiting a microwave network approach based on ABCD matrix and, then, retrieving the transmission, reflection and absorption coefficient through the generalized S-parameter transformation. It is expected that the availability of a close-form expression for the transmission coefficient allows to analyze the unit-cell when varying the properties of the substrate and to identify the geometrical and electromagnetic characteristics needed to achieve full 2π phase-coverage with unitary transmission.

For what concerns the modelling of the individual plasma element (meta-atom) composing the metadevices, different approaches will be explored. For 2D and 3D elementary shapes, such as spheres or cylinders, the electromagnetic response will be rigorously characterized using Mie scattering theory. It is expected that plasma elements have a quite complex scattering response as their complex-valued electric permittivity spans within a wide range of possible values. It is therefore needed to identify the best conditions for the applications involved in the project. In addition, the effect of the dielectric shell used to enclose the gas discharge should be taken into proper account by generalizing the analysis to core-shell configurations. The main goal of the analysis will be to identify the combinations of size (i.e., electrical radius) and material parameters (i.e., plasma

frequency, pressure, etc.) able ensuring low backscattering from the isolated particle (*i.e.*, full forward scattering) and minimizing the absorption cross section.

When moving from the single element to the modelling of uniform arrangement of plasma elements, electromagnetic homogenization approaches (both surface and volumetric) will be used. This term refers to the process of modeling and analyzing the electromagnetic properties of complex, heterogeneous materials as if they were homogeneous on a macroscopic scale. In other words, it involves simplifying the behavior of a composite material made up of multiple components with varying electromagnetic properties into an equivalent homogeneous material with effective electromagnetic properties.

For two-dimensional composites (e.g., consisting of a single layer of plasma elements), we plan to use a surface impedance homogenization approach able describing the macroscopic behavior (*i.e.*, reflection and transmission coefficient) of an array of homogenous plasma elements in terms of effective electric and magnetic surface impedance. In this approach, the response of the individual element can be directly derived by the Mie scattering coefficients, while the interaction between the elements can be estimated through appropriate theoretical considerations.

For three-dimensional or electrically thick composites, we plan to apply retrieval procedures for evaluation of effective material parameters (*i.e.*, permittivity, permeability) from reflection and transmission data. Moreover, we will employ the Coherent Potential Approximation (CPA) homogenization scheme and compare with Maxwell-Garnett and with the retrieval procedure results, to evaluate the most suitable homogenization scheme for different plasma operation conditions. CPA is based also on the Mie theory, and it is applicable beyond quasi-static limit, as it accounts for the scatterer resonances. Furthermore, it can be applied to a broad range of materials (metals, dielectrics, resonant materials) and provides closed, semi-analytic formulas for the effective parameters.

The main goal of the homogenization approaches will be to identify the combinations of size, material parameters (including the background) and interaction ensuring (ideally) 2π phase-coverage with unitary transmission. In the case of surface homogenization, the possibility of cascading multiple homogenous surfaces to increase the phase coverage will be considered and analyzed using a microwave matrix approach.

Regarding the modelling of the gradient metasurfaces and meta-gratings, we will explore the use of the Floquet-Bloch theorem, which guarantees that the reflected and transmitted fields can be expressed as a series of modes with different propagation directions. Once known the period of the metadvice and its impedance profile (for the case of gradient metasurfaces), the transmission and reflection coefficient of each mode can be calculated and optimized.

When the **time-varying designs** are considered, the extension of the Mie theory to isolated objects made from dispersive materials with periodically time-varying parameters will be considered. Time-domain and Fourier analysis of the reflection coefficient will allow to estimate the induced frequency-shift by a homogenous time-modulated metasurface. Alternative approaches to achieve non-reciprocity based on non-equilibrium plasma will be also considered.

Finally, for the **plasma modelling**, it is planned to exploit a lossy Drude model, where the plasma and collision frequencies depend on the electron density and gas pressure and composition. This approach heavily reduces the computational cost of describing the plasma formation and spatiotemporal behavior. The latter will be approximated based on literature data as well as experimental measurements from the fabricated plasma sources, under various operating

conditions. If needed, a more complex self-consistent approach will be used to describe plasma breakdown and discharge evolution based on the fluid-closure of the Boltzmann equations under the drift-diffusion and local field approximations, coupled with Poisson's equation for the electrostatic fields. This self-consistent approach will allow to obtain both spatial characteristics of the discharge (occupied volume, plasma density profiles etc.) as well as temporal behavior in terms of discharge inception towards quasi steady-state operation which can feed the lossy Drude model with more accurate spatiotemporal profiles (or be directly coupled with the EM solvers). Due to the extremely high computational cost of such simulations, the plasma chemistry will be approximated by simple (typically air-plasma) chemistry sets.

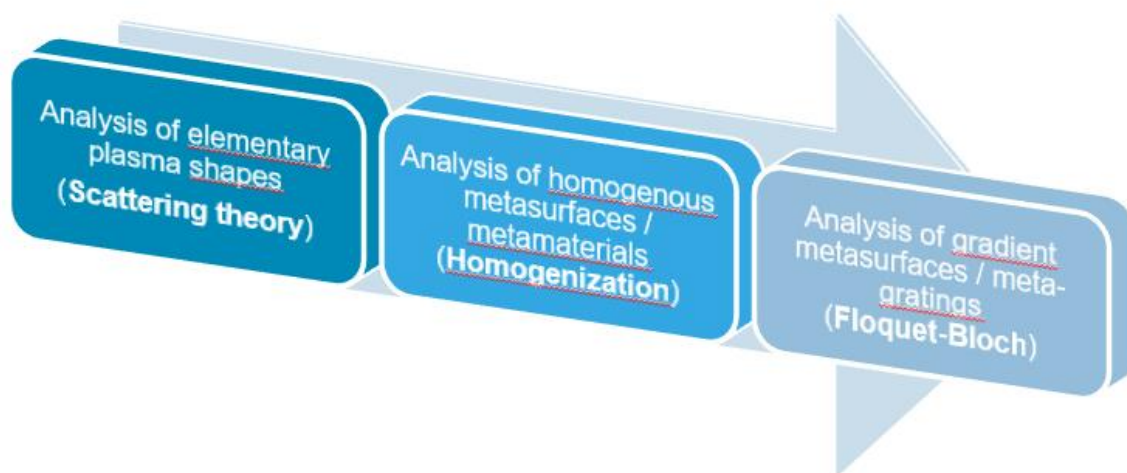


Figure 2: Workflow of the different approaches used to model and design the metadevices with plasma meta-atoms.

1.2. Numerical simulations

As for the **numerical simulations**, they will be based on commercial software whenever possible and, especially, in advanced in-house computational electromagnetic codes for accurate and reliable simulation of the unprecedented electrical phenomena under study, which propose a synergy between plasma physics and electrodynamics.

Both, steady-state numerical solutions to time-harmonic Maxwell's equations as well as numerical approximations to analyze the transient behavior in time-domain Maxwell's equations will be considered. As such, integral equation solvers, finite element approaches and finite difference methodologies, for both time-domain and frequency-domain analyses, are fundamental numerical codes available in the Consortium. In addition, model-order reduction techniques in time-domain and steady-state analyses will be taken into account to carry out an efficient computer-aided design and sensitivity analysis of the prototypes detailed in this project.

1.3. Manufacturing

The research activities dealing with the **manufacturing** of the plasma-based metadevices will be focused on the identification of the most suitable materials for the production of the components and on the development of the processes for the manufacturing of the devices. Two different fundamental geometries will be considered: single- or multi-column plasma meta-device and plasma dots matrix. In both cases, the manufacturing process is expected to be realized in five steps:

1. *Engraving of the dielectric matrix to create the elements.* This step will be carried out using either micromilling machine or a femtosecond laser. The electromagnetic and mechanical characteristics of different dielectric materials, such as PDMS (polydimethylsiloxane), PMMA (polymethylmethacrylate), PEEK (polyetheretherketone), Flexdym (by Eden Tech), glass and ceramics, will be explored. The geometries to be investigated include holes, cavities and channels and will be characterized using optical microscopes and interferometers.
2. *Filling of the elements under controlled atmosphere and pressure.* This step will be accomplished through a vacuum chamber equipped with sensors for relative humidity, temperature, oxygen concentration and pressure gauge.
3. *Sealing of the elements.* For this purpose, different technical solutions, such as plasma-assisted oxidation, gluing, welding using dichloromethane, and simple compression, will be explored, depending on the chosen dielectric matrix.
4. *Addition and control of the electrodes for controlling individual plasma elements and/or sub-groups of them.* Electrodes will be made of stainless-steel and can be placed either in direct contact with plasma discharge or in dielectric-mediated contact with plasma discharge. Both AC and DC power supply will be considered.
5. *Ignition and characterization of the plasma discharges* in terms of gas discharge uniformity, voltage breakdown, electron density, switching velocity, etc.

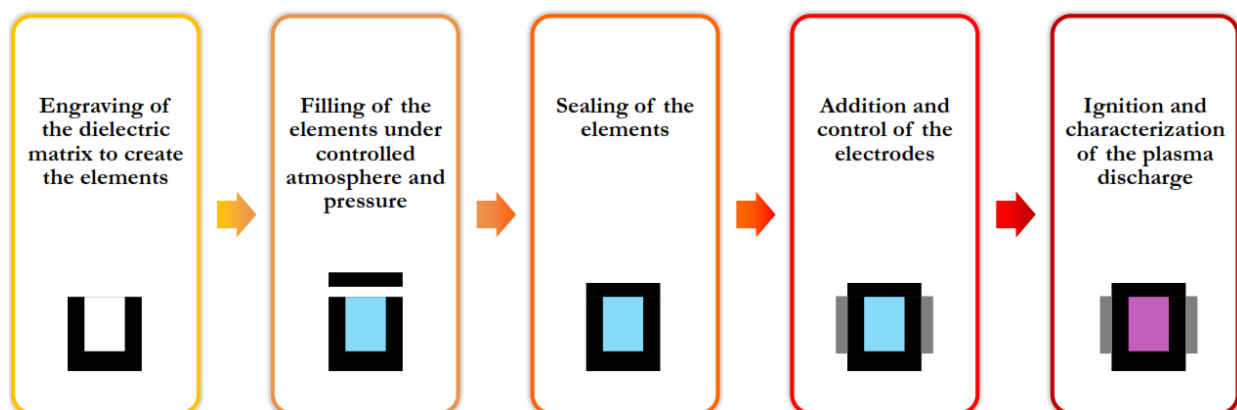


Figure 3: Envisioned steps towards the realization of the target plasma meta-devices.

1.4. Characterization

The **electrical characterization** of the metadevices will be carried out using voltage and current probes and oscilloscopes. Different strategies will be considered, based on the use of a signal generator with different waveforms (e.g., sine, square, triangle, sawtooth, etc.) combined with either a passive or an active amplifier, the use of a DC high voltage generator combined with a MOSFET and the use of a resonator generator, custom produced on the capacity of the plasma device.

The **electromagnetic characterization** will be carried out with both conventional and innovative procedures and equipment (employing, among others, multiport microwave network analyzers coupled with different horn and dipole antennas), able to measure the full EM wave transmission and reflection amplitude, phase and radiation pattern of the structures under investigation in the range of 300 kHz to 40 GHz. The typical setup for plasma-lens testing used for antenna characterization is shown in Figure 4. In this setup, the transmitter and the receiver are separated

by a known distance. The transmitter antenna is connected to a signal generator, and the receiver is mounted on an extended arm on a linear positioner, wherein the extended arm moves in azimuth.

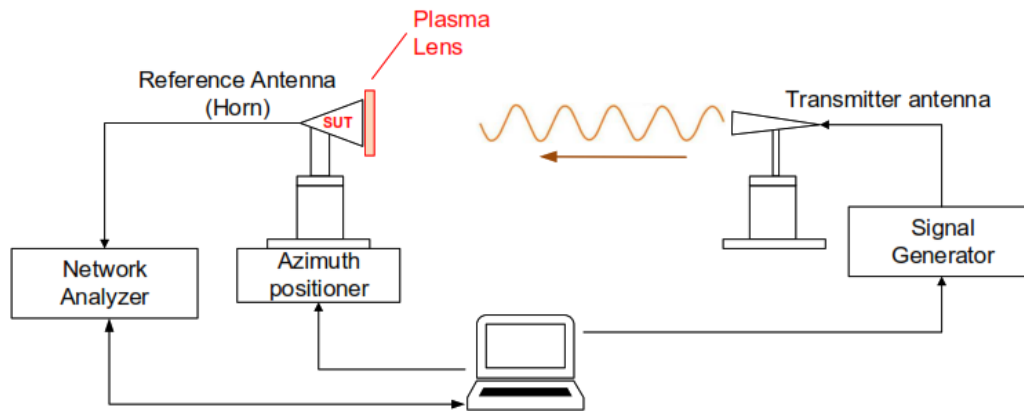


Figure 4: Envisioned typical setup for plasma-lens testing.

The horn antenna is used as standard receiving antenna. The Antenna Under Test (AUT) is used as receiving antenna in the setup. The AUT is placed on a rotating table or positioner. The RF synthesizer or sweeper is used at the transmitter which feeds the signal of desired frequency and power. AUT is rotated in azimuth and the receiving characteristics are recorded for post-processing analysis.

Besides free-space measurements, wave-guide measurements will be also considered for an easier assessment of the effective parameters of any particular structure.

1.5. Market analysis

The realized prototypes will be also analyzed in terms of **industrial exploitability**. The features to be considered include materials (cost, durability), machining techniques (cost, duration), sealing (cost, efficacy, durability), power supply (cost, safeness, durability, size, power consumption) and gas (cost, pressure, safeness).

1.6. Final remarks

It is agreed that, to minimize the scientific and technological uncertainties involved in the project, the research methodology will be based on a *dividi-et-impera* approach. In particular, before the design and the realization of the final prototypes, some proof-of-principle devices will be designed, simulated, manufactured and cross-validated to assess the suitability and the agreement between theoretical, numerical and experimental approaches. This methodology will allow to identify, at a preliminary stage, potential misleading assumptions and to refine theoretical models, co-simulation routines and manufacturing processes.

4. Attachment list

<i>Name</i>	<i>Short name</i>	<i>Description</i>
ROMA TRE University presentation	Att#1	Slide used to introduce and discuss the general research guidelines of ROMA TRE UNIVERSITY
ALMA SISTEMI presentation	Att#2	Slide used to introduce and discuss the general research guidelines of ALMA SISTEMI S.R.L.
FORTH presentation	Att#3	Slide used to introduce and discuss the general research guidelines of FORTH
AALTO University presentation	Att#4	Slide used to introduce and discuss the general research guidelines of AALTO
METAMORPHOSE-VI presentation	Att#5	Slide used to introduce and discuss the general research guidelines of METAMORPHOSE-VI
UNIVERSIDAD POLITECNICA DE MADRID presentation	Att#6	Slide used to introduce and discuss the general research guidelines of UPM
UNIVERSITY OF BOLOGNA presentation	Att#7	Slide used to introduce and discuss the general research guidelines of UNIVERSITY OF BOLOGNA
ALMAPLASMA presentation	Att#8	Slide used to introduce and discuss the general research guidelines of ALMAPLASMA S.R.L.



Plasma reconfigurable metaSurface technologies



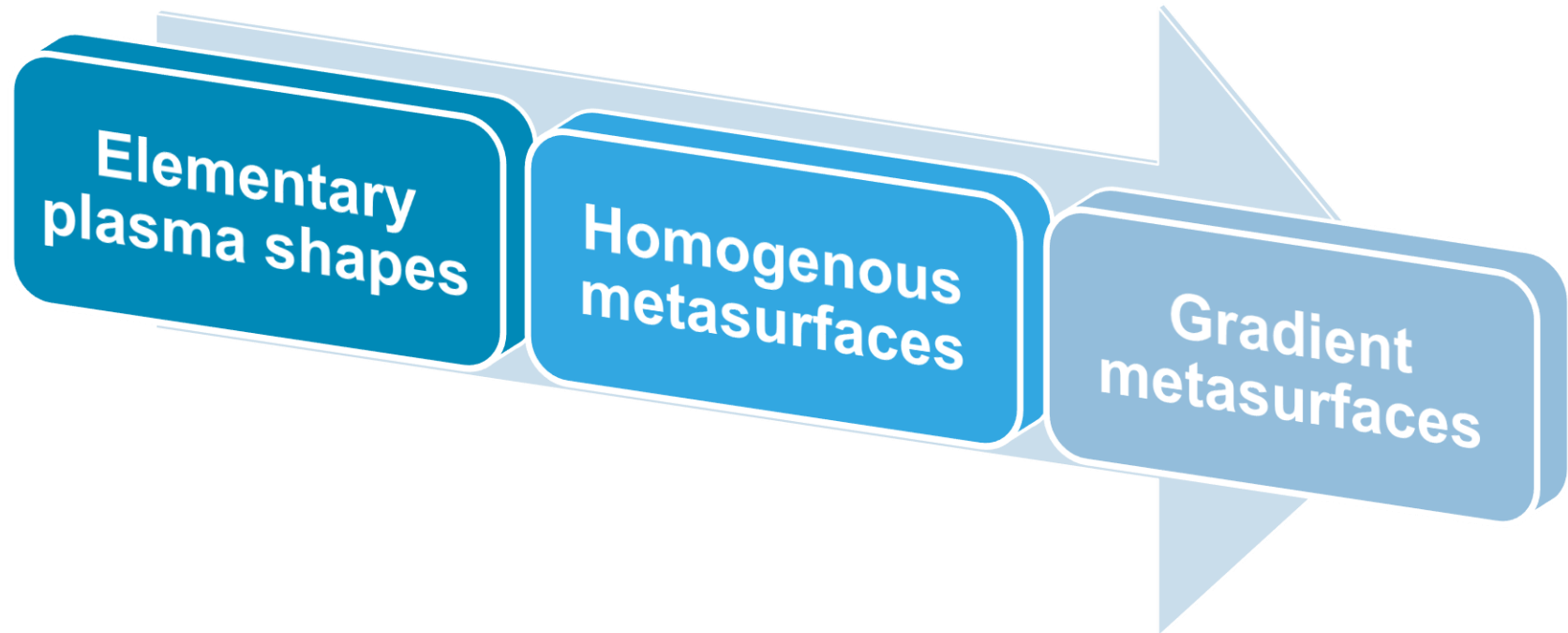
PULSE

Internal workshop

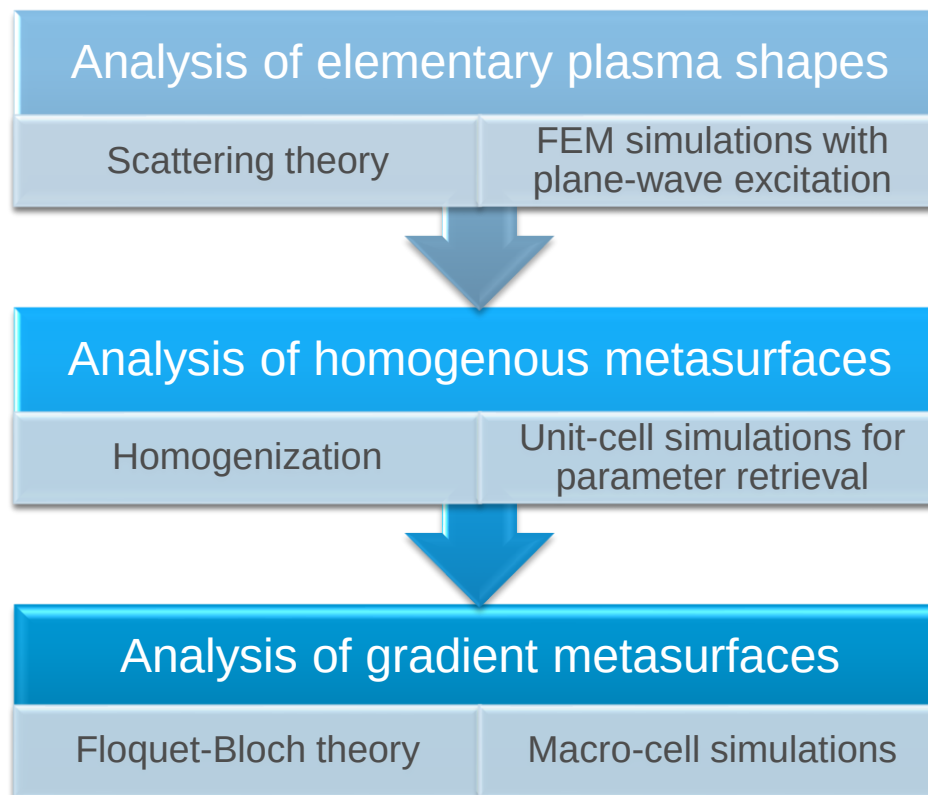
Roma Tre main scientific involvement

Task / WP	Description	Approaches
Task 1.1 Metasurface & meta- grating analysis	The task aims at systematically reviewing the relevant scientific literature about reconfigurable metadevices working at the target frequency ranges. The potentialities and the limitations of each approach, as well as the relevant fundamental limitations, will be emphasized in order to define realistic benchmarks for the demonstrators	• Selection of appropriate keywords • Systematic search on the relevant scientific research database • Taxonomic classification of the results • Definition of inclusion/exclusion criteria (frequency range, application area, experimental characterization, relevance to the project).
WP 2 Metalenses for antennas	Designing, and numerically characterizing plasma-based metadevices working as reconfigurable lenses for wire and aperture antennas.	• Scattering theory • Homogenization theory • Floquet-Bloch theory • Numerical simulations

Analyses & Design workflow

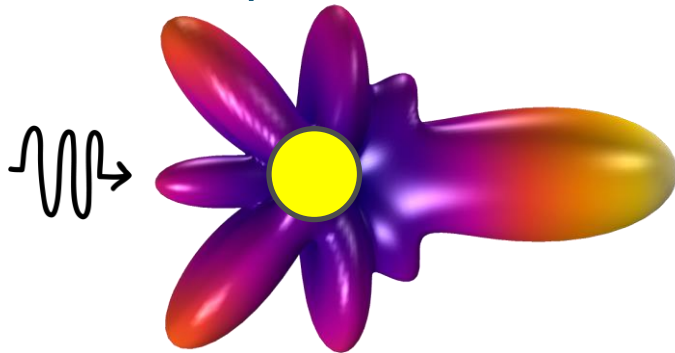


Theoretical & numerical approaches



Scattering theory

- The electromagnetic response of the individual element can be rigorously characterized using Mie scattering theory for elementary shapes.



$$a_n = \frac{m \psi_n(m x) \psi'_n(x) - \psi_n(x) \psi'_n(m x)}{m \psi_n(m x) \xi'_n(x) - \xi_n(x) \psi'_n(m x)}$$

$$b_n = \frac{\psi_n(m x) \psi'_n(x) - m \psi_n(x) \psi'_n(m x)}{\psi_n(m x) \xi'_n(x) - m \xi_n(x) \psi'_n(m x)}$$

$$Q_{\text{sca}} = \frac{2}{x^2} \sum_{n=1}^{\infty} (2n+1) (|a_n|^2 + |b_n|^2)$$

$$Q_B = \frac{1}{x^2} \left| \sum_n (2n+1) (-1)^n (a_n - b_n) \right|^2 \quad Q_F = \frac{1}{x^2} \left| \sum_n (2n+1) (a_n + b_n) \right|^2$$

$$m = \frac{n_{\text{sphere}}}{n_{\text{back}}} = \frac{\sqrt{\epsilon_{\text{sphere}}}}{\sqrt{\epsilon_{\text{back}}}}$$

$$x = ka = \frac{2\pi a}{\lambda_0} n_{\text{sphere}} = \frac{2\pi a}{\lambda_0} \sqrt{\epsilon_{\text{sphere}}}$$

Bohren and Huffman, *Scattering and absorption of light by small particles*



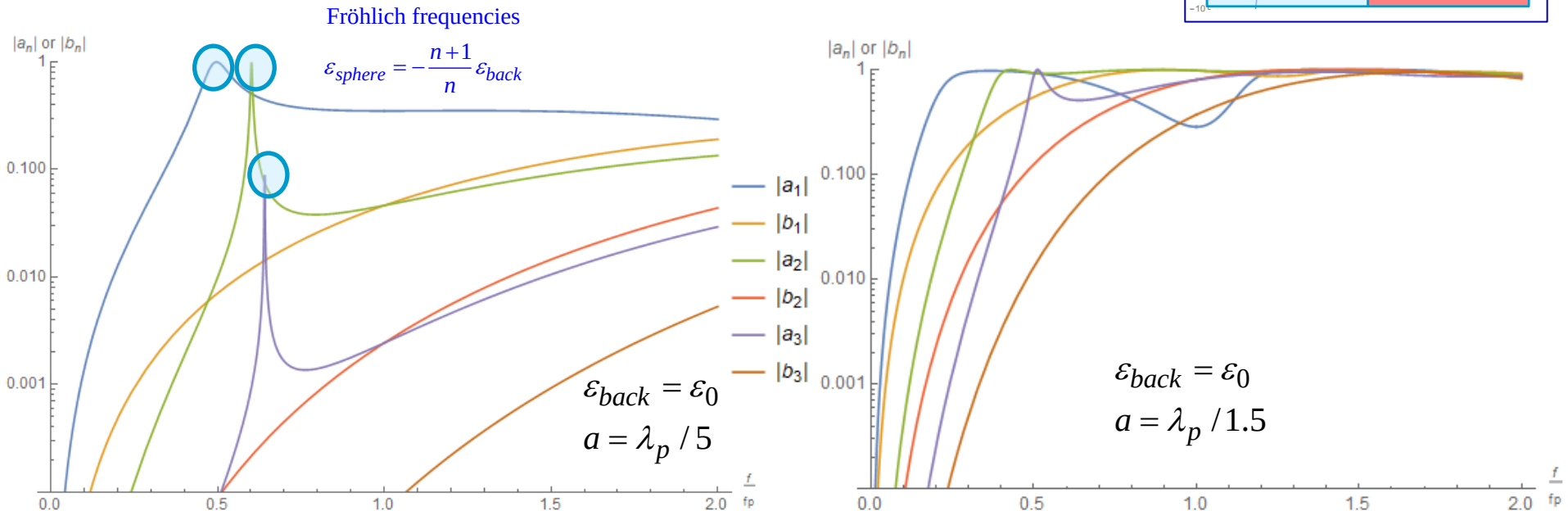
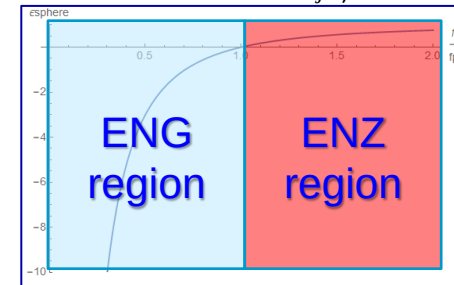
Scattering theory

- ❑ Plasma elements have a quite complex scattering response as their complex-valued electric permittivity spans within a wide range of possible values. It is therefore needed to identify the best conditions for the applications involved in the project.
- ❑ In addition, the effect of the shell used to enclose the gas discharge should be taken into proper account (i.e., core-shell configuration).
- ❑ The main goal of the analysis will be to identify the combinations of size (i.e., electrical radius) and material parameters (i.e., plasma frequency, pressure, etc.) able ensuring low backscattering from the isolated particle (i.e., full forward scattering).

Scattering by a plasma sphere

- Collision-less plasma sphere ($f_p = 7.5$ GHz).

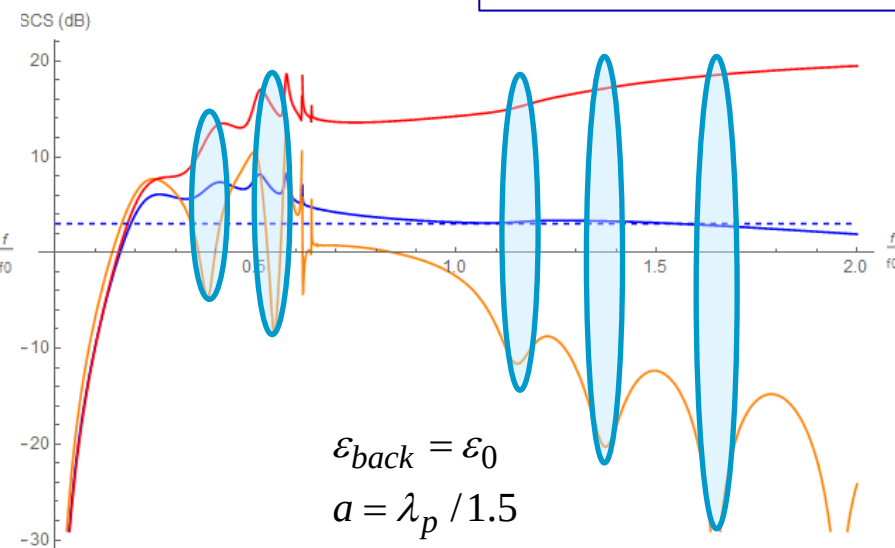
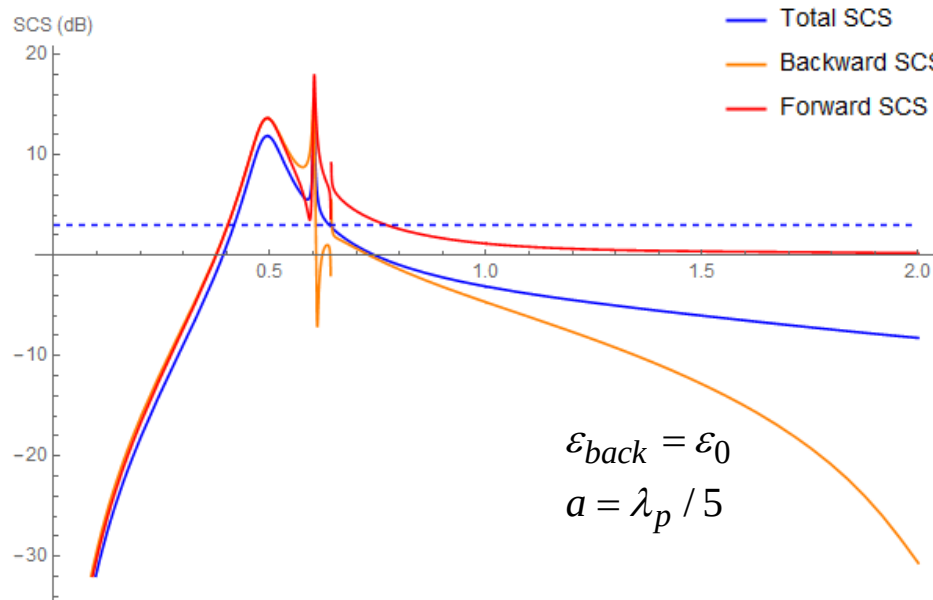
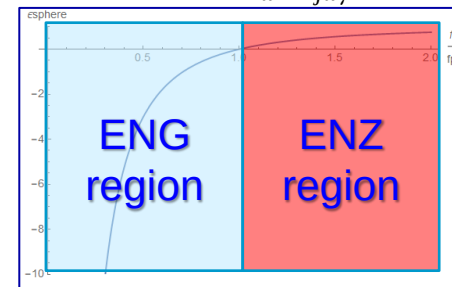
$$\epsilon_{\text{sphere}} = 1 - \frac{\omega_p^2}{\omega^2 - j\omega\gamma}$$



Scattering by a plasma sphere

- Collision-less plasma sphere ($f_p = 7.5$ GHz).

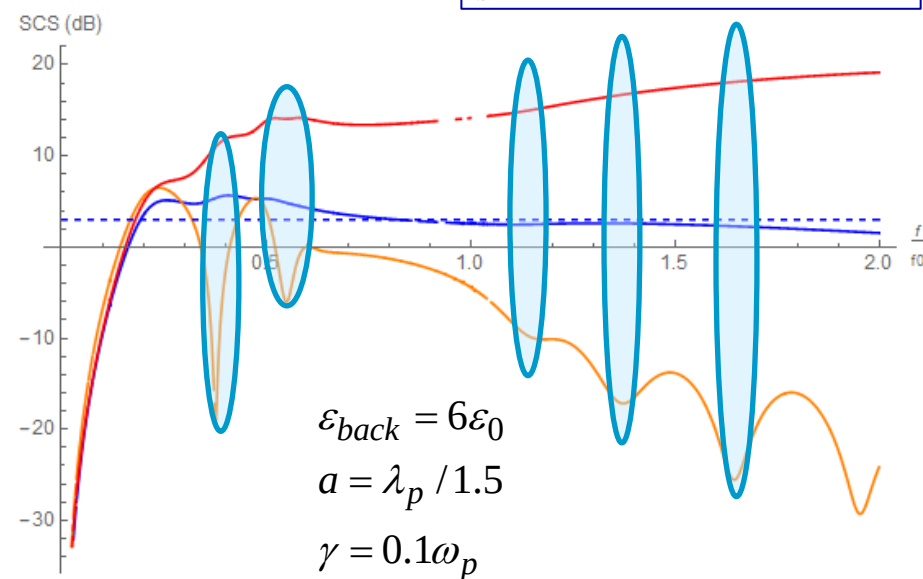
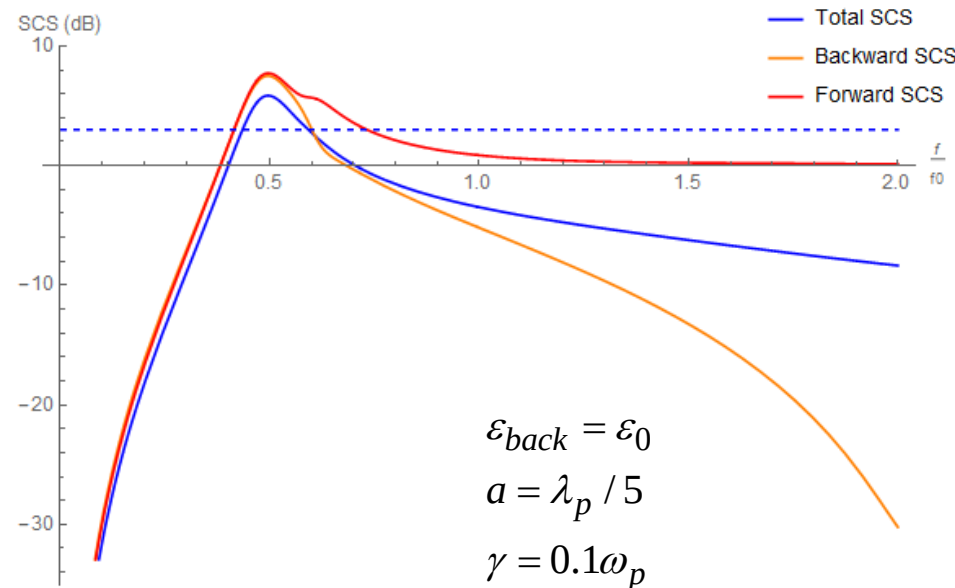
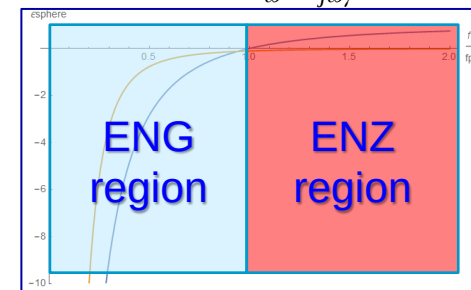
$$\epsilon_{\text{sphere}} = 1 - \frac{\omega_p^2}{\omega^2 - j\omega\gamma}$$



Scattering by a plasma sphere

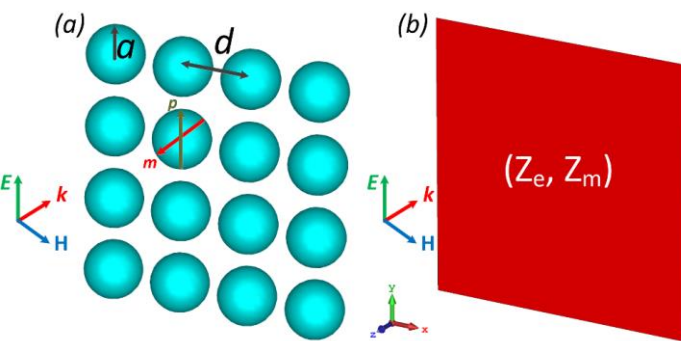
- Collision plasma sphere ($\gamma = 0.1 \omega_p$).

$$\epsilon_{\text{sphere}} = 1 - \frac{\omega_p^2}{\omega^2 - j\omega\gamma}$$



Homogenization theory

- ❑ Electromagnetic homogenization allows to estimate the effective electromagnetic properties of complex composite materials.
- ❑ We plan to use a 2D homogenization approach with the aim to describe the macroscopic behavior (i.e., reflection and transmission coefficient) of an array of homogenous plasma elements in terms of electric and magnetic surface impedance.



$$\Gamma(\vartheta_0) = \frac{-\eta_0}{2Z_{\text{symm}} \cos(\vartheta_0) + \eta_0} + \frac{Z_{\text{asymm}}}{Z_{\text{asymm}} + 2\eta_0 \sec(\vartheta_0)}$$

$$T(\vartheta_0) = 1 - \frac{\eta_0}{2Z_{\text{symm}} \cos(\vartheta_0) + \eta_0} - \frac{Z_{\text{asymm}}}{Z_{\text{asymm}} + 2\eta_0 \sec(\vartheta_0)}$$

$$Z_{\text{symm}} = Z_e^t + Z_m^n$$

$$Z_{\text{asymm}} = Z_m^t$$

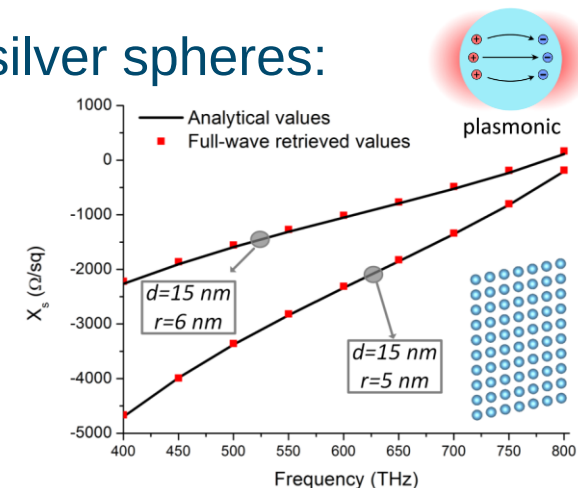
Homogenization theory

- In this surface-impedance homogenization approach, the response of the individual element can be derived by the Mie scattering coefficients, while the interaction between the elements can be estimated through appropriate theoretical considerations.
- For instance, for an array of electrically-small silver spheres:

$$\frac{Z_e}{\eta_h} = -\frac{d^2}{k} \left[\left(\text{Im} \left[\alpha_e^{-1} \right] - \frac{k^3}{6\pi} \right) + i \left(\text{Re} \left[\alpha_e^{-1} - \beta_e \right] \right) \right]$$

$$\alpha_e = -i \left(\frac{6\pi}{k^3} \right) a_1$$

$$\beta_e = \text{Re} \left[\frac{jk}{4(R_0 d)^2} \left(1 + \frac{1}{jkR_0} \right) e^{jkR_0} \right] + j \left(-\frac{k^3}{6\pi} + \frac{k}{2(R_0 d)^2} \right)$$



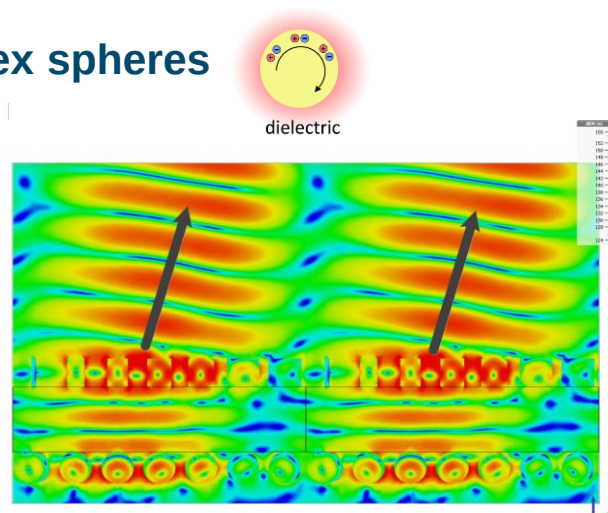
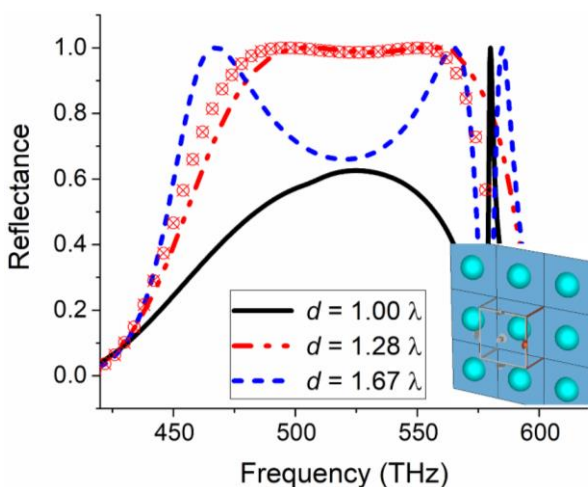
S. Tretyakov, *Analytical modelling in applied electromagnetics*, Artech House, 2003

Monti et al., JAP **117**, 123103, 2015

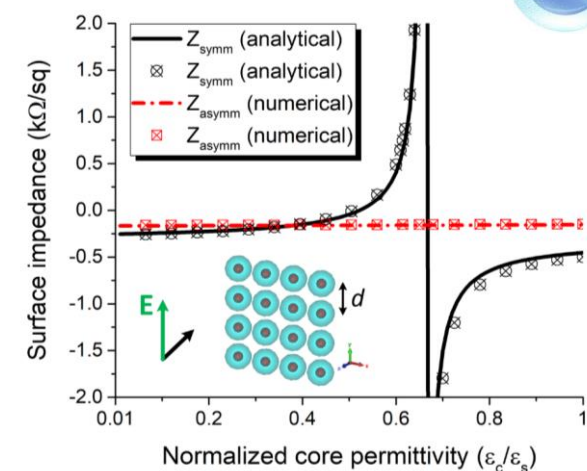
Homogenization theory

- Homogenization of more complex structures.

High-index spheres



Core-shell spheres

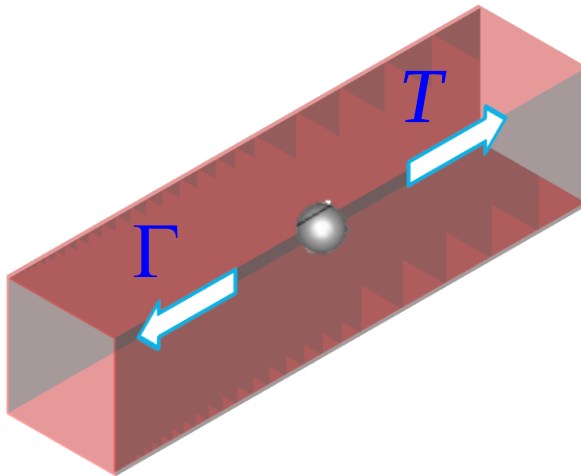


A. Monti et al., IEEE TAP **68**, pp. 1799-1811, 2020

A. Monti et al., IEEE TAP **69**, pp. 5142-5147, 2020

Numerical-based retrieval procedure

- Numerical results of unit-cell simulations (periodic conditions) can be used to retrieve the electric and magnetic surface impedance.

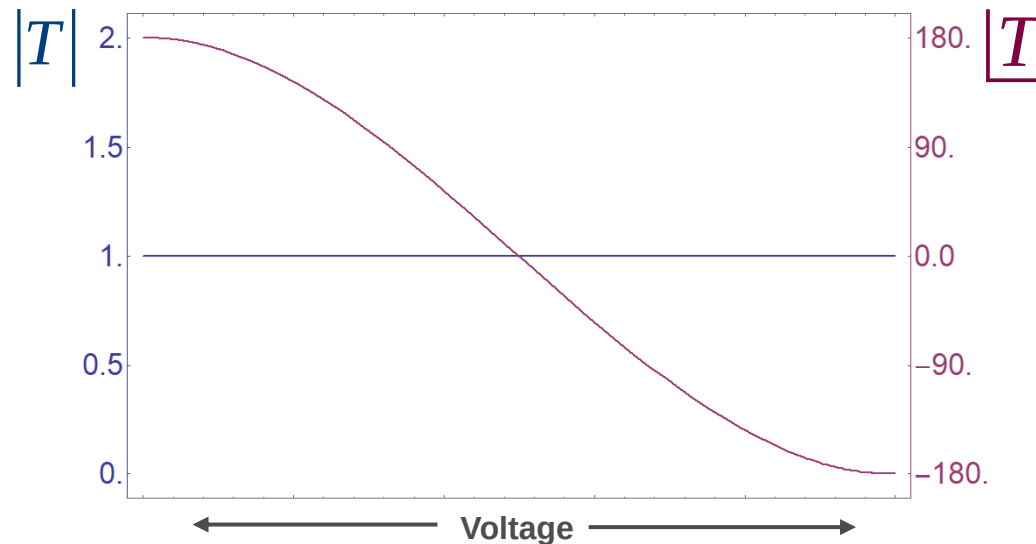


$$Z_e = \frac{-\eta_0 (1 + \Gamma + T)}{2(-1 + \Gamma + T)}$$

$$Z_m = \eta_0 \left(-2 + \frac{4}{1 - \Gamma + T} \right)$$

Homogenization theory

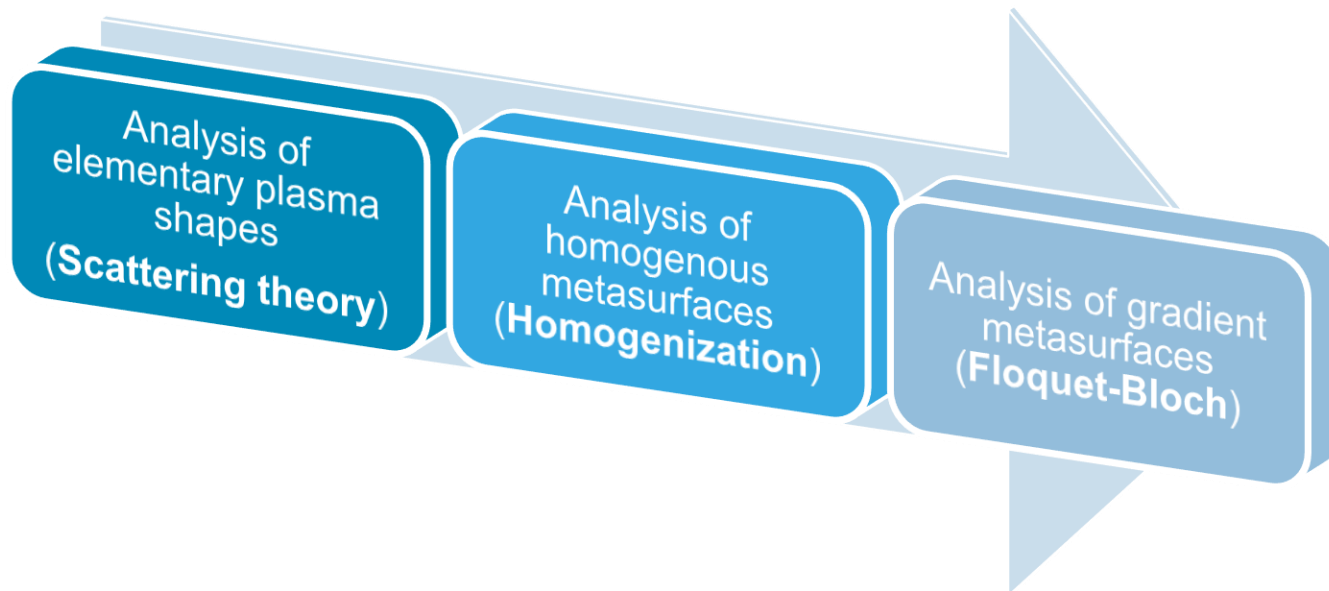
- The main goal of the analysis will be to identify the combinations of size, material parameters (including the background) and interaction ensuring (ideally) 2π phase-coverage with unitary transmission.



Floquet-Bloch theory

- ❑ The metasurface needed for the project scopes are non-homogenous (a transmission phase profile is required).
- ❑ The *Floquet-Bloch theorem* guarantees that the reflected and transmitted fields can be expressed as a series of modes.
- ❑ Once known the surface impedance profile, the transmission and reflection coefficient of each mode can be calculated.
- ❑ Optimization of the impedance profile is also possible, in principle.

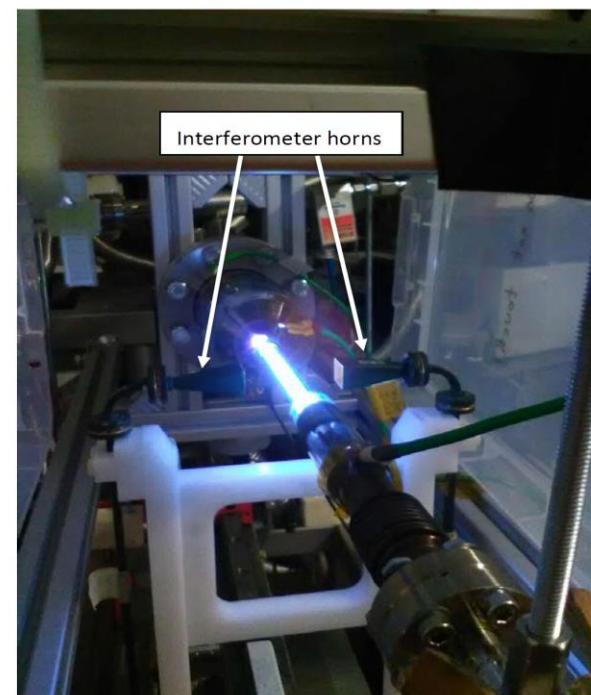
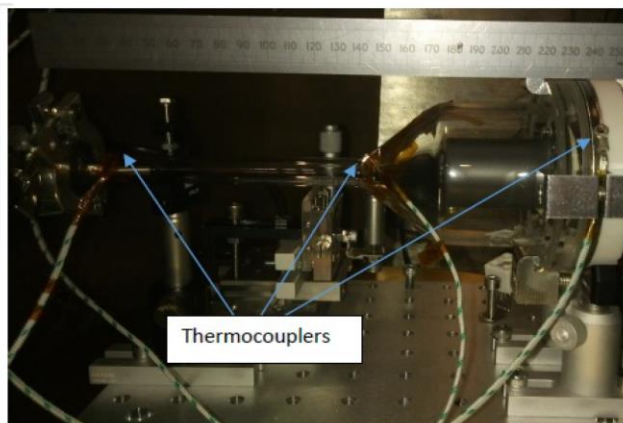
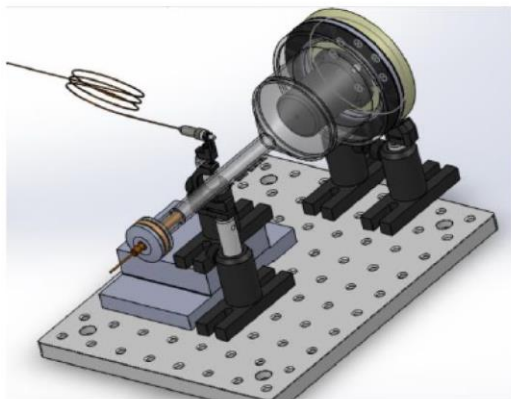
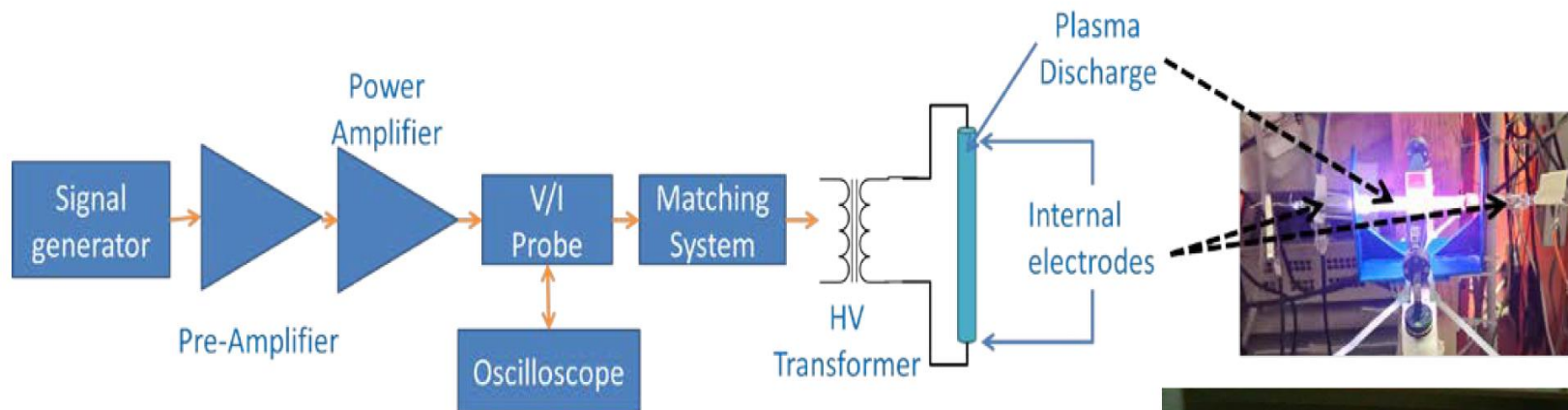
Approaches





Company Overview – February 23

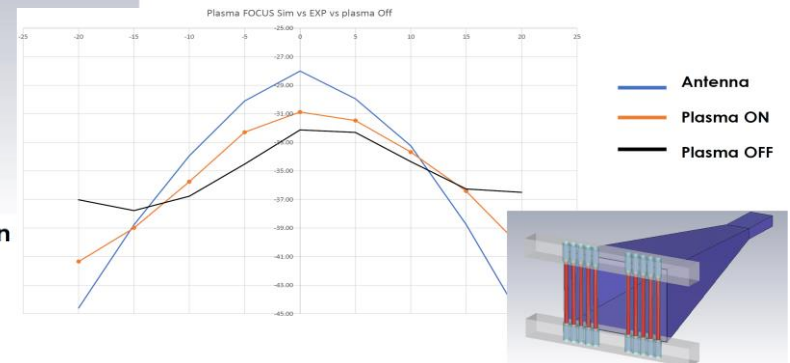
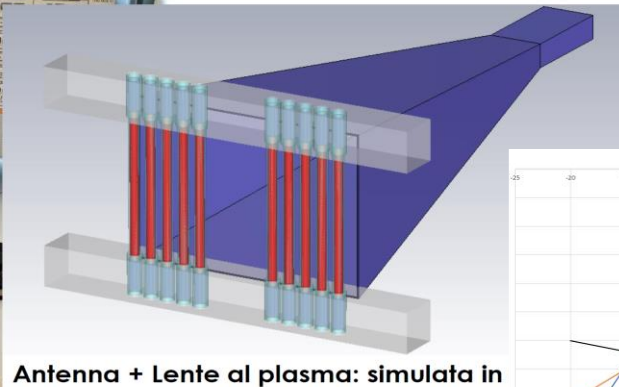
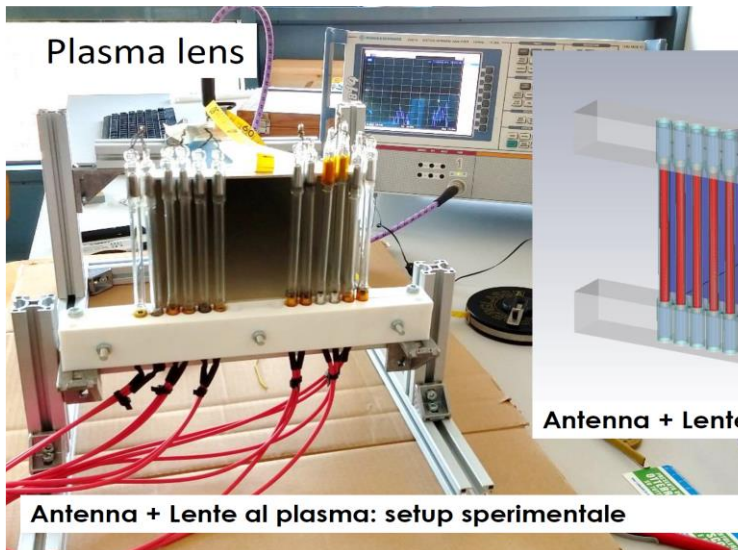
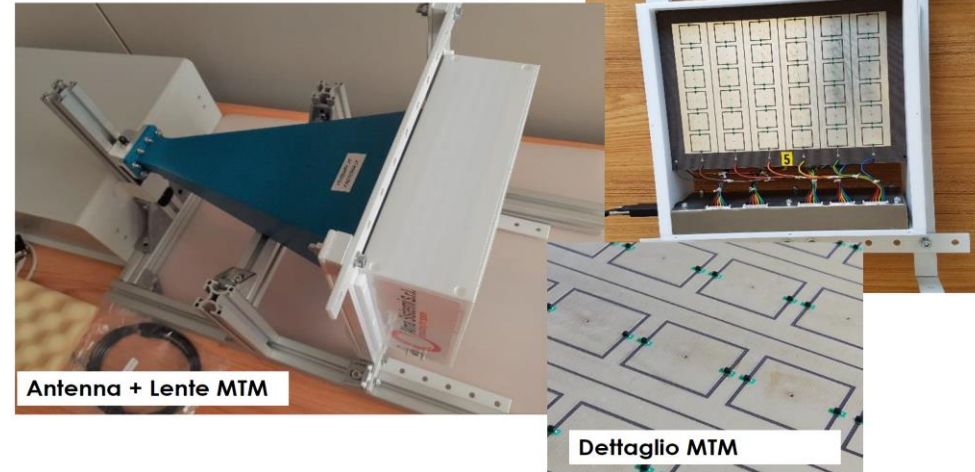
RTD Projects: PATH



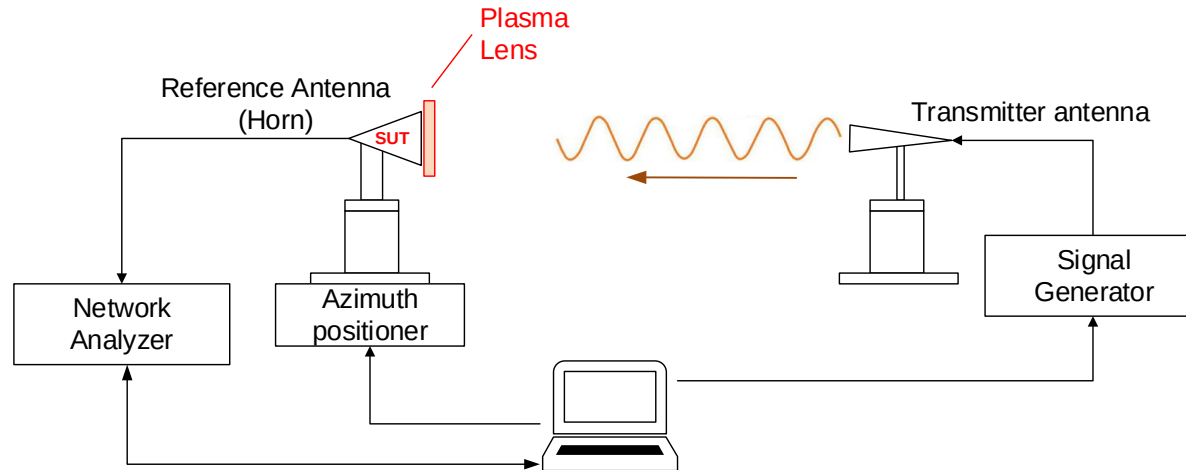
M2P Projects: Metamaterial & Plasma Antenna



Metamaterials lens



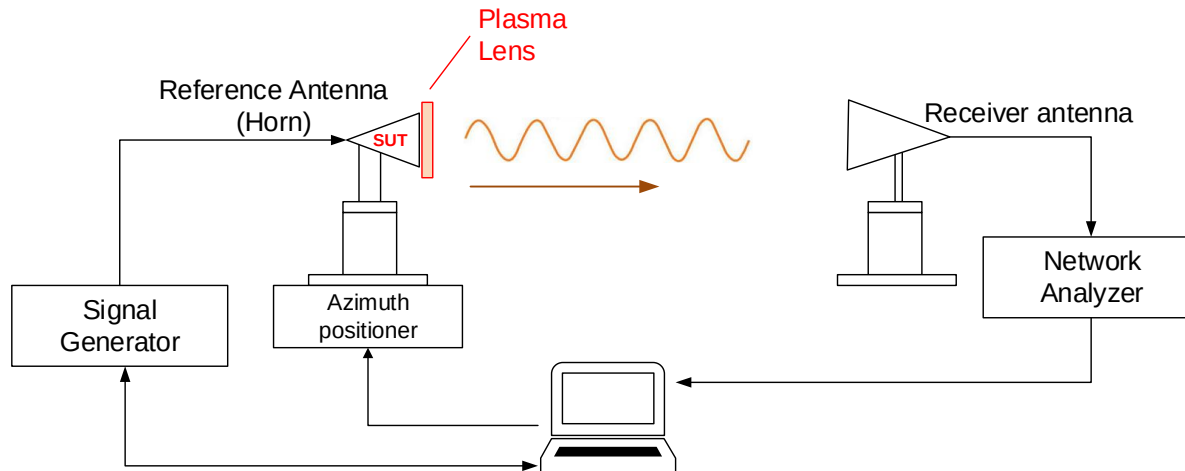
Typical setup for Plasma Lens testing used for receiving antenna measurements.



Transmitter and receiver are separated by a known distance. Transmitter antenna is connected to a signal generator, and receiver is mounted on an extended arm on a linear positioner, wherein the extended arm moves in azimuth.

The horn antenna is used as standard receiving antenna. The Antenna Under Test (AUT) is used as receiving antenna in the setup. The AUT is placed on rotating table or positioner. The RF synthesizer or sweeper is used at transmitter which feeds the signal of desired frequency and power. AUT is rotated in azimuth and receiving characteristics are recorded for post processing analysis.

Typical setup for Plasma Lens testing used for transmitting measurements.



Transmitter antenna is mounted on the positioner.

The horn antenna is used as standard transmitting antenna. The Antenna Under Test (AUT) is used as transmitting antenna in the setup. The AUT is placed on rotating table or positioner. The RF signal generator is used at transmitter which feeds the signal of desired frequency and power. AUT is rotated in azimuth and radiation pattern is recorded at the receiver.



FORTH

FOUNDATION FOR RESEARCH AND TECHNOLOGY – HELLAS

PULSE, September 2023

FORTH Partner: Photonics, Phononics and Metamaterials (PPM) group

Institute of Electronic Structure & Laser (IESL)

Foundation for Research & Technology, Hellas (FORTH)

Crete, Greece

Web: <http://esperia.iesl.forth.gr/~ppm>

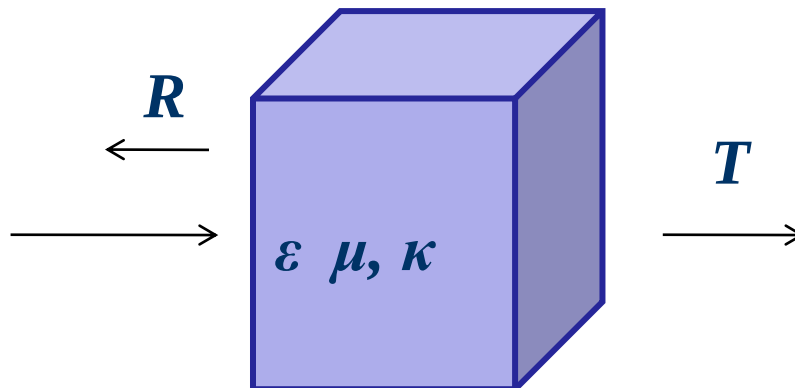
Theoretical capabilities and approaches

Simulation of **transmission (T)**, **reflection (R)**, **electromagnetic fields**, **eigenmodes**, **multipole analysis**, through:

- CST, COMSOL
- Home-made T/R code for multilayer chiral slabs
- Home-made FDTD codes

Effective parameters determination through:

- **Inversion of R, T data for bulk metamaterials and thin-films**
- **Coherent Potential Approximation (CPA) for cylinder systems**



Plasma – wave interactions

Oscillations of the mean electron velocity with a phase shift with respect to the field between 0 and $\pi/2$ depending on the **momentum-transfer frequency** – which depends on pressure.

k_z is **complex**! Waves are partially reflected, absorbed and propagating in a plasma

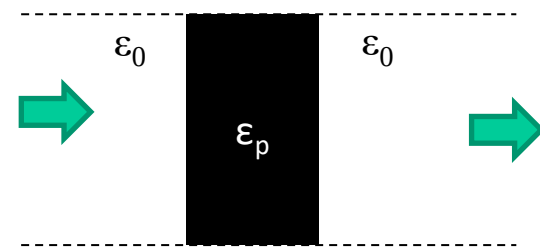
$$\omega_p = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}} \quad k_z^2 E - \frac{\omega^2}{c^2} \epsilon_p E = 0 \quad \rightarrow \quad k_z^2 = \frac{\omega^2}{c^2} \epsilon_p$$

Plasma frequency $\epsilon_p = 1 - \frac{\omega_p^2}{\omega^2(1+i\nu_m/\omega)} \rightarrow$ Single Negative nature (SNG)
Drude when $\omega_p > \omega$

$$\omega_p \left[\frac{rad}{sec} \right] = \sqrt{3180 \times n_e [m^{-3}]}$$

$$n = \frac{\lambda_0 k_z}{2\pi}$$

Refractive index



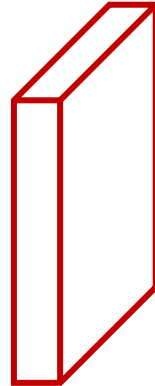
The plasma-wave interactions depend on

- 1) **Plasma frequency** increases with electron density. Typically, electron density scales with input plasma power and gas pressure.
- 2) **Collision frequency** increases with gas pressure and depends on gas composition.
- 3) **Wave frequency** is controlled by EM power circuit.

First simple systems to be studied

Planar plasma slab

sizes: 1 mm to 1 cm



Transmission/reflection/absorption
for different plasma parameters

Plasma single cylinder

diameter: 500 μm to 1 mm

height: up to 10 cm

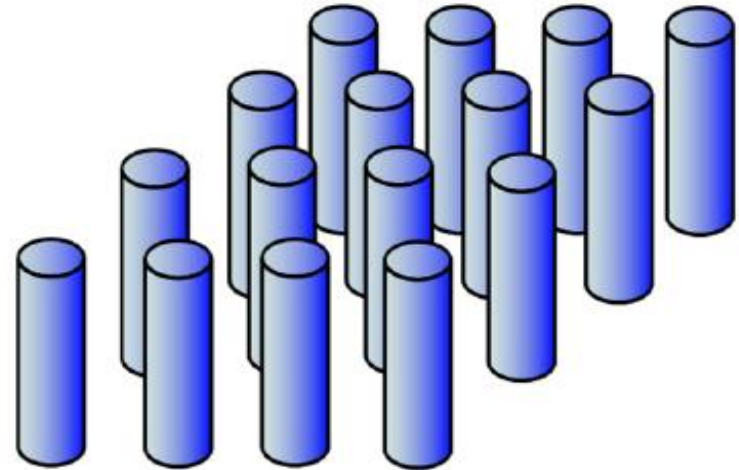


Scattering and extinction cross-section
for different plasma parameters

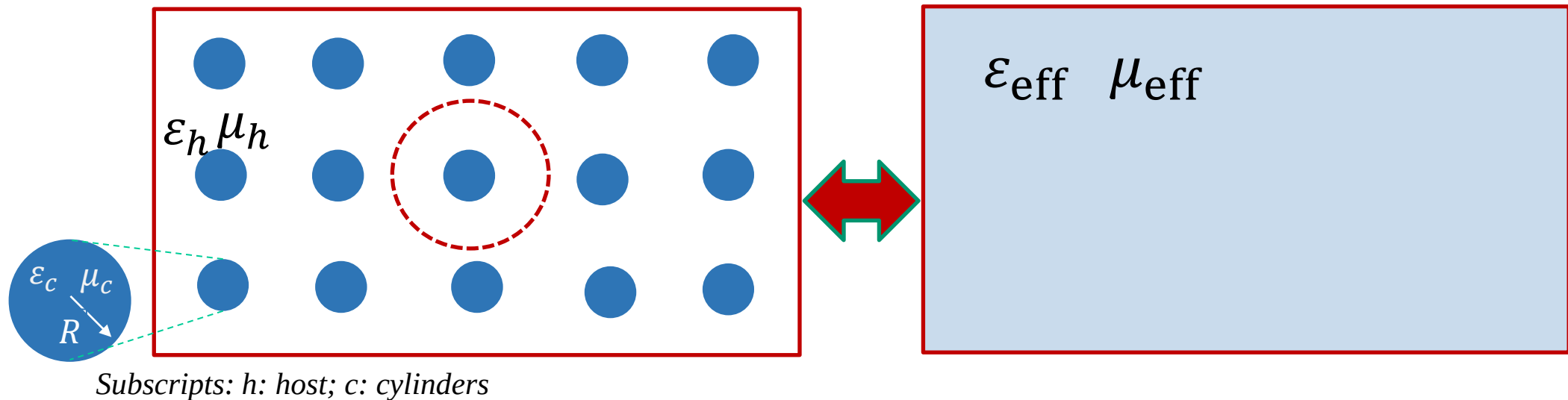
Metamaterial systems studied

Effective medium

Apply **Coherent Potential Approximation (CPA)** and compare **Maxwell-Garnett** with for different plasma operation conditions



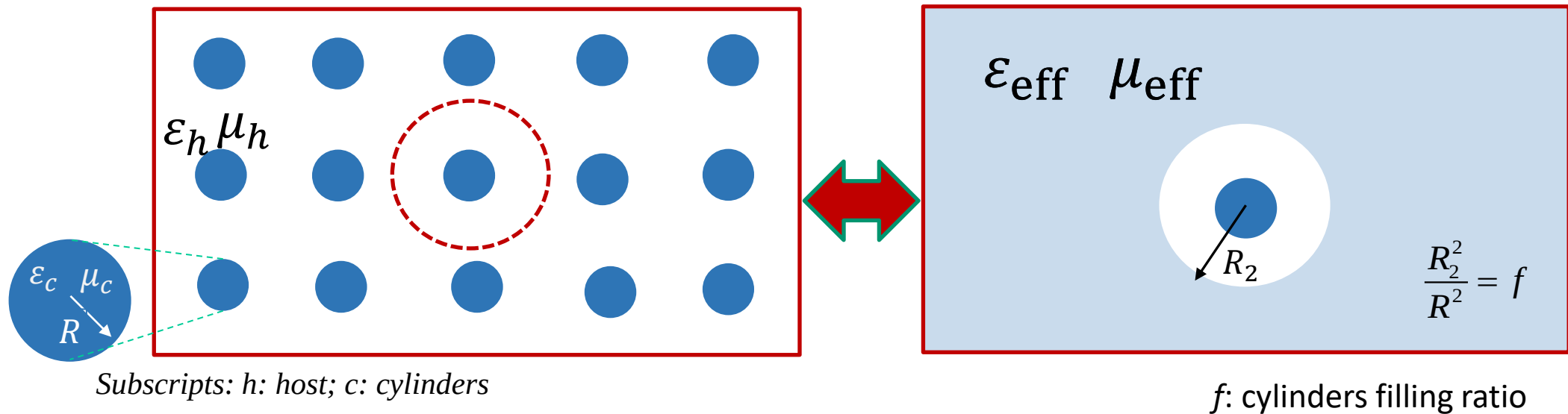
Coherent Potential Approximation (CPA)



- Applicable **beyond quasi-static limit** (takes into account scatterer resonances)
- Applicable **for a broad range of materials** (metals, dielectrics, resonant materials)
- Provides **closed, semi-analytic formulas** (useful e.g. in Artificial Intelligence treatment)

Basic CPA idea: Vanishing of the average scattering between effective and actual medium

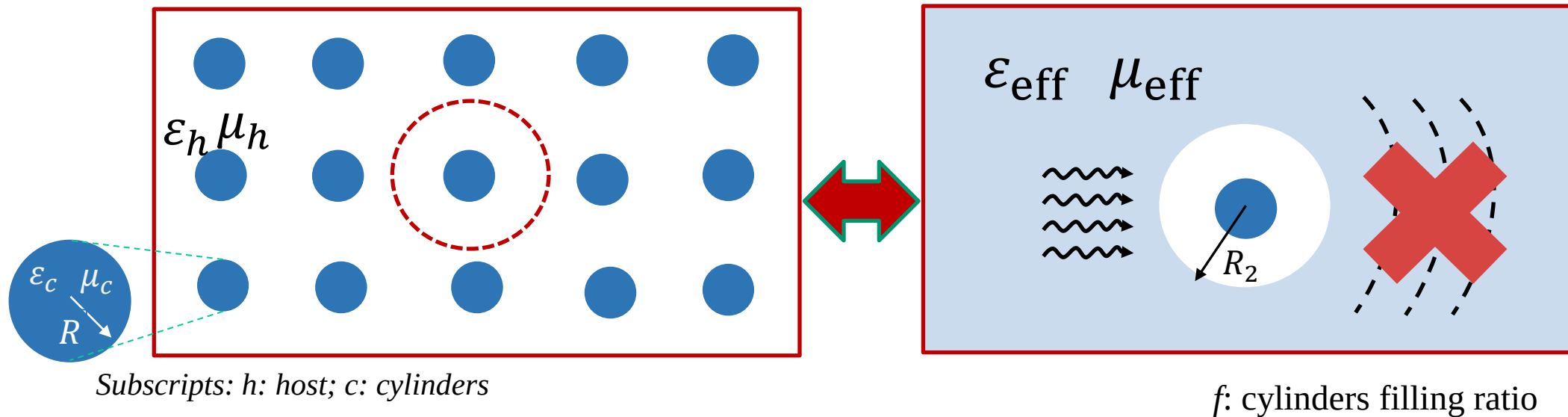
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Basic CPA idea: Vanishing of the average scattering between effective and actual medium

Coherent Potential Approximation (CPA)



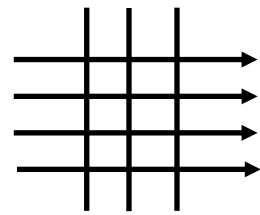
Our CPA approach: Vanishing of the scattered field of the coated-cylinder in the effective medium

Single scattering formulation

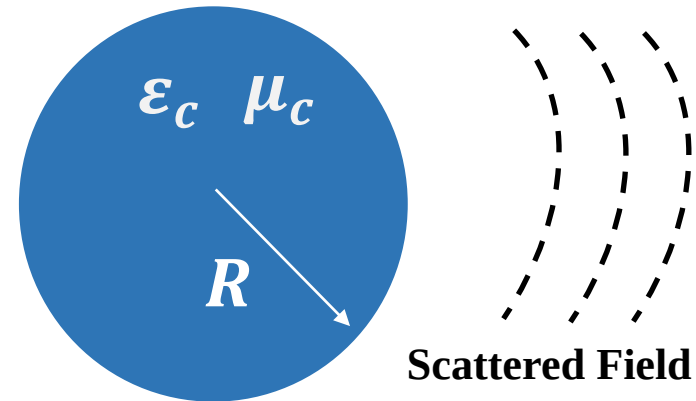
Mie theory – E // cylinders

Scattered Field

$$E_{sc} \sim \sum_{\nu} a_{\nu} H_{\nu}(k_h r) e^{i\nu\varphi}$$



Plane wave



Scattered Field

Inside the cylinder

$$E_{in} \sim \sum_{\nu} b_{\nu} J_{\nu}(k_c r) e^{i\nu\varphi}$$

a_{ν} : scattering coefficients

ν : order of cylindrical harmonic

J_{ν}, H_{ν} : Bessel, Hankel functions

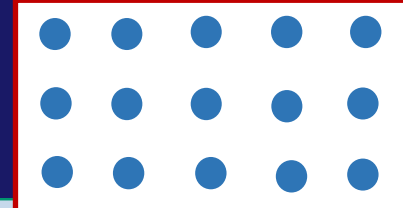
k_c, k_h : wavenumbers in cylinder, host

Boundary Conditions at the interface $r = R$

$$\hat{\rho} \times [\mathbf{E}_{out} - \mathbf{E}_{in}] = \mathbf{0}$$

$$\hat{\rho} \times [\mathbf{H}_{out} - \mathbf{H}_{in}] = \mathbf{0}$$

Main CPA equations



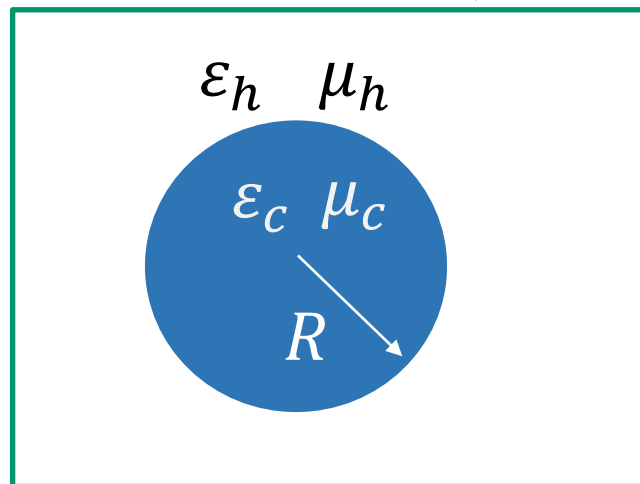
Scattered Field

$$E_{sc} \sim \sum_{\nu} a_{\nu}^{\text{eff}} H_{\nu}(k_{\text{eff}} r) e^{i\nu\varphi}$$

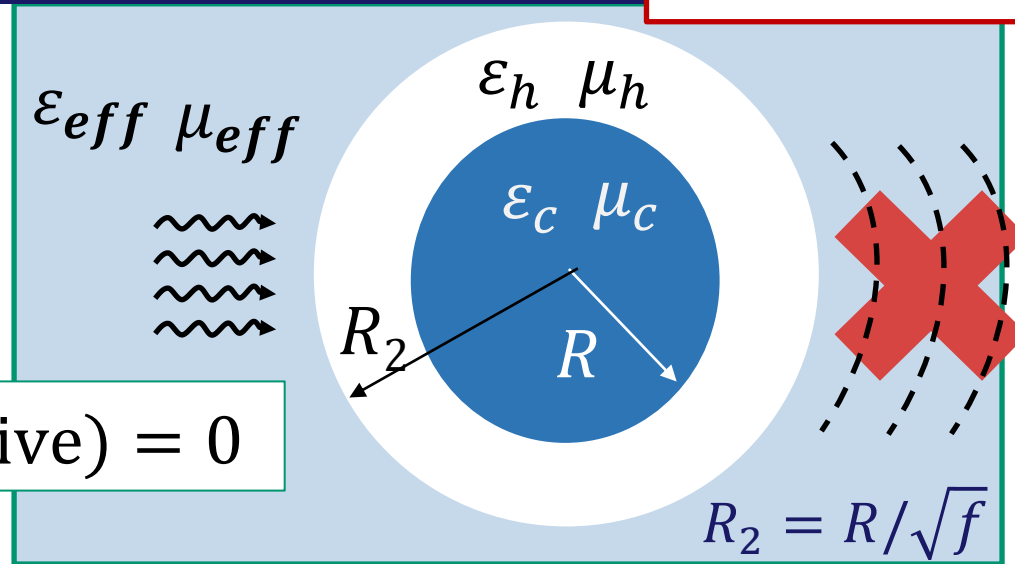
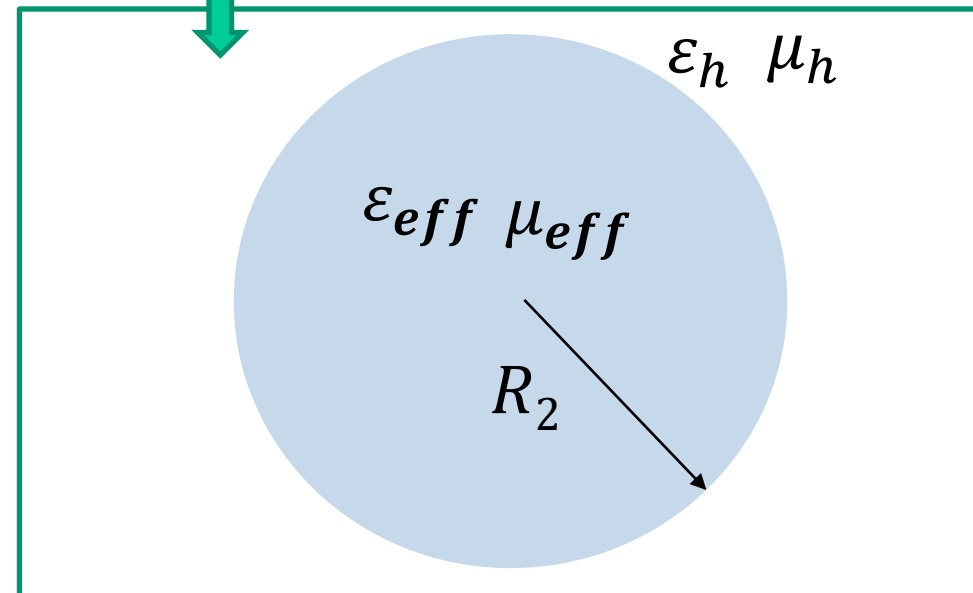
$$a_{\nu}^{\text{eff}} = a_{\nu}(R_2; \text{coated cyl. in effective}) = 0$$



$$a_{\nu}(R; \text{orig. cylinder in host}) = a_{\nu}(R_2; \text{effective cyl. in host})$$



=



Effective medium formulas – Semi-analytic

$$a_\nu(R; \text{cylinder in host}) = a_\nu(R_2; \text{effective in host})$$

Considering only the **first two modes per polarization** ($\nu=0$ and $\nu=1$) (reasonable if $k_h R < 1$) and taking the limit $k_{\text{eff}} R_2 \rightarrow 0$:

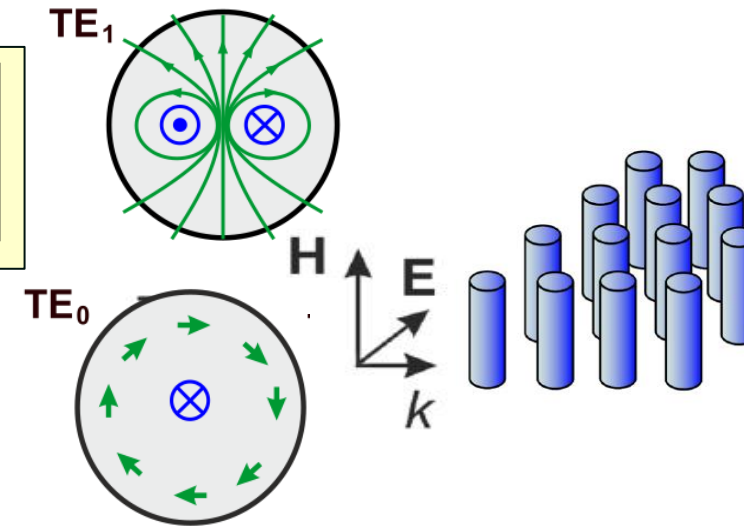
$$R_2 = R/\sqrt{f}, f: \text{filling ratio}$$

TE: **H field parallel to cylinder**

Electric field / **Magnetic field**

$$\epsilon_{\text{eff}}^\perp = \frac{\epsilon_h}{k_h R_2} \left[\frac{J_1(k_h R_2) + H_1(k_h R_2) a_1^{\text{TE}}}{J_1'(k_h R_{N+1}) + H_1'(k_h R_{N+1}) a_1^{\text{TE}}} \right]$$

$$\mu_{\text{eff}}^\parallel = \frac{-2\mu_h}{k_h R_2} \left[\frac{J_0'(k_h R_2) + H_0'(k_h R_2) a_0^{\text{TE}}}{J_0(k_h R_2) + H_0(k_h R_2) a_0^{\text{TE}}} \right]$$



a_ν : scattering coefficients for the original cylinder in the host

$$k_h = \sqrt{\epsilon_h \mu_h} \omega / c \quad J, H: \text{Bessel, Hankel functions}$$

$k_h R_2, k_h R, k_c R$ are not restricted.

Only limitation: $k_{\text{eff}} R_2 \sim R_2 / \lambda_{\text{eff}} \ll 1$. No restriction for the wavelength inside cylinder

Possible structure parameters

Microplasma arrays (at second step)

Unit cell in literature 400 μm (seems rather difficult)

$n_e = 10^{18} - 10^{19} \text{ m}^{-3}$ (required for GHz plasma frequencies but the 10^{19} difficult to achieve at low pressures)

Collision frequency (strongly pressure dependent) (pressure range aimed: 1-760 Torr – main target: argon @ 1 Torr)

Shape/size of plasma elements?

Rectangular/slab: *minimum size: 1 mm, maximum: few cm*

Cylindrical: *diameter: 500 μm to 1.5+ mm; height: up to 10 cm*

Circle or hemi-circle?

Electrode minimum size: ~200 μm

Modulation frequency?



Aalto University
School of Electrical
Engineering

PULSE on Crete

Sergei Tretyakov

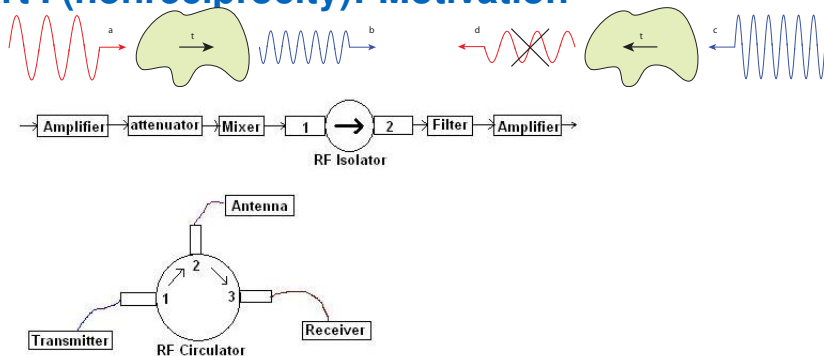
Department of Electronics and Nanoengineering
School of Electrical Engineering
Aalto University (Finland)

September 2023

Outline

- ▶ A new mechanism for breaking reciprocity?
- ▶ New effects at SLOW time modulations of plasma?

Part I (nonreciprocity): Motivation



Known technology: ferrimagnetic/magneto-optical materials (in circuits, also active components)

Emerging **metatechnology**: time-space modulated metamaterials and metasurfaces, switchable and nonlinear components. Compact realizations, new functionalities

Schematics picture from <https://www.rfwireless-world.com/Terminology/rf-isolator-versus-rf-circulator.html>

Notion of *reactions* and the definition of reciprocal systems

Consider two sets, A and B , of electric current sources, $\mathbf{J}_A(\mathbf{r})$ and $\mathbf{J}_B(\mathbf{r})$, producing the fields $\mathbf{E}_A$ and $\mathbf{E}_B$, respectively.

Definition: reaction of source A to field B

$$\langle A, B \rangle = \int_V \mathbf{J}_A \cdot \mathbf{E}_B dv$$

Definition: reaction of source B to field A

$$\langle B, A \rangle = \int_V \mathbf{J}_B \cdot \mathbf{E}_A dv$$

Definition: A system is called *reciprocal* if for any set of sources $\mathbf{J}_A(\mathbf{r})$ and $\mathbf{J}_B(\mathbf{r})$ we have

$$\langle A, B \rangle = \langle B, A \rangle$$

The symmetry of kinetic coefficients

L. Onsager, *Reciprocal relations in irreversible processes* (1931):

$$\langle x_1(t)x_2(t+\tau) \rangle = \langle x_2(t)x_1(t+\tau) \rangle$$

Onsager, Casimir, Landau-Lifshitz, et al.: **Time-reversal invariance of dynamic equations, thermodynamic equilibrium, linear response, and causality:**

$$\text{Response}_i = \alpha_{ij} \text{Force}_j \quad \Rightarrow \quad \alpha_{ij} = \alpha_{ji}$$

In particular, if $\mathbf{E}_A(\mathbf{r}_B) = \overline{\overline{G}}(\mathbf{r}_B, \mathbf{r}_A) \cdot \mathbf{J}_A(\mathbf{r}_A)$, and the field equations are time-reversal symmetric, then

$$\overline{\overline{G}}(\mathbf{r}_B, \mathbf{r}_A) = \overline{\overline{G}}^T(\mathbf{r}_A, \mathbf{r}_B)$$

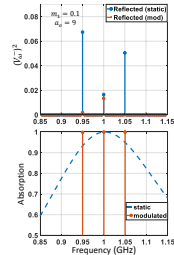
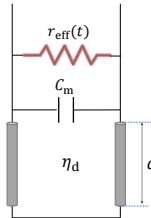
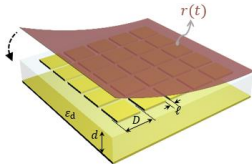
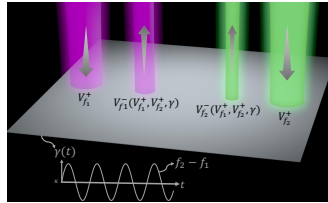
Physical assumptions used in proving the symmetry of kinetic coefficients (the reciprocity principle)

- ▶ Time-reversal symmetry of microscopic equations
- ▶ Linear response
- ▶ Causal response
- ▶ Thermodynamic equilibrium

Is it possible to make a nonreciprocal device using NONEQUILIBRIUM plasma?

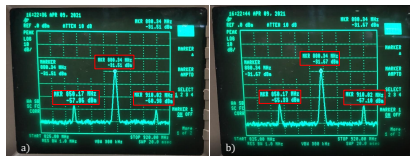
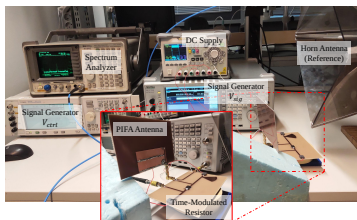
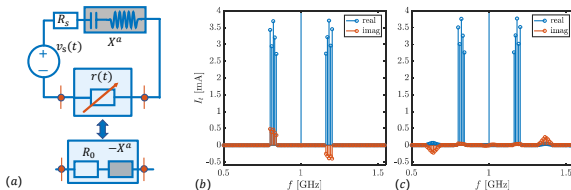
???

Part II (slow modulations): Initial work



M. H. Mostafa, A. Díaz-Rubio, M. S. Mirmoosa, and S. A. Tretyakov, Coherently time-varying metasurfaces, Phys. Rev. Applied, vol. 17, p. 064048, 2022.

Antenna with a time-varying resistance



M. H. Mostafa, N. Ha-Van, P. Jayathurathnage, X. Wang, G. Ptitsyn, and S. A. Tretyakov, Antenna bandwidth engineering through time-varying resistance, Appl. Phys. Lett., vol. 122, no. 17, p. 171703, 2023.

Can we modulate the loss factor of a radiating plasma volume? Any ideas on phenomena in plasma under excitation at multiple frequencies?

???

METAMORPHOSE VI AISBL

The Virtual Institute for Artificial Electromagnetic Materials and Metamaterials

EIC PATHFINDER: PULSE

Plasma reconfigurable metaSurface technologies

Internal Workshop

10 September 2023, Crete, Greece



Plasma reconfigurable metaSurface technologies



PULSE



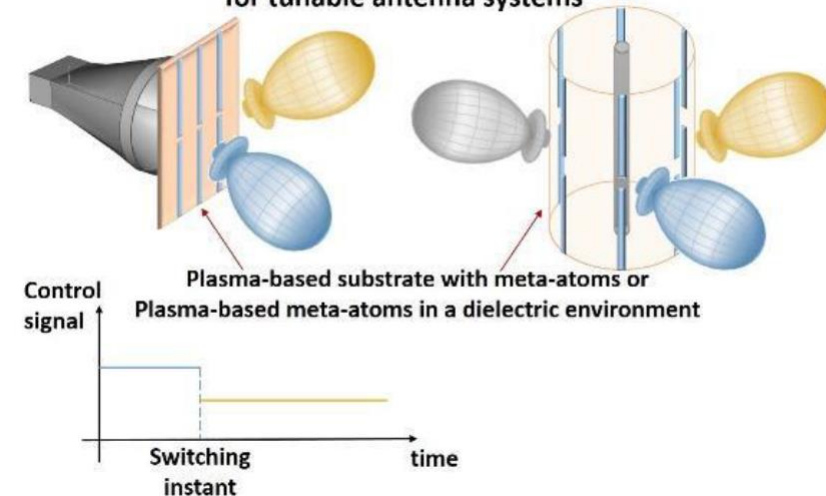
Metamorphose VI role in the PULSE project

- ✓ WP1 – Physical Investigation
 - Task 1.1 Metasurface & meta-grating analysis (**RM3**, FORTH, MVI, AALTO).
 - Task 1.2 Plasma Physics (**FORTH**, MVI, UNIBO, AALTO, FORTH).
 - **Task 1.3 Theoretical modelling** (**MVI**, FORTH, AALTO).
 - Task 1.6 Validation (**FORTH**, ALMA, MVI, RM3, UNIBO, APLA, AALTO).
- ✓ WP2 – Metalenses for antennas
 - Task 2.1 Design and numerical simulations (**RM3**, UPM, FORTH, AALTO, MVI).
- ✓ WP3 – Time-space modulated structures and components
 - Task 3.2 Simulation code development (**UPM**, AALTO, FORTH, MVI).

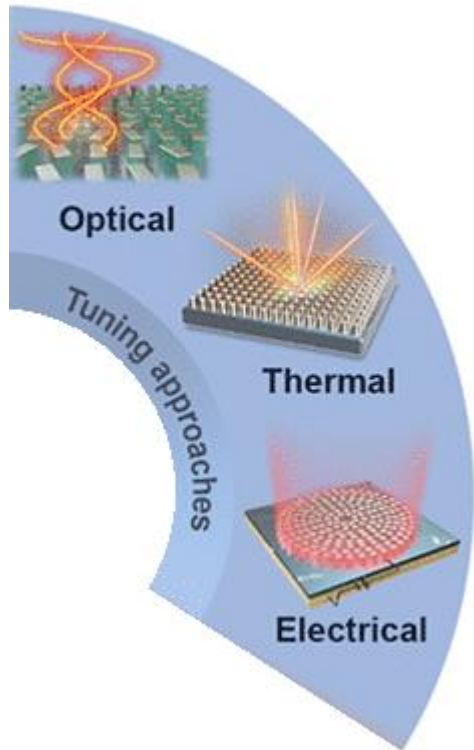
Goals

- ❑ WP1-Task 1.3: Development of appropriate analytical and semi-analytical models to analyze and design plasma-based and time-invariant MTS. The modelling efforts will take into account and extend the results of the investigations carried out in T1.1 and T1.2.
- ❑ Final goal of the project: design of plasma based metadevices working as **reconfigurable lenses** for wire and aperture antennas.

Examples of planar and circular plasma-based metasurfaces for tunable antenna systems



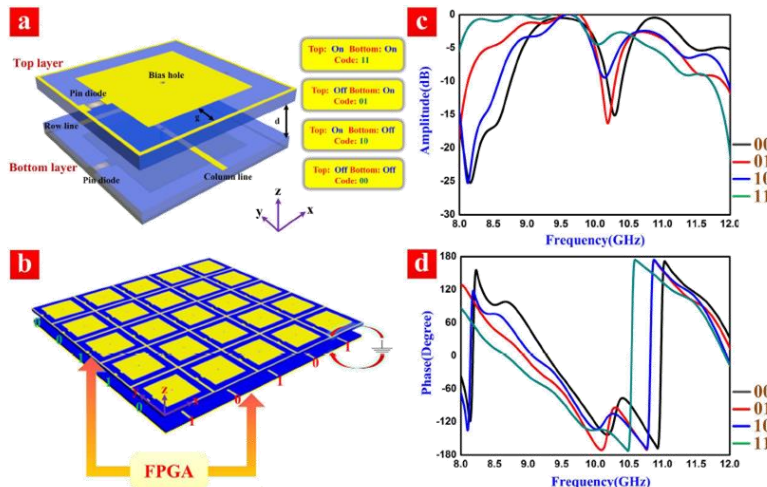
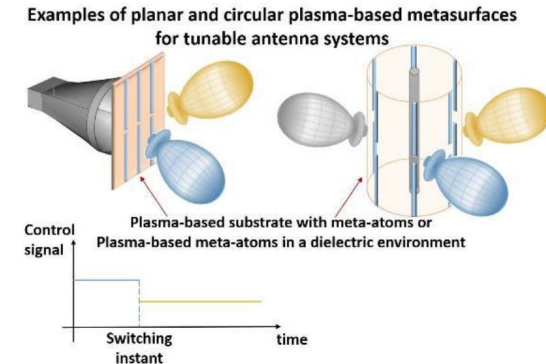
Current technology for EM reconfigurability



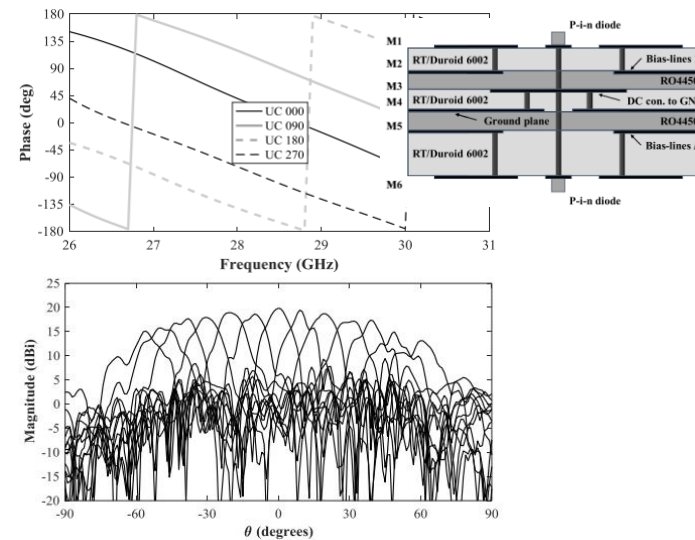
- ❑ MTSs have paved the way to exciting possibilities to engineer wave radiation and propagation in unprecedented ways, provided that **means for effective tuning of these new MTSs are available.**
- ❑ Current technological paradigms for achieving EM reconfigurability:
 - **Electronic tuning**
 - **Geometrical tuning**
 - **Material tuning**

Planar electronic tunable surface

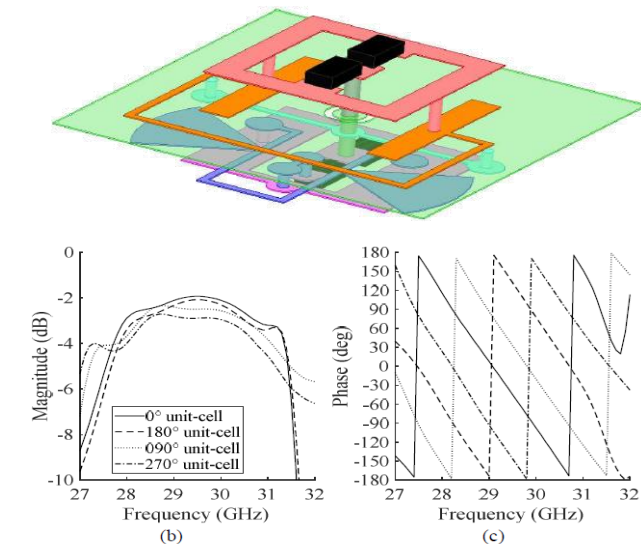
- Antenna **beam steering** is achieved through an electronic modulation of the MTS/transmittarray phase-gradient profile .



T. J. Cui, et al., Nature, Sci. Rep, 6, 23731, 2016



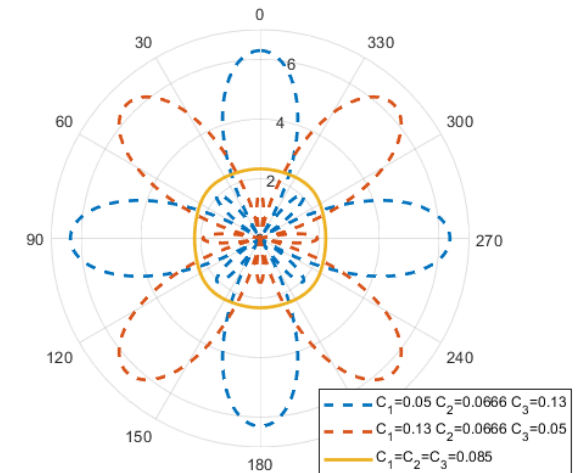
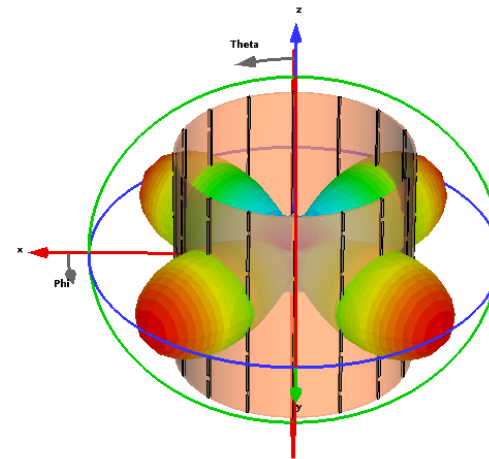
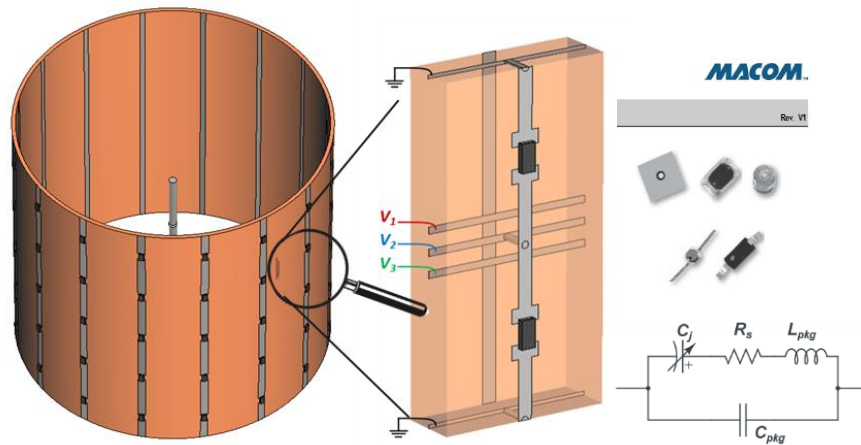
F. Diaby, et. al., IEEE TA-P, 68, 5003, 2020



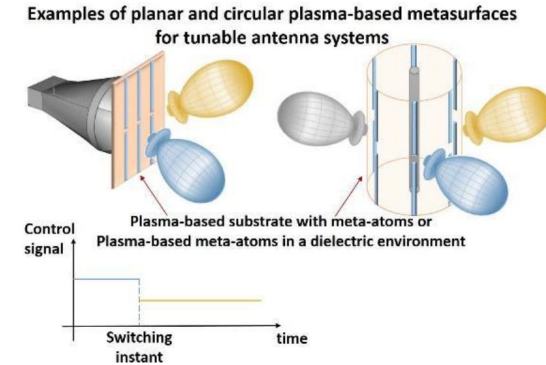
A. Clemente et al., EuCAP 2023

Circular electronic tunable metasurface

- The radiation pattern can be dynamically steered in different directions and shaped from the original omnidirectional one by the simple **tuning of the varactors**. By fixing the lumped capacitances to the same value the omnidirectional pattern is restored.



S. Vellucci, et. al., IEEE TA-P, 2023

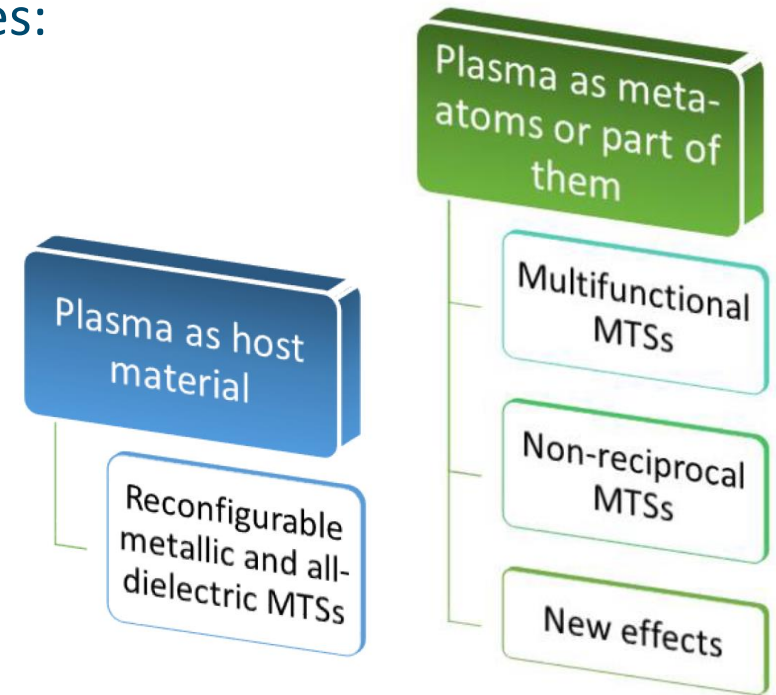
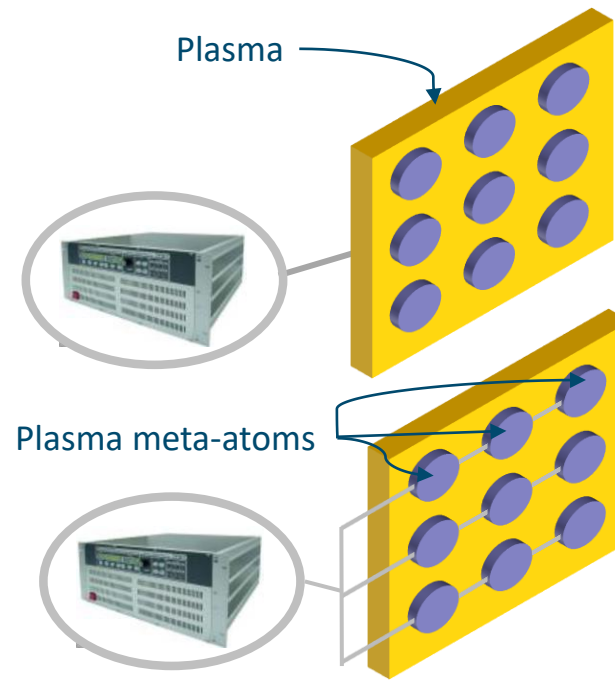


PULSE technological lines:

□ At the scope, PULSE aims at exploring two main technological lines:

- Plasma as host materials

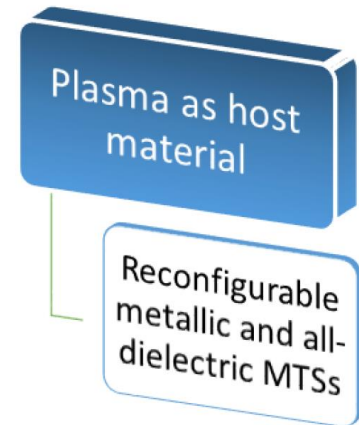
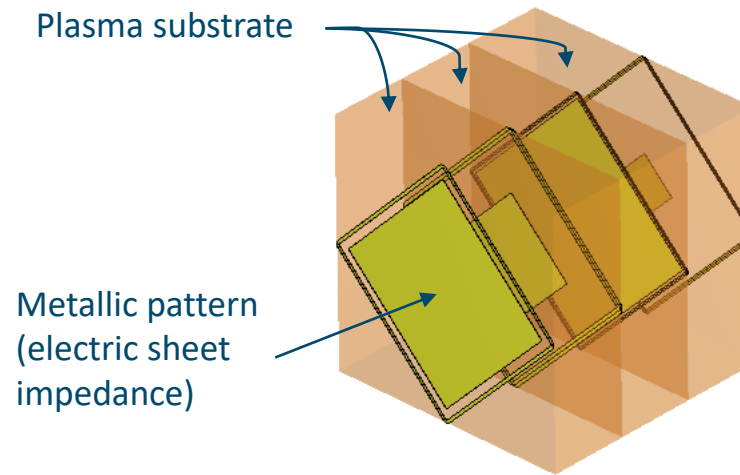
- Plasma as meta-atoms



Plasma as host materials

❑ Plasma is used as a reconfigurable environment for EM metasurfaces. The change of the EM properties of the host material allows reconfiguring the behaviour of the metasurface.

❑ In this scenario the single unit cell of the metasurface structure can be implemented through a cascade configuration of **metallic layers deposited onto plasma substrates**:



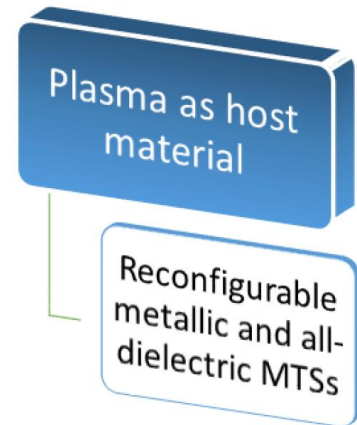
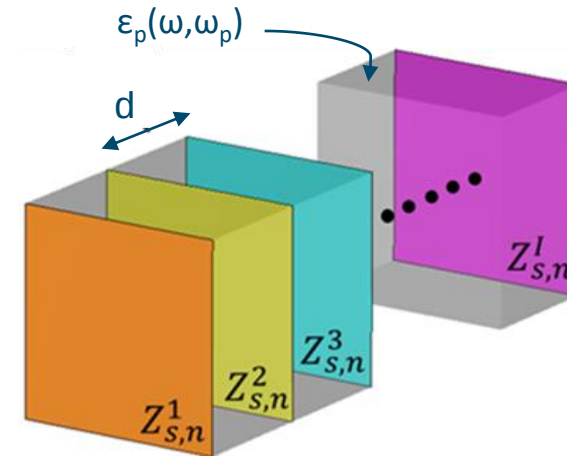
Plasma as host materials

- The structure can be simplified to a cascade configuration of ideal electric impedance sheets separated by (*reconfigurable*) dielectric substrate of thickness d . The configuration can be conveniently modeled exploiting a **microwave network approach**. The ABCD matrix of a structure relates the total electric field on its two sides.

$$\begin{pmatrix} A_n & B_n \\ C_n & D_n \end{pmatrix} = \mathbf{Y}_{s,n}^1 \cdot \mathbf{d} \cdot \mathbf{Y}_{s,n}^2 \cdot \mathbf{d} \dots \mathbf{Y}_{s,n}^I$$

ABCD matrix of the plasma substrates

ABCD matrix of the n-th impedance sheet

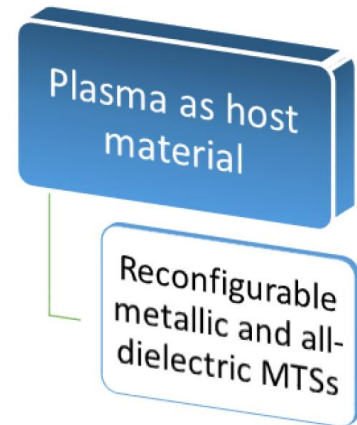
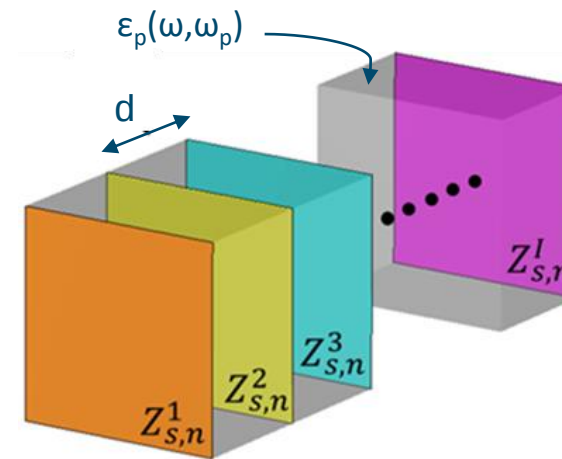


Plasma as host materials

- Assuming that the impedance sheets are *isotropic* on their plane, characterized by *low-losses* and do exhibits *weak spatial* dispersion:

$$\begin{pmatrix} A_n & B_n \\ C_n & D_n \end{pmatrix} = \mathbf{Y}_{s,n}^1 \cdot \mathbf{d}_n \cdot \mathbf{Y}_{s,n}^2 \cdot \mathbf{d}_n \dots \mathbf{Y}_{s,n}^I$$

$$\mathbf{Y}_{s,n}^i = \begin{pmatrix} 1 & 0 \\ 1/jX_{s,n}^i & 1 \end{pmatrix}$$

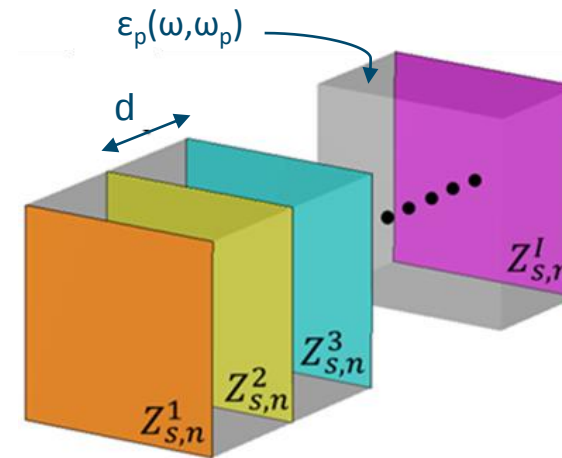


Plasma as host materials

□ The ABCD matrix of the dielectric spacers is written as:

$$\begin{pmatrix} A_n & B_n \\ C_n & D_n \end{pmatrix} = \mathbf{Y}_{s,n}^1 \cdot \mathbf{d}_n \cdot \mathbf{Y}_{s,n}^2 \cdot \mathbf{d}_n \dots \mathbf{Y}_{s,n}^I$$

$$\mathbf{d}_n = \begin{pmatrix} \cos(k_z d) & j\eta_{T,n} \sin(k_z d) \\ \frac{j \sin(k_z d)}{\eta_{T,n}} & \cos(k_z d) \end{pmatrix}, k_z = k_0 \sqrt{\varepsilon_r(\omega, \omega_p)} \cos \vartheta_i^d$$



Plasma as host material

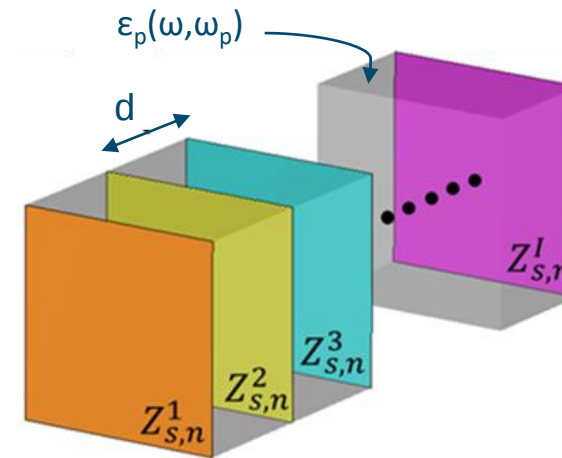
Reconfigurable metallic and all-dielectric MTSS

Plasma as host materials

□ Where the wave impedance $\eta_{T,n}$ depends on the polarization of the incident wave, i.e:

$$\mathbf{d}_n = \begin{pmatrix} \cos(k_z d) & j\eta_{T,n} \sin(k_z d) \\ \frac{j \sin(k_z d)}{\eta_{T,n}} & \cos(k_z d) \end{pmatrix}, k_z = k_0 \sqrt{\epsilon_r(\omega, \omega_p)} \cos \vartheta_i^d$$

$$\eta_{T,i} = \begin{cases} \frac{\eta_0}{\cos \vartheta_i^d \sqrt{\epsilon_r(\omega, \omega_p)}}, & TE \\ \frac{\eta_0 \cos \vartheta_i^d}{\sqrt{\epsilon_r(\omega, \omega_p)}}, & TM \end{cases}, \vartheta_d^i = \arcsin \frac{\sin(\vartheta_i - 90^\circ)}{\sqrt{\epsilon_r(\omega, \omega_p)}}.$$



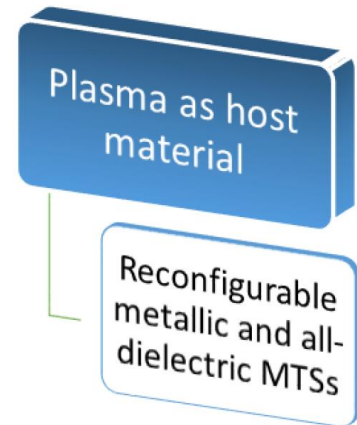
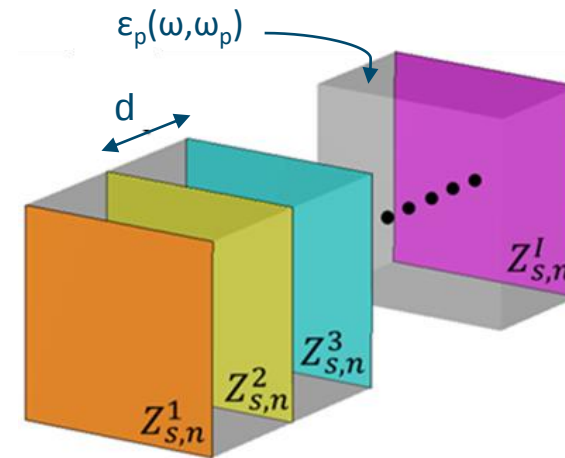
Plasma as host material

Reconfigurable metallic and all-dielectric MTSs

Plasma as host materials

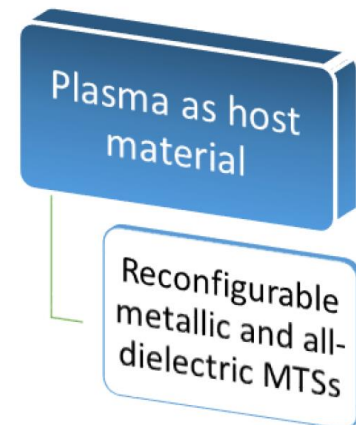
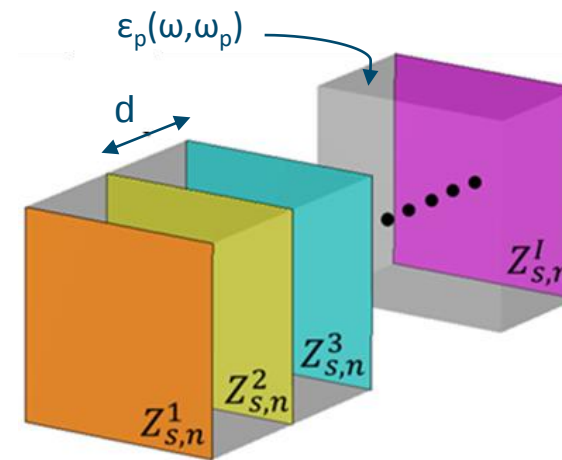
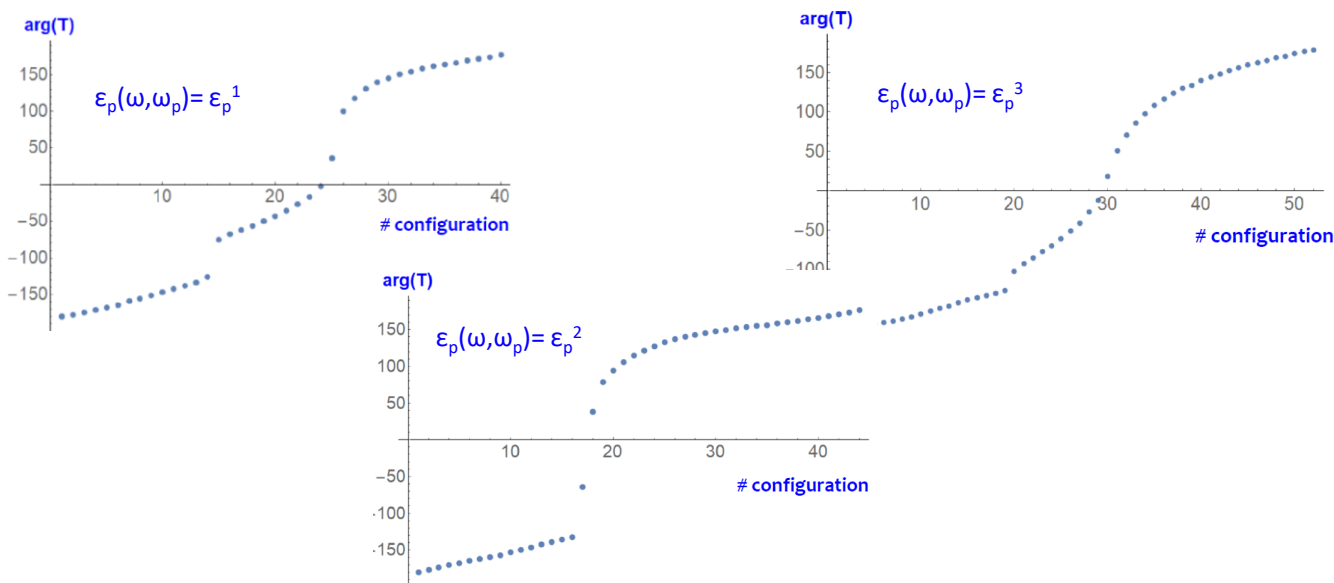
- Once the ACBD matrix of the cell has been calculated, the polarization-dependent transmission coefficient are evaluated through the generalized S -parameter transformation matrix.

$$S_{21}^{n,TE/TM} = \frac{2\sqrt{\eta_0^{in}\eta_0^{out}}}{A_n\eta_0^{out} + B_n + \eta_0^{in}\eta_0^{out}C_n + \eta_0^{in}D_n},$$



Plasma as host materials

- The availability of a close-for expression for the transmission coefficient allows to analyze the unit-cell phase-coverage when varying the properties of the substrate.

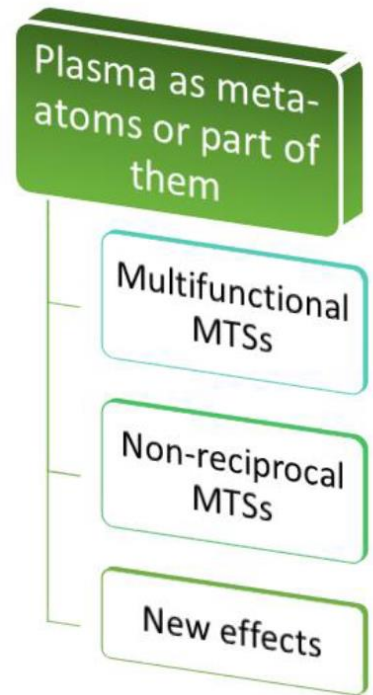
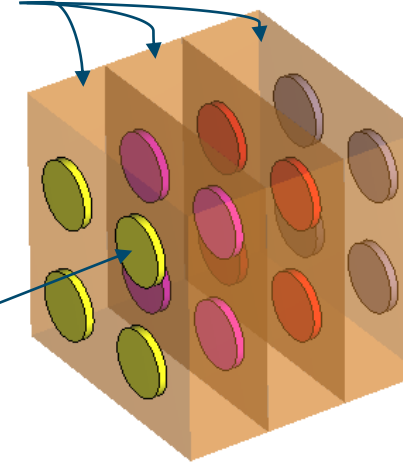


Plasma as meta-atoms

- ❑ Plasma can **replace metals** as the constituent material of the meta-atoms. This enables the following scenarios:
 - The metasurface can be modulated in space by activating only some specific meta-atoms.
 - The individual properties of each meta-atom can be continuously time-modulated with an appropriate function.
 - Plasma allows a conceptually new scenario in which both size and shape of a meta-atom are modulated in time during their interaction with the EM field.

dielectric substrate

Reconfigurable
plasma meta-
atoms



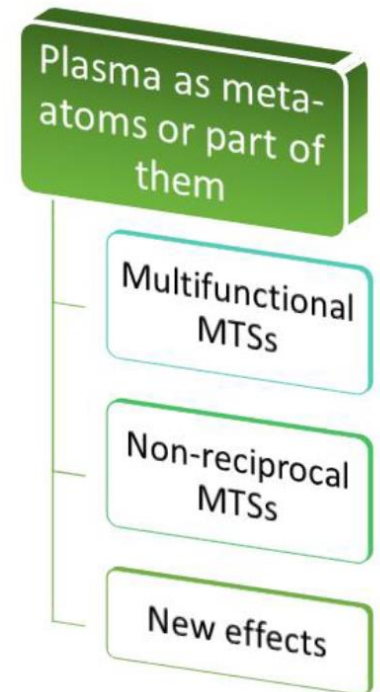
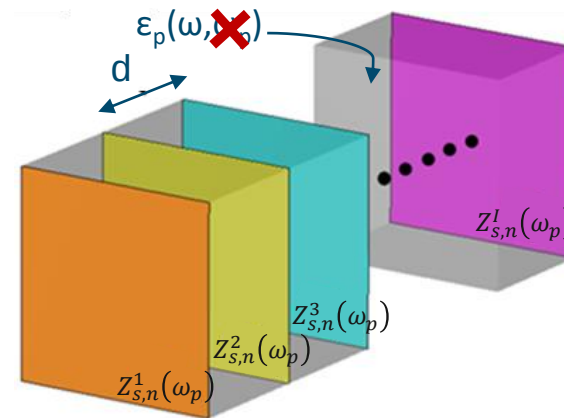
Plasma as meta-atoms

- Provided that the homogenization theory can be effectively **applied** to the array of homogeneous plasma elements, the UC structure can be *still simplified to a cascade configuration* of (reconfigurable) ideal impedance sheets separated by dielectric substrate.

$$\begin{pmatrix} A_n & B_n \\ C_n & D_n \end{pmatrix} = \mathbf{Y}_{s,n}^1 \cdot \mathbf{d} \cdot \mathbf{Y}_{s,n}^2 \cdot \mathbf{d} \dots \mathbf{Y}_{s,n}^I$$

ABCD matrix of the dielectric substrates

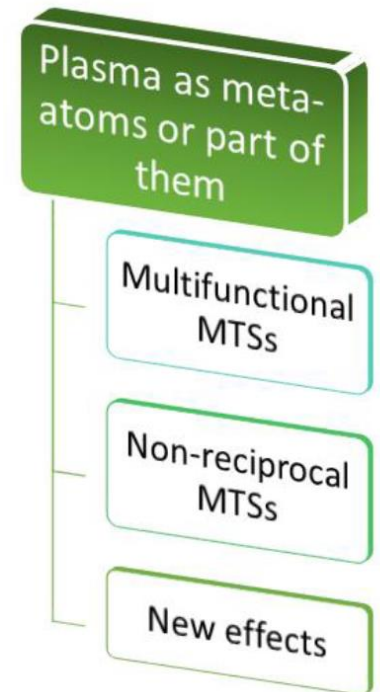
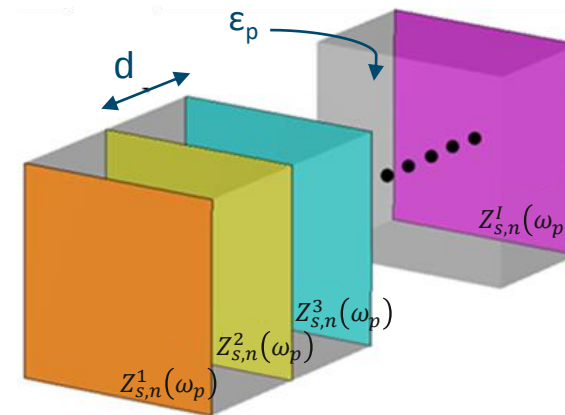
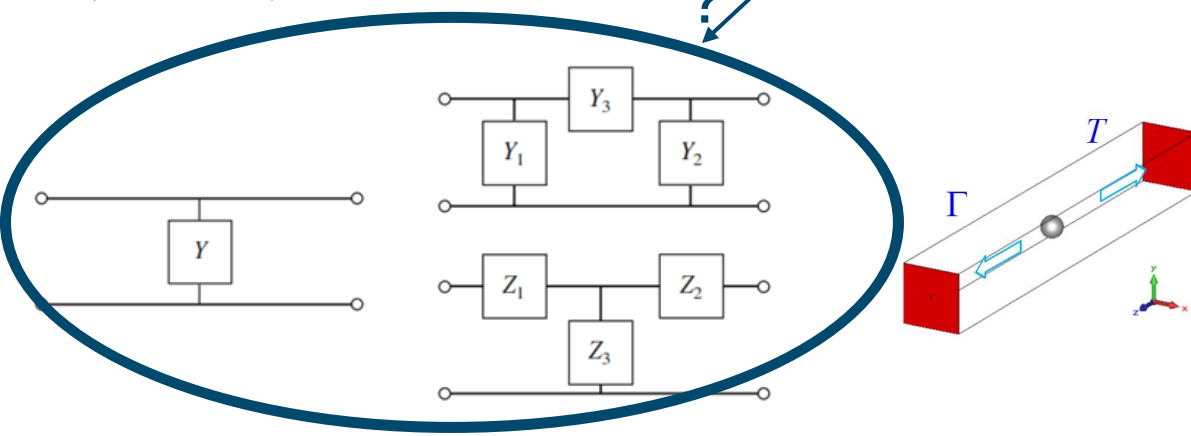
ABCD matrix of the n-th reconfigurable impedance sheet



Plasma as meta-atoms

- Assuming that the impedance sheets are *isotropic* on their plane, and do exhibits *weak spatial* dispersion:

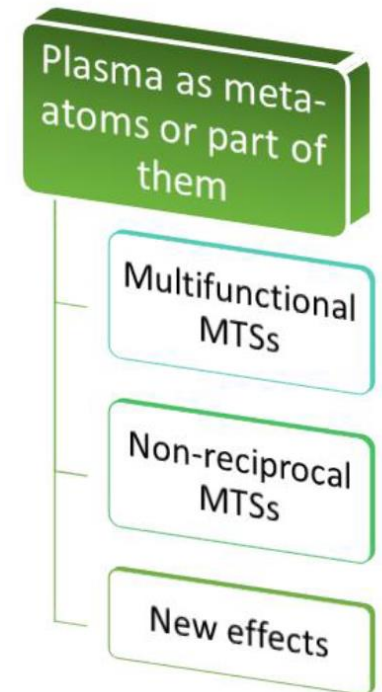
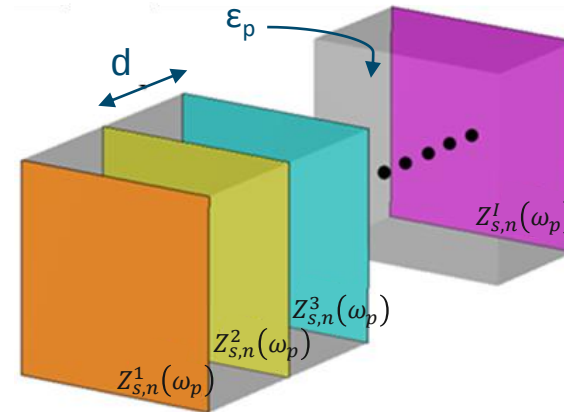
$$\begin{pmatrix} A_n & B_n \\ C_n & D_n \end{pmatrix} = \mathbf{Y}_{s,n}^1(\omega, \omega_p) \cdot \mathbf{d}_n \cdot \mathbf{Y}_{s,n}^2(\omega, \omega_p) \cdot \mathbf{d}_n \dots \mathbf{Y}_{s,n}^I(\omega, \omega_p)$$



Plasma as meta-atoms

- Following a **similar modelling procedure** for the plasma host material scenario, the polarization-dependent transmission coefficient are evaluated through the generalized S -parameter transformation matrix.

$$S_{21}^{n,TE/TM} = \frac{2\sqrt{\eta_0^{in}\eta_0^{out}}}{A_n\eta_0^{out} + B_n + \eta_0^{in}\eta_0^{out}C_n + \eta_0^{in}D_n},$$



Challenges

❑ Plasma as host material:

- Verify that the tunability range of the plasma substrate can guarantee the required phase coverage.
- Analysis possible new effect coming from negative/ENZ permittivity values.
- Evaluate the effect of the losses on the transmission amplitude and phase.

❑ Plasma as meta-atoms:

- Verify that the homogenization approach can be efficiently applied to the modelling of the plasma-based impedance sheets in the cascade configuration.
- Analysis of the mutual-coupling effect among the plasma layers.
- Evaluate the effect of the losses on the transmission amplitude and phase coverage.



PULSE, UPM node

Salvador Jiménez

Universidad Politécnica de Madrid



Tasks

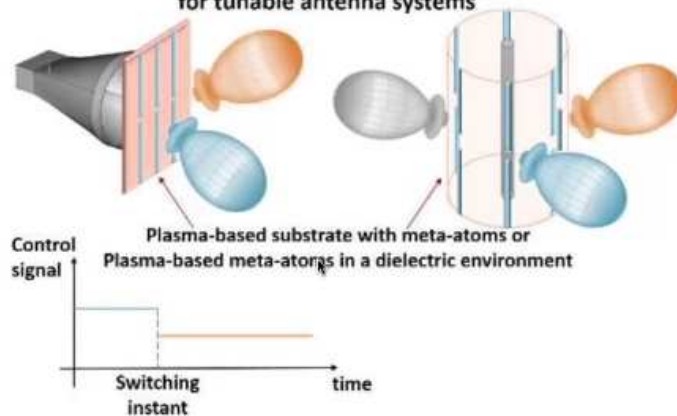
- WP1, Task 1.4 Multi Physics Simulation (FORTH, UPM, RM3).
- WP1, Task 1.5 Experimental characterization (ALMA, UNIBO, ALPLA, UPM, FORTH).
- WP2, Task 2.1 Design and numerical simulations (RM3, UPM, FORTH, AALTO, MVI).
- WP2, Task 2.4 Experimental testing (ALMA, ALPLA, UPM, RM3).

- WP3, Task 3.2 Simulation code development ([UPM](#), AALTO, FORTH, MVI).
- WP3, Task 3.4 Experimental setup & testing (ALMA, ALPLA, [UPM](#)).
- WP3, Task 3.6 Demonstrator proof of concept (UNIBO, AALTO, ALMA, RM3, [UPM](#)).

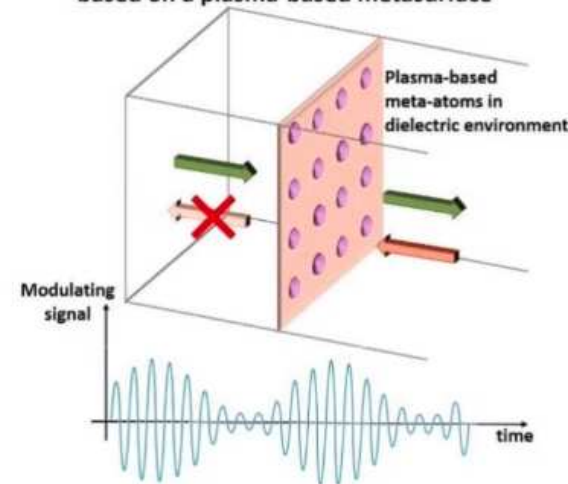
Modeling: we are looking forward to participate in the analysis and theoretical study of the different models.

Simulations: the software is ready to simulate different possible configurations

Examples of planar and circular plasma-based metasurfaces for tunable antenna systems



Sketch of non-reciprocal waveguide device based on a plasma-based metasurface



Deliverables

- WP3, D3.2 Simulation code ([UPM](#)), month 18 (dissemination level “sensitive”).

Milestones

- M4, Mid-Term Review MTR ([UPM](#)), month 18, final designs and models.

Other

- Hardware: we are preparing the acquisition of a more powerful server.
- Contracts: we are preparing to hire some help.



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

PULSE Project

II Progress Meeting

10/09/2023

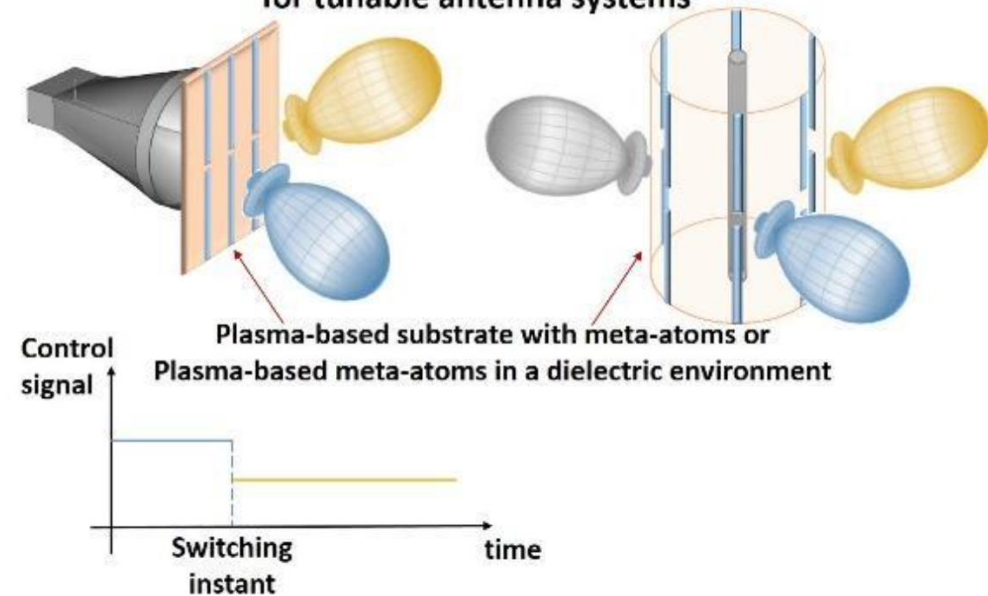
Prof. Matteo Gherardi, Prof. Romolo Laurita,
Dr. Giulia Laghi, Dr. Filippo Capelli

Our role in the PULSE project

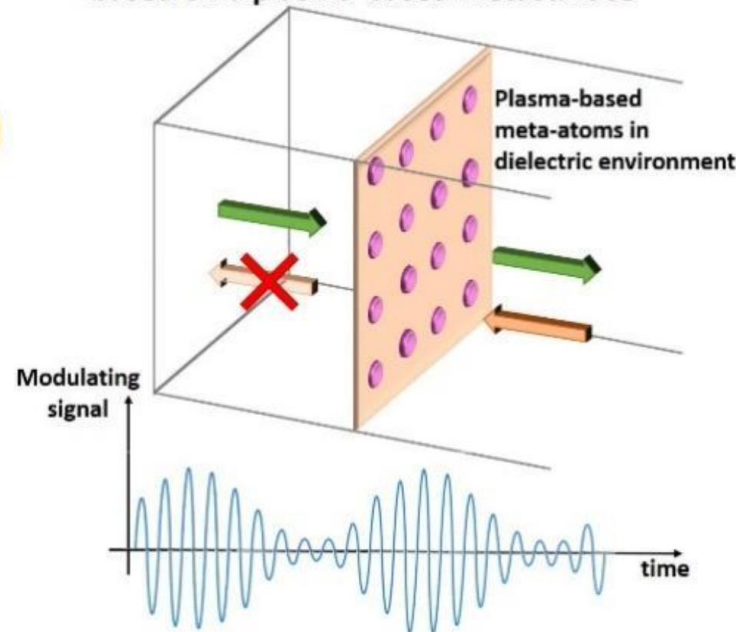
➤ Main tasks:

- **Participate in the review of the relevant scientific literature** about plasma discharges for metamaterial devices, focusing on working principles, physical characteristics and manufacturing aspects to point out potentialities and limitations in the context of the project
- **Manufacturing and characterizing plasma meta-devices**
- **Validate theoretical and numerical models**

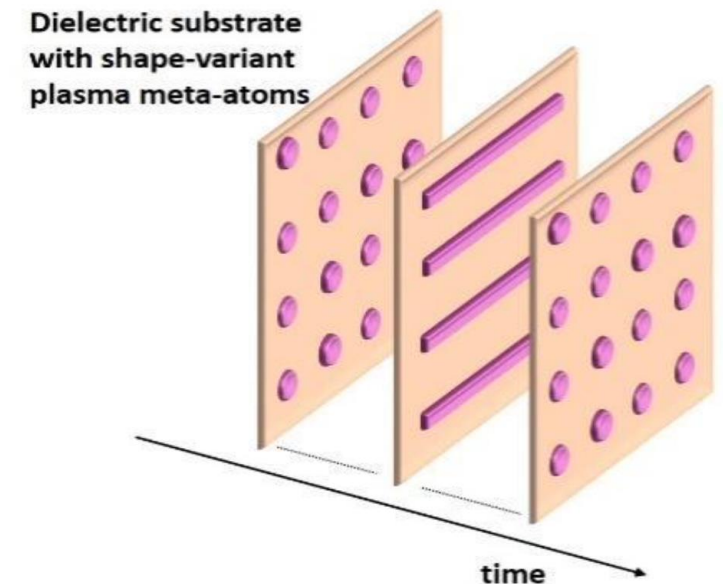
Examples of planar and circular plasma-based metasurfaces for tunable antenna systems



Sketch of non-reciprocal waveguide device based on a plasma-based metasurface



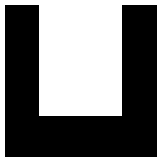
Sketch of a 4D device



Task 2: Manufacturing and characterizing plasma metadevices

Envisioned steps towards the realization of the target plasma meta-device

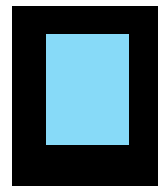
Engraving of
the dielectric
matrix to create
the elements



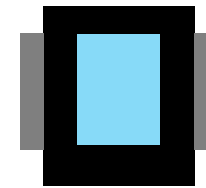
Filling of the
elements under
controlled
atmosphere and
pressure



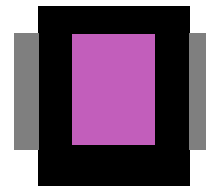
Sealing of the
elements



Addition and
control of the
electrodes



Ignition and
characterization
of the plasma
discharge



Task 2: Manufacturing and characterizing plasma metadevices

➤ Engraving of dielectric matrix

❖ Techniques:

- micromilling machine (currently available at UNIBO)
- femtosecond laser (date of arrival: Oct 2023)

❖ Dielectric materials:

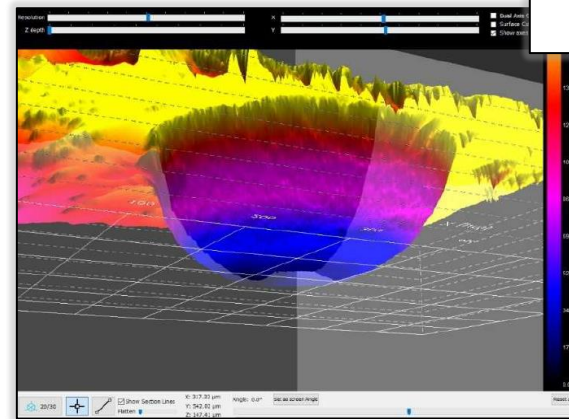
- PDMS (polydimethylsiloxane)
- PMMA (polymethylmethacrylate)
- PEEK (polyetheretherketone)
- Flexdym™ (by Eden Tech)
- glass
- ceramics

❖ Geometries to be created in the dielectric matrix:

- holes
- cavities
- channels

❖ Characterization of the geometries:

- optical microscope (currently available at UNIBO)
- interferometer (date of arrival: within the end of 2023)



Task 2: Manufacturing and characterizing plasma metadevices

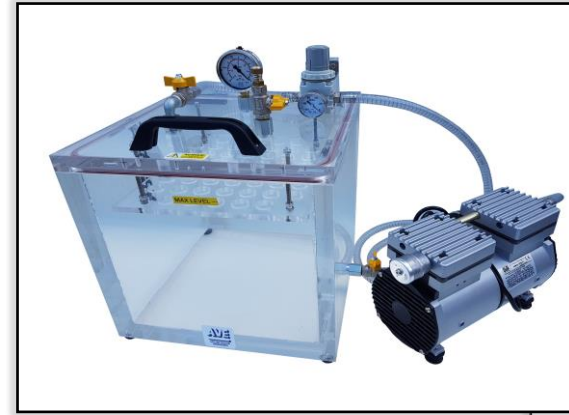
➤ Design of the filling process

❖ Vacuum chamber:

- walls in PMMA
- transparent
- pump able to reach up to 0.1 mbar

❖ Accessories for vacuum chamber:

- gas filling system
- sealing system:
 - holder to align the two pieces
 - linear actuator to bring the two pieces together and apply pressure
- sensors for:
 - relative humidity
 - temperature
 - oxygen concentration
 - pressure gauge
- control system: placed outside the chamber to preserve electronics from vacuum



Task 2: Manufacturing and characterizing plasma metadevices

➤ Design of the sealing process

❖ Solutions to be explored:

- Plasma-assisted oxidation: only viable with PDMS
- Glueing: viable for every material
- Welding using dichloromethane: only viable with PMMA or PC
- Simple compression: only viable with Flexdym™



➤ Addition and control of the electrodes

❖ Electrode material: stainless-steel

❖ Electrode position:

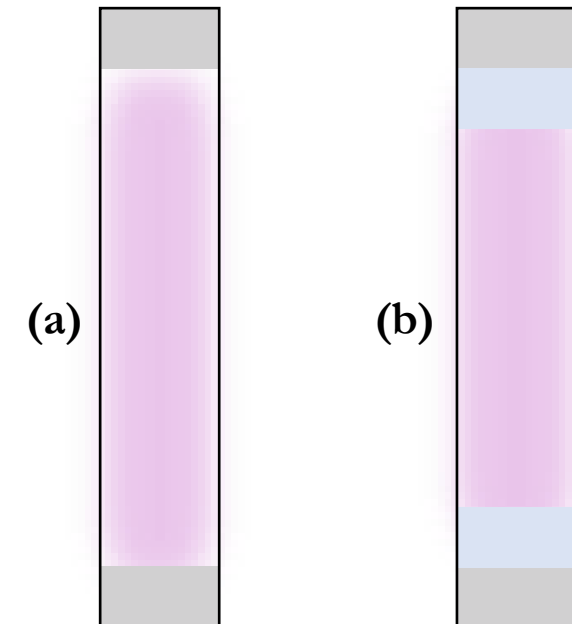
- in direct contact with plasma discharge (a)
- in dielectric-mediated contact with plasma discharge (b)

❖ Power supply:

- DC
- AC

❖ Each plasma element:

- independently controlled
- controlled together with the others



Next steps

First tests towards the realization of the first prototype: single-column plasma meta-device

➤ *In the next months*

- ❖ Engraving of the selected dielectric materials using the micromilling machine
 - Parameters to be varied:
 - material (PMMA, PC)
 - dimensions of the engravings (diameter, length)
- ❖ Sealing in air at atmospheric pressure
 - Parameters to be varied:
 - sealing strategy (glue, dichloromethane)
- ❖ Positioning of the electrodes
 - Parameters to be varied:
 - distance between the electrodes and the plasma discharge
 - type of contact between electrodes and discharge

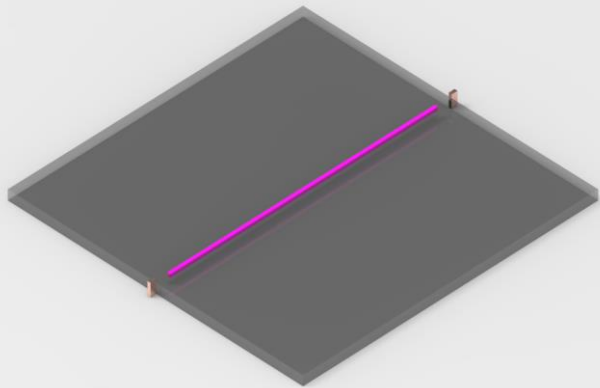
➤ *As soon as the vacuum chamber will be available*

- ❖ Filling and sealing of the elements under controlled atmosphere and pressure
 - Parameters to be varied:
 - Type of gas
 - Pressure
- Ignition of the plasma discharge:
 - Parameters to be varied:
 - Power supply
 - Control of the electrodes (independent, together)
- Characterization of the plasma-element (uniformity, breakdown voltage, ...)

Scientific guidelines of the research

Our goal: «Provide reference plasma meta-devices to contribute to the 360-degree understanding of the interaction between plasmas and EM waves»

Single-column plasma meta-device for horn antennas
(reference meta-device)



This device can be studied on several levels:

➤ **Experimental level**

- **From a constructive point of view:**

- Machining techniques
- Element dimensions
- Materials
- Sealing strategies
- Positioning of the electrodes
- Power supply
- Pressure

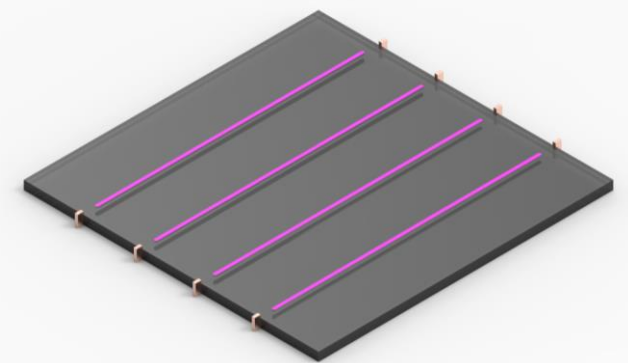
- **From a characterization point of view:**

- Gas discharge uniformity
- Voltage breakdown
- Electron density
- Switching velocity

➤ **Modelling level**

➤ **Industrial exploitability level**

Multi-column plasma meta-device for horn antennas
(target meta-device)



This approach will be adopted for all the families of plasma meta-devices that we aim to realize in the PULSE project



Dr. Filippo Capelli
10th September 2023

Progetto HORIZON- EIC "PULSE -
Plasma reconfigurable metasurface
technologies". **G.A. n.101099313**



PULSE

European
Innovation
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Our role in the PULSE project

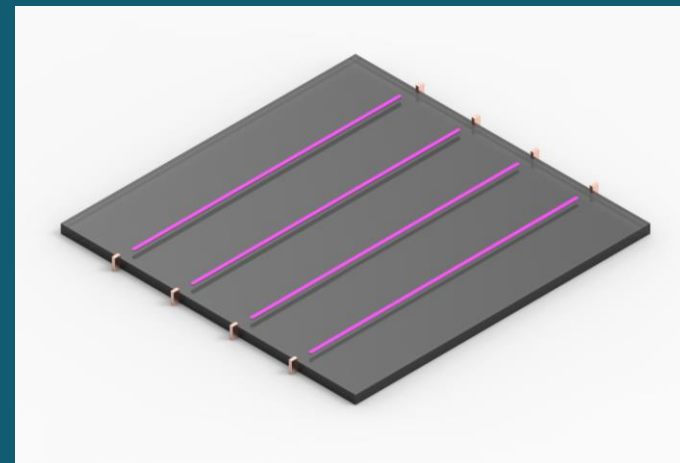
Main tasks

#	Task	Starting month
1.5	Experimental setup & testing	6
1.6	Validation	18
2.4	Experimental testing	12
3.4	Experimental setup & testing	18
4.2	Exploitation	24
4.3	Workshop & conference organization	-
5.5	Final report	-

Experimental setup & testing



Plasma device



High voltage generator

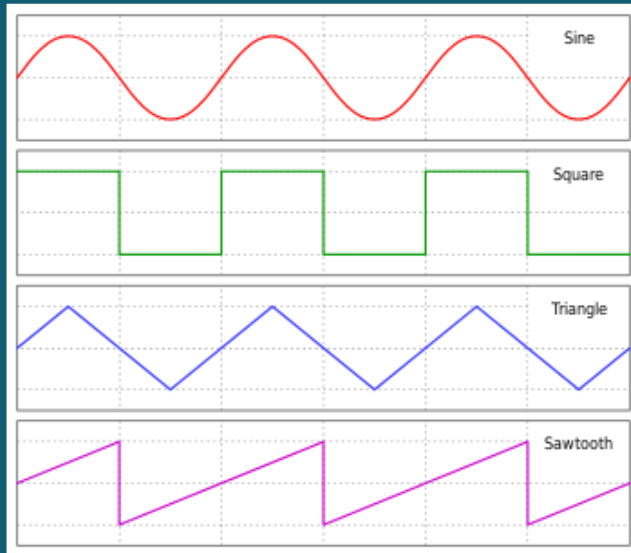


High voltage generator

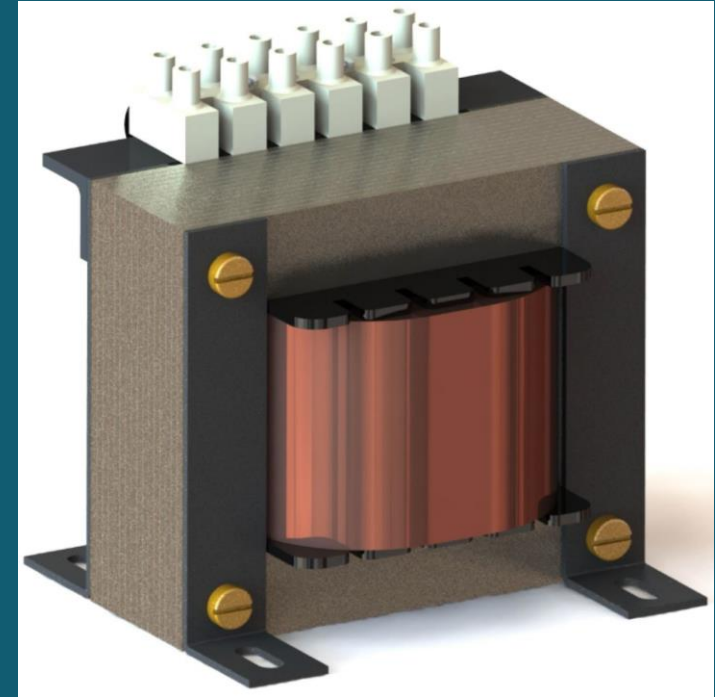
Signal generator

+

Passive amplifier



Produces waveforms with variable shapes and frequency, the peak voltage is limited between 10 and 50 V



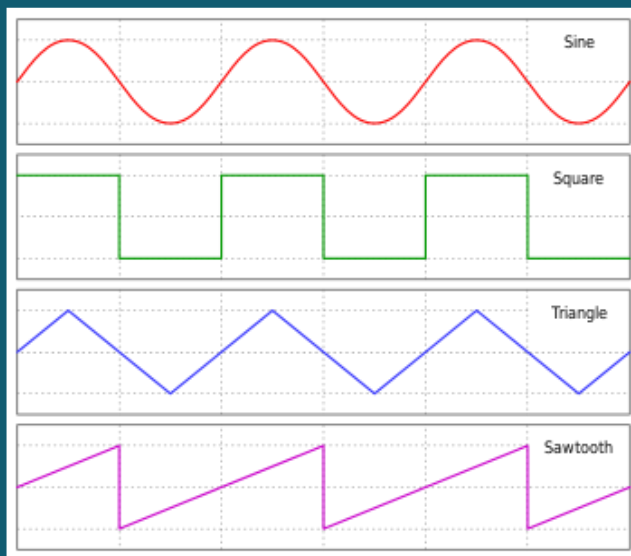
Increase the voltage of the input waveform without changing the frequency, the electrical power output is the same of the input power

High voltage generator

Signal generator

+

Active amplifier



Produces waveforms with variable shapes and frequency, the peak voltage is limited between 10 and 50 V



Increase the voltage of the input waveform without changing the frequency (in a certain range), the electrical power output is higher than the input power

High voltage generator

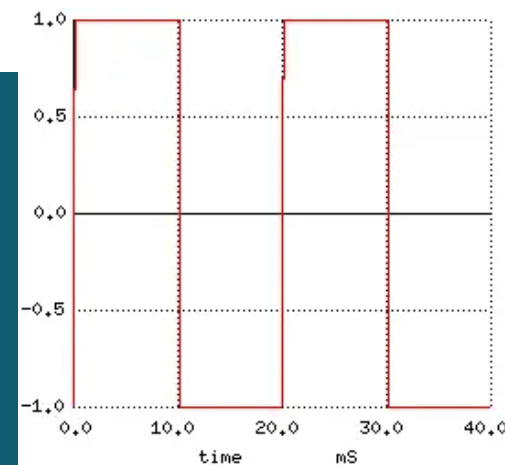
DC high voltage generator

+

MOSFET



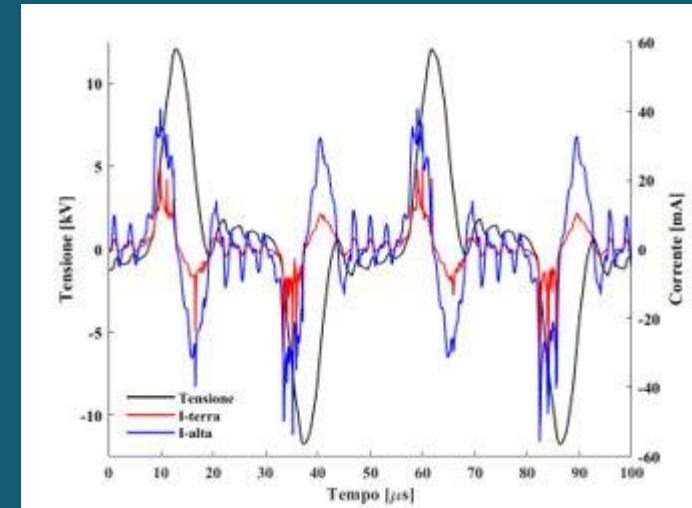
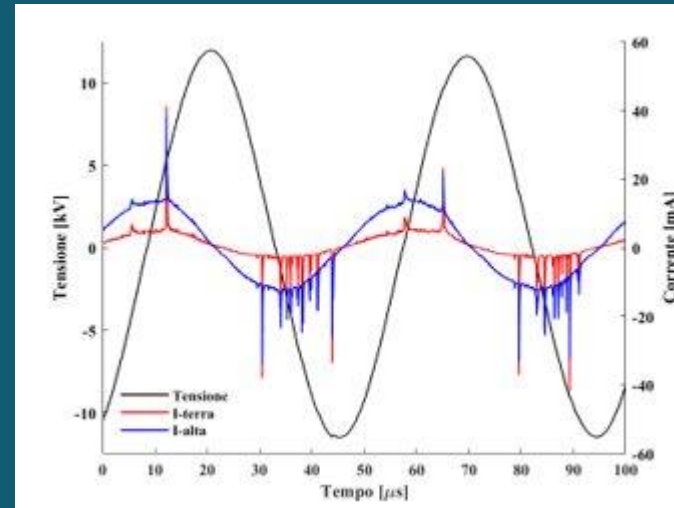
Produces a direct current at variable high voltages



Produces a square waveform with the peak voltage of the DC input and variable frequency

High voltage generator

Resonant generator



Sinusoidal or pulsed waveform

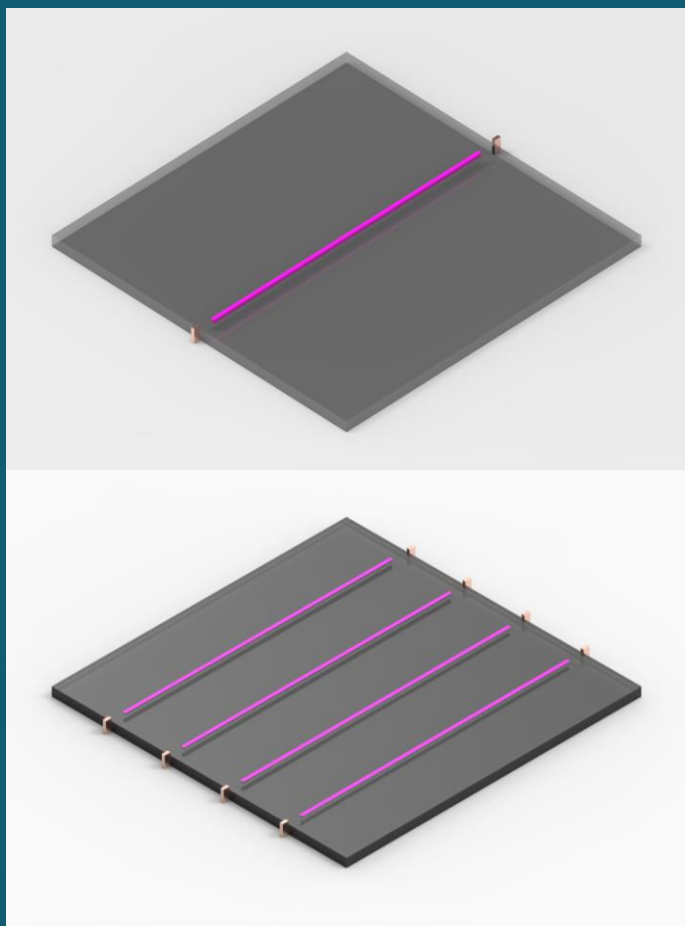
This particular high voltage generator is custom produced for a specific application. It is designed on the capacity of the plasma device and has a narrow range of operation (voltage and frequency are *almost* fixed).

Once the device is fixed, this kind of power supply is the most interesting: it is more reliable and cheaper than the previous ones.

General guidelines of the research: AlmaPlasma

The main task of AP in this project is to analyze and support the industrial exploitability of the produced devices

DEVICES



ANALYZED FEATURES

- Materials: cost, durability
- Machining techniques: cost, duration
- Sealing: cost, efficacy, durability
- Power supply: cost, safeness, durability, size, power consumption
- Gas: cost, pressure, safeness

Thanks for your time

Filippo.Capelli@almaplasma.com