



PULSE – Plasma reconfigURabLe metaSurface tEchnologies

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Deliverable: Report on reconfigurable techniques for metadevices with a focus on limitations and fundamental bounds

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1 Purpose and scope of the deliverable

This document reports the systematical analysis and review the relevant scientific literature about the design of reconfigurable metadevices working at the target frequency ranges. Moreover, the potentialities and the limitations of each approach are discussed, as well as the relevant fundamental limitations, aiming at defining realistic benchmarks for the demonstrators.

This deliverable is divided into five (5) main chapters: introduction, literature review on electromagnetic reconfigurability, electromagnetic reconfigurability, limitations and fundamental bounds, database of the relevant state-of-the-art.

The introduction chapter briefly summarizes the main objective of the PULSE project and the importance to identify the most relevant works in the literature as starting point for the design of the PULSE plasma-based devices.

The chapter dedicated to the review of the literature on electromagnetic reconfigurability reports an overview of the entire state of the art available in the open technical literature on reconfigurable metastructures. Specifically, in this chapter, we report the analysis per category and per year of publication of the literature related to tunable and reconfigurable metamaterials and metasurfaces, as well as a comparison between them. Moreover, we describe the criteria applied to the entire literature for limiting it to the relevant works for the PULSE project.

The chapter on electromagnetic reconfigurability provides a detailed description of the three main tuning approaches proposed in the literature: geometrical-based, material-based and electronic-based tuning. For each approach, we describe the main methodologies to achieve it and the specific limitations.

The Key Performance Indicators (KPI) and the fundamental bounds identified in the state of the art are discussed in the penultimate chapter. Here, we review and discuss the KPIs identified for each Application Area of the PULSE project, and we report their fundamental bounds according to the works presenting in the open technical literature.

This deliverable ends with the description of the database collecting all the relevant works for this report.

2 Introduction

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.

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 radically new strategy we investigate in this research project will allow:

- to extend the applicative scenarios of reconfigurable metasurfaces to the millimeter-wave frequency range, where effective and fast tuning approaches are currently not available;
- to define a completely new approach for designing meta-atoms whose properties change both in time and space;
- to provide the scientific and technological fundamentals of an unprecedented family of metadevices composed by shape-varying meta-atoms;
- to improve the power efficiency and the reconfigurable capability of discharge technology with the aim to make plasma MTS a plausible candidate for everyday equipment.

The definition of these unprecedented technological lines, ensuring reliability at high frequencies and fast tunability rates, is of paramount importance to address the requirements of the future information society, especially in the area of **security** and **critical safety** applications. Therefore, we expect this technology to have a **huge social and economic impact**, as it will affect many application fields, such as telecommunication and navigation (compact antennas and EM shields, multi-/narrow-/broad-band, reconfigurable, electronically steerable, jamming resistant), Information and Communication Technologies (antennas embedded in internal/external surface of buildings, cars, aircrafts, mobile phones or wearable tissues open new horizons allowing high data rate interlink communication between users), aerospace, aviation and ground transportation, consumer electronics and health, driven by a major innovation in the physical layer of the future RF, microwave, and mm-wave systems.

PULSE aims at **exploring new research and technological lines based on plasma-based meta-atoms and meta-structure** to be used for realizing novel reconfigurable les for antennas and time-modulated devices. **To measure the novel aspects in comparison with the state of the art from the technological point of view, a comprehensive review of the open technical literature has been performed and presented in this deliverable.** In the following chapters, we present an overview of the technical literature on reconfigurable and tunable metastructures, illustrating the three main tuning approaches (geometrical-based, material-based and electronic-based tuning), and their fundamental bounds.

3 Literature Review on Electromagnetic Reconfigurability

The field of reconfigurable and tunable electromagnetic (EM) metamaterials and metasurfaces has witnessed a remarkable increase in the research effort, which is evident by considering the over 10,000 published articles in the past 15 years.

The works of reconfigurable and tunable EM metamaterials and metasurfaces has been extracted from body of literature by using the public research tool *Dimensions.ai*, that provide access to the world's largest research information database [1]. *Dimensions.ai* provides full text search for more than 200 million documents, with metadata filters, similarity search, and advanced features that enable the possibility to structure the search in the way you want and define your own groups of entities.

Thanks to *Dimensions.ai*, this extensive body of literature has been classified into four primary categories:

- **Reconfigurable Metamaterials:** These metamaterials exhibit dynamic electromagnetic properties that can be manipulated in real-time. This capability stems from the incorporation of active elements, such as varactor diodes or phase-change materials, into the metamaterial structure.
- **Tunable Metamaterials:** Tunable metamaterials offer a more gradual adjustment of their electromagnetic properties, typically achieved through external stimuli such as temperature changes, mechanical actuation, or optical illumination.
- **Reconfigurable Metasurfaces:** Metasurfaces, composed of subwavelength structures with reduced electrical thickness, can dynamically alter their scattering or transmission characteristics. Reconfigurable metasurfaces achieve this control through active elements integrated into the surface.
- **Tunable Metasurfaces:** Tunable metasurfaces, analogous to tunable metamaterials, enable the controlled modulation of their electromagnetic response through external stimuli.

The considered body of literature encompasses all the publications that include the searching keywords "*reconfigurable metamaterials*," "*tunable metamaterials*," "*reconfigurable metasurfaces*," or "*tunable metasurfaces*" in the title and/or abstract.

In the next sections, we report the temporal evolution of each of the four categories over the years, identifying the year when these technologies have become of interest for the scientific community, and then we refine our research according to a set of pertinent criteria, allowing to limit the body of the literature to the relevant works of interest for the PULSE project.

3.1 On the Reconfigurable/Tunable Metamaterials

In this section, we discuss the open technical literature on reconfigurable and tunable metamaterials that has been published between 2005 and 2023.

In particular, Figure 1(a) reports the number of publications per year on the topic *reconfigurable metamaterials*, which encompasses more than 1250 publications in the last 17 years. The line graph shows a steady increase in the number of publications per year on reconfigurable metamaterials, from around 20 in 2005 to almost 200 in 2022. This trend reflects the growing interest in this field, driven by the potential of reconfigurable metamaterials to revolutionize a wide range of applications. The graph also highlights the recent increasing of the published articles on this topic, with the number of papers increasing by over 50% in the past five years. This suggests that the field of reconfigurable metamaterials is rapidly maturing.

Similarly, Figure 1(b) reports the number of publications per year on the topic *tunable metamaterials*. The line graph shows a similar trend to the one for reconfigurable metamaterials, with a steady increase in the number of publications per year on tunable metamaterials with a total of almost 5000 publications over the past 17 years. The number of papers has increased from around 30 in 2005 to over 600 in 2022, representing a more than 20-fold increase. It is worth noting that the number of publications on tunable metamaterials is higher than the number of publications on reconfigurable metamaterials. This suggests that tunable metamaterials may be a more mature field, with a wider range of applications already being explored. However, it is also important to note that the field of reconfigurable metamaterials is rapidly growing. As this field continues to develop, we can expect to see a convergence of the two fields, since the trend is to have tunable metamaterials that allows to achieve reconfigurable capabilities.

Overall, the graphs in Figure 1 provide a clear indication of the growing interest in the investigation and development of tunable and reconfigurable metamaterials.

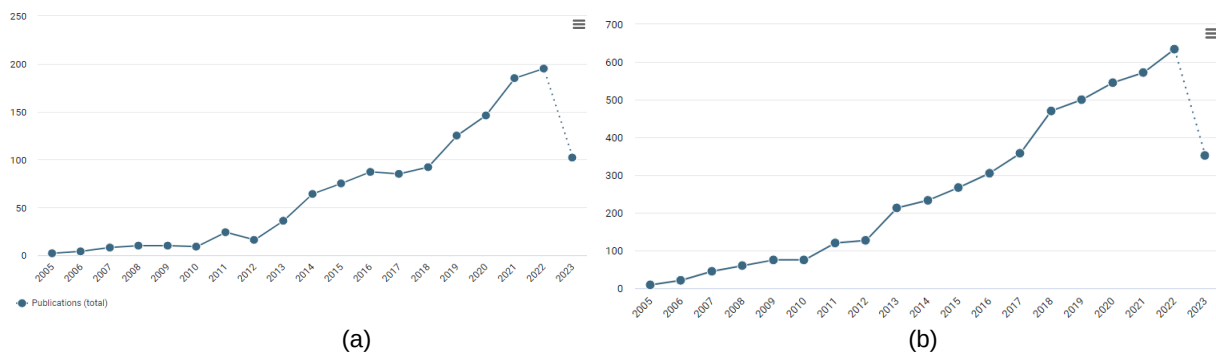


Figure 1: Number of publications per year on (a) Reconfigurable MTMs (1,278 pubs), and (b) Tunable MTMs (4,987 pubs).

Some of the key factors driving the growth of reconfigurable and tunable metamaterials include:

- Advances in materials science: The development of new materials with tunable properties has enabled the creation of more sophisticated and effective reconfigurable metamaterials.
- Improved fabrication techniques: Advances in fabrication techniques have made it possible to produce reconfigurable metamaterials with greater precision and control.
- The development of new materials with tunable properties: As mentioned previously, the development of new materials with tunable properties has enabled the creation of more sophisticated and effective tunable metamaterials. Some examples of these materials include phase-change materials, liquid crystals, and they will be discussed in the next chapter of this deliverable.
- Growing demand for real-time control: The increasing demand for real-time control of electromagnetic waves in a variety of applications is fueling the development of new reconfigurable metamaterials.

3.2 On the Reconfigurable/Tunable Metasurfaces

In this section, we discuss the open technical literature on reconfigurable and tunable metasurfaces that has been published between 2005 and 2023.

The number of publications per year on the *reconfigurable metasurfaces* is reported in Figure 2(a). The graph clearly illustrates the exponential growth in research activity related to reconfigurable metasurfaces, with the number of publications increasing from around 15 in 2005 to 400 in 2022. It is worth noting that the number of publications starts to increase much later than the reconfigurable

metamaterials (see Figure 1(a) for comparison), but the number of publications is much higher (1637 publications for metasurfaces vs. 1278 publications for metamaterials). This trend is indicative of the growing interest in reconfigurable metasurfaces, which offer the ability to dynamically control their electromagnetic properties by using a thinner structure. Indeed, one possible explanation is related to their typical bidimensional structure that makes them easier to fabricate than metamaterials. As a result, metasurfaces may be more attractive for practical applications.

Similarly, Figure 2(b) shows the number of publications per year on the *tunable metasurfaces*. The line graph showing the number of publications per year on tunable metasurfaces shows a similar trend to the graphs for reconfigurable metasurfaces, with a rapid increase in the last 10 years. The number of papers has increased from around 50 in 2005 to over 500 in 2022, representing a 10-fold increase. Compared to the data discussed earlier, the current number of publications on reconfigurable metasurfaces is slightly lower than that of tunable metasurfaces. However, reconfigurable metasurfaces offer a wider range of functionalities than tunable metasurfaces, making them the preferred technology for realizing devices with adaptive capabilities.

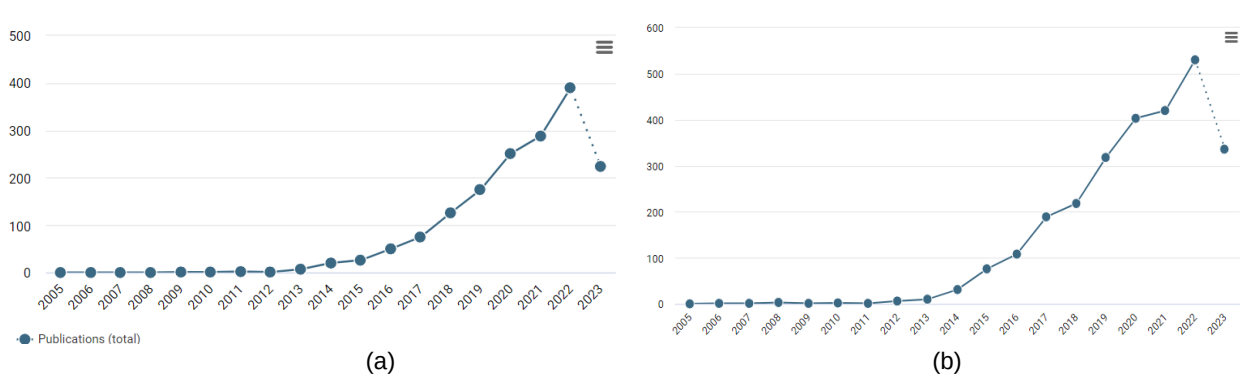


Figure 2: Number of publications per year on (a) Reconfigurable MTs (1,637 pubs), and (b) Tunable MTs (2,655 pubs).

Some of the key factors driving the growth of reconfigurable and tunable metasurfaces include:

- **Reduced space occupancy:** The metasurfaces are bidimensional structures with an extremely high surface-to-thickness ratio, enabling the possibility to be curved or wrapped around objects or antennas.
- **Easy fabrication:** Advances in fabrication techniques of printed circuit boards (PCBs) have made possible to fabricate reconfigurable metasurfaces with greater precision, control and at extremely lower costs.
- **Growing demand for real-time control:** The increasing demand for real-time control of electromagnetic waves in a variety of applications is fueling the development of new reconfigurable metasurfaces.

3.3 Comparison between categories

As reported in Table 1, all four categories have experienced significant growth in the past 17 years. However, reconfigurable metasurfaces have seen the highest growth rate, suggesting that this may be the most promising area of research in the field.

Table 1: Comparison between the number of articles published in 2005 and 2022.

Material	# of publications (year 2005)	# of publications (year 2022)	Fold increase
Reconfigurable metamaterials	20	200	10x
Tunable metamaterials	30	600	20x
Reconfigurable metasurfaces	15	400	25x
Tunable metasurfaces	50	500	10x

Reconfigurable and tunable metasurfaces are both rapidly developing fields with the potential to revolutionize a wide range of applications. Reconfigurable metasurfaces offer a wider range of applications, while tunable metasurfaces offer more precise control of electromagnetic waves. As research continues to advance and integration challenges are overcome, we can expect to see metasurfaces play a pivotal role in shaping the future of electromagnetic technologies.

3.4 Selected Literature for PULSE project

In the previous section, the entire body of literature has been based only on the research terms, without any consideration of the actual works that are of interest for the PULSE project. The literature analysis in Sections 3.1 - 3.2 considers all possible works regardless the publication year, operative frequency range and validation method. This wide literature can be represented in the three-dimensional space as shown in Figure 3, where each dots represents a specific work in the state of the art.

The graphical location of a specific work in the literature as shown in Figure 3 is achieved by considering three specific features of the work, i.e., 1) year of publication; 2) operative frequency, 3) validation model.

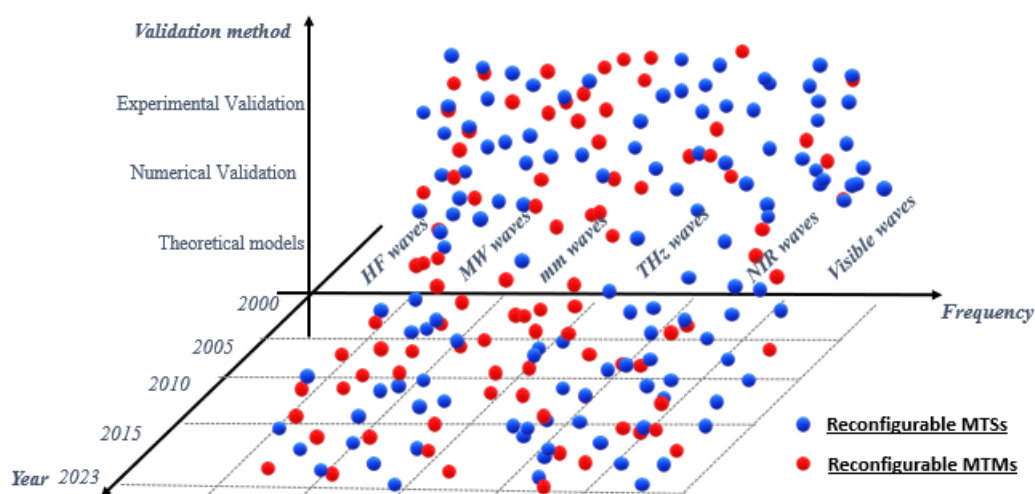


Figure 3: Graphical distribution of published articles in the classification 3D space

The field of reconfigurable and tunable metasurfaces is relatively new, and there is a limited body of literature available that meets the specific criteria of the PULSE project, as shown in Figure 4. We focus our attention on the works that cover the entire frequency range from L to Ka bands and provide experimental validation. Indeed, experimental validation is essential to establish the practical feasibility and performance of reconfigurable and tunable metasurfaces. This allows to limit the body of literature as represented in Figure 4. It is worth mentioning that the limited number of experimental studies in the literature is limited, particularly for devices operating at higher frequency bands. Therefore, some relevant works that have been validated using a proper set of numerical simulations and theoretical models will be also considered.

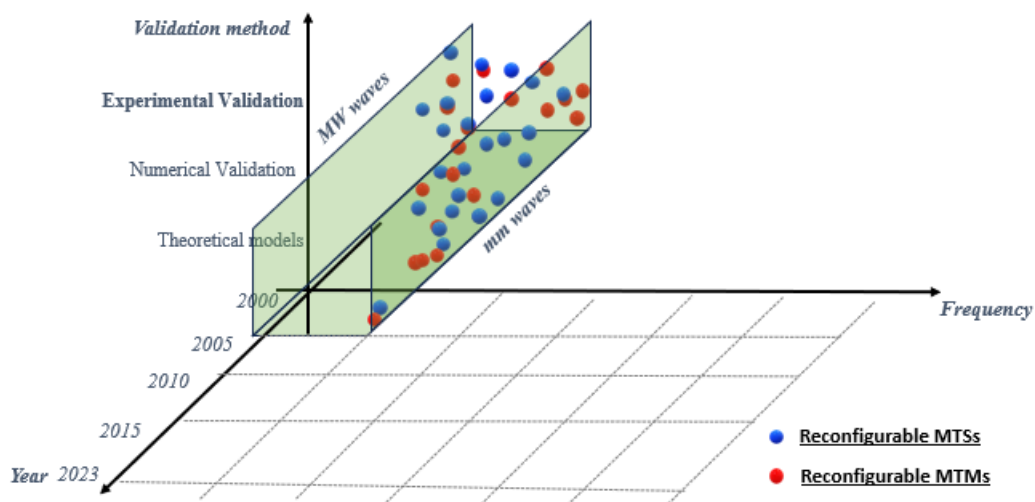


Figure 4: Graphical distribution of selected published articles in the classification 3D space

In the next chapter, we describe the reconfigurable and tunable metamaterials and metasurfaces proposed in the state of the art that satisfy the above criteria. Moreover, we classify them according to the three primary approaches to achieve electromagnetic reconfigurability.

4 Electromagnetic reconfigurability

Electromagnetic reconfigurability is a transformative technology that empowers electromagnetic devices to dynamically alter their properties in response to external stimuli [2],[3]. This capability opens a plethora of possibilities for manipulating electromagnetic waves.

Three primary approaches to achieving electromagnetic reconfigurability have emerged:

- **Geometrical Tuning:** This approach is based on a mechanical deformation of the physical structure of the metamaterial and the metasurface. This can be achieved through various mechanisms, such as actuating microelectromechanical systems (MEMS) or utilizing shape-memory alloys. By changing the geometry of the metamaterial or metasurface, its electromagnetic properties can be dynamically tuned (Figure 5a).
- **Material Tuning:** This approach exploits the intrinsic tunability of certain natural materials to modify the electromagnetic response of the metamaterial or metasurface. Common examples of tunable materials include ferroelectric materials, phase-change materials, and liquid crystals. By applying external stimuli, such as temperature changes, electric fields, or optical illumination, the material properties can be altered, leading to a corresponding change in the electromagnetic properties of the metamaterial or metasurface (Figure 5b).
- **Electronic Tuning:** This approach employs active electronic components, such as transistors or diodes, to control the electromagnetic response of the metamaterial or metasurface. By adjusting the biasing voltages or currents applied to these electronic components, the electromagnetic properties of the metamaterial or metasurface can be dynamically tuned (Figure 5c).

These three approaches, along with their various implementation methods, provide a versatile toolkit for achieving electromagnetic reconfigurability. The choice of approach depends on the specific application requirements, including the desired tuning range, frequency band, and power consumption.

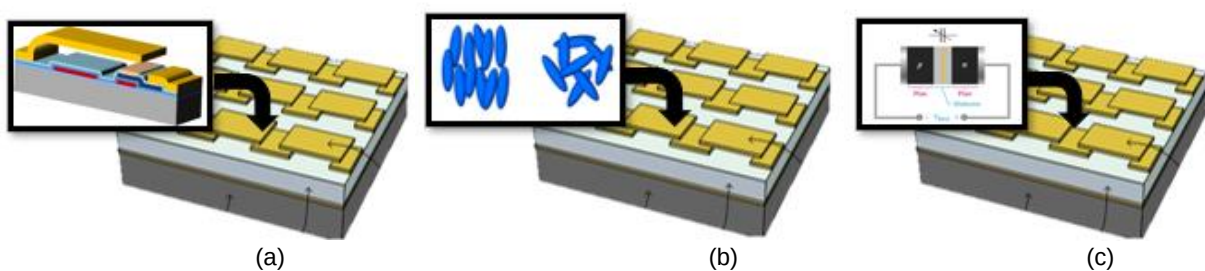


Figure 5: Graphical representation of the three reconfigurability methods:
(a) geometrical tuning, (b) material tuning, (c) electronic tuning.

4.1 Geometrical tuning

Geometrical tuning involves manipulating the physical structure of the unit cells composing the metamaterials. By dynamically altering the shape, size, orientation, or proximity of the conducting elements within the unit cells, their electromagnetic properties can be effectively tuned, enabling real-time control of electromagnetic waves.

As shown in Figure 6, the three primary methods employed for geometrical tuning include:

- **Mechanical Movement:** This method is based on the physical movement of the unit cells to modify the interaction level among them. By changing their relative positions or orientations of

the elements, the electromagnetic properties of the metamaterial or metasurface can be dynamically tuned. Relevant examples falling in this category are reported in Refs. [5].

- **Microfluidics:** This approach utilizes microfluidic channels to control the movement of fluids within the metamaterial or metasurface structure. By altering the fluid distribution, the effective electromagnetic parameters of the metamaterial or metasurface can be modified, leading to a change in its electromagnetic response. In this case, a relevant example falling in this category is reported in Ref. [6].
- **Cantilever-based unit cell:** This method employs cantilever-shaped elements within the unit cells. By applying external forces or stimuli, such as magnetic fields or electrostatic fields, the cantilevers can be deformed, causing a variation in the metamaterial's electromagnetic properties, as discussed in Refs. [7], [8].

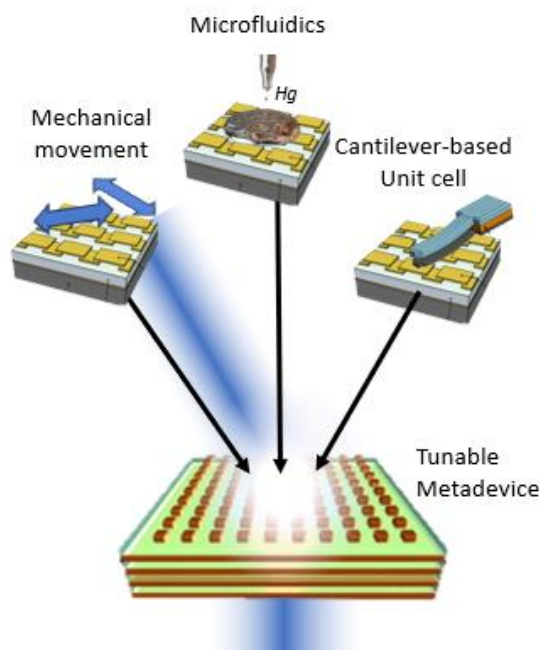


Figure 6: Representation of the three primary methods employed for geometrical tuning.

4.1.1 Mechanical movement

In the realm of geometrical reconfigurability, the use of mechanical movement stands as a pioneering technique, first introduced by D. Sievenpiper in 2002 [4]. The core principle of geometrical tuning by mechanical movement lies in altering the physical arrangement of the metasurface constituent elements. By manipulating their relative positions or orientations, the electromagnetic properties of the metasurface can be effectively modified.

In the Sievenpiper's work, a reflective metasurface whose local reflection coefficient is tuned by changing the geometry of the unit cells has been proposed. This solution has been developed as an alternative to reflect arrays, which typically rely on a vast array of phase shifters and other radio frequency (RF) elements. By ingeniously coupling a high-impedance metasurface with a movable patterned metasurface, Sievenpiper demonstrated the ability to dynamically tune the phase of the reflection coefficient of the structure when illuminated by an electromagnetic wave.

In Figure 7(a), we report the tunable impedance surface proposed in [4]. The main board consists of an array of square patches printed on a metal-baked dielectric substrate and connected to the bottom metallic screen using metallic vias. Another board with only metallic patches printed on one side is placed in front of it and can be freely moved as shown in Figure 7(a). The phase of the reflection coefficient of the tunable surface as a function of frequency for ten different positions of the upper board is shown in Figure 7(b). By varying the overlap area of the capacitive patches, the resonance frequency is tuned from roughly 1.7–3.3 GHz.

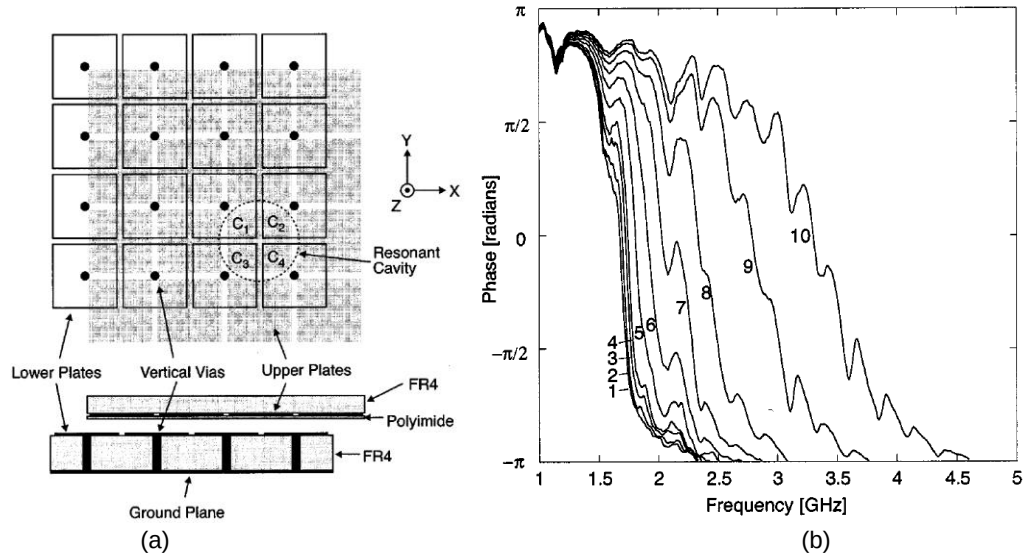


Figure 7: (from [4]) (a) A mechanically tunable impedance surface consisting of two printed circuit boards designed to slide against each other. The Offset changes the electromagnetic response of the unit-cells. (b) The reflection coefficient phase of the tunable impedance surface for various positions of the top tuning board.

Another relevant example of geometrical tuning based on mechanical movement has been proposed by K. Fuchi et al. in 2021 [5]. Incorporating origami concepts in the engineering design process is gaining importance as a mechanism to facilitate the synthesis of innovative structures. Here a set of SRRs are printed on a surface folded into a periodic pattern that can be un-folded by controlling one free folding parameter. The inner and outer rings are printed on different surfaces so that when the folding parameter is varied, the gap between the rings, and thus the capacitance of the resonators, is altered. A simple example of such an arrangement is illustrated in the folded surface of Figure 8(a), which may be unfolded to form the surface in Figure 8(b). The change in capacitance is used as a tuning mechanism to shift the resonance frequency of an array of SRRs. It is shown that a large shift in frequency may be obtained from a small change in the folding parameter, due to the way the structure unfolds.

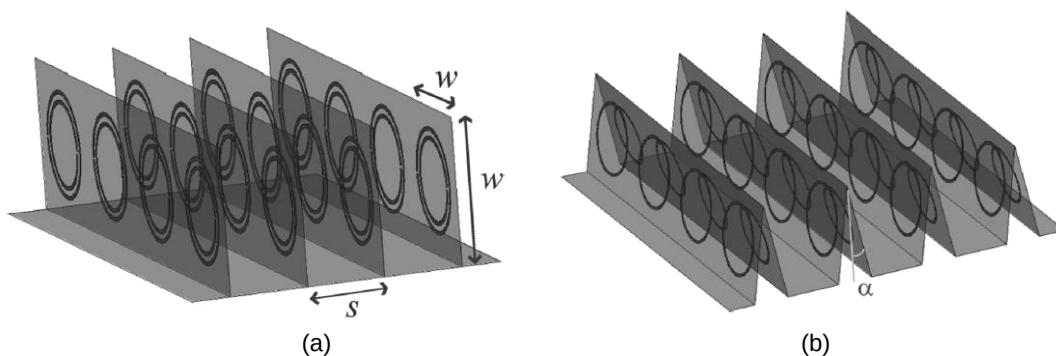


Figure 8: (from [5]) Corrugated sheet with SRRs with (left) $\alpha=0^\circ$ and (right) $\alpha=10^\circ$

Transmission coefficients are plotted in Figure 9 for the angle α that varies from 0° to 10° in 2° increments. The figure shows that the resonance frequencies shift upwards as α is increased. A 2° change in α produces a resonance shift of 28%, a 5° change produces a shift of 45%, and a 10° change produces a shift of 58%. Thus, the upward shift in resonance frequency is quite rapid as the sheet begins to unfold, with the magnitude of the shift tapering off as α increases. The result is a metamaterial that can be tuned mechanically over a wide band of frequencies with only slight physical movement.

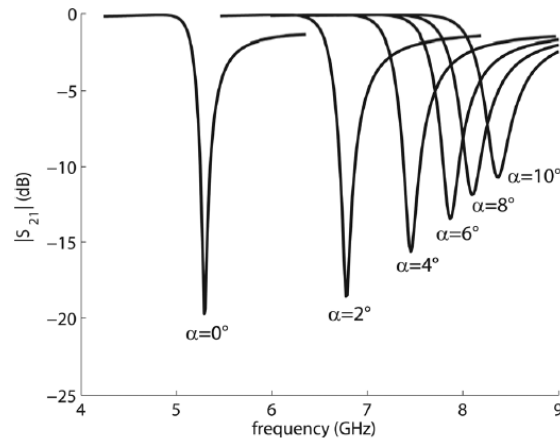


Figure 9: (from [5]) Transmission coefficient of the origami structure in Figure 8 for different values of the angle α .

4.1.2 Microfluidics

Microfluidics tuning utilizes the controlled flow of fluids within microfluidic channels to dynamically alter the metamaterial structure and properties. This technique offers several distinct advantages over tuning methods that will be presented in this report, including almost zero power consumption, and the ability to achieve intricate geometrical modifications.

In one notable example proposed in 2009 by T. Serkan Kasirga et al. [6], a mercury-based microfluids able to dynamically add or remove metallic parts to the unit cell of a metamaterial have been fabricated and measured. They were able to effectively alter its geometry and electromagnetic response in real time. The Authors investigated the electromagnetic response of a microfluidic splitting resonator (MF-SRR) made of an elastomeric material poly-dimethyl-siloxane (PDMS). Rapid prototyping techniques has been used to fabricate the MF-SRR and its channels in PDMS polymer as shown in Figure 10.

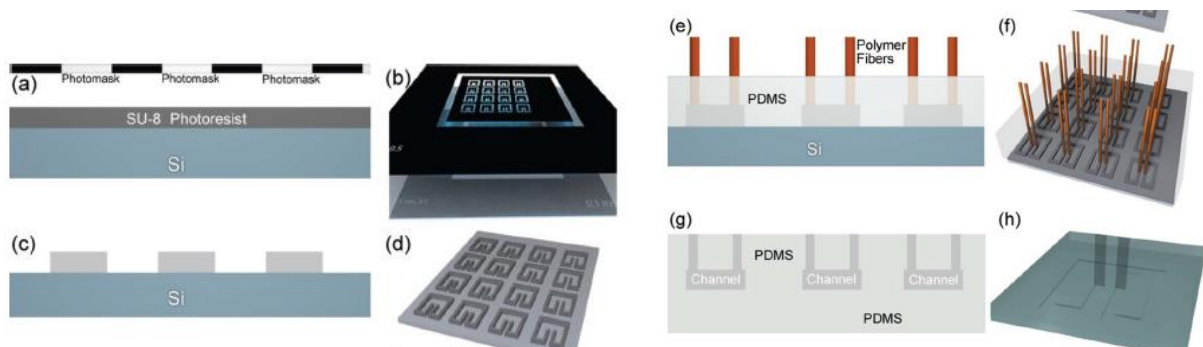


Figure 10: (from [6]) Fabrication steps of MF-SRRs. (a)-(b) MF-SRR patterns on SU-8 50 photoresist, by using photolithography. (c)-(d) Defining positive relief of MF-SRR array on Si wafer. (e)-(f) Placing polymer fibers to define in and out channels. (g) Sealing of SRRs with bottom PDMS slab after exposing both surfaces to oxygen plasma. (h) A single MF-SRR cut from the MF-SRR array is ready for metal injection.

Transmission measurements are performed for a mercury-injected single MF-SRR, and a magnetic resonance is observed at microwave frequencies. Figure 11(a) shows the comparison between the measured and calculated responses of empty and mercury-filled MF-SRR. Mercury-filled MFSRR exhibits a sharp magnetic resonance at 5.41 GHz, while empty MF-SRR the spectra show no resonances. The transmission parameter is measured considering the setup reported in Figure 11(b), where two monopole antennas, one transmitting and one receiving, have been placed near the MF-SRR

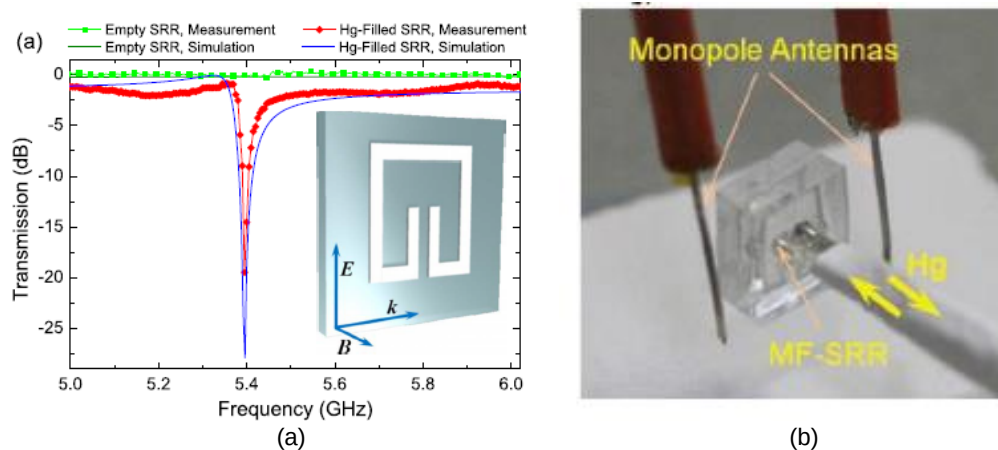
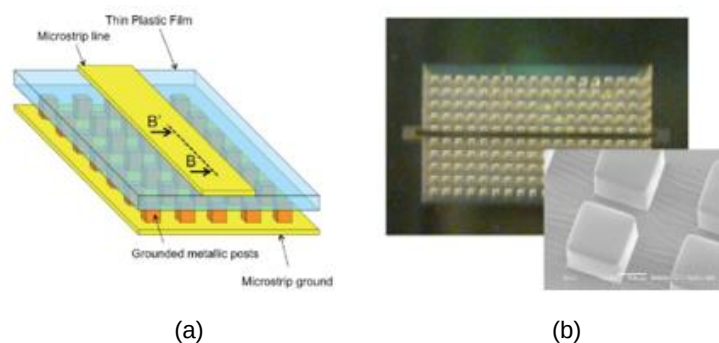


Figure 11: (from [6]) (a) Measured and calculated transmission spectrum of a single MF-SRR before and after metal injection. A magnetic resonance exists at the frequency of 5.41 GHz. The inset shows orientation of MF-SRR structure. (b) Microwave transmission measurement setup with two monopole antennas.

4.1.3 Cantilever-based unit cell

Electromagnetic reconfigurability of metamaterials based on geometrical tuning can be achieved using suspended metallic or dielectric parts that can be moved for altering the interaction with other parts of the unit cell. This approach falls within the class of cantilever-based reconfigurable metamaterials that employ mechanically movable cantilever arms. These metastructures consist of an array of cantilevers, each acting as a unit cell that contributes to the overall electromagnetic response of the structure. By dynamically altering the position or orientation of the cantilever arms, the electromagnetic properties of the metastructure can be effectively tuned, enabling real-time control of electromagnetic waves.

One of the very first examples proposed in the state-of-the-art is the one authored by D. Dubuc et al. and published in 2009 [7]. In this work, the authors demonstrate, for the first time, the fabrication and testing of an artificial dielectric featuring wide dielectric tunability using a very simple technology. The architecture of the proposed device is shown in Figure 12(a)-(b).



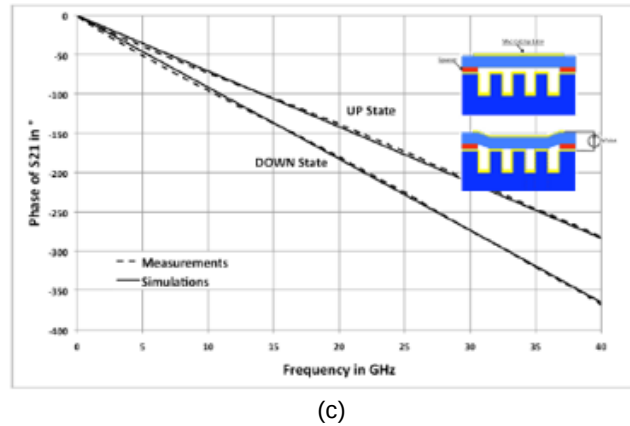


Figure 12: (from [7]) (a) Investigated circuit architecture and (b) Fabricated proof of concept (c) Measured and simulated phase of S_{21} parameter in both UP and DOWN state shown in the inset.

Figure 12(c) reports the measured (dashed line) and simulated (solid line) phase of the transmission coefficient up to 40GHz for the two states of the cantilever. For both states, the insertion loss was lower than 1.4dB in the entire band, demonstrating that high tunable-low losses operation can easily be achieved.

An application of cantilever-based electromagnetic metastructures to antenna systems have been proposed in 2018 by A. Kesavan et al. [8]. The authors propose the design and fabrication of a cantilever-enabled transmitting metasurface to be used as cover of a dielectric resonator antenna (DRA), enabling the conversion of the omnidirectional pattern into a directive pattern that can be steered. The schematic structure of the FSS unit-cell, which consists of four layers, is shown in Figure 13(a). The top layer is made of stainless steel, having four cantilever arms and four connecting lines. The two metal layers are separated using a thin dielectric layer acting as an isolation layer.

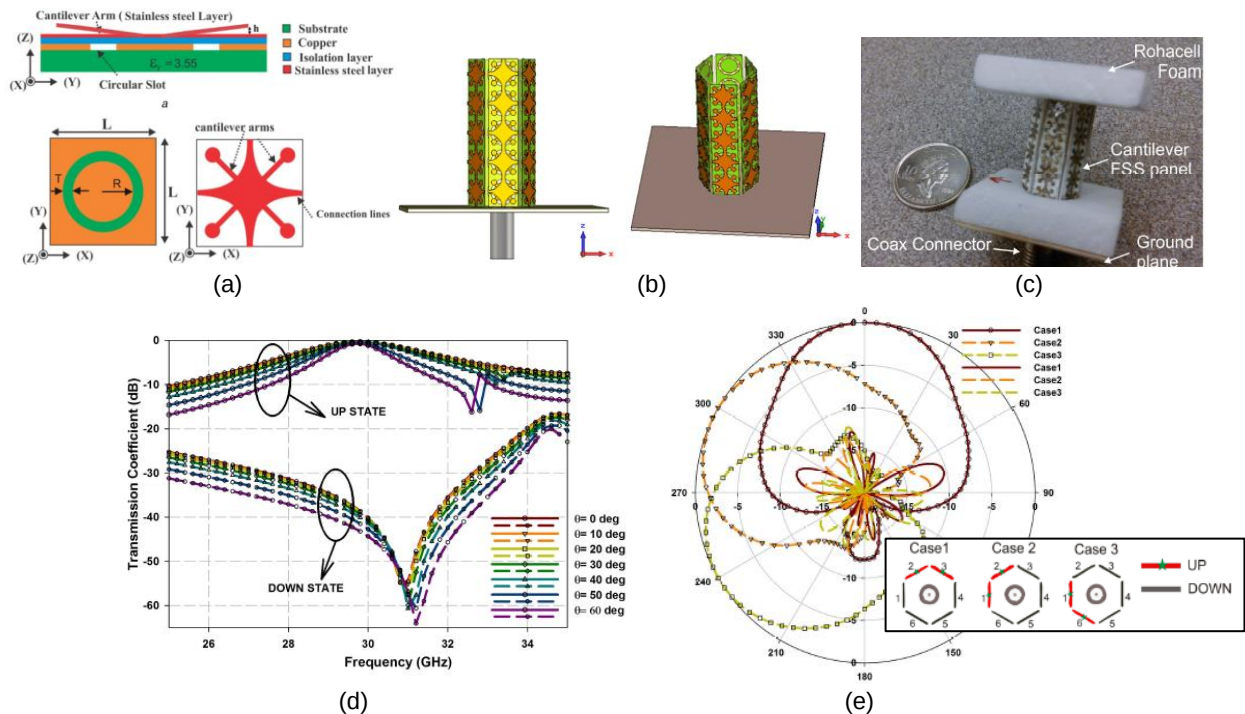


Figure 13: (from [8]) Schematic representation of the (a) proposed FSS and (b) beam-switching DRA. (c) Fabricated prototype of beam-switching DRA. (d) Comparison of transmission coefficients of FSS unit cell at UP state and DOWN state for different incident angles. (e) Comparison of normalized radiation patterns at azimuth plane for the different cases shown in the inset.

The proposed reconfigurable metasurface is embedded with a conventional DRA for the beam-switching applications. The DRA consisting of a cylindrical dielectric resonator is placed over a ground plane and fed with a coaxial feed as shown in Figure 13(b)-(c). The omnidirectional radiation pattern of the DRA in the azimuth plane is converted into a directive beam by incorporating the proposed metasurface around it. To verify that the metasurface is a good candidate for achieving high and low transmission according to its current state, Figure 13(d) report its transmission coefficients in both UP and DOWN states for various angle of incidence. In Figure 13(e), the radiation patterns at 30 GHz measured for each setup shown in the inset are reported, demonstrating the beam-switching capability.

The results reported in [8] are relevant for the **PULSE Application Area 1**, where the reconfigurability applied to antenna systems is investigated during the project.

4.1.4 Geometrical tuning limitations

In general, geometrical tuning based faces several limitations that hinder its widespread adoption in practical applications:

- Extremely Low Reconfigurability Rate: Mechanical actuation mechanisms often exhibit slow response times, typically in the range of fractions of a Hertz. This limitation restricts the dynamic range of the metamaterial's reconfigurability, making it unsuitable for applications requiring rapid switching or real-time control.
- Fine Control Not Allowed: Mechanical tuning techniques often lack the precision necessary to achieve fine-grained control over the metamaterial's electromagnetic properties. This limitation can lead to performance degradation and reduced flexibility in device operation.
- Not Robust Against Mechanical Stress: Mechanical actuation mechanisms can be susceptible to wear and tear, making them less robust against mechanical stress and vibrations. This vulnerability can limit the lifetime of metamaterial devices and increase their susceptibility to malfunctions.
- Complex Tuning Mechanism: Microfluidics tuning often involves intricate microfluidic channel designs and precise control over fluid flow parameters. This complexity can increase the fabrication and maintenance costs of metamaterial devices, making them less practical for large-scale applications.

These limitations underscore the need for further research and development in geometrical tuning techniques based on mechanical movements. Addressing these challenges will pave the way for more practical and versatile metamaterial devices capable of dynamic electromagnetic manipulation.

4.2 Material Tuning

Material tuning is based on the use of materials whose electromagnetic properties can be varied by using an external stimulus. By embedding these materials in the metamaterial unit cell, the overall electromagnetic properties of the metamaterials can be dynamically controlled, enabling an effective tunability and a real-time control of electromagnetic waves.

As shown in Figure 14, three primary methods employed for material tuning can be identified:

- **Ferroelectric Materials:** These materials exhibit a spontaneous electric polarization that can be reversed by an external electric field. By applying an electric field, the permittivity of the ferroelectric material can be modified [9], leading to a change in the metamaterial or metasurface electromagnetic response. In this report, relevant examples falling in this category are reported in Refs. [10],[11],[12],[13],[14],[15].
- **Liquid Crystals:** These materials possess a unique orientation-dependent optical and dielectric permittivity. By applying an external electric or magnetic field, the orientation of the liquid crystal molecules can be controlled, altering the material electromagnetic properties. Relevant examples on tunability based on liquid crystals are reported in Refs. [17],[20]
- **Phase-change Materials:** These materials can reversibly switch between two distinct structural phases, each of which characterized by a different electromagnetic property. By applying an external stimulus, such as heat or light, the phase-change material can be transitioned between its phases, leading to a change in the metamaterial or metasurface electromagnetic response. In this category, we can mention the relevant examples reported in Refs. [23][24][25].

Other methods may be identified in the state of the art, such as graphene and photo-conducting materials (see, e.g., refs. [26][27],[28]), but the limited number of relevant works suggests that they may not be as readily applicable for the project's specific requirements.

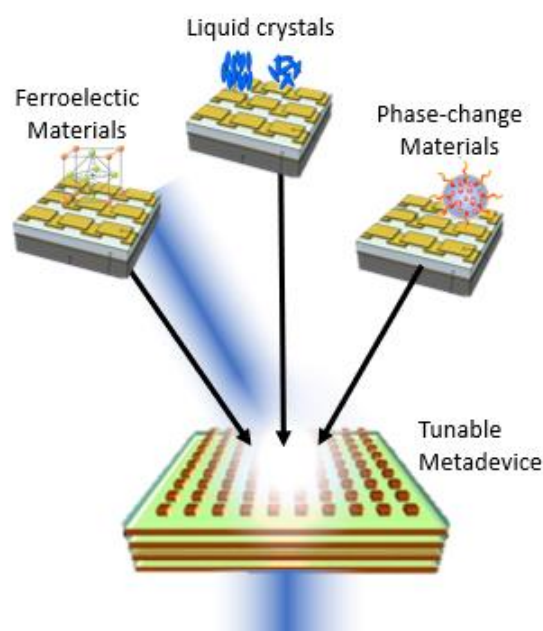


Figure 14: Representation of the three primary methods employed for material tuning.

In the following, these three methods will be discussed in more details, illustrating the relevant examples proposed in the state of the art.

4.2.1 Ferroelectric Materials

Ferroelectric materials, a class of materials exhibiting a spontaneous electric polarization that can be reversed by an external electric field, have been investigated in the last years as promising candidates for achieving tunability and reconfigurability in metamaterials, metasurfaces, and electromagnetic devices. Initially ferroelectric materials were proposed to realize agile microwave circuits exploiting their high power-handling capability, negligible DC power consumption, and potential for low loss and cost. This makes ferroelectric materials also good candidates to achieve metamaterial and metasurface tunability and reconfigurability.

One of the very first application of the ferroelectric materials for achieving reconfigurability in a complex electromagnetic device was proposed by Romanofsky et al. [11]. The work presents the design of a phase shifter to achieve a dynamic phase tuning by changing the effective electrical path of microstrip lines connected to a reflect array operating in K-band. Specifically, the authors use the ferroelectric material Barium-Strontium-Titanate (BST), whose dielectric constant can be tuned in the range 700-1500, with $\tan\delta = 0.05$.

A tunable ferroelectric-based metamaterials operating in the frequency band of interest for the PULSE project have been proposed in the first years of 2000s. Cummer et al. [14] proposed a tunable magnetic metamaterial composed of SRRs loaded with voltage tunable BST thin film capacitors. The metamaterial consisted of nine cells, each of which composed of a BST-loaded SRR as shown in Figure 15(a)-(b).

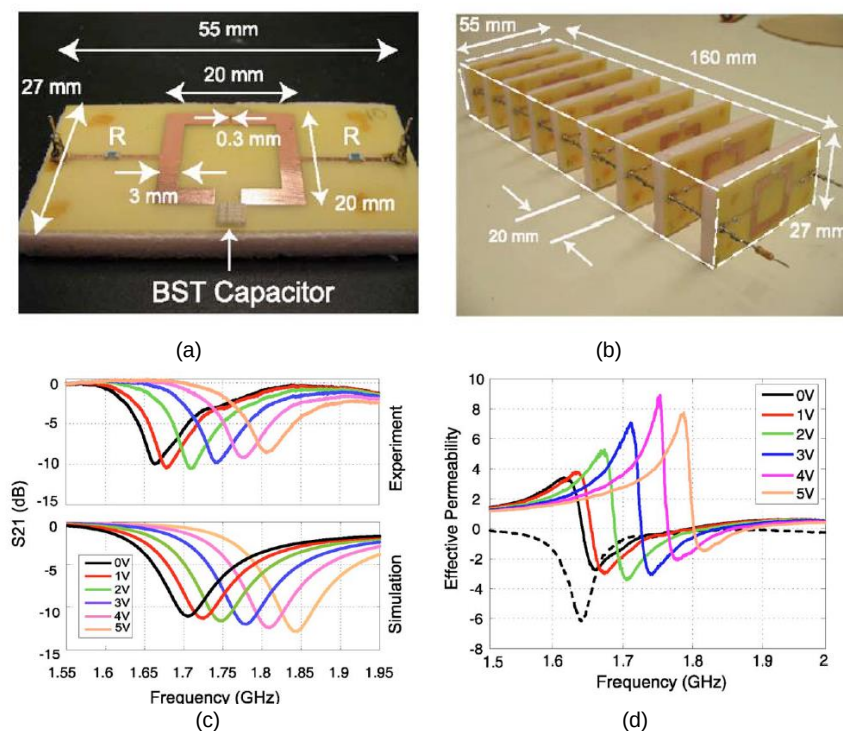


Figure 15: (from [14]) (a) View of an individual unit cell of the tunable slab, (b) Photograph showing the fabricated tunable magnetic metamaterial slab used in experiment (c) S_{21} vs bias voltage for both simulation and experiment for biases from 0 to 5 V. (d) Extracted permeability for the nine cell slab used in the experiment.

Small metal pins were used as DC bias buses that provided equal voltage level to all unit cells in addition to giving the slab mechanical support. Gold wire bonds were used to connect the thin film pads to the copper rings, and two surface mount 127k Ω resistors were used to isolate the DC bus from the SRR. The fabricated slab was resonant with center frequency $f_0 = 1.75$ GHz and could tune

over roughly a 140 MHz band from 1.67 to 1.81 GHz, as reported in Figure 15(c). The corresponding equivalent permeability values as a function of frequency has been extracted from the scattering parameters (Figure 15(d)).

Some years later M. Sezgar et al. investigated the use of ferroelectric materials to achieve metasurface reconfigurability for antenna applications. They proposed a reconfigurable reflective [12] and transmitting metasurface [13] in 2009 and 2012, respectively, where the operative frequency of a high-impedance surface and a frequency selective surface were dynamically tuned applying an intense DC field. In particular, the reflective metasurface has been proposed as flat reflect array able to reflect and rectify the illuminating spherical phase front radiated by the feed antenna located in offset position with respect to the normal direction as shown in Figure 16(a). The energy coming from the feed is reflected by the patches composing the metasurface. To get a co-phased reflected wave in a certain direction like in the case from a parabolic reflector, a phase correction at each element is necessary to compensate the pathlength difference between the flat surface and the corresponding parabolic surface. Such a tuning has been performed by using ferroelectric-based unit cells, whose main advantages are the continuous tunability with a high-power handling capability as well as a negligible power consumption for tuning. In Figure 16(b) the measured reflection coefficients of the tunable unit-cell are shown. With a tuning field of $E_{DC} = 11.5 \text{ V}/\mu\text{m}$ a phase shift of 250° is achieved at 10.5 GHz. In a bandwidth of 200 MHz, a phase shift between 230° to 250° is achievable. However, the losses in the metasurface at the resonance, *i.e.*, when the phase of the reflection coefficient approaches 0° , are not negligible. This is mainly due to the dielectric losses of the materials composing the metasurface.

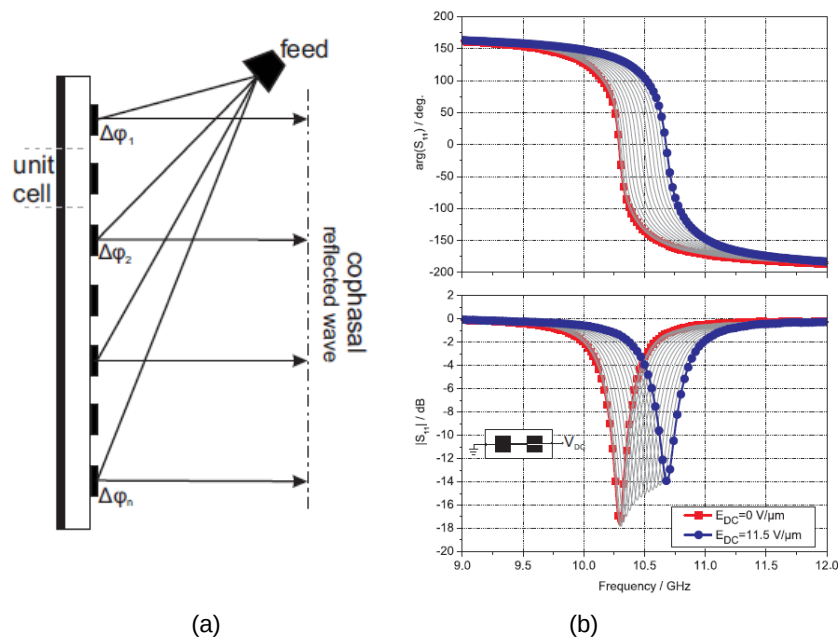


Figure 16: (from [12]) Reconfigurable reflective metasurface used as reflect array; (b) Measured reflection coefficient of the partitioned patches for applied tuning fields between 0 to 11.5 V/ μm .

Designing low loss ferroelectric-based metasurfaces enables the possibility to use them also in transmitting mode due to their lower insertion loss. In this scenario, M. Sezgar et al. proposed in 2012 the design of a transmitting metasurface to be used as transmit array for antenna applications. The metasurface was designed to steer the direction of propagation of the transmitted wave with respect to the incident one coming from a regular antenna [13]. The proposed concept of beamsteering metasurface and its unit-cell are illustrated in Figure 17(a). In particular, the unit-cell is composed of three patterned metallic layers separated by two dielectric substrates. The outer

Despite the narrow scanning range, this work is in line with the scope of the **PULSE Application Area 1**, where the design of a plasma based metasurface for beamsteering/ beam forming applications will be developed.

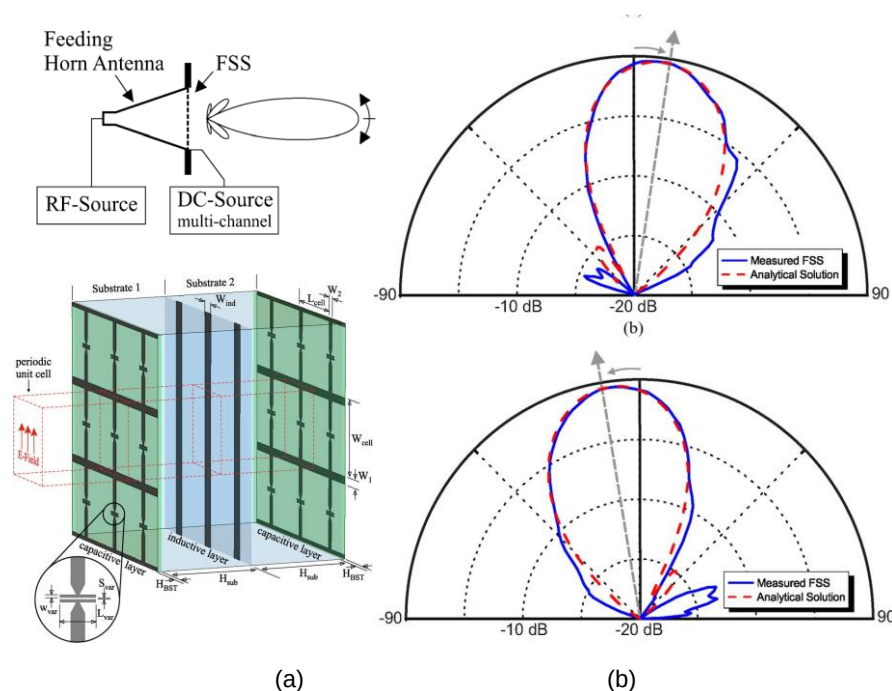


Figure 17: (from [13]) (a) The concept of a transmit array for beam steering and prospective view of the unit cell. Green substrates are made of ferroelectric material. (b) Measured radiation patterns in two tuning states. All curves are normalized to the maximum power in the untuned case. The radiation angle is steered to $\pm 10^\circ$.

Liquid crystals belong to a class of materials exhibiting unique orientation-dependent optical and dielectric permittivity, controlled by an external electric or magnetic field. This material has been investigated from the first years of 2000s as possible candidate for achieving tunability and reconfigurability in metamaterials and metasurfaces. Liquid crystals have a large optical anisotropy extremely sensitive to external fields and, before being used in metamaterial-based devices, they have been widely used to tune the band gaps of photonic crystal at optical frequency and the phase shifter at millimeter wave frequency. The use of liquid crystals in metamaterials have been firstly investigated for achieving dynamic control of the permittivity of the metamaterials, and thus to tune the reversed electromagnetic behaviors [16][17].

One of the first applications in antenna field of reconfigurable metamaterials and metasurface based on liquid crystals have been reported in 2006. A. Moessinger et al. [18] designed, fabricated, and characterized the reconfigurable mm-wave reflecting metasurface based on liquid crystals

shown in Figure 18(a). The tunable unit cells are filled with nematic liquid crystal, that exhibits different effective permittivity values according to the applied control voltage. This led to a different response of the unit cell in terms of complex reflection coefficient. Figure 18(b) shows the measured phase and magnitude of reflection coefficient of tunable unit cell filled with the liquid crystal BL006 from Merck company. The phase of the reflection coefficient can be dynamically tuned from $+100^\circ$ to about -150° , by applying a control voltage in the range 0V-15V. By properly tuning the unit cells composing the metasurface, they have demonstrated that a continuous beam steering in the angular range $\pm 20^\circ$ can be obtained, as shown in Figure 18(c). However, the overall performances of the reflecting metasurface were not compatible with the standard applications in terms of a maximum insertion loss. Indeed, as shown in in Figure 18(b), the reflection coefficient reaches -10dB for an applied voltage of about 6.5V, meaning that a strong dissipative phenomenon is taking place for that configuration.

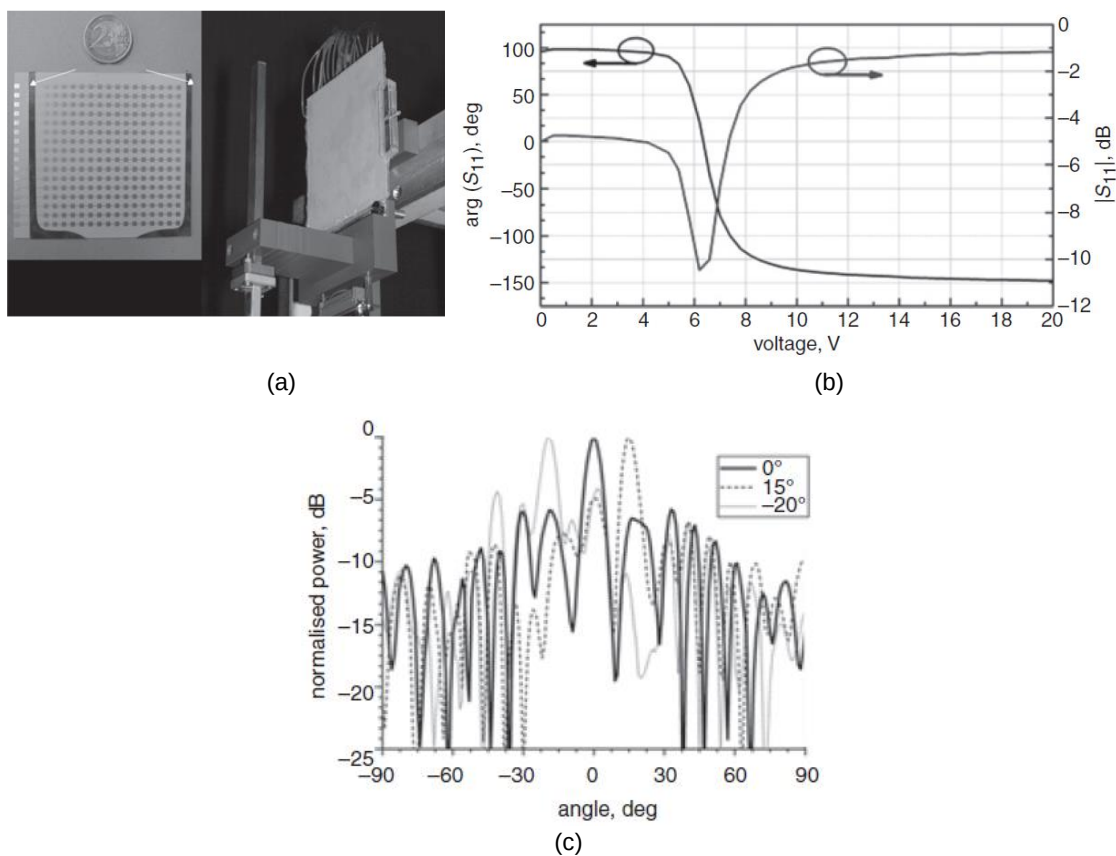


Figure 18: (from [18]) (a) Metasurface with beam scanning in one plane (b) Measured phase and magnitude of reflection coefficient of tunable unit cell filled with LC BL006 from Merck company; (c) Measured far-field patterns at 34 GHz.

In 2011, a new design of a reflecting metasurface based on liquid crystals has been proposed by G- Perez-Palomino et al. [19]. A multi-resonant unit-cell based on liquid crystals has been proposed for reconfigurable reflect array antennas and shown in Figure 19(a). The unit cell element is made of up of three parallel dipoles closely packed into a single cell and a tunable liquid crystal has been used as substrate. To apply the control voltage, all the dipoles in the unit cell are interconnected by a bias line to obtain the same molecular orientation in the LC volume below them, so that a constant permittivity can be assumed throughout the cell. The unit cell exhibits three independent resonances, each one associated with one dipole. This allows to enlarge both operative bandwidth and tunable phase range, without introducing further losses in the system. Indeed, as shown in Figure 19(b), the unit cell reaches the desired phase range of 360° for relative permittivity values varying from 2.3 to 2.91, with a maximum loss of 4.7 dB. These performances are achieved within a fractional bandwidth

of 7.4% (from 33.7 to 36.3 GHz). These results represent a significant improvement with respect to the performances reported in previous works, such as [18].

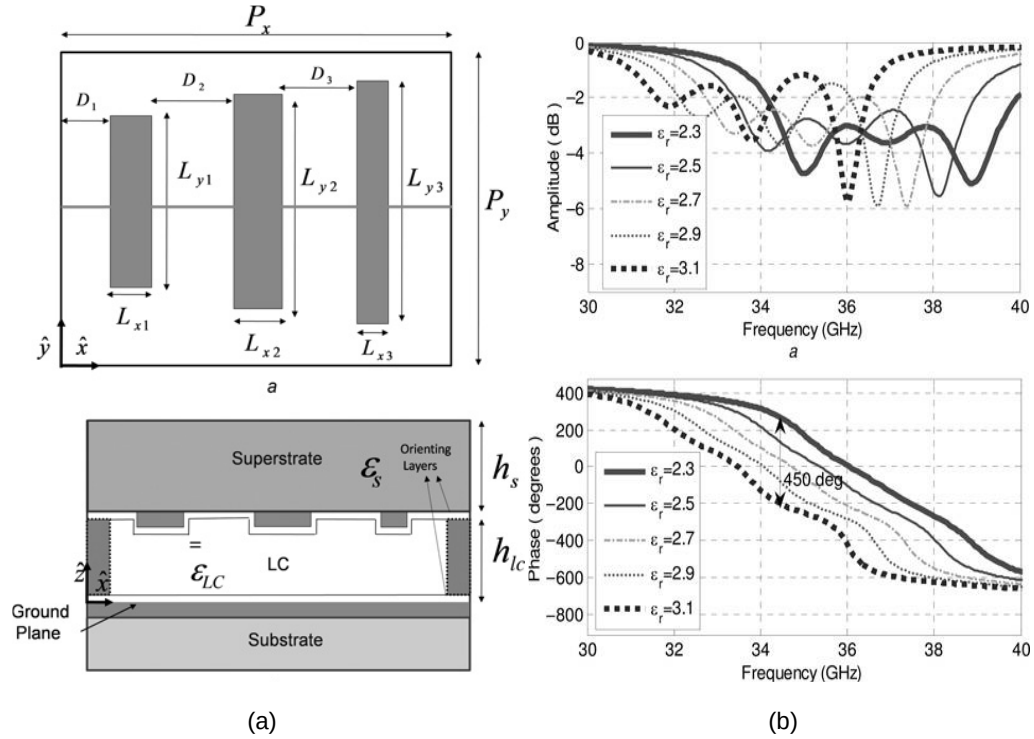


Figure 19: (from [19]) (a) Top and lateral schematic view of the multi-resonant reflect array unit cell based on liquid crystal; (b) Amplitude (top) and Phase (bottom) of the reflection coefficient for the multi-resonant unit cell at normal incidence as a function of the frequency for different states of permittivity.

4.2.3 Phase Change Materials

Phase change materials (PCMs) refer to a class of materials that can undergo a significant transformation in their material phase through external excitations such as conductive heating, optical stimulation, or the application of electric or magnetic fields, which in turn, results in changes in their electrical and optical properties. PCMs exhibit different degrees of volatility of their properties, with some being classified as *volatile PCMs* that require constant stimulation to maintain their transition state, while others are *non-volatile PCMs* that maintain their phase change even after the stimulus is removed until a certain level of stimulus is reached again. This variability in volatility is an important consideration when working with PCMs, and researchers are exploring new ways to leverage this unique property to create more dynamic and tunable materials.

Several PCM that can be identified in the literature, but the phase change materials based on **vanadium oxides** have attracted the attention of the research community for applications at microwave and millimeter wave frequencies since they exhibit a very low resistivity and thus are more suitable for realizing low loss tunable electromagnetic devices [21]. Among them, Vanadium dioxide (VO_2) is a phase change material that has been observed to undergo a thermally induced insulator-metal phase transition around a temperature of 68°C . Therefore, the VO_2 transition is commonly controlled through thermal means, allowing to modify the electric response of the material from an insulator phase (at lower temperatures) to a metallic phase (at higher temperatures). At intermediate temperature VO_2 exists as a mixture of the two constituent phases and its properties could be described using the effective medium theory (EMT) from the electromagnetic point of view [22]. By incorporating VO_2 material into metasurface structures, researchers have created devices

whose electromagnetic properties can effectively controlled. In the open technical literature, it is possible to identify many works based on metamaterials and involving VO₂, but in the bands of interest for the PULSE project, *i.e.*, microwave and millimeter waves, the main application of tunable metasurfaces based on VO₂ is metasurface absorbers.

One of the first relevant examples selected for the PULSE project is the work by Q. Wen *et al.* [23], where a metasurface absorber whose unit cells are loaded by VO₂ has been presented. A graphical representation of the unit cells composing the metasurface is reported in Figure 20(a), where it is easy to identify the presence of an underlying VO₂ patch below the inner resonator, while the outer resonators contact the substrate directly. The area of the VO₂ patch is equal to that of the inner resonator. This absorber has been designed to present two distinct absorption peaks at around 9 GHz and 18 GHz, respectively. The measured absorptivity curves, shown in Figure 20(b), confirms the metasurface absorption and demonstrate that different level of absorptivity can be obtained by changing the operative temperature of the device. Two strong peaks are clearly observed at 9.36 GHz and 18.6 GHz with maximum absorptivity of 87.0% and 93.0%, respectively.

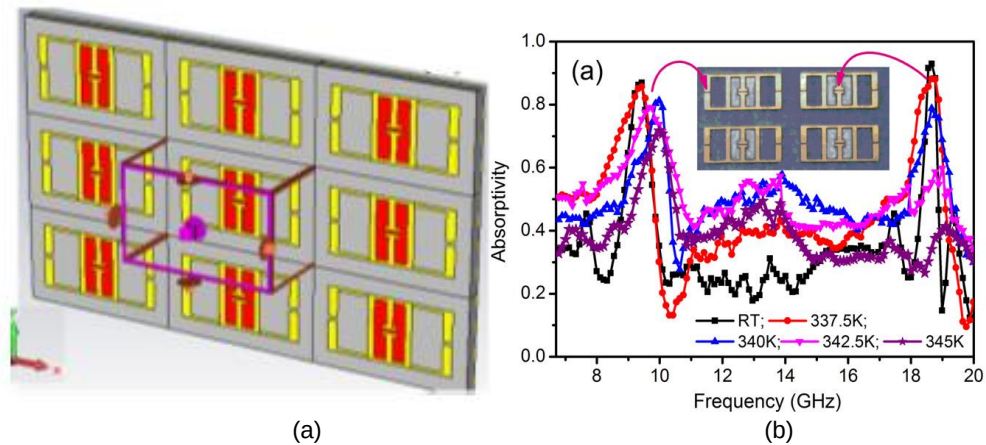


Figure 20: (from [23]) (a) Perspective view of the absorber sheet with VO₂ patches; (b) Measured absorption curves of the VO₂-based MA with respect to the device temperature. Inset is the image of the fabricated device.

Although the phase transition of Vanadium dioxide may be explored for achieving tunable devices, in 2017 G. Zhang *et al.* [24] proposed a microwave tunable metamaterial based on Semiconductor-to-Metal Phase Transition of VO₂, showing that the material tunability is affected by hysteresis. Indeed, the temperature-dependent behavior of VO₂'s conductivity is a typical hysteresis loop, which means that the conductivity is a double-value function of temperature.

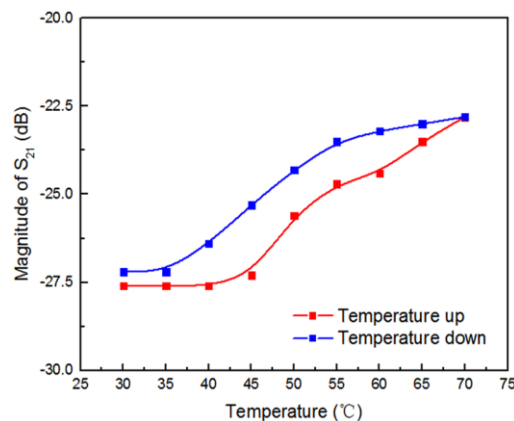


Figure 21: (from [24]) Measured temperature-dependent hysteresis curve of transmission with incident power set to -15 dBm.

To reduce the hysteresis effects on the overall metasurface response, the amount of VO_2 to be used for controlling and tuning the metasurface response should be significantly reduced in volume. An interesting example in this direction has been proposed by Z. Wang et al. [25]. The authors propose to use a VO_2 lumped element to load a metasurface unit cell, instead of using VO_2 as a substrate. The thermal-dependent tunable resistance exhibited by such a VO_2 -based element has been exploited to modify the overall response of the metasurface absorber.

The structure of the absorber in [25] is reported in Figure 22(a). The surface structure consists of an array of square rings, each of which is loaded by four VO_2 chips. The entire metasurface absorber consists of 2×12 units with a size of $108 \text{ mm} \times 18 \text{ mm}$, as shown in Figure 22(b). The VO_2 chips are of dimensions $1.5 \text{ mm} \times 0.5 \text{ mm}$ and are bonded to the sample by silver paste. The heating plates of the same size are bonded to the back of the sample to control the phase change of the VO_2 chips. The comparison between numerical and experimental reflection coefficients of the metasurface absorber for the insulating and metal states is reported in Figure 22(c). The sample exhibits absorption of 16 dB at 7.1 GHz at room temperature; after the VO_2 phase transition, the sample exhibits absorption of 8 dB at 6.3 GHz.

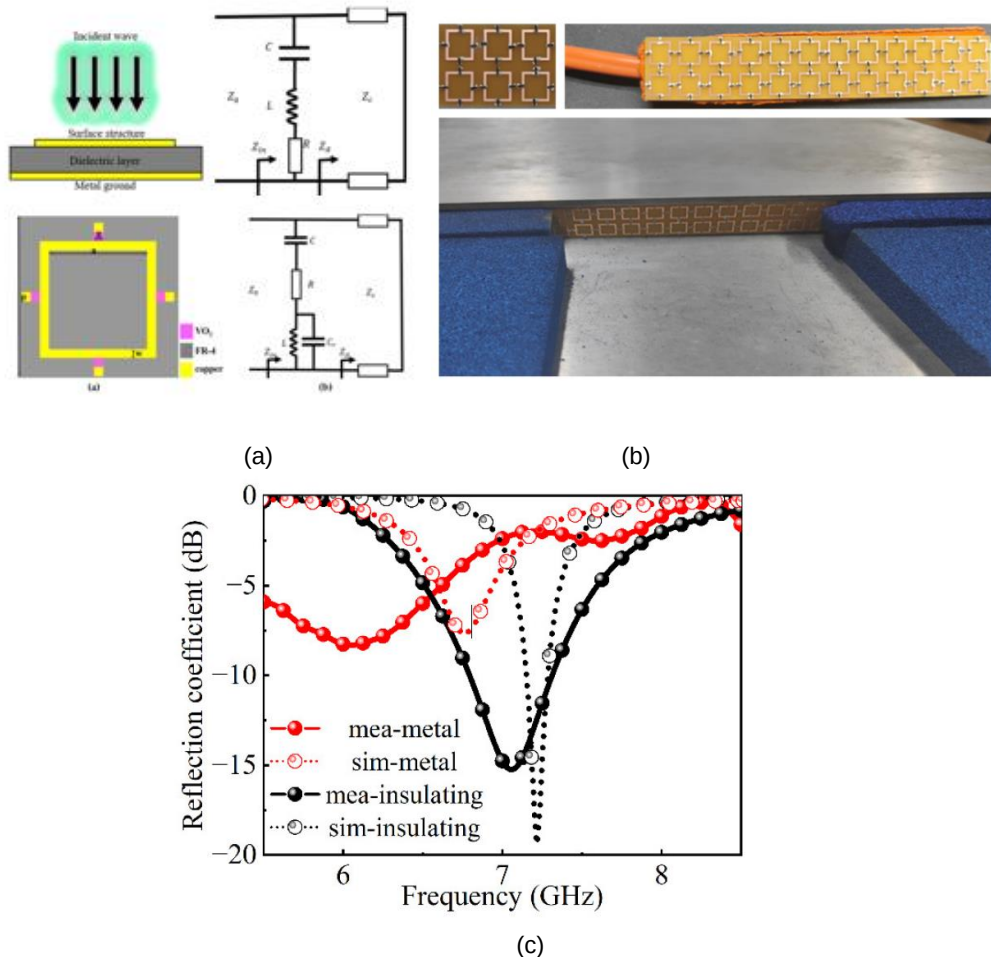


Figure 22: (from [25]) (a) The models of the metamaterial absorber and the equivalent circuit; (b) The thermal-switchable metasurface absorber unit, sample with the heating plate, and test device. (c) Comparison between numerical and experimental reflection coefficients of the metasurface absorber for the insulating and metal states.

4.2.4 Material tuning limitations

While material-based reconfigurability and tunability offer several advantages, they also face certain drawbacks that limit their applicability in specific applications. In particular, we can conclude that:

- Ferroelectric materials, despite their ability to dynamically modulate their electromagnetic properties, suffer from relatively high insertion losses exceeding 3dB, restricting their use in applications requiring high transmission efficiency. Additionally, their low scanning angular aperture of less than 10° limits their beam-steering capabilities. Furthermore, their reconfigurability rate, with a maximum of 50 kHz, may not be sufficient for applications demanding rapid switching speeds.
- Liquid crystals, though exhibiting tunable electromagnetic properties, also face limitations. Their losses, comparable to those of dielectric materials, can hinder their performance in applications requiring low loss characteristics. Moreover, their reconfigurability rate, with a maximum of 100 kHz, may not be suitable for applications demanding extremely fast switching speeds.
- Phase-change materials are not currently considered relevant for the project due to the lack of specific applications that align with the project's objectives. Additionally, their extremely low reconfigurability rate, falling into the sub-Hz range, makes them impractical for applications requiring rapid switching capabilities.

4.3 Electronic Tuning

The subwavelength dimensions that characterize the constitutive elements of metamaterials and metasurfaces have enabled since the beginning the possibility to describe their electromagnetic response in terms of electronic circuits that models the main energetic phenomena that take place within a metamaterial unit cell. Indeed, resistors model the illuminating energy dissipated by the structure, capacitors model the electric energy storing and inductors the magnetic energy storing. Using simple electric circuits to model the metamaterial response in frequency allows to identify in a straightforward way the role of the different geometrical parts composing the metamaterial unit cell and how it can be modified to alter the overall electromagnetic response of the metamaterial and metasurface. In this scenario, the exploration of electronic circuit integration within the unit cell has been investigated as a promising approach to achieve tunability and reconfigurability. This technique involves embedding active electronic components directly into the metamaterial or metasurface structure, enabling real-time modulation of their electromagnetic properties. By incorporating these active elements, researchers have unlocked the potential to manipulate the electromagnetic response of metamaterials and metasurfaces in real time, paving the way for a new generation of reconfigurable and tunable electromagnetic devices.

The key advantage of electronic circuit-based tunability lies in its ability to independently control each unit cell, that can be controlled by a dedicated electronic circuit lumped element, such as varactor diodes, PIN diodes, or RF MEMS. This granular control enables the creation of electrically reconfigurable metasurfaces with tunable amplitude and phase profiles, opening new possibilities for manipulating electromagnetic waves.

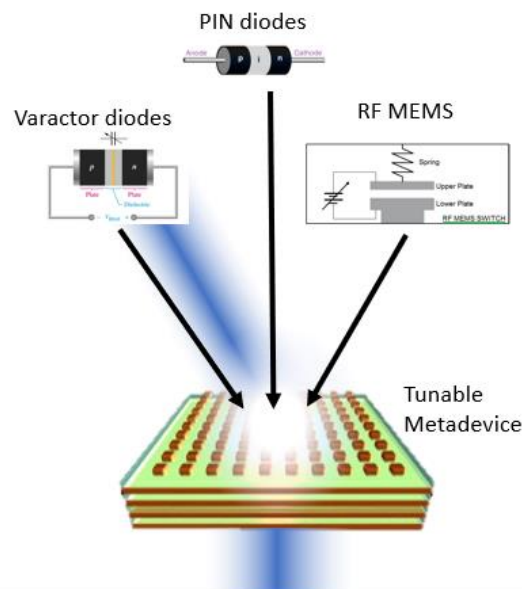


Figure 23: Representation of the three primary methods employed for electronic tuning.

As shown in Figure 23, the three primary methods employed for electronic tuning include:

- Varactor diode-based method: This method involves the use of voltage-controlled variable capacitors to achieve tunability. Varactors are semiconductor devices that exhibit a capacitance that varies with the applied voltage. This unique property makes them ideal for tuning the resonant frequency of metamaterial and metasurface unit cells by dynamically adjusting the capacitance response of each unit cell, leading to a corresponding change in the overall

electromagnetic response of the device. Relevant examples falling in this category are reported in Refs. [29] - [46].

- **RF-MEMS-based method:** This method utilizes RF MEMS (microelectromechanical systems) devices that can be actuated using electrical signals. By incorporating RF MEMS into metamaterial and metasurface structures, it has been demonstrated that precise and rapid tuning of their electromagnetic properties can be achieved. The mechanical movement of the RF MEMS elements can alter the capacitive response of the metamaterial or metasurface unit cells, leading also in this case to a corresponding change in their resonant frequencies and other electromagnetic characteristics. Relevant examples in the literature falling in this category are reported in Refs. [47] - [57].
- **PIN Diode-based method:** This method employs PIN diodes as controlling lumped elements of the metamaterial unit cell. PIN diodes are semiconductor devices that consist of a wide and undoped intrinsic semiconductor region between a p-type and an n-type semiconductor region. Thanks to the very low reverse recovery time of PIN diode, this is the preferred method when fast reconfiguration is required. Moreover, this diode appears more like a resistor than any other non-linear device [58], making it perfect in case of a discrete number of reconfiguration states of the metamaterial and metasurface. In the last year, a very high number of works based on this method have been published in the literature. The most relevant works for the PULSE project are reported in Refs. [59] - [79].

Figure 24 shows the percentage of works published in the literature that presents metamaterials and metasurfaces that exhibits electronic reconfigurability based on varactors, PIN diodes, and RF MEMS. The works have been also grouped according to their publication year in 4 periods: 2001-2005, 2006-2010, 2011-2015, and 2016-2023.

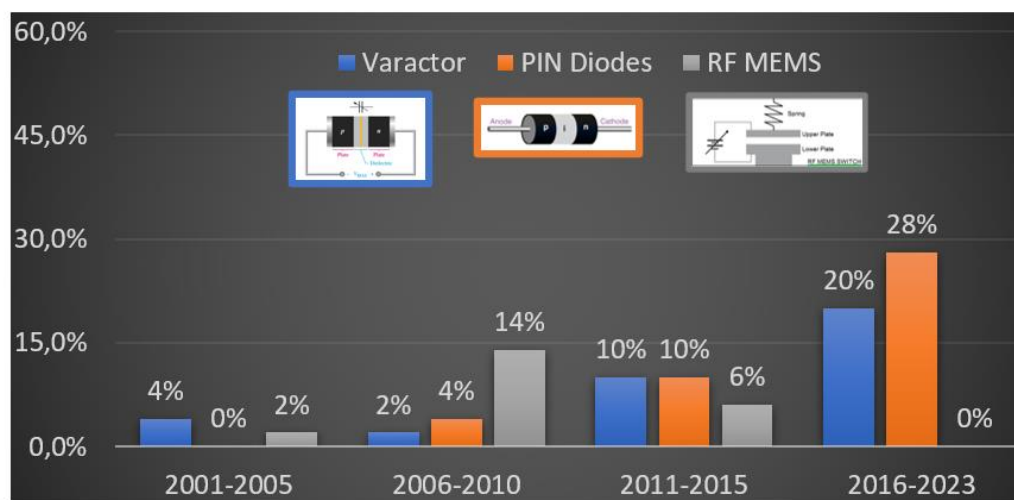


Figure 24: Percentage of selected works relevant for PULSE project published in the literature in different periods of time for achieving electronic tunability.

The graph shows that varactor diode-based method has been exploited since the beginning of the considered period, with a constant increasing in the last 15 years and a total of more than 35% of all selected works relevant for PULSE project based on electronic reconfigurability. This is likely due to their several advantages, including good reconfigurable speeds and continuous tuning ranges. On the contrary, RF MEMS devices have been deeply investigated as reconfigurable technology for metamaterials and metasurfaces during the period 2006-2010, but it was abandoned mainly due to their complex fabrication processes and relatively slow switching speeds. Indeed, starting from 2010, PIN diode-based metamaterials and metasurfaces have seen a significant

increase in popularity, with their share of published works growing from around 4% in the period 2006-2010 to almost 30% in the period 2016-2023. This is likely due to their fast-switching speed and low insertion losses, making them suitable for applications where these factors are critical. Overall, the graph suggests that in the last years, electronic tunability based on diode elements (PINs or Varactors) remain the dominant method for electronic tuning.

4.3.1 Varactor Diodes

One of the first tuned metadvice using varactors has been proposed by D. Sievenpiper et al. in 2003 [29]. In this work, the authors propose to incorporate varactor diodes into the texture of a high-impedance surface consisting of a periodic surface texture covering a metal ground plane, as shown in Figure 25(a). Each unit cell in the periodic surface texture is connected to its four neighbors by reverse-biased diodes. By changing the voltage on the diodes, the effective gap capacitance between neighboring cells is adjusted, and thus the resonance frequency tuned. The required voltage to control the varactors is applied in a checkerboard pattern. At the center of each biased cell, a metal via passes through a hole in the ground plane and connects to a control line located on a separate circuit layer on the back of the surface. By controlling the varactors from the back of the surface in this way, the bias lines do not interfere with the microwave fields on the front side. The varactors are oriented in opposite directions in each alternate row, so that when a positive voltage is applied to control lines, all the diodes are reverse-biased. By individually addressing each cell, the reflection phase can be programmed as a function of position across the surface. The fabricated demonstrator and measured reflection phase for various voltages applied to the varactors are reported in Figure 25(b) and Figure 25(c), respectively. This first example of electronic tuning based on varactors exhibits a resonance frequency that can be tuned over a range of about 2.5 to 4.5 GHz, by controlling the voltage on the varactors from 0 to 20 V. Since the work by D. Sievenpiper in 2003, the use of varactor diodes to control the electromagnetic response of metasurfaces have been widely exploited by the scientific community due to the simple control mechanisms, low costs, and stability of varactor diodes.

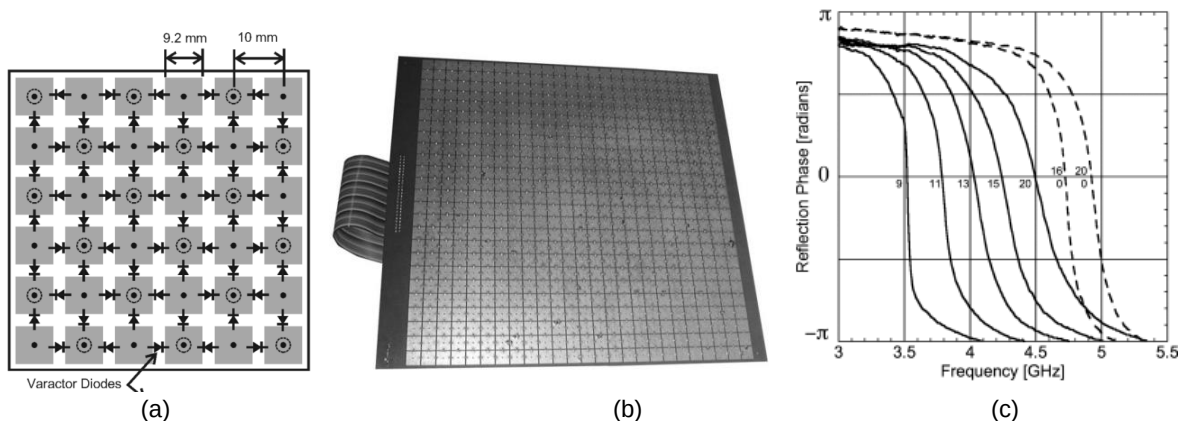


Figure 25: (from [29]) (a) Electrically tunable impedance surface, with varactor diodes between neighboring pairs of plates. (b) Photograph of the electronically steerable reflector. The lattice period is 1 cm, and there are 25x25 cells. (c) Reflection phase for various voltages. The solid lines correspond to a uniform voltage ranging from 9 to 20 V, which provide a tuning range of 3.5 to 4.5 GHz

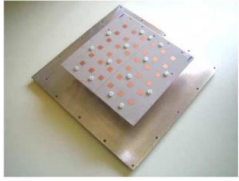
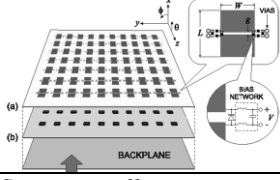
Among all the works exploiting the varactor-based tuning mechanism relevant for the PULSE project [30]-[46], we focus our attention on a selection of them classified into two categories: (1) the works that use varactor-based tunability for achieving quasi-static tunability and (2) the works that use it for achieving dynamic tunability. The main difference between the two categories is the speed of modulation of the metasurface and metamaterial properties: in quasi-static tunability the

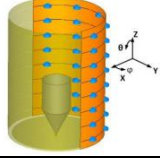
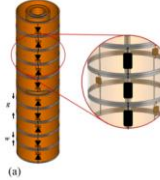
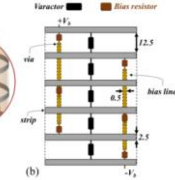
modulation speed is extremely slow with respect to the frequency of the illuminating electromagnetic field, that in turns will interact with a surface whose properties may be assumed quasi-constant during the interaction. On the contrary, in dynamic tunability, the modulation speed is extremely faster and comparable with the frequency of the illuminating electromagnetic field, enabling a frequency mixing process at metasurface level. It is worth mentioning that both categories are extremely relevant for PULSE project, identifying the possibilities, applications, and fundamental limits of the electronic tunability according to the modulation frequency of the material or surface properties.

Varactor-based quasi-static tunability

In the following, we consider four **works on metasurfaces that implement the varactor-based quasi-static tunability that are relevant for the PULSE Application Area 1**. The main characteristics, in terms of controlled quantity, tuning range, operative bandwidth and used varactor technology, have been reported in the following Table 2.

Table 2: Varactor-based quasi-static tunability relevant for PULSE Application area 1.

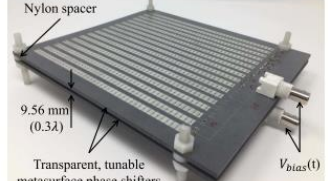
Work #1 – Ref. [39]	
P. Padilla et al., "Electronically Reconfigurable Transmit array at Ku Band for Microwave Applications," IEEE Transaction on Antennas and Propagation, vol. 58, no. 8, pp.2571-2579, Aug. 2010	
Varactor-based reconfigurable metadvice	
Tuned quantity	<i>Phase of the transmission coefficient</i>
Tuning range	0° - 360°
Unaltered quantity during tuning	<i>Amplitude of the transmission coefficient</i>
PULSE-relevant characteristics and performance	<i>Measured beam steering $\pm 10^{\circ}$</i>
Operative bandwidth	<i>X- band</i>
Fractional bandwidth	<i>20%</i>
Varactor model	<i>M/A-COM mod. MA46585-1</i>
Work #2 – Ref. [37]	
S. V. Hum, et al., "Realizing an electronically tunable reflect array using varactor diode-tuned elements," IEEE Microw. Wireless Components Lett., vol. 15, no. 6, pp. 422-424, June 2005	
Varactor-based reconfigurable metadvice	
Tuned quantity	<i>Phase of the reflection coefficient</i>
Tuning range	0° - 360°
Unaltered quantity during tuning	<i>Amplitude of the reflection coefficient</i>
PULSE-relevant characteristics and performance	<i>Measured beam steering $\pm 40^{\circ}$</i>
Operative bandwidth	<i>C- band</i>
Fractional bandwidth	<i>0.1%</i>
Varactor model	<i>Metelics MGV-100-21</i>

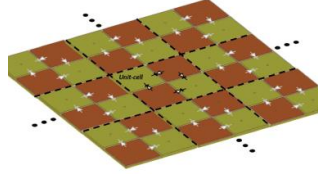
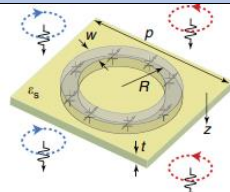
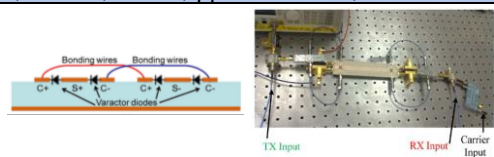
Work #3 – Ref. [45] C. Gu et al., "Frequency-Agile Beam-Switchable Antenna," IEEE Transactions on Antennas and Propagation, vol. 65, no. 8, pp. 3819-3826, Aug. 2017	
Varactor-based reconfigurable metadvice	 
Tuned quantity	Amplitude of the transmission coefficient
Tuning range	0-1
Unaltered quantity during tuning	Phase of the reflection coefficient
PULSE-relevant characteristics and performance	Transmissive frequency band shift 700MHz
Operative bandwidth	L-band
Fractional bandwidth	35%
Varactor model	-----
Work #4 – Ref. [46] S. Vellucci et al., "Multi-Layered Coating Metasurfaces Enabling Frequency Reconfigurability in Wire Antenna," IEEE Open Journal of Antennas and Propagation, vol. 3, pp. 206-216, 2022	
Varactor-based reconfigurable metadvice	 
Tuned quantity	Surface reactance of the metasurface coating
Tuning range	-5 to -5000 Ω/sq
Unaltered quantity during tuning	-----
PULSE-relevant characteristics and performance	Operative frequency band of the antenna (tuning over 700MHz frequency range)
Operative bandwidth	L-band
Fractional bandwidth	50%
Varactor model	-----

Varactor-based dynamic tunability

In the following, we consider four **works on metasurfaces that implement the varactor-based dynamic tunability that are relevant for the PULSE Application Area 2**. The main characteristics, in terms of controlled quantity, tuning range, operative bandwidth and used varactor technology, have been reported in the following Table 3.

Table 3: Varactor-based dynamic tunability relevant for PULSE Application area 1.

Work #1 – Ref. [32] Z. Wu and A. Grbic, "Serrodyne Frequency Translation Using Time-Modulated Metasurfaces," IEEE Transactions on Antennas and Propagation, vol. 68, no. 3, pp. 1599-1606, March 2020	
Varactor-based reconfigurable metadvice	
Tuned quantity	Phase of the transmission coefficient
Tuning range	0°-360°
Unaltered quantity during tuning	Amplitude of the transmission coefficient

PULSE-relevant characteristics and performance	<i>Tuning velocity 1MHz</i>
Operative bandwidth	<i>X- band</i>
Fractional bandwidth	<i>Monochromatic</i>
Varactor model	<i>M/A-COM mod. MAVR-000120-1411</i>
Work #2 – Ref. [30] D. Ramaccia, et al., "Phase-Induced Frequency Conversion and Doppler Effect With Time-Modulated Metasurfaces," IEEE Transactions on Antennas and Propagation, vol. 68, no. 3, pp. 1607-1617, March 2020,	
Varactor-based reconfigurable metadvice	
Tuned quantity	<i>Phase of the reflection coefficient</i>
Tuning range	<i>-180°; +150°</i>
Unaltered quantity during tuning	<i>Amplitude of the reflection coefficient</i>
PULSE-relevant characteristics and performance	<i>Tuning velocity 0.5 MHz</i>
Operative bandwidth	<i>L- band</i>
Fractional bandwidth	<i>0.3%</i>
Varactor model	<i>Infineon BB53</i>
Work #3 – Ref. [31] D. Sounas, et al., "Giant non-reciprocity at the subwavelength scale using angular momentum-biased metamaterials" Nature Communications, vol. 4, p. 2407, 2013.	
Varactor-based reconfigurable metadvice	
Tuned quantity	<i>Amplitude of the transmission coefficient</i>
Tuning range	<i>0-1</i>
Unaltered quantity during tuning	-----
PULSE-relevant characteristics and performance	<i>Tuning velocity 500 MHz</i>
Operative bandwidth	<i>X-band</i>
Fractional bandwidth	<i>Monochromatic</i>
Varactor model	-----
Work #4 – Ref. [33] S. Qin, Q. Xu and Y. E. Wang, "Nonreciprocal Components with Distributedly Modulated Capacitors," IEEE Transactions on Microwave Theory and Techniques, vol. 62, no. 10, pp. 2260-2272, Oct. 2014	
Varactor-based reconfigurable metadvice	
Tuned quantity	<i>Transmission line capacitance</i>
Tuning range	<i>±0.14 pF</i>
Unaltered quantity during tuning	-----
PULSE-relevant characteristics and performance	<i>Tuning velocity 500 MHz</i>
Operative bandwidth	<i>L-band</i>
Fractional bandwidth	<i>120%</i>
Varactor model	-----

4.3.2 RF MEMS

RF MEMS (Radio Frequency Microelectromechanical Systems)-based technology combines mechanical actuation with electrical control. At the heart of RF MEMS tunability lies the concept of mechanical varactors. These MEMS devices, typically composed of microfabricated cantilevers, act as variable capacitors whose capacitance can be dynamically altered by mechanical movement. The key mechanism behind this tunability is the change in the mechanically induced “depletion area”, the region between the capacitor plates where the mobile charge carriers are depleted. By varying the spacing between the cantilever and the substrate by using an electrostatic force, *i.e.*, an applied electrical signal, the depletion area can be effectively adjusted, leading to a corresponding change in its capacitance. The main advantage to use of RF-MEMS, instead of varactors diodes, is given by the reduced losses exhibited by the metasurface and metamaterial due to the lower resistive component of MEMS device. Moreover, the nonlinear effects caused by RF modulation of the varactor capacitance is removed, as well as difficulties in operating at high frequencies due to substantial diode package parasitic reactive components.

One of the first applications of RF-MEMS tunability approach to a metasurface have been proposed by S.V. Hum et al. in 2006 [48], where the design of an electronically tunable metasurface systems whose elements loaded by MEMS capacitors has been presented and discussed. The RF-MEMS capacitive value is tuned by using an electrostatic force that moves the movable part of the varactors, acting as a conventional tunable parallel plate capacitor. In Figure 26(a) we report the view of MEMS varactor bridge geometry proposed in [48], where it is possible to note the moving part of the RF-MEMS capacitor in a bridge configuration. Conversely to the traditional cantilever arm, this configuration allows to maintain always separated the moving and fixed parts even in case of extraordinary high electrostatic force. As reported in Figure 26(b), the capacitance of the RF-MEMS can be tuned from about 170fF to more than 500fF by applying a voltage signal between 0 to 30 Volts.

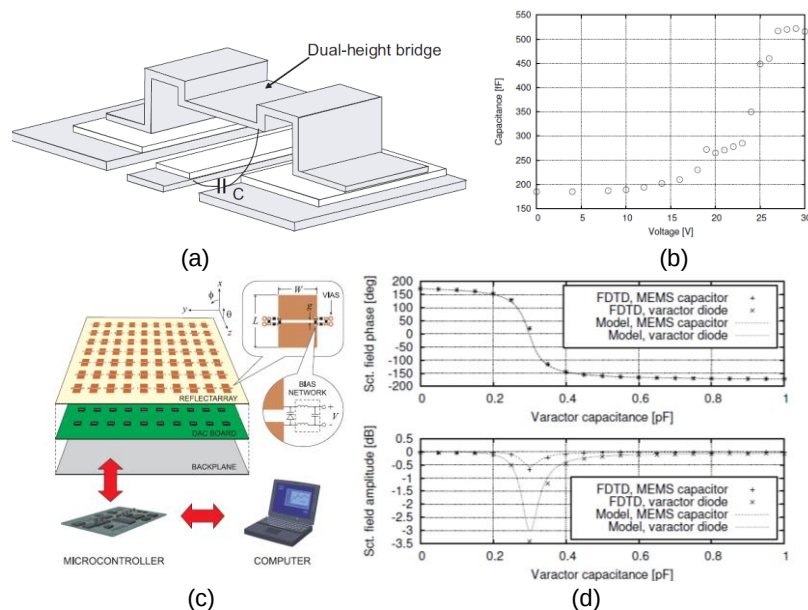


Figure 26: (from [48]) (a) View of MEMS varactor bridge geometry; (b) RF- MEMS capacitance versus voltage at 5 GHz; (c) Electronically tunable reflect array system; (d) Scattering properties of reflect array elements at 5.5 GHz

The RF-MEMS is integrated into a reflective metasurface composed by a bidimensional array of rectangular patches, whose gap capacitance is modulated by the RF-MEMS, as shown in Figure 26(c). In Figure 26(d), the numerically computed phase and amplitude of the reflection coefficient is

reported showing that it is possible to tune the reflection phase exhibited by the metasurface unit cell by varying the RF-MEMS-based varactor.

However, fabrication tolerances and mechanical instability of the bridge realizing the variable capacitance have been the main reasons for which the RF-MEMS technology have been more appreciated as RF switch than as mechanical varactor. Therefore, the works published after the second half of 2010s presenting MEMS-based reconfigurable metasurfaces exploit the capability of RF-MEMS to rapidly switch between the open- and short-circuit state by controlling the voltage applied to it. One of the first examples has been proposed by J. Perruisseau-Carrier and A. Skirrvik in 2008, where a reconfigurable metasurface operating as a reflect array at 12 GHz and fabricated in a monolithic MEMS process has been reported [49]. The proposed metasurface unit cell consists of two single layer pseudo-ring elements backed by a ground plane. To achieve reconfigurability, the pseudo-rings are loaded with 5 pairs of variable digital series MEMS capacitors (shown in Figure 27(a)), which enable the selection of 2^5 discrete states. As stated before, the two states of the single MEMS are mechanically stable and insensitive to control voltage imprecision, since this voltage is zero in the up-state and that a variation of voltage in the down-state will only induce a negligible error in the capacitance value, as the MEMS membrane is already pulled-in.

Figure 27(b) shows the reflection phase of the cell as a function of the MEMS state for a normal incidence at 12 GHz. To assess the relative distribution of the phase states within the range, the states are sorted according to the phase. Such plot allows characterizing the range while visualizing the relative distribution of the 32 states. We observe that the full 360 range is covered. The phase distribution is also good, except that few states exhibit phases between -45° and -135° .

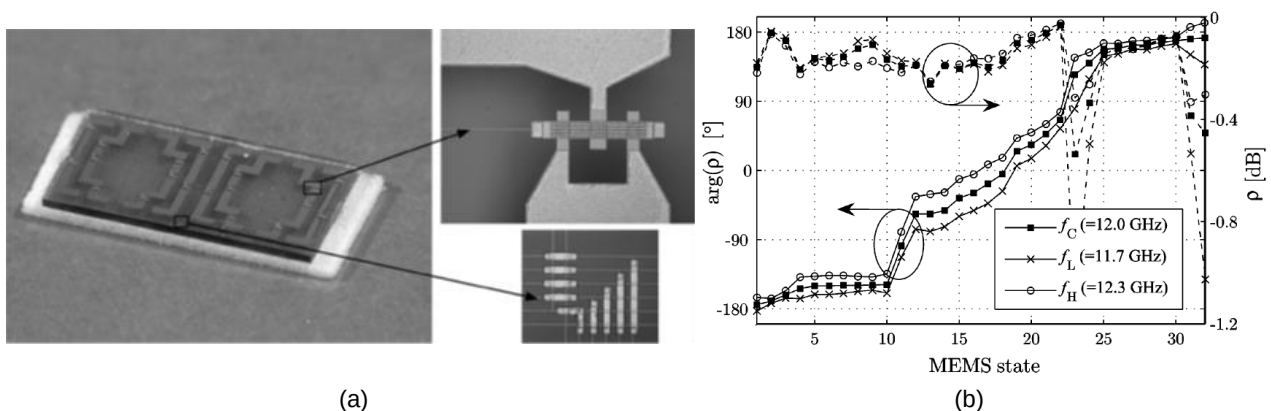


Figure 27: (from [49]) (a) Pictures of a fabricated metasurface 2-cell. The insets show close views on a MEMS series capacitor and the bias lines distribution network; (b) Reflection phase and loss as a function of the MEMS states at the limits of a 5% BW at 12 GHz.

More recently, the RF-MEMS tunability and reconfigurability has been also applied to transmitting metasurfaces, making this class of reconfigurable metastructures of relevant interest for the PULSE Application Area 1.

In 2009, C.C. Cheng et al. proposed a millimeter-wave reconfigurable lens for antennas. The tuning is achieved by using five RF-MEMS per unit cell as shown in Figure 28(a). In this work, the RF-MEMS is used again as a RF switch exhibiting two main operating states, *i.e.*, open- and short-circuit, respectively, enabling four different transmission modes, each of which is characterized by a specific phase level in transmission ($0^\circ, 90^\circ, 180^\circ, 270^\circ$), as reported in Figure 28(b). The metasurface operates at millimeter waves and has been used to steer the main beam of a low gain horn antenna up to 40° with respect to the broadside direction in either the E- or the H-plane (Figure 28(d)).

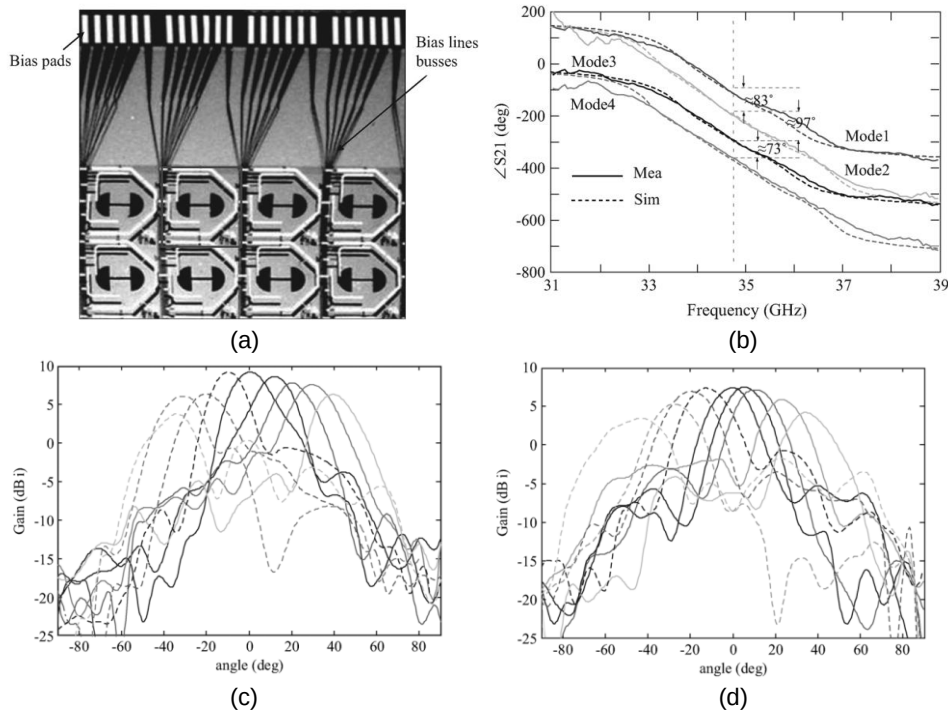


Figure 28: (from [57]) (a) Photograph of the bottom wafer showing the bias lines controlling the RF-MEMS; (b) Measured phase of the transmission coefficients in the four modes; (c)-(d) Measured radiation pattern of beam-steerable antenna: (c) E-plane scan, (d) H-plane scan.

4.3.3 PIN Diode

Metasurface tunability and reconfigurability based on PIN diodes have garnered significant attention in the very last few years as shown in Figure 24 due to the unique properties of PIN diodes. This kind of diodes possess a wide, undoped intrinsic semiconductor region situated between a p-type and an n-type semiconductor region. One of the primary advantages lies in their switching velocity from an isolator to a conductor state that is extraordinary faster than the one exhibited by traditional diodes [58]. The PIN diode behaves nearly as a perfect tunable resistor at high frequencies, exhibiting exceptional linearity even for large signals. The high-frequency resistance is inversely proportional to the DC bias current, offering tunability. In the "off" state (zero or reverse bias), a PIN diode exhibits low capacitance, limiting the passage of RF signals. Conversely, in the "on" state (forward bias of 1 mA), the PIN diode becomes a proficient RF conductor with an approximate RF resistance of 1 ohm, making it an excellent candidate for RF switching applications. This feature is of particular interest when PIN diodes are used to realize reconfigurable metasurfaces for antenna applications, falling into the relevant applications for the PULSE Application Area 1.

In this scenario, A. Clemente et al. proposed an electronically reconfigurable transmitting unit-cell embedding two PIN diodes that allows achieving two transmission phase ($0^\circ/180^\circ$) [63]. The unit cell is represented in Figure 29(a) and a photograph of the fabricated unit cell is reported in Figure 29(b). It consists of a rectangular patch antenna loaded by a U-slot on one side and a patch antenna of the same size loaded by an O-slot on the opposite side. Two Al-Ga-As flip chip p-i-n diodes are integrated in the O-slot loaded patch and they are oriented in opposite ways, so they are biased in opposite states when using a single biasing signal. In Figure 29(c)-(d) the magnitude and phase of the S-parameters of the unit cell are reported, showing that the insertion loss is about 2 dB within the 3-dB transmission bandwidth that spans from 8.88 to 10.35 GHz (14.7%). Moreover, it is possible to note the 180° transmission phase difference obtained between the two states in Figure 29(d).

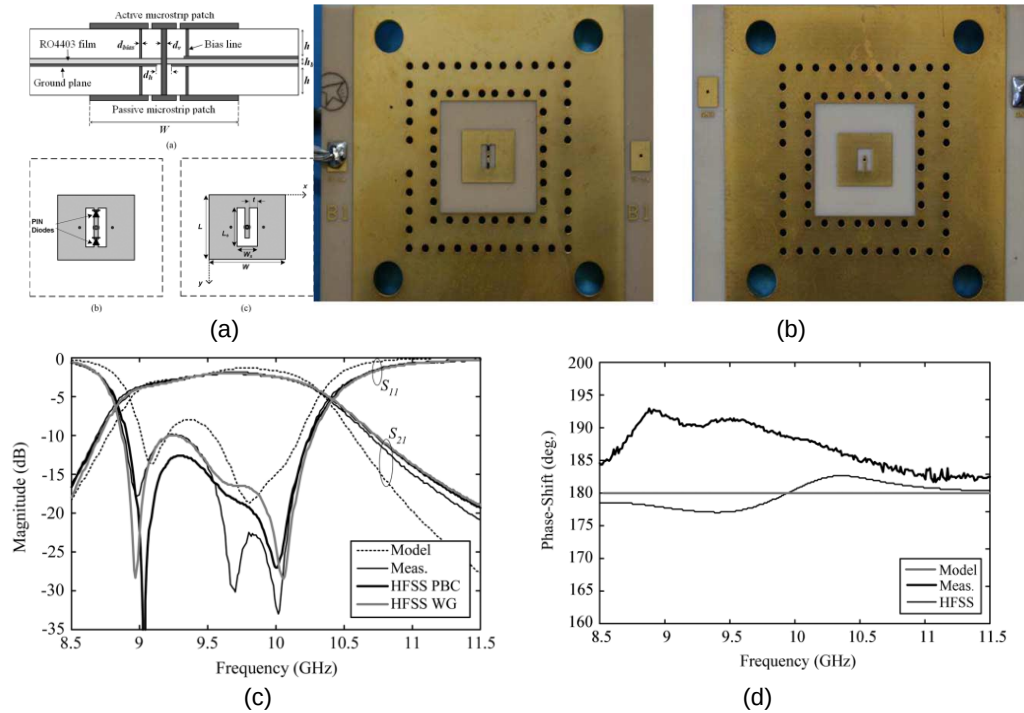
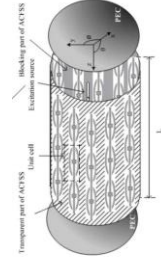


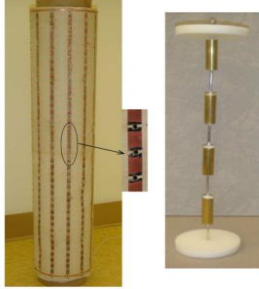
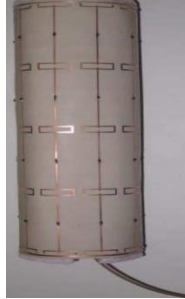
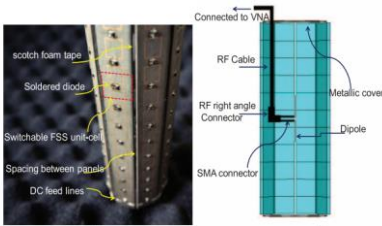
Figure 29: (from [63]) (a) Top, front and back view of the geometry of the unit cell; (b) Photographs of the unit-cell prototype; (c)-(d) Comparison between the (c) amplitude and (d) phase difference of the S -parameters of the unit cell obtained from the lumped-element model, numerical simulations and measurements.

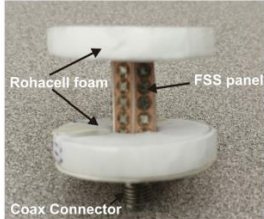
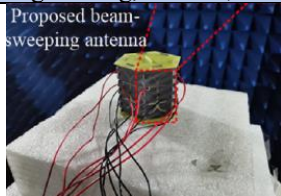
However, the PIN diodes can be also used to reconfigure the amplitude of a transmitting metasurface to make it totally or in part opaque to the electromagnetic field. This feature has been deeply exploited by the group of Prof. Denidni that in the very last years has proposed several different covers with in common the ability to exhibit transparency or opacity in specific angular sectors for achieving directivity from omnidirectional antennas [66]-[68], [70], [72], [73].

Since all these works are relevant for PULSE Application Area 1, in the following, we present all of them in Table 4 that summarizes the main characteristics, in terms of controlled quantity, in-band insertion loss, PULSE relevant characteristics and achieved performance, operative bandwidth and PIN diode model.

Table 4: PIN diode-based tunable covers for antennas relevant for PULSE Application area 1.

Work #1 – Ref. [66]	
M. Niroo-Jazi and T. A. Denidni, "Electronically Sweeping-Beam Antenna Using a New Cylindrical Frequency-Selective Surface," in IEEE Transactions on Antennas and Propagation, vol. 61, no. 2, pp. 666-676, 2013.	
PIN diode-based reconfigurable cover for antennas	
Tuned quantity	Amplitude of transmission coefficient
In-band average insertion loss (transparent mode)	2.5dB
PULSE-relevant characteristics	Conversion from omnidirectional to directive antenna
Performance	Steering of directive main beam up 72°
Operative band	S-band

Central frequency/Bandwidth	2.45GHz / 400MHz
PIN diode model	GMP-4201
Work #2 – Ref. [67] A. Edalati and T. A. Denidni, "High-Gain Reconfigurable Sectoral Antenna Using an Active Cylindrical FSS Structure," in IEEE Transactions on Antennas and Propagation, vol. 59, no. 7, pp. 2464-2472, July 2011	
PIN diode-based reconfigurable cover for antennas	
Tuned quantity	Amplitude of transmission coefficient
In-band average insertion loss (transparent mode)	2.0 dB
PULSE-relevant characteristics	Conversion from omnidirectional to directive antenna
Performance	Steering of directive main beam up 30°
Operative band	L-band
Central frequency/Bandwidth	2.10GHz / 300MHz
PIN diode model	GMP-4201
Work #3 – Ref. [68] M. N. Jazi and T. A. Denidni, "Frequency Selective Surfaces and Their Applications for Nimble-Radiation Pattern Antennas," IEEE Transactions on Antennas and Propagation, vol. 58, no. 7, pp. 2227-2237, July 2010	
PIN diode-based reconfigurable cover for antennas	
Tuned quantity	Amplitude of transmission coefficient
In-band average insertion loss (transparent mode)	1.9 dB
PULSE-relevant characteristics	Conversion from omnidirectional to directive antenna
Performance	Directive main beam pointing towards 0°
Operative band	S-band
Central frequency/Bandwidth	2.45GHz / 100MHz
PIN diode model	GMP-4201
Work #4 – Ref. [70] S. M. Mahmood and T. A. Denidni, "Pattern-Reconfigurable Antenna Using a Switchable Frequency Selective Surface With Improved Bandwidth," IEEE Antennas and Wireless Propagation Letters, vol. 15, pp. 1148-1151, 2016	
PIN diode-based reconfigurable cover for antennas	
Tuned quantity	Amplitude of transmission coefficient
In-band average insertion loss (transparent mode)	2.0 dB

PULSE-relevant characteristics	<i>Conversion from omnidirectional to directive antenna</i>
Performance	<i>Steering of directive main beam up 72°</i>
Operative band	<i>S-band</i>
Central frequency/Bandwidth	<i>3.87GHz / 1200MHz</i>
PIN diode model	<i>GMP-4201</i>
Work #5 – Ref. [72]	
A. Kesavan et al. "A Dual-Plane Beam-Sweeping Millimeter-Wave Antenna Using Reconfigurable Frequency Selective Surfaces," IEEE Antennas Wireless Propagation Letters, vol. 17, no. 10, pp. 1832-1836, Oct. 2018	
PIN diode-based reconfigurable cover for antennas	
Tuned quantity	<i>Amplitude of transmission coefficient</i>
In-band average insertion loss (transparent mode)	<i>0 dB</i>
PULSE-relevant characteristics	<i>Conversion from omnidirectional to directive antenna</i>
Performance	<i>360°-steering of the directive main beam</i>
Operative band	<i>Ka-band</i>
Central frequency/Bandwidth	<i>30 GHz / 1000 MHz</i>
PIN diode model	<i>-----</i>
Work #6 – Ref. [73]	
Jianqiang Hou, Zhenghong Chen, Zhefei Wang, Dayong Huang, Tayeb A. Denidni, "Beam-sweeping antenna with beamwidth reconfigurable response," Int. J. RF and MW Computer aided Engineering, Vol. 31, No. 12, Dec. 2021	
PIN diode-based reconfigurable cover for antennas	
Tuned quantity	<i>Amplitude of transmission coefficient</i>
In-band average insertion loss (transparent mode)	<i>0 dB</i>
PULSE-relevant characteristics	<i>Conversion from omnidirectional to directive antenna</i>
Performance	<i>360°-steering of the directive main beam</i>
Operative band	<i>L-band</i>
Central frequency/Bandwidth	<i>1.9GHz / 300MHz</i>
PIN diode model	<i>Infineon BAR63-04</i>

In addition to the previous works, it is worth mentioning also the work proposed by M. Bouslama et al. in 2016 reporting the design of a reconfigurable cover with a reduced number of PIN diodes [71]. The metasurface is composed of two different resonant elements: a set of ring loops and a discontinuous strip, as shown in Figure 30(a). To reconfigure the response of the unit cell, a PIN diode is placed in the discontinuity of the strip. When the diode is deactivated, two stopbands are generated by the ring loops and strip at the higher frequencies with respect to the operative frequency of the antenna, *i.e.*, 1.80 GHz, making the metasurface to be opaque at that frequency. However, by biasing the diode, a passband response with a desired transparency level appears at the operating frequency of 1.8 GHz. The authors demonstrated that the metasurface cover does not alter the operative frequency of the antenna by measuring the reflection coefficient at the terminals of the antenna as shown in Figure 30(b). Finally, the radiation patterns, which show a reasonably

good radiation pattern with the lowest back lobe in the azimuth plane, have been measured at the frequency of 1.8 GHz. Figure 30(c) shows the measured radiation patterns along with the simulated ones. These results indicate that the agile antenna can provide a directive radiation pattern, and the best radiation performance is observed in the desired operating frequency. Moreover, for a greater clarification of the functioning antenna, the simulated radiation patterns at 1.8 GHz are provided for some sweeping directions in Figure 30(d).

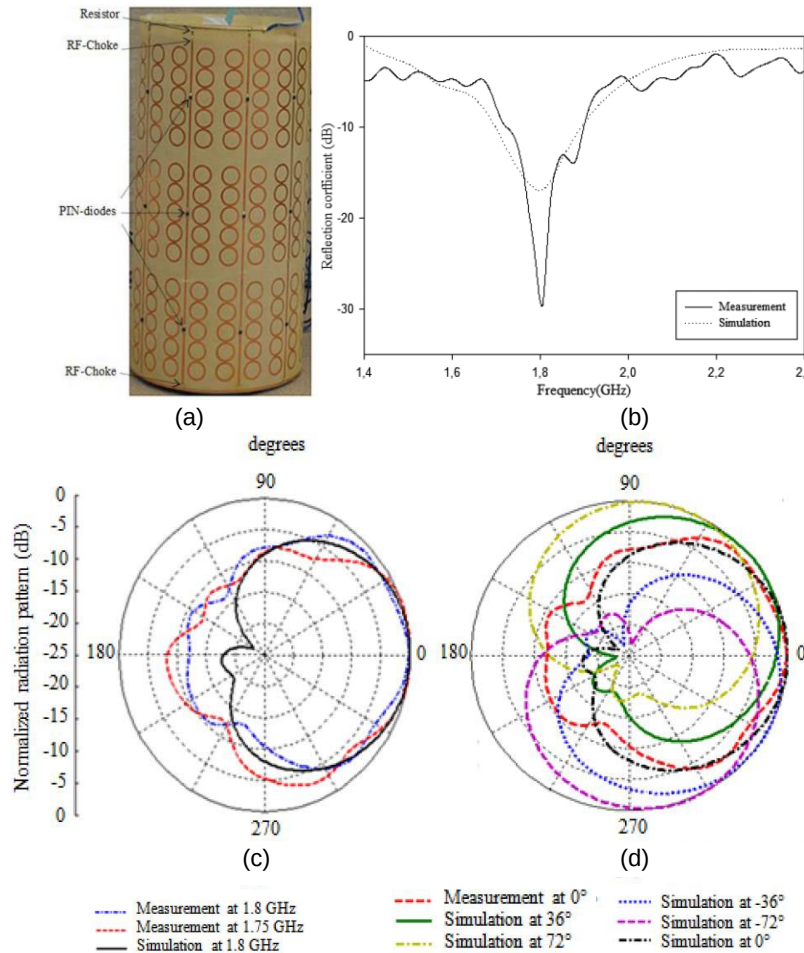


Figure 30: (from [71]) (a) Photograph of the fabricated antenna prototype; (b) Reflection coefficient at the antenna terminals when the cylindrical cover is present; (c)-(d) Measurement and simulation radiation pattern in the azimuth plane: comparison for different (c) frequencies and (d) directions.

4.3.4 Electronic tuning limitations

Electronic tunability of metamaterials and metasurfaces using varactor diodes, RF MEMS varactors, and PIN diodes has revolutionized the field of electromagnetic control, enabling dynamic manipulation of electromagnetic waves. However, each method faces certain limitations that hinder their applicability in specific scenarios.

Varactor diodes, while offering fast switching speeds and broad tuning ranges, suffer from relatively high insertion losses. This can significantly reduce the overall efficiency of the metamaterial or metasurface device. Additionally, their limited power handling capabilities may restrict their use in high-power applications. On the contrary, RF-MEMS varactors offers lower insertion losses due to their mechanical structure, but are limited by their slow switching speeds, typically falling into the kHz range. This makes them unsuitable for applications requiring rapid switching between different electromagnetic states. Their fabrication processes can also be complex and expensive, increasing

the overall cost of the device. Finally, PIN diodes exhibit a very good level of insertion losses and power handling capabilities. Despite their switching speed is faster than RF MEMS varactors, it rarely exceeds 1 GHz, making it insufficient for certain applications demanding ultra-fast switching.

The limitations of the electronic tuning can be therefore categorized into three main areas:

- Tuning Range: The tuning range achievable with electronic tuning methods is often limited, particularly for PIN diodes and RF MEMS. Varactor diodes, on the other hand, offer a broader tuning range, making them suitable for applications requiring significant variations in electromagnetic properties.
- Switching Speed: The switching speed of electronically tunable devices can vary depending on the specific technology employed. PIN diodes generally offer the fastest switching speeds, while Varactor diodes and RF MEMS may exhibit slower switching times. For applications demanding rapid switching capabilities, PIN diodes are the preferred choice.
- Power Consumption: The power consumption of electronically tunable devices is also a factor to consider. Varactor diodes and PIN diodes typically exhibit higher power consumption, and thus higher insertion loss, compared to RF MEMS. In applications where power efficiency is critical, RF MEMS are more suitable.

In summary, each electronic tuning method has its own set of advantages and limitations. The choice of the most suitable method depends on the specific application requirements, considering factors such as tuning range, switching speed, power consumption, device size, and cost constraints. Careful consideration of these limitations is crucial for designing and optimizing metamaterial and metasurface devices with the desired functionalities.

5 KPIs and Fundamental bounds of the SoA

5.1 Key performance indicators of interest

In this section we summarize the Key Performance Indicators (KPIs) of interest for the Application Areas of the PULSE project.

Application Area 1 - Tunable lenses for antennas

The Application Area 1 is dedicated to Tunable lenses for antennas. The PULSE project aims at providing lens for high frequency range (e.g., mm-wave and sub-THz) by using plasma-based metasurface technology. In particular, the two families of devices are considered:

1) **Meta-gratings for aperture antennas** in which the plasma tubes replace the commonly used lens made of metal wires periodically loaded by bulk capacitors. In this way, the pointing angle of the antenna can be quickly reconfigured by changing the properties of the plasma environment. This also allows overcoming some typical drawbacks of antenna arrays when pointing towards extreme angles, such as the presence of grating lobes and scan losses, as graphically represented in Figure 31(a).

2) **Cylindrical metasurfaces covering dipole antennas**. The metasurface can shape the radiation pattern of the antenna in the desired fashion without producing any reflection back to the antenna itself, as graphically represented in Figure 31(b). In this scenario, the metasurface can be even tuned for reducing the out-band scattering signature of the dipole and, thus, its blockage on nearby antennas, with clear advantages for the design of highly dense platforms required by the future communication and wireless systems. Finally, the metasurface can be used as electromagnetic shield to block signals coming from unwanted source, thus highly increasing resilience to jamming and spoofing.

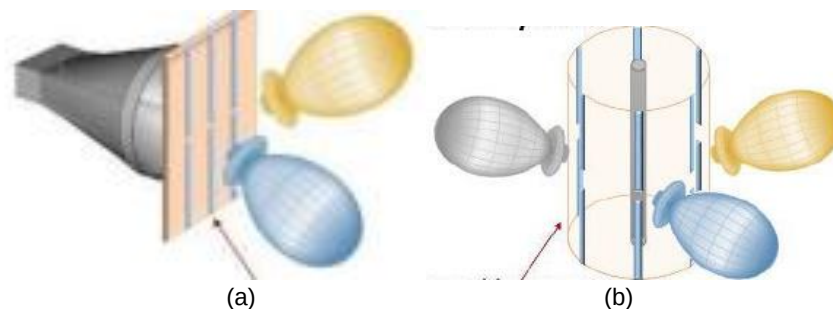


Figure 31: Graphical representation of (a) Meta-gratings for aperture antennas and (b) Cylindrical metasurfaces covering dipole antennas.

The identified KPIs for the Application Area 1 are listed in the following:

- Operative target band (X, Ku, K, Ka)
- Bandwidth
- Pointing angle / Max deflection angle
- Scan loss
- Insertion loss
- Side lobe level
- Radiation efficiency

- Tunability rate
- Max directivity/gain
- Scattering (Absorption) Cross Section

Application Area 2 - Non-reciprocal devices

The Application Area 2 is dedicated to non-reciprocal devices. The PULSE project aims at investigating the space-time modulation of plasma-based meta-atoms to realize magnet-less isolator for waveguides, as shown in Figure 32. This device has the potential for improving security, resilience, and overall performances of a communication system.

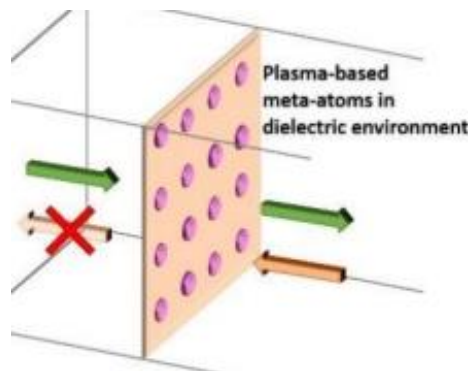


Figure 32: Graphical representation of a non-reciprocal waveguide device based on a plasma-based metasurface.

The identified KPIs for the Application Area 2 are listed in the following:

- Operative target frequency (L)
- Isolation
- Insertion loss
- Power handling
- Bandwidth

Application Area 3 - Four-dimensional (4D) devices

The Application Area 3 is dedicated to novel four-dimensional (4D) devices. The PULSE project aims at exploiting one of the plasma discharge properties that allows the creation of plasma volumes that change their shape and size very quickly. This area explores new physics of radiation and scattering from plasma-based meta-atoms with modulated size and shape and metadevices based on these meta-atoms. A representation of this family of devices is reported in Figure 33.

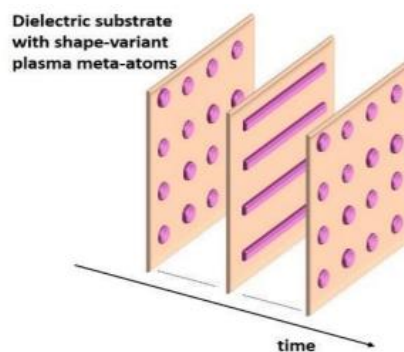


Figure 33: Graphical representation of a generic 4D device composed by plasma meta-atoms.

The identified KPIs for the Application Area 3 are listed in the following:

- Bandwidth
- Tunability rate

5.2 Fundamental bounds identified in the literature

In this section, we present the fundamental bounds identified in the literature for the three Application Areas of the PULSE project. They are listed in the following three Tables, each of which dedicated to a specific Application Area.

Table 5: Fundamental bounds identified for Application Area 1

KPI	Value	Conventional Reconfig. Technique
Fractional BW	36%	MTS with Varactors
Max deflection angle	90 deg	MTS with Varactors
Scan loss (lens)	0,26dB	MTS with Varactors
Scan loss (covers)	0 dB	MTS with PIN diodes
Insertion loss (lens)	0,26dB	MTS with Varactors
Insertion loss (cover)	0 dB	MTS with PIN diodes
Side lobe level	2,5 dB	MTS with Varactors
Radiation efficiency	0,8	MTS with Varactors
Tunability rate	2 MHz	MTS with Varactors
Max directivity/gain	28,6 dB	MTS with PIN diodes

Table 6: Fundamental bounds identified for Application Area 2

KPI	Value	Conventional Reconfig. Technique
Bandwidth	120%	TL with Varactors
Insertion loss	2 dB	MTS with Varactors
Power handling	15 dBm	TL with Varactors
Isolation	15 dB	MTS with Varactors

Table 7: Fundamental bounds identified for Application Area 3

KPI	Value	Conventional Reconfig. Technique
Bandwidth	NA	NA
Tunability Rate	NA	NA

It is worth mentioning that the Application Area 3 is totally new in the state of the art and there is no possibility to identify conventional reconfigurable techniques for establishing a fundamental bound.

6 Database of the relevant State-of-the-Art

The database of relevant State-of-the-Art for the PULSE project is organized in a dedicated Microsoft Excel file. It is composed by four sections:

1) **Reconfigurable Approach:** this section is dedicated to the identification of the reconfigurable method used in the work and its relevance in one of the three Application Areas of the project. As shown in Figure 34.

Reconfig. Approach		
	Reconfigurability Technology	Appl. Area

Figure 34: Screenshot of the section on reconfigurable approach of the PULSE literature database.

2) **Database Nomenclature:** it reports the information on the name assigned to the PDF files of the works. The name of the file has been designed to report all the relevant information for the PULSE project, such as the Article Classifies (review or original article, and tuning methodology), year of publication, operative band, type of device (reflecting or transmitting metamaterial / metasurface), acronym of the journal, last name of the corresponding author. Moreover, in this section, we also report the title of the work and the hyperlink to the publisher webpage. In Figure 35 we report the screenshot of the section on nomenclature of the PULSE literature database.

Database Nomenclature						
Art. Classifie	Year	Band Type	Device Type	Journal (Acron.)	Corr. Author	Title (Hyperlink)

Figure 35: Screenshot of the section on nomenclature of the PULSE literature database

3) **Reconfigurability performances:** it reports the performances exhibited by the device proposed in the current work. Specifically, we report the operative frequency and bandwidth, Tunability rate and range for time-modulated and reconfigurable devices, respectively, and the tuned quantity (amplitude or phase of the transmission/reflection coefficient), as shown in Figure 36.

Reconfigurability Performances				
Operative frequency (GHz)	Bandwidth (MHz)	Tunability Rate (MHz) for Time-modulated	Tunability range for Reconfigurable	Tuned EM quantity

Figure 36: Screenshot of the section on reconfigurability performances of the PULSE literature database

4) **Implementation details:** this section is dedicated to list the tunable element used in the current work, the device fabrication technology and performance validation method (theoretical, numerical, or experimental). In Figure 37, we report the screenshot of the section on implementation details of the PULSE literature database.

Implementation details		
Tunable Element	Device Fabrication technology	Performance Validation method

Figure 37: Screenshot of the section on implementation details of the PULSE literature database

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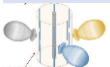
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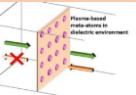
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Reconfig. Approach			Database Nomenclature							Reconfigurability Performances					Implementation details		
	Reconfigurability Technology	Appl. Area	Art. Classifier	Year	Band Type	Device Type	Journal (Acron.)	Corr. Author	Title (Hyperlink)	Operative frequency (GHz)	Bandwidth (MHz)	Tunability Rate (MHz) for Time-modulated	Tunability range for Reconfigurable	Tuned EM quantity	Tunable Element	Device Fabrication technology	Performance Validation method
Electronic tuning	PIN diodes	-----	[Orig-Ele]	2018	X	R-SUR	NatComm	Cui	Space-time-coding digital metasurfaces	10,00 GHz	200 MHz	200,00 MHz	NA	Reflection phase	M/A-COM MADP-000907-14020x	PBC technology	Experimental
	PIN diodes	-----	[Orig-Ele]	2017	C	R-SUR	SciRep	Luo	Dynamical beam manipulation based on 2-bit digitally-controlled coding metasurface	7,20 GHz	800 MHz	NA	800 MHz	Reflection phase	M/A-COM Chip Chip MAAFP5502	PCB technology	Experimental
	PIN diodes	-----	[Orig-Ele]	2016	X	R-SUR	SciRep	Li	A programmable metasurface with dynamic polarization, scattering and focusing control	11,00 GHz	1000 MHz	NA	NA	Reflection phase	MADCOM MADP-000907-14020	PCB technology	Experimental
	PIN diodes	-----	[Orig-Ele]	2010	X	R-SUR	IEEE-TAP	Carrier	Dual-Polarized and Polarization-Flexible Reflective Cells With Dynamic Phase Control	8	500	NA	-180°/+100°	Reflection phase	Aeroflex-Metelics M/V5125-08 (varactor) and MPV7310 (PIN diodes)	PCB technology	Experimental
	PIN diodes	Lens	[Orig-Ele]	2012	X	T-SUR	IEEE-TAP	Pouligen	1-Bit Reconfigurable Unit Cell Based on PIN Diodes for Transmit-Array Applications in -Band	9,75 GHz	1500 MHz	NA	0°-180°	Transmission phase	MAAAGP907 and MAAAGPCP910 AlGaAs flip chip PIN diodes	PCB technology	Experimental
	PIN diodes	Lens	[Orig-Ele]	2013	X	T-SUR	IEEE-TAP	Clemente	Wideband 400-element electronically reconfigurable transmitarray in X band	9,60 GHz	1500 MHz	NA	binary 0-180°	Transmission phase	NA	PCB technology	Experimental
	PIN diodes	Lens	[Orig-Ele]	2018	X	T-SUR	IEEE-AWPL	Pichot	Unit-Cell Loaded With PIN Diodes for 1-Bit Linearly Polarized Reconfigurable Transmitarrays	11,50 GHz	2000 MHz	NA	binary 0-180°	Transmission phase	AlGaAs MA4AGBLP912	PCB technology	Experimental
	PIN diodes	Cover	[Orig-Ele]	2013	S	RT-SUR	IEEE-TAP	Denidni	Electronically Sweeping-Beam Antenna Using a New Cylindrical Frequency-Selective Surface	2,45 GHz	400 MHz	NA	Zero-One	Transmission amplitude	GMP4201	PCB technology	Experimental
	PIN diodes	Cover	[Orig-Ele]	2011	L	RT-SUR	IEEE-TAP	Denidni	High-gain reconfigurable sectoral antenna using an active cylindrical PSS structure	2,10 GHz	300 MHz	NA	Zero-One	Transmission amplitude	GMP4201	PCB technology	Experimental
	PIN diodes	Cover	[Orig-Ele]	2010	S	RT-SUR	IEEE-TAP	Denidni	Frequency Selective Surfaces and Their Applications for Nimble-Radiation Pattern Antennas	2,45 GHz	100 MHz	NA	Zero-One	Transmission amplitude	GMP4201	PCB technology	Experimental
	PIN diodes	Cover	[Orig-Ele]	2016	L	RT-SUR	IEEE-AWPL	Gharsallah	Beam-Switching Antenna With a New Reconfigurable Frequency Selective Surface	1,80 GHz	200 MHz	NA	Zero-One	Transmission amplitude	BAR64-03 W	PCB technology	Experimental
	PIN diodes	Cover	[Orig-Ele]	2016	S	RT-SUR	IEEE-AWPL	Denidni	Pattern-Reconfigurable Antenna Using a Switchable Frequency Selective Surface With Improved Bandwidth	3,78 GHz	1200 MHz	NA	Zero-One	Transmission amplitude	GMP4201	PCB technology	Experimental
	PIN diodes	Cover	[Orig-Ele]	2016	L	RT-SUR	ET-MAP	Gharsallah	Reconfigurable frequency selective surface for beam-switching applications	2,10 GHz	200 MHz	NA	Zero-One	Transmission amplitude	NA	PCB technology	Experimental
	PIN diodes	Cover	[Orig-Ele]	2018	Ka	RT-SUR	IEEE-AWPL	Denidni	A Dual-Plane Beam-Sweeping Millimeter-Wave Antenna Using Reconfigurable Frequency-Selective Surfaces	30,00 GHz	1000 MHz	NA	Zero-One	Transmission amplitude	NA	PCB technology	Experimental
	PIN diodes	Cover	[Orig-Ele]	2021	L	RT-SUR	Wiley-IJMCE	Denidni	Beam-sweeping antenna with beamwidth reconfigurable response	1,90 GHz	300 MHz	NA	Zero-One	Transmission amplitude	BAR63-04 from Infineon	PCB technology	Experimental
	PIN diodes	Cover	[Orig-Ele]	2023	C	RT-SUR	IEEE-AWPL	Denidni	Wideband and Wide-Angle Switchable Spatial Filter/Shielding With Polarization-Independent Response	4,10 GHz	1700 MHz	NA	Zero-One	Transmission amplitude	BAP 70-03 from NXP	PCB technology	Experimental
	PIN diodes	Cover	[Orig-Ele]	2015	S	RT-SUR	IEEE-TAP	Batchelor	Cylindrical Slot PSS Configuration for Beam-Switching Applications	2,45 GHz	100 MHz	NA	Zero-One	Transmission amplitude	BAR64-02	PCB technology	Experimental
	PIN diodes	-----	[Orig-Ele]	2020	X	R-SUR	AdvFunMat	Galdi	Joint Multi-Frequency Beam Shaping and Steering via Space-Time-Coding Digital Metasurfaces	9,50 GHz	0 MHz	5,00 MHz	-90°/270°	Reflection phase	M/A-COM MADP-000907-14020x	PCB technology	Experimental
	PIN diodes	-----	[Orig-Ele]	2017	CK	R-SUR	AdvOptMat	Luo	Reconfigurable Metasurface for Multifunctional Control of Electromagnetic Waves	10,00 GHz	6700 MHz	NA	binary 0-180°	Reflection phase	Macom MA46H120 & MA4FCP305	PCB technology	Experimental
	PIN diodes	Lens	[Orig-Ele]	2023	Ka	T-SUR	EuCAP	Sauleau	Reconfigurable Transmitarrays at Ka-Band with Beam-Forming and Polarization Agility	30,25 GHz	4500 MHz	NA	0°-360°	Reflection phase	NA	PCB technology	Experimental
	PIN diodes	Lens	[Orig-Ele]	2020	Ka	T-SUR	IEEE-TAP	Dussot	2 Bit Reconfigurable Unit-Cell and Electronically Steerable Transmitarray at Ka-Band	28,50 GHz	3000 MHz	NA	0°-360°	Reflection phase	MA4AGP907	PCB technology	Experimental
	PIN diodes	-----	[Orig-Ele]	1977	All	All	SSElectr.	Berz	A simplified theory of the p-n diode	NA	NA	NA	NA	NA	NA	NA	NA
	Varactor diodes	-----	[Orig-Ele]	2003	C	R-SUR	IEEE-TAP	Sievenpiper	Two-dimensional beam steering using an electrically tunable impedance surface	4,50 GHz	100 MHz	NA	1500 MHz	Reflection Phase	MHV500-19-1	PCB technology	Experimental
	Varactor diodes	NR-Device	[Orig-Ele]	2020	L	R-SUR	IEEE-TAP	Ramaccia	Phase-Induced Frequency Conversion and Doppler Effect With Time-Modulated Metasurfaces	1,50 GHz	50 MHz	0,50 MHz	NA	Reflection Phase	Varactor Infineon BB535	PCB technology	Numerical
	Varactor diodes	NR-Device	[Orig-Ele]	2013	X	T-SUR	NatComm	Alu	Giant non-reciprocity at the subwavelength scale using angular momentum-biased metamaterials	8,90 GHz	50 MHz	500,00 MHz	NA	Transmission amplitude	Ideal elements	PCB technology	Numerical
	Varactor diodes	NR-Device	[Orig-Ele]	2020	X	T-SUR	IEEE-TAP	Grbic	Serrordyne Frequency Translation Using Time-Modulated Metasurfaces	10,00 GHz	0 MHz	1,00 MHz	NA	Transmission Phase	MAVR-000120-1411	PCB technology	Experimental
	Varactor diodes	NR-Device	[Orig-Ele]	2014	L	T-MTM	IEEE-TMTT	Wang	Nonreciprocal components with distributedly modulated capacitors	1,00 GHz	1800 MHz	500,00 MHz	NA	Transmission Phase	M/A-COM GaAs hyperabrupt junction diodes	PCB technology	Experimental
	Varactor diodes	Lens	[Orig-Ele]	2018	C	T-SUR	PRX	Liu	Huygens' Metadevices for Parametric Waves	4,00 GHz	0 MHz	2,00 MHz	NA	Transmission Phase	SMV1405	PCB technology	Experimental
	Varactor diodes	-----	[Orig-Ele]	2019	S	R-SUR	NatSciRev	Li	Programmable time-domain digital-coding metasurface for non-linear harmonic manipulation and new wireless communication systems	3,60 GHz	0 MHz	0,30 MHz	NA	Reflection amplitude/phase	SMV2019	PCB technology	Experimental
	Varactor diodes	Lens	[Rev-Ele]	2014	NA	T-SUR	IEEE-TAP	Carrier	Reconfigurable Reflectarrays and Array Lenses for Dynamic Antenna Beam Control: A Review	Review	Review	Review	Review	Review	NA	NA	NA
	Varactor diodes	-----	[Orig-Ele]	2005	C	R-SUR	IEEE-MWCL	Hum	Realizing an Electronically Tunable Reflectarray Using Varactor Diode-Tuned Elements	5,80 GHz	93 MHz	NA	+/- 40 deg	Reflection pointing angle	MCE Metelics MGV-100-21	PCB technology	Experimental
	Varactor diodes	Lens	[Orig-Ele]	2012	C	T-MTM	IEEE-TMTT	Ran	Low-DC Voltage-Controlled Steering-Antenna Radome Utilizing Tunable Active Metamaterial	4,70 GHz	150 MHz	NA	0°-360°	Transmission phase	Philips Semiconductors BB143	PCB technology	Experimental
	Varactor diodes	Lens	[Orig-Ele]	2010	X	T-SUR	IEEE-TAP	Sierra-Perez	Electronically Reconfigurable Transmitarray at Ku-Band for Microwave Applications	12,00 GHz	2500 MHz	NA	0°-360°	Transmission phase	M/A-COMMA46585-1	PCB technology	Experimental
	Varactor diodes	Lens	[Orig-Ele]	2019	K	T-SUR	IEEE-AWPL	Koelpin	Electronically Reconfigurable 6 × 6 Element Transmitarray at K-Band Based on Unit Cells With Continuous Phase Range	24,60 GHz	0 MHz	NA	0°-360°	Transmission phase	MAVR-000120- 1411	PCB technology	Experimental
	Varactor diodes	Lens	[Orig-Ele]	2012	S	T-SUR	IEEE-TMTT	DiMazza	Multilayer Antenna-Filter Antenna for Beam-Steering Transmit-Array Applications	4,00 GHz	400 MHz	NA	+45°/-80°	Transmission phase	MDT MV39002 M46	PCB technology	Experimental
	Varactor diodes	Lens	[Orig-Ele]	2016	C	T-SUR	IEEE-TAP	Gomes	PSS-Inspired Transmitarray for Two-Dimensional Antenna Beamsteering	5,35 GHz	400 MHz	NA	0°-360°	Transmission phase	NA	PCB technology	Experimental
	Varactor diodes	Lens	[Orig-Ele]	2019	C	T-SUR	IEEE-Acc	Denidni	Wide-Angle Beam Steering Based on an Active Conformal Metasurface Lens	5,75 GHz	100 MHz	NA	0°-192°	Transmission phase	Skyworks SMV1405	PCB technology	Experimental
	Varactor diodes	Lens	[Orig-Ele]	2020	C	T-SUR	IEEE-TAP	Ran	Reconfigurable Fresnel Lens Based on an Active Second-Order Bandpass Frequency-Selective Surface	5,00 GHz	1000 MHz	NA	0°-190°	Transmission phase	MACOM MA46H120	PCB technology	Experimental
	Varactor diodes	Cover	[Orig-Ele]	2017	S	RT-SUR	IEEE-TAP	Cheng	Frequency-Agile Beam-Switchable Antenna	2,00 GHz	700 MHz	NA	700 MHz	High-transmission window	NA	PCB technology	Experimental

	Varactor diodes	Cover	[Orig-Ele]	2022	L	T-SUR	IEEE-OJAP	Biłotti	Multi-Layered Coating Metasurfaces Enabling Frequency Reconfigurability in Wire Antenna	1.00 GHz	500 MHz	NA	1-1.5 GHz	Antenna operative frequency	GC15006 Microsemi	PCB technology	Numerical
	RF MEMS varactors	-----	[Orig-Ele]	2003	Ku	R-SUR	IEEE-ISPAST	Gillard	A steerable reflectarray antenna with MEMS controls	18.30 GHz	1500 MHz	NA	120°-250°	Reflection phase	NA	Assembled device	Experimental
	RF MEMS varactors	-----	[Orig-Ele]	2006	C	R-SUR	EuCAP	Okoniewski	Integrated MEMS Reflectarray Elements	5.80 GHz	NA	NA	150-500 pF	Effective capacitance	Aeroflex MGV-100-20	Advanced Microfabrication integration	Experimental
	RF MEMS varactors	-----	[Orig-Ele]	2008	X	R-SUR	IEEE-AWPL	Skrivervik	Monolithic MEMS-Based Reflectarray Cell Digitally Reconfigurable Over a 360-Degree Range	12.00 GHz	1200 MHz	NA	0-360°	Reflection phase	NA	Used silica substrates coated with low temperature oxide (LT/O)	Experimental
	RF MEMS varactors	-----	[Orig-Ele]	2010	X	R-SUR	EuCAP	Carrier	Analysis of a Reconfigurable Reflectarray Cell Comprising a Multitude of MEMS Control Elements	12.50 GHz	NA	NA	0-360°	Reflection phase	NA	NA	Numerical
	RF MEMS varactors	-----	[Orig-Ele]	2007	X	R-SUR	EuCAP	Raveu	Satellite Antennas based on MEMS Tunable Reflectarrays	12.10 GHz	800 MHz	NA	-180°/+180°	Reflection phase	NA	NA	Experimental
	RF MEMS varactors	-----	[Orig-Ele]	2012	K	R-SUR	IEEE-TAP	Akin	Beam Switching Reflectarray Monolithically Integrated With RF MEMS Switches	26.50 GHz	1000 MHz	NA	-150°/-400°	Reflection phase	NA	PCB technology	Experimental
	RF MEMS varactors	-----	[Orig-Ele]	2012	X	R-SUR	IEEE-TAP	Encinar	Characterization of a Reflectarray Gathered Element With Electronic Control Using Ohmic RF MEMS and Patches Aperture-Coupled to a Delay Line	10.40 GHz	2000 MHz	NA	0°/-800°	Reflection phase	NA	PCB technology	Experimental
	RF MEMS varactors	Lens	[Orig-Ele]	2012	C	T-SURF	IEEE-TAP	Hum	Reconfigurable Transmitarray Design Approaches for Beamforming Applications	5.00 GHz	500 MHz	NA	+/- 40 deg	Pointing angle	NA	PCB technology	Experimental
	RF MEMS varactors	-----	[Orig-Ele]	2006	All	All	SensAct	Kattelus	Amorphous metal alloy based MEMS for RF applications	ALL	ALL	NA	NA	NA	NA	Used silica substrates coated with low temperature oxide (LT/O)	Experimental
	RF MEMS varactors	-----	[Orig-Ele]	2008	L	R-SUR	IEEE-TAP	Imbriale	RF MEMS Actuated Reconfigurable Reflectarray Patch-Slot Element	2.05 GHz	200 MHz	NA	-180°/+120°	Reflection phase	Radant MEMS SPST-RMSW100	PCB technology	Experimental
	RF MEMS switch	Lens	[Orig-Ele]	2009	Ka	T-SUR	IEEE-TMIT	Cheng	A Programmable Lens-Array Antenna With Monolithically Integrated MEMS Switches	34.80 GHz	2000 MHz	NA	0°-360°	Reflection Phase	NA	PCB technology	Experimental
Geometrical Tuning	MEMS	Cover	[Orig-Geo]	2018	Ka	RT-SUR	IET-MAP	Denidni	Beam-switching millimetre-wave antenna using cantilever-based FSSs	30.00 GHz	2000 MHz	NA	Zero-One	Transmission amplitude	NA	NA	Experimental
	MEMS	-----	[Orig-Geo]	2009	K	R-SUR	EuCAP	Toshiyoshi	Micro-fabricated tunable artificial dielectric for reconfigurable microwave circuits	30.00 GHz	10000 MHz	NA	Binary 0°-60°	Reflection Phase	NA	Wafer	Experimental
	Mechanical movement	-----	[Orig-Geo]	2002	S	R-SUR	IEEE-TAP	Sievenpiper	A Tunable Impedance Surface Performing as a Reconfigurable Beam Steering Reflector	3.00 GHz	1600 MHz	NA	1.7GHz - 3.3GHz	HIS Zero-phase frequency	NA	PCB technology	Experimental
	Mechanical movement	-----	[Orig-Geo]	2012	C	R-MTM	JAP	Tang	An origami tunable metamaterial	6.50 GHz	0 MHz	NA	5.5 GHz - 8 GHZ	Reflection amplitude deep	NA	PCB technology	Experimental
	Microfluidics	-----	[Orig-Geo]	2009	C	RT-MTM	APL	Bayindir	Microfluidics for reconfigurable electromagnetic metamaterials	5.40 GHz	10 MHz	NA	Zero-One	Transmission amplitude	Mercury-filled SRR	Photolithography	Experimental
Material tuning	Ferroelectrics Materials	-----	[Orig-Mat]	2007	K	R-SUR	ProdIEEE	Romanofsky	Advances in Scanning Reflectarray Antennas Based on Ferroelectric Thin-Film Phase Shifters for Deep-Space Communications	19.00 GHz	Na	NA	0°-320°	Reflection phase	perovskite crystal - high power handling capability, negligible dc power	NA	Experimental
	Ferroelectrics Materials	-----	[Orig-Mat]	2009	X	R-SUR	EuMC	Jakoby	Reconfigurable unit cell for reflectarray antenna based on barium-strontium-titanate thick-film ceramic	10.00 GHz	20 MHz	NA	-180°/+180°	Reflection phase	ferroelectric thick-film ceramic of Barium-Strontium-Titanate (BST)	PCB technology	Experimental
	Ferroelectrics Materials	-----	[Orig-Mat]	2000	Ka	R-SUR	IEEE-TMIT	Canedy	K-Band Phased Array Antennas Based on Ba0.60Sr0.40TiO3 Thin-Film Phase Shifters	19.00 GHz	10000 MHz	NA	0°-450°	Reflection phase	ferroelectric thin-film ceramic of Barium-Strontium-Titanate (BST)	PCB technology	Experimental
	Ferroelectrics Materials	Lens	[Orig-Mat]	2012	X	T-SUR	IEEE-TAP	Jakoby	Beam Steering Transmitarray Using Tunable Frequency Selective Surface With Integrated Ferroelectric Varactors	12.00 GHz	2500 MHz	NA	0°-400°	Transmission phase	Barium-Strontium-Titanate (BST)	PCB technology	Experimental
	Ferroelectrics Materials	-----	[Orig-Mat]	2008	L	R-MTM	JAP	Cummer	Frequency tunable electromagnetic metamaterial using ferroelectric loaded split rings	1.75 GHz	150 MHz	NA	1.7GHz - 1.85 GHz	Transmission amplitude deep	BST capacitor HP4284A LCR	PCB technology	Experimental
	Ferroelectrics Materials	-----	[Orig-Mat]	2009	S	R-MTM	EleLett	Martin	Electrically tunable split-ring resonators at microwave frequencies based on barium-strontium-titanate thick films	2.50 GHz	0 MHz	NA	2.25-2.75 GHz	Transmission amplitude deep	Barium-Strontium-Titanate (BST)	PCB technology	Experimental
	Ferroelectrics Materials	-----	[Rev-Mat]	2022	All	All	Jmateriomics	Lynch	A review of ferroelectric materials for high power devices	NA	NA	NA	NA	NA	All	NA	Experimental
	Fluidic media	-----	[Orig-Mat]	2011	S	R-SUR	IEEE-TAP	Huff	A Fluidic Loading Mechanism for Phase Reconfigurable Reflectarray Elements	3.00 GHz	NA	NA	EpsR: 2-7 & Phi: +7- 180°	Relative perm. & Refl. phase	colloidal barium strontium titanate (BSTO)	PCB technology	Experimental
	Liquid crystals	-----	[Orig-Mat]	2011	Ka	R-SUR	IET-MAP	Carrasco	Design and evaluation of multi-resonant unit cells based on liquid crystals for reconfigurable reflectarrays	35.00 GHz	5000 MHz	NA	EpsR: 2.3-3.1 & Phi: '-160°/+50°	Relative perm. & Refl. phase	LC MDA-03-2838	PCB technology	Experimental
	Liquid crystals	-----	[Orig-Mat]	2006	Ka	R-SUR	IET-EL	Jakoby	Electronically reconfigurable reflectarrays with nematic liquid crystals	34.00 GHz	NA	NA	Phi: -150°/+100°	Refl. Phase	LC BLO06	PCB technology	Experimental
	Liquid crystals	-----	[Orig-Mat]	2008	X	R-MTM	APL	Lippens	Magnetic control of negative permeability metamaterials based on liquid crystals	11.00 GHz	100 MHz	NA	10.75GHz-11.25GHz	Transmission amplitude deep	NA	NA	Experimental
	Liquid crystals	-----	[Orig-Mat]	2007	X	R-MTM	APL	Zhou	Electrically tunable negative permeability metamaterials based on nematic liquid crystals	11.00 GHz	500 MHz	NA	10.9GHz-11.1GHz	Transmission amplitude deep	NA	NA	Experimental
	Liquid crystals	-----	[Orig-Mat]	1996	All	All	JLTech	Johnson	High-speed continuously tunable liquid crystal filter for WDM networks	NA	NA	NA	NA	NA	NA	NA	Experimental
	Carbon fiber	-----	[Orig-Mat]	2014	C	R-MTM	IEEE-TAP	Trueman	Reconfigurable TX/RX Antenna Systems Loaded by Anisotropic Conductive Carbon-Fiber Composite Materials	Dual 4 GHz/5.5GHz	700 MHz	NA	1.5 GHZ	Operative frequency	Reinforced continuous carbon fiber composite (RCCFC)	PCB technology	Experimental
	photoconducting semiconductors	-----	[Orig-Mat]	2007	X	R-MTM	OptEx	Smith	Modulating and tuning the response of metamaterials at the unit cell level	8.90 GHz	100 MHz	NA	Zero-One	Transmission amplitude	NA	PCB technology	Experimental
	Phase-change materials	-----	[Orig-Mat]	2009	X	R-SUR	JPhysD	Zhang	A tunable hybrid metamaterial absorber based on vanadium oxide films	9.00 GHz	100 MHz	NA	9-10GHz	Absorption frequency	Vanadium Dioxide film	NA	Experimental
	Phase-change materials	-----	[Orig-Mat]	2017	X	R-SUR	SciRep	Zhou	Microwave Tunable Metamaterial Based on Semiconductor-to-Metal Phase Transition	8.75 GHz	800 MHz	NA	8.5-9GHz	Transmission amplitude deep	Vanadium Dioxide film	NA	Experimental
	Phase-change materials	-----	[Orig-Mat]	2022	C	T-SUR	NanoMat	Fu	A Thermal-Switchable Metamaterial Absorber Based on the Phase-Change Material of Vanadium Dioxide	7.00 GHz	200 MHz	NA	6-7 GHz	Reflection amplitude deep	Vanadium Dioxide elements	PCB technology	Experimental

PULSE technological classification			Database Nomenclature						Key Performance Indicators													
Application Area	Reconfig. Approach	Reconfigurability Technology	Art. Classifier	Year	Band Type	Device Type	Journal (Acron.)	Corr. Author	Operative frequency (GHz)	Bandwidth (MHz)	FB(%)	Max deflection angle (deg)	Scan loss (dB)	In-band Average Insertion loss (dB)	SLI (dB)	Rad. Efficiency	Tunability Rate	Pointing angle (deg)	Max Dir/Gain	SCS (dB)	ACS (dB)	
Tunable lenses for antennas 	Electronic	PIN diodes	[Orig-Ele]	2012	X	T-SUR	IEEE-TAP	Pouligen	9,75 GHz	1500,00 MHz	15,38%	NA	NA	3,0 dB	NA	NA	NA	NA	NA	NA	NA	
	Electronic	PIN diodes	[Orig-Ele]	2013	X	T-SUR	IEEE-TAP	Clemente	9,60 GHz	1500,00 MHz	15,63%	70 deg	7,40 dB	3,0 dB	6,70 dB	NA	NA	NA	+/-70 deg	22,80 dB	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2018	X	T-SUR	IEEE-AWPL	Pichot	11,50 GHz	2000,00 MHz	17,39%	40 deg	3,00 dB	1,2 dB	10,00 dB	NA	NA	NA	+/-40 deg	21,00 dB	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2023	Ka	T-SUR	EuCAP	Sauleau	30,25 GHz	4500,00 MHz	14,88%	60 deg	4,00 dB	2,0 dB	13,00 dB	NA	NA	NA	+/-60 deg	28,60 dB	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2020	Ka	T-SUR	IEEE-TAP	Dussopt	28,50 GHz	3000,00 MHz	10,53%	60 deg	5,00 dB	3,00 dB	NA	NA	NA	NA	+/-60 deg	19,8	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2015	Ka	T-SUR	IEEE-TAP	Pouliguen	28,50 GHz	4000,00 MHz	14,04%	45 deg	6,00 dB	2,00 dB	15,00 dB	0,58	NA	NA	+/-45 deg	28,1	NA	NA
	Electronic	Varactor diodes	[Orig-Ele]	2020	C	T-SUR	IEEE-TAP	Ran	5,15 GHz	400,00 MHz	7,77%	40 deg	2,60 dB	1,50 dB	8,00 dB	NA	NA	NA	0-40 deg	16,70 dB	NA	NA
	Electronic	Varactor diodes	[Orig-Ele]	2019	C	T-SUR	IEEE-Acc	Denidni	5,75 GHz	100,00 MHz	1,74%	60 deg	2,00 dB	5,00 dB	9,60 dB	NA	NA	NA	+/-60 deg	14,30 dB	NA	NA
	Electronic	Varactor diodes	[Orig-Ele]	2010	X	T-SUR	IEEE-TAP	Sierra-Perez	12,00 GHz	2500,00 MHz	20,83%	9 deg	NA	3,00 dB	10,00 dB	NA	NA	NA	+/-9 deg	16,00 dB	NA	NA
	Electronic	Varactor diodes	[Orig-Ele]	2017	C	T-SUR	AdvMat	Aliu	6,90 GHz	400,00 MHz	5,80%	NA	NA	3,0 dB	NA	NA	0,10 MHz	NA	NA	NA	NA	
	Electronic	Varactor diodes	[Orig-Ele]	2020	S	RT-SUR	IEEE-TAP	Bilotti	3,50 GHz	100,00 MHz	2,86%	60 deg	0,26 dB	0,26 dB	NA	NA	NA	NA	+/-60 deg	NA	NA	NA
	Electronic	Varactor diodes	[Orig-Ele]	2018	C	T-SUR	PRX	Liu	4,00 GHz	0,00 MHz	0,00%	90 deg	NA	0,97 dB	NA	NA	2,00 MHz	All	NA	NA	NA	
	Electronic	Varactor diodes	[Orig-Ele]	2019	K	T-SUR	IEEE-AWPL	Koelpin	24,60 GHz	0,00 MHz	0,00%	50 deg	5,00 dB	10,00 dB	6	NA	NA	NA	+/-60 deg	-12 dB	NA	NA
	Electronic	Varactor diodes	[Orig-Ele]	2012	C	T-MTM	IEEE-TMTT	Ran	4,70 GHz	150,00 MHz	3,19%	30 deg	4,00 dB	13,00 dB	0,00 dB	0,37	NA	NA	+/-30 deg	8,00 dB	NA	NA
Tunable covers for antennas 	Electronic	Varactor diodes	[Orig-Ele]	2012	S	T-SUR	IEEE-TMTT	DiMassa	4,00 GHz	400,00 MHz	10,00%	NA	NA	NA	2,50 dB	NA	NA	NA	NA	NA	NA	
	Electronic	Varactor diodes	[Orig-Ele]	2016	C	T-SUR	IEEE-TAP	Gomes	5,35 GHz	400,00 MHz	7,48%	25 deg	2,50 dB	2,80 dB	5,30 dB	NA	NA	NA	25 deg	17,30 dB	NA	NA
	Electronic	RF MEMS Varactors	[Orig-Ele]	2012	C	T-SUR	IEEE-TAP	Hum	5,00 GHz	500,00 MHz	10,00%	50 deg	0,50 dB	2,20 dB	10,00 dB	NA	NA	NA	+/-50 deg	15,00 dB	NA	NA
	Geometrical	RF MEMS Switch	[Orig-Ele]	2009	Ka	T-SUR	IEEE-TMTT	Cheng	34,80 GHz	2000,00 MHz	5,75%	40 deg	5,20 dB	8,00 dB	5,60 dB	NA	NA	NA	+/-40 deg	9,20 dB	NA	NA
	Material	Ferroelectrics Materials	[Orig-Mat]	2012	X	T-SUR	IEEE-TAP	Jakoby	12,00 GHz	2500,00 MHz	20,83%	10 deg	2,00 dB	2,9 dB	15,00 dB	NA	NA	NA	+/-10 deg	NA	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2013	S	RT-SUR	IEEE-TAP	Denidni	2,45 GHz	400,00 MHz	16,33%	72 deg	0,00 dB	2,5 dB	NA	NA	NA	NA	+/-72 deg	7,50 dB	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2011	L	RT-SUR	IEEE-TAP	Denidni	2,10 GHz	300,00 MHz	14,29%	30 deg	0,00 dB	2,0 dB	13,00 dB	NA	NA	NA	+/-30 deg	12,00 dB	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2010	S	RT-SUR	IEEE-TAP	Denidni	2,45 GHz	100,00 MHz	4,08%	0 deg	NA	1,94 dB	NA	NA	NA	0 deg	7,50 dB	NA	NA	
	Electronic	PIN diodes	[Orig-Ele]	2016	L	RT-SUR	IEEE-AWPL	Gharsallah	1,80 GHz	200,00 MHz	11,11%	72 deg	0,00 dB	0,00 dB	NA	NA	NA	NA	+/-72 deg	9,00 dB	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2016	S	RT-SUR	IEEE-AWPL	Denidni	3,87 GHz	1200,00 MHz	31,01%	0 deg	0,00 dB	2,00 dB	0,00 dB	NA	NA	NA	0 deg	8,50 dB	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2016	L	RT-SUR	IET-MAP	Gharsallah	2,10 GHz	200,00 MHz	9,52%	360 deg	0,00 dB	0,00 dB	0,00 dB	NA	NA	NA	360 deg	8,90 dB	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2018	Ka	RT-SUR	IEEE-AWPL	Denidni	30,00 GHz	1000,00 MHz	3,33%	360 deg	0,00 dB	0,00 dB	0,00 dB	NA	NA	NA	360 deg	9,00 dB	NA	NA
	Electronic	PIN diodes	[Orig-Geo]	2018	Ka	RT-SUR	IET-MAP	Denidni	30,00 GHz	2000,00 MHz	6,67%	360 deg	0,00 dB	0,00 dB	0,00 dB	NA	NA	NA	360 deg	6,10 dB	NA	NA
	Electronic	PIN diodes	[Orig-Ele]	2021	L	RT-SUR	Wiley-JMCE	Denidni	1,90 GHz	300,00 MHz	15,79%	360 deg	2,00 dB	0,00 dB	0,00 dB	0,8	NA	NA	360 deg	6,80 dB	NA	NA
Electronic	PIN diodes	[Orig-Ele]	2023	C	RT-SUR	IEEE-AWPL	Denidni	4,10 GHz	1700,00 MHz	41,46%	NA	NA	0,10 dB	NA	NA	NA	NA	NA	NA	NA	NA	
Electronic	PIN diodes	[Orig-Ele]	2015	S	RT-SUR	IEEE-TAP	Batchelor	2,45 GHz	100 MHz	4,08%	70 deg	NA	0,30 dB	NA	NA	NA	NA	0° & 70°	8,90 dB	NA	NA	
Electronic	Varactor diodes	[Orig-Ele]	2017	S	RT-SUR	IEEE-TAP	Cheng	1,90 GHz	700,00 MHz	36,84%	360 deg	NA	2,00 dB	NA	NA	NA	NA	360 deg	10,00 dB	NA	NA	
Electronic	Varactor diodes	[Orig-Ele]	2022	L	T-SUR	IEEE-OJAP	Bilotti	1,00 GHz	100,00 MHz	10,00%	NA	NA	NA	NA	0,8	NA	NA	NA	NA	NA	NA	

PULSE technological classification			Database Nomenclature						Key Performance Indicators				
Application Area	Reconfig. Approach	Reconfigurability Technology	Art. Classifier	Year	Band Type	Device Type	Journal (Acron.)	Corr. Author	Operative frequency (GHz)	Bandwidth (MHz)	In-band Avarage Isolation (dB)	Max Power handling	In-band Avarage Insertion loss (dB)
	Electronic	Varactor diodes	[Orig-Ele]	2020	L	R-SUR	IEEE-TAP	Ramaccia	3,15 GHz	0,00 MHz	4,0 dB	NA	2,0 dB
	Electronic	Varactor diodes	[Orig-Ele]	2014	L	T-MTM	IEEE-TMTT	Wang	1,00 GHz	1200,00 MHz	15,0 dB	15,0 dBm	2,0 dB
	Electronic	Varactor diodes	[Orig-Ele]	2020	X	T-SURF	IEEE-TAP	Grbic	10,00 GHz	NA	15,0 dB	-26,5 dBm	
	Electronic	Varactor diodes	[Orig-Ele]	2013	X	T-SUF	NatComm	Alu	8,90 GHz	50,00 MHz	30,0 dB	NA	1,0 dB

