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Electromagnetic metamaterials for biomedical applications: short review and trends

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Abstract. This mini-review examines the most prominent features and usages of metamaterials, such as metamaterial-based and metamaterial-inspired RF components used for biomedical applications. Emphasis is given to applications on sensing and imaging systems, wearable and implantable antennas for telemetry, and metamaterials used as flexible absorbers for protection against extreme electromagnetic (EM) radiation. A short discussion and trends on the metamaterial composition, implementation, and phantom preparation are presented. This review seeks to compile the state-of-the-art biomedical systems that utilize metamaterial concepts for enhancing their performance in some form or another. The goal is to highlight the diverse applications of metamaterials and demonstrate how different metamaterial techniques impact EM biomedical applications from RF to THz frequency range. Insights and open problems are discussed, illuminating the prototyping process.

Keywords: Metamaterials / metasurfaces / biomedical / antennas / phantoms / metamaterial absorbers / metamaterials for MRI / metasurface absorbers

1 Introduction

Metamaterials are an emerging technological concept which offers many different design approaches in RF systems, including antennas and other RF components [1]. The primary goal of using metamaterials is to enhance the main characteristics of these systems. There are two different approaches to achieving this. The first is through metamaterial-based systems, which involve designing components from scratch with a metamaterial approach. Huygens antennas and metasurfaces are examples of this approach [2,3]. The second approach is through metamaterial-inspired systems, which use the unique design perspective offered by metamaterials to improve the performance metrics of an RF system [2,4]. In this work, the emphasis is given to the stage where metamaterials and metasurfaces are used to enhance the main characteristics of an RF system.

Biomedical electromagnetics is an upcoming research domain, both for academic research and in terms of industrial interest and development. This can be substantiated if we observe the research trends available in scholarly databases, e.g., Scopus and Google Scholar, to chart the ongoing trends in this domain. In Figure 1, the publishing trends (including journal articles and conference papers) reveal a steady increase in related literature. Moreover, emerging ideas, such as the fusion of biomedical applications with metamaterials and metasurfaces, show a straightforward indicative ascent. In terms of industrial interest, we explore the number of patents published, i.e., granted, over the last 20 years—the results presented in Figure 2. It is interesting to note that the amount of patent work that incorporates metamaterials in biomedical devices is as large as the produced academic research. Surprisingly, patented antennas for biomedical applications are three to four times larger than the published biomedical antenna papers. In the electromagnetic (EM) spectrum, biomedical applications utilizing radio frequency (RF) radiation encompass medical telemetry, imaging, sensing, hyperthermia. The infrastructure for RF/microwave imaging and hyperthermia, RF to terahertz (THz) sensing, and the establishment of a body area network hinge on the utilization of one or multiple biomedical antennas, which may also be designed for wearability or implantation.

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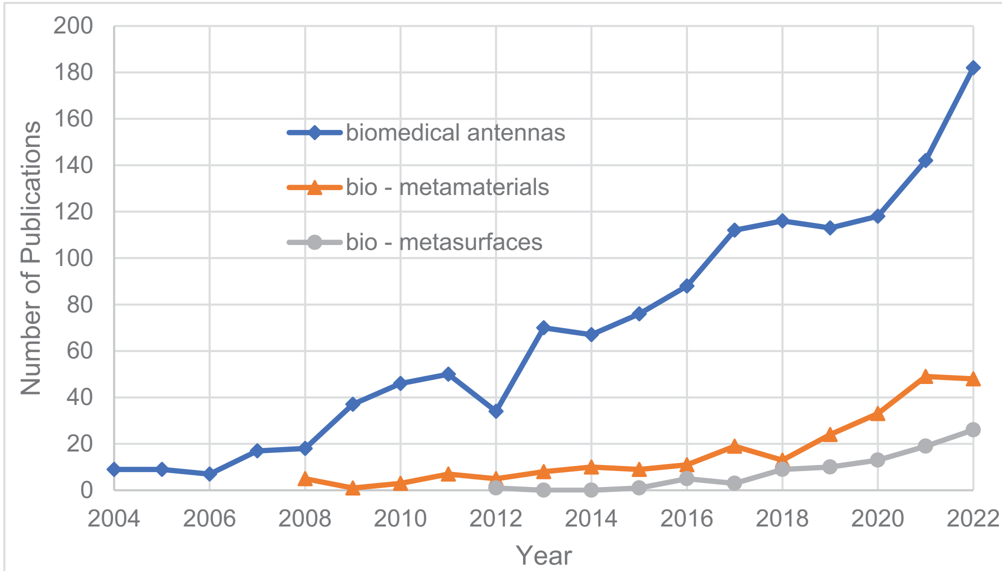


Fig. 1. The number of publications (Journals and Conference proceedings) that contain the words biomedical and (a) antennas (blue line), (b) metamaterials (orange line), and (c) metasurfaces (gray line) in their abstract. Note that both metamaterial and metasurface concepts have emerged in recent years. The results were retrieved from Scopus [5].

The incorporation of metamaterials, metasurfaces, and related techniques in conjunction with biomedical antennas is intended to manipulate emitted EM radiation, enhancing the overall performance of the system. Besides biomedical antennas, other medical systems and clinical imaging golden standards, as well as wearable protective systems, can also benefit from metamaterial techniques to enhance or to suppress radiation with compact, low-cost and reconfigurable components. There are two categories of design trends in engineering: new component design using new design tools and old component redesign using new ideas. The first category, new component design based on metamaterials, involves creating entirely new components using innovative design tools. The second category, metamaterial-inspired, involves incorporating various metamaterial ideas into traditionally designed components. These two categories represent different approaches to design in engineering, which is evident in the discussion that follows in the next sections.

The focus of this review is on industrial and clinical applications of metamaterials in biomedical devices based on EM radiation in the RF to THz frequency spectrum. First, we focus on metamaterials used for biomedical antennas (Sect. 2) and clinical biomedical imaging (Sect. 3). Then, we examine the example of metamaterials used as protective/absorbing materials for shielding from EM radiation (Sect. 4). At the same time, we focus on trends regarding metamaterial composition (Sect. 5) and phantom preparation (Sect. 6) that are usually developed in parallel with the metamaterial composition.

It is important to note that there is a wide range of biomedical applications in the optical range, from optical coherence tomography and fluorescent imaging to biosensing of large molecules, where metamaterials and metasurfaces exhibit great potential [7]. Nevertheless, due to differences in technology and materials between designing and developing photonic medical devices in the optical spectrum [7] and those in the RF spectrum, they have not been incorporated into this review.

2 Metamaterials for biomedical antennas

RF, microwave, and mm-wave biomedical applications for imaging, sensing, and communication include single or multiple antennas close to or inside a tissue. Recent progress in the field of biomedical engineering includes the development of wearable, implantable, and ingestible antennas for monitoring various physiological parameters, i.e., glucose, lactose, water levels [8–10] or temperature and conductivity sensing [11,12], devices equipped with antenna arrays for imaging and detection purposes, i.e., stroke and tumor detection [13,14], as well as antennas for treatments, i.e., RF and microwave hyperthermia and ablation [15,16]. Of paramount significance is the need for medical telemetry and the interconnection of diverse body sensors and devices, which necessitates the utilization of multiple telecommunications antennas both within and on the human body [17–19].

Every application sets specific requirements for antennas, such as frequency range, size, materials, etc. Despite the extensive list of biomedical antennas discussed in academic literature, most of them are affected by the high load introduced by the presence of the tissue in their near field, altering their radiating characteristics and input impedance. This effect is often intentionally introduced and is integral to the design process. Nonetheless, the EM characteristics of human tissues exhibit considerable diversity between different tissues and individuals, which poses a challenge in the design process. This variability can

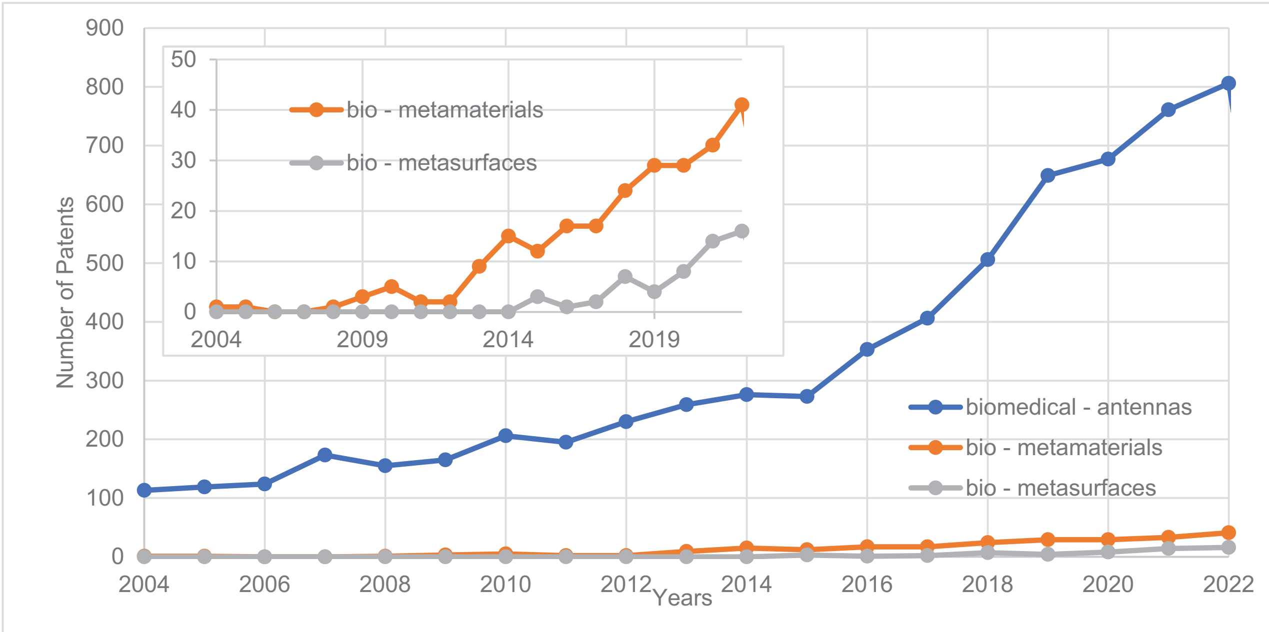


Fig. 2. The number of patents published (granted) related to biomedical (a) antennas (blue line), (b) metamaterials (orange line), and (c) metasurfaces (gray line). The inset figure highlights only the metamaterial and metasurface-related patents, highlighting a growing number, especially in very recent years. Still, the number of antenna-related patents for biomedical applications surpasses 800 granted patents per year. The data was retrieved from the Google Patents repository, while the query included the word found only in the abstract of the patents [6].

significantly impact antennas, particularly those intended for biomedical telecommunications, where it is essential to maintain consistent performance regardless of the specific tissue they are targeted for.

In this context, exploring alternative designs and materials could enhance the performance of these antennas. Metamaterials and metamaterial-inspired techniques are proposed for improving the radiating properties of antennas. The primary objective is to tailor a conventional radiating element to the distinctive tissue attributes of each individual. Another approach involves using metamaterials to concentrate the antenna's field on a specific tissue area, providing the setup with focusing capabilities. This is achieved by incorporating a customized setup as an integral part of the antenna or by introducing a matching layer between the antenna and the tissue. Finally, the third option is to use metamaterial features as part of the antenna for adding properties: multi-frequency operation, non-predictable polarization, or miniaturized topology. Adding features toward these goals, as well as for tissue coupling/decoupling, focusing, and miniaturization, are primary objectives for developing metamaterial and metamaterial-inspired antennas for biomedical applications (Fig. 3).

The concept of metamaterial antennas for biomedical applications and metamaterials for biomedical antennas has been introduced recently in the literature. Layers of subwavelength metallic structures, such as crosses and split-ring resonators (SRRs) [21], have been proposed to enhance the EM coupling with the targeted tissue by achieving impedance matching for applications such as brain stroke detection [26,27] and glucose monitoring [28]. SRRs have also been used to introduce capacitive and inductive resonance properties to a biomedical sensing antenna. At the same time, Hilbert fractal structures on its ground have helped towards miniaturization [23]. Implantable and wearable antennas also incorporate metamaterial-inspired features to achieve extra miniaturization [29–31]. Metamaterial-inspired techniques have also been applied to improve the gain of various biomedical antennas or to reshape their radiation pattern to enhance directivity for breast and brain imaging applications [24,32,33].

Additionally, wearable antennas printed on flexible substrates or weaved on fabric suffer from bending and unpredictable deformations. Textile antennas incorporating artificial magnetic conductor (AMC) planes have been employed to separate the radiator from the human body and enhance the antenna's gain by functioning as a radiator themselves [22,34]. This approach ensures that deformations of the primary radiator, i.e., a dipole antenna, do not adversely impact the overall antenna performance.

The design process for creating metamaterial setups for biomedical antennas is contingent upon their intended purpose. The metamaterial design can either be integrated into the antenna design itself or treated as a separate task that follows from the antenna's development. The selection of a subwavelength structure is aligned with the intended function of the metamaterial. For instance, SRRs add capacitive and inductive features to the antenna that enhances near-field radiation [35] or that increases the operating bandwidth [36] through the excitation of sharp resonances, especially due to the zeroth order resonating mode ($n = 0$). Additionally, the careful design of micro-structure arrays, such as crosses, meanders etc., provides

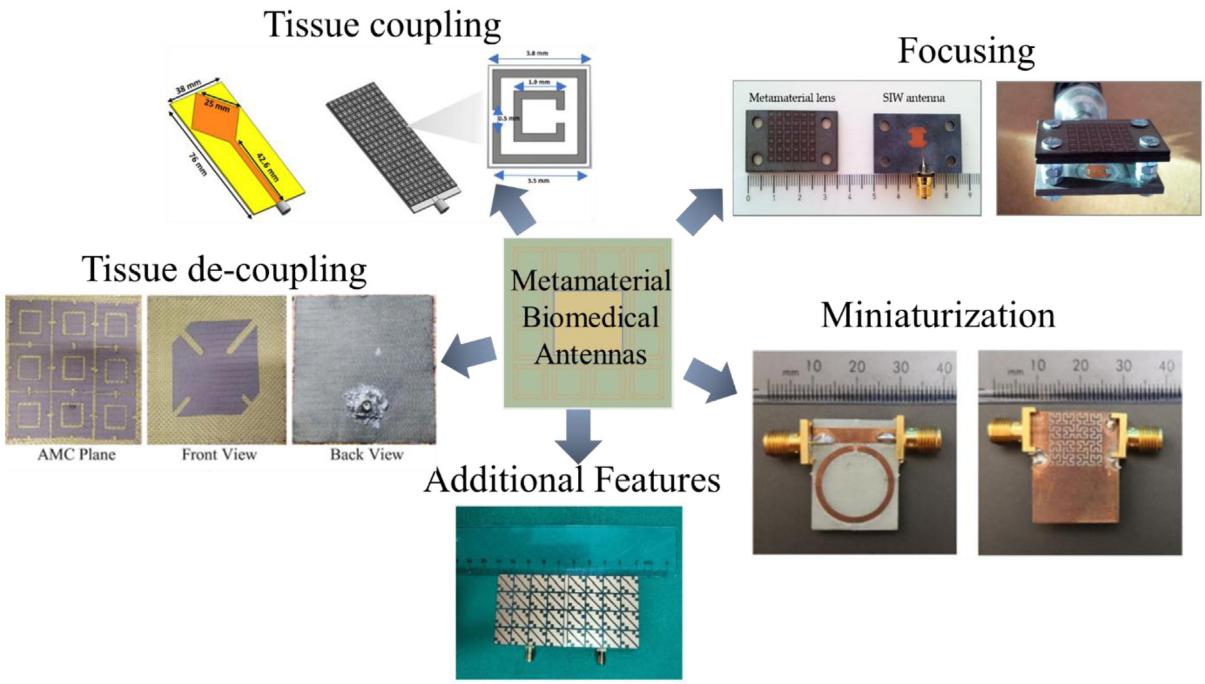


Fig. 3. Main objectives for the development of metamaterial antennas for biomedical applications: Tissue coupling for maximizing radiation transfer to the body (example figure: a printed square monopole antenna with metamaterial superstrate based on double SSRs for brain imaging [20]); Focusing (example figure: a metamaterial lens on a substrate integrated waveguide (SIW) cavity-backed patch antenna [21]; Tissue decoupling (example figure: Topology of a dual-dual polarized textile antennas on an AMC plane for WBAN/WLAN and GPS applications. Reproduced with permission from R. Joshi et al., published by IEEE, 2020 [22]); Miniaturization (example figure: metamaterial-based sensor design using split ring resonator and Hilbert fractal for sensing breast cancer cells [23]); High gain metamaterial Vivaldi antenna for microwave breast imaging applications [24]; Addition of features such as circular polarization (CP) (example figure: a wearable two-port MIMO antenna with a metasurface layer composed of 4×4 symmetrical crown-shaped units, which are used to realize CP radiation [25]).

effective permittivity values that improve the antenna-tissue EM radiation coupling [37]. Moreover, AMCs are typically used as antenna grounds to enhance gain and directivity, allowing miniaturization without affecting the antenna's efficiency [38]. Lastly, careful consideration must be given to the choice of dielectric materials, as they significantly impact the effective permittivity of the setup. Off-the-shelf laminates offer specific permittivity values from $\varepsilon_r = 2$ to $\varepsilon_r = 12$, while there is growing interest in custom-made dielectrics of varying permittivity values and mechanical properties [39,40].

In summary, this section has shown that numerous topologies, geometries, and techniques, rooted in and inspired by metamaterials (MMs), are playing a significant role in enhancing various characteristics of biomedical antennas. The choice of approach often depends on the specific application, frequency range, and available space. To provide a quick overview of recent endeavors, Table 1 offers a summary of efforts leveraging MMs to boost antenna performance in biomedical applications, complete with metrics describing the enhancements achieved in comparison to reference non-metamaterial antennas.

3 Metamaterials in clinical medical imaging

The previous section focused on metamaterials for biomedical antennas that typically involve imaging, sensing, and therapy at frequencies from RF to THz, as well as implantable and wearable antennas for biotelemetry. In addition, metamaterials offer unique opportunities for imaging techniques that are clinically significant diagnostic tools, such as Magnetic Resonance Imaging (MRI) that uses RF coils to excite and receive RF signals from the body area of interest and Positron Emission Tomography (PET) that detects gamma radiation.

Signal-to-Noise Ratio (SNR) is a critical parameter in MRI techniques, primarily due to its direct influence on scanning time reduction and image resolution enhancement. Additionally, an improved SNR can offer image quality comparable to what one might expect from transitioning to higher static magnetic fields, such as moving from 1.5 T to 3.0 T, a shift often linked to elevated expenses, tissue heating, and increased artifacts. Metamaterials and metasurfaces present a promising choice for SNR increase during MRI scans by amplifying and/or focusing the RF field, all without the need for higher

Table 1. List of characteristic metamaterial (MM) techniques applied to biomedical antennas in literature since 2018.

Objective	Application	Improvement	MM topology	References
Miniaturization and multiple resonances	Communication/ wearable	First resonance moved from 1.25 GHz to 0.4 GHz	Complementary Minkowski fractal geometry on radiating element and ground	[41]
Gain enhancement and CP	Communication/ implant	3-dB AR bandwidth improved by 6%	H-shaped slot patches on superstrate of high epsilon	[29]
Bandwidth and gain enhancement	Microwave imaging	6 dBi gain enhancement	A radiating element of concentric square rings	[42]
Miniaturization and sensitivity enhancement	Cancerous cell sensor	Miniaturization to λ/10 size	SRR as radiating element and Hilbert fractal curve on ground	[23]
Tissue coupling and focusing	Power transfer to implant	From 0% to 280% efficiency enhancement	Vertically stacked SRRs with capacitors on superstrate	[43]
Tissue coupling and focusing	Power transfer to implant	10 dB improvement in S21	Ring array on superstrate	[44]
Miniaturization and bandwidth enhancement	Microwave imaging	Cut-off frequency from 1.8 GHz to 1.2 GHz	Triple SRRs on substrate and on ground	[45]
Gain enhancement	Biomedical applications	4 dBi gain enhancement	Loop with cross slots on superstrate	[46]
Transmission and sensitivity enhancement	Microwave imaging	8 dB transmission enhancement	Jerusalem crosses on superstrate	[20]
Suppression of backward radiation and maintaining performance when bent	GPS/wearable	Front to back ratio always above 10 dB	AMC ground	[22]
Focusing	Microwave hyperthermia	~5 dBi gain enhancement	Double SRRs on superstrate	[21]
Achieving CP	Communication/ wearable	22.94% 3 dB axial ratio bandwidth (ARBB)	Crown-shaped units on superstrate	[25]
Directivity enhancement	Microwave imaging	27% near-field directivity enhancement	Meanders and rods at end-fire antenna's opening	[24]

Table 2. List of metasurfaces for improving local SNR for MRI in literature.

References	Metasurface topology	Magnetic field	Maximum local SNR improvement
[48]	Magnetoinductive lens consisting of two parallel arrays rings	1.5 T	200%
		3 T	250%
[49]	Array of capacitively-loaded copper rings	1.5 T	260%
[50]	Hexagonal close-packed array of "swiss rolls"	0.5 T	SNR = 32 with the metasurface
[51]	Brass wires embedded in a high permittivity low loss medium	1.5 T	330%
[52]	Active metasurface of brass wires embedded in a high permittivity low loss medium	1.5 T	250%
[53]	Array of metallic helices	1.5 T	400%
[54]	Two size zig zag copper strips immersed in water	7 T	200%

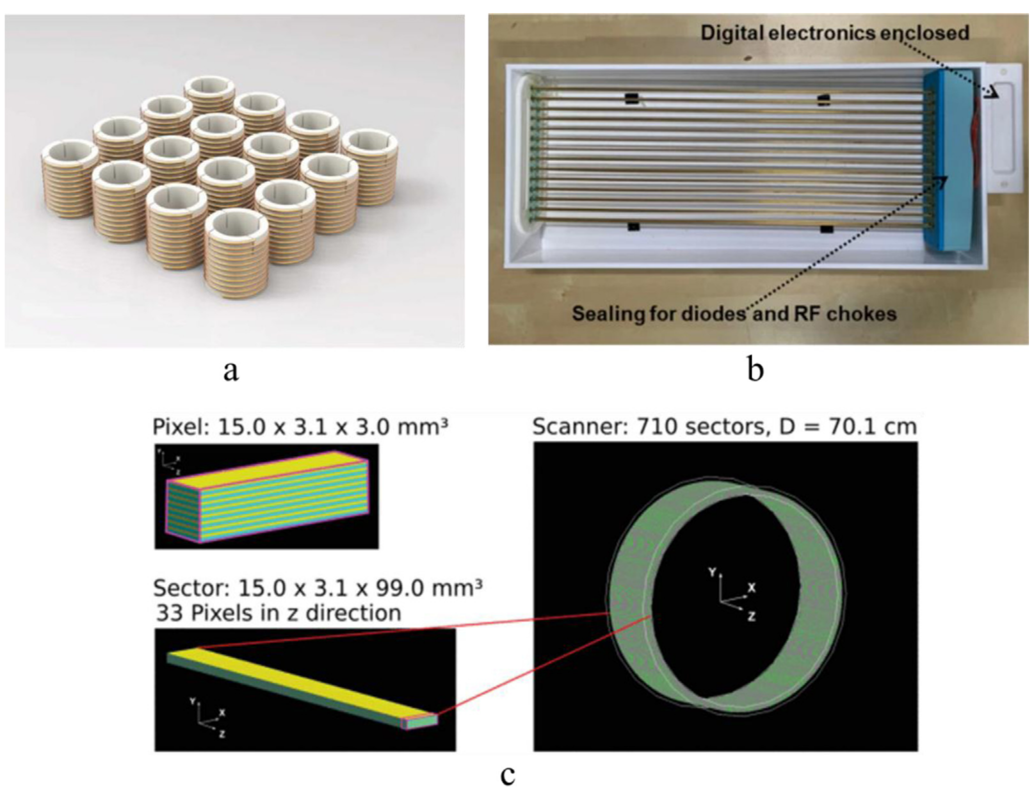


Fig. 4. (a) Schematic of a magnetic metamaterial array featuring metallic helices for 1.5 T SNR improvement [53]. (b) A metasurface resonator based on discrete wires embedded in Di water with the switching circuit in a watertight casing connected to the wires [55]. (c) A "pixel", a "sector" and the entire cylindrical PET scanner made by a BGO/plastic heterostructured scintillator that is repeated in the axial direction to create the scanner's modules [56].

magnetic field strengths [47]. Table 2 presents a list of metasurfaces found in literature for local SNR enhancement for MRI.

Arrays of metallic structures have been proposed to boost the RF field locally to the tissue of interest in imaging scans. A metamaterial featuring an array of metallic helices that are made of copper wiring with central polymeric scaffolding has been used during 1.5 T scanning resulting to an approximately 4 times increase to SNR [53] (Fig. 4a). Other subwavelength elements used for the development of MRI metamaterials are SRRs [49] and discrete wires inside high permittivity and low loss dielectrics, such as ceramics and distilled water [57], or printed on flexible biocompatible substrates for 1.5 T, 3 T and 7 T MRI [58,59].

However, an important aspect that must be considered when designing metasurfaces for MRI is the spatially inhomogeneous field enhancement created by a two-dimensional structure. Typically, field strength varies with distance from the metasurface, leading to non-uniform image intensity from the same tissue—an undesirable feature to clinicians [60]. To address this issue, a reconfigurable discrete wire metasurface has been developed to passively tune into and off the Larmor frequency during receive and transmit mode, respectively, by integrating a sensing switch matrix to the metasurface elements [55] (Fig. 4b). This way, the metasurface can maintain homogeneous excitation during receive mode while enhancing the field during transmit mode [55].

Additionally, novel approaches towards fast timing in PET imaging techniques have also been proposed. More specifically, enhancing the performance of silicon photomultipliers (SiMP) involves the development of a metamaterial structure that integrates both microelectronic and nanophotonic properties for handling the photo-electron interactions in a more effective manner [61]. The use of the composite materials made from alternating layers of BGO as a dense material and plastic as a fast light emitter significantly, such as EJ-322, reduced time resolution (CTR) distribution compared to bulk BGO [56] (Fig. 4c). In a different effort, plastic heterostructure scintillators have been made by combining 250 μm BC-422 plates with LYSO and BGO 200 μm thick crystal plates [62]. While PET metamaterial techniques might not fall strictly within the scope of this review, scope of this review, they are worth mentioning for underscoring the widespread use of metamaterials in clinical devices employing EM radiation.

4 Bio-protection against EM radiation with metamaterial absorbers

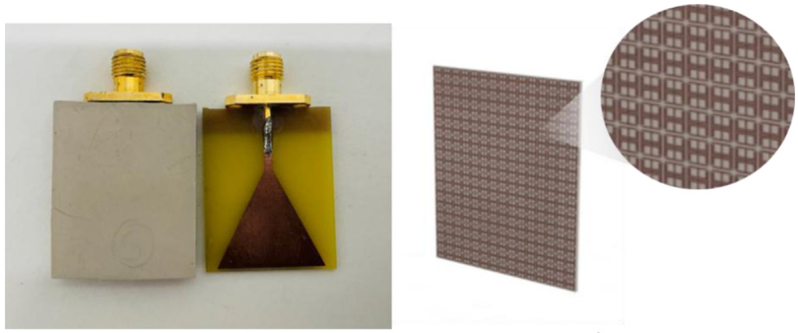
In this section, we extend the previous discussion on metamaterials for biomedical applications (e.g., imaging, sensing, etc.) to bio-protection from EM radiation. EM bio-protection has become very relevant nowadays as current wireless communication and sensing technologies inevitably increase the number of artificial sources of EM radiation around us. This results in interference which affects the smooth operation of other communication devices, and more importantly it can be potentially hazardous to humans and other living beings, i.e., depending on the frequency and intensity of the EM fields. For example, heating is the main biological effect of radiofrequency (RF) signals while waves of high power and frequency can disrupt the normal bodily functions of the exposed person. It is, therefore, imperative to develop suitable materials and methods to mitigate the detrimental effects of EM radiation on human health [63].

Mobile phones (MPs) are one of the most common EM sources. As known, the chief effect of the power radiated by MP antennas is the heating of the user's head, which is quantified by the specific absorption rate (SAR) measured in watts per kilogram of tissue (W/kg) [64]. Conventional SAR reduction techniques include placing a ferrite sheet or a metallic reflector between the radiating antenna and the user's head. Nonetheless, the former can degrade the radiation efficiency of the MP antenna, while the latter might not provide adequate protection due to edge scattering [65]. To this end, [66] presented a solution based on SRRs designed to operate around the 900 MHz and 1800 MHz GSM bands. Each SRR comprises two square rings with gaps appearing on the opposite sides. Numerical simulations showed that the proposed structure provides a higher SAR decrease than a perfect electric conductor (PEC) sheet, and the maximum degradation of the far-field pattern of the MP dipole antenna does not exceed 1.21 dB. Overall, a peak SAR reduction of 22.2% is achieved at 900 MHz using this metamaterial, and a similar performance is retained over a 5% frequency bandwidth.

The authors in [67] proposed a compact metamaterial-inspired MP antenna, which exhibits 70% radiation efficiency and 4.4 dBi gain at 2.4 GHz though with reduced SAR compared to conventional designs such as planar inverted-F antennas (PIFAs) and monopoles [68]. The proposed antenna consists of a SRR and a meandered line, and its simulated SAR was 1.21 W/kg which is well below the 2 W/kg limit of the EU standard measured for 1 gram tissue [69].

Moving beyond SAR reduction from MP antennas, flexible metamaterial absorbers have been recently proposed which can be integrated into various wearables and gadgets. Specifically, [70] presented an ultra-thin and bendable absorber for the 5 GHz band. The top layer of the resonant structure is a set of four diagonal Y-inspired metallic traces in a concentric pattern and the bottom layer is grounded by copper. The substrate is a polyimide-based Kapton film of 50.8 μm thickness. Due to the symmetrical design, the absorption is polarization insensitive and is 98% at 5.23 GHz. Furthermore, it was experimentally demonstrated that the absorber exhibits high absorptivity for conformal configurations with a maximum curvature radius of up to 35 mm.

In a similar spirit, [71] proposed a wearable metamaterial absorber for protection from radar emissions. It consists of square SRRs of different sizes to attain two closely spaced absorption frequencies for broadband operation. The structure was fabricated with conductive textile materials of 0.02 Ohm/sq sheet resistance on a felt



a b

Fig. 5. (a) A metasurface attached in front of a triangular antenna [26]. (b) Finite metamaterial periodic structure comprising an inner metallic pattern in between two high dielectric substrates Rogers 3010TM substrate. Figure adapted from [26].

substrate of 1 mm thickness. Experimental results showed a peak absorptivity of 90.1% and 92.8% at 9 GHz and 9.85 GHz, respectively, under normal incidence. The designed absorber had good absorption characteristics under various bending levels, with tested radii 30, 60, and 100 mm.

In addition to classic absorber design recipes like the SRRs, topology optimization (TO) techniques can create non-intuitive geometries with promising performance and features [72]. To this end, [73] proposed an optically transparent and flexible absorber using TO. Specifically, the transparent conductive geometry is made of indium-tin-oxide (ITO) and is optimized using a genetic algorithm. The resulting structure provides at least 90% absorptivity from 5.3 to 15 GHz. Also, its broadband performance remains unchanged for incident angles up to 30 degrees, exhibiting significant angular stability.

5 Discussion on metamaterial composition

Here, we discuss some of the metamaterial composition creation/implementation nuances. The three main mechanisms for metamaterial fabrication are addressed: chemical composition, geometrical composition (effective medium), and metamaterial composition (using electric, magnetic, and other inclusions).

The composition of metamaterials comprises a subset of materials categories, including polymers, ceramics, and metals [74]. These can be engineered and fabricated in various shapes and sizes using fabrication techniques such as additive manufacturing (AM), also referred to as "3D Printing," and subtractive fabrication, such as laser cutting techniques. Rapid prototyping and testing have significantly assisted in recent years in optimizing the composition of multifunctional metamaterials [75]. Regardless of the type of properties pursued in the design of metamaterials, a recurrent theme is the need to incorporate differential material response into a single construct because many advanced functionalities are dependent on the co-existence of highly different material properties next to each other and within the structure of a single metamaterial construct. Examples include conductive vs. non-conductive vs. semiconductive materials for electronics applications, magnetic vs. non-magnetic properties for magnetic applications, and soft vs. hard materials for creating simultaneously rigid and stiff materials.

Optimization and functionality-driven approach for designing metamaterials for biomedical applications use computational techniques and EM simulators to enable improved canvassing of the space of possible designs and more robust approaches to the rational design of metamaterials. The traditional method of designing metamaterials is based on full-wave simulations and S-parameter retrieval. The numerical simulations are repeated to optimize the constitutive parameters for a single metamaterial particle [75]. Metamaterial slabs can also be used as a matching medium to couple EM energy into the region of interest. An impedance mismatch occurs when EM waves propagate between media with different permittivity and permeability values, reducing the transmitted energy. This issue becomes significant in diagnostic imaging and other non-invasive biomedical applications [76]. The design of metamaterials is an essential path between theory and practice, and it is critical to achieve the desired performance in an experimental environment.

For the use of metamaterials and metasurfaces in the proximity of the skin, the choice of material depends on the specific requirements of the biomedical application and the patient's needs. In many applications where metamaterials are near the skin, biocompatible materials are used, such as medical-grade silicone, biodegradable polymers, and biocompatible metals. Improving transmission and reducing reflection are significant challenges while testing complex body geometry and lossy biological tissues [77]. The metamaterial desired performance will dictate its composition using parameters such as the thickness of various off-the-self substrates, i.e., Rogers Corp laminates, single materials such as acrylonitrile butadiene styrene (ABS), polylactide (PLA), high impact polystyrene (HIPS) (3D printed materials) and other polymers acting as a material base for dielectric matching using additives usually of higher permittivity to control the properties as well as custom made dielectric substrates that can be both mechanically robust as well as conformal to the area of

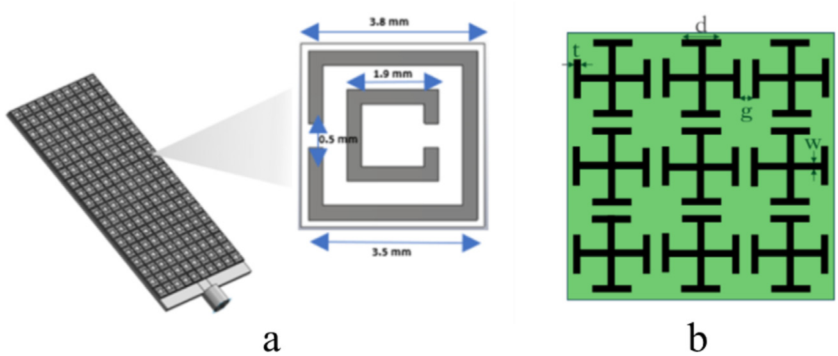


Fig. 6. (a) CAD design of a DS-SRR-based unit cell design patterned on a printed square monopole antenna with metasurface superstrate loading (figure from [20]); (b) a generic representation of Jerusalem crosses as unit cells for metasurface designs (figure from [78]).

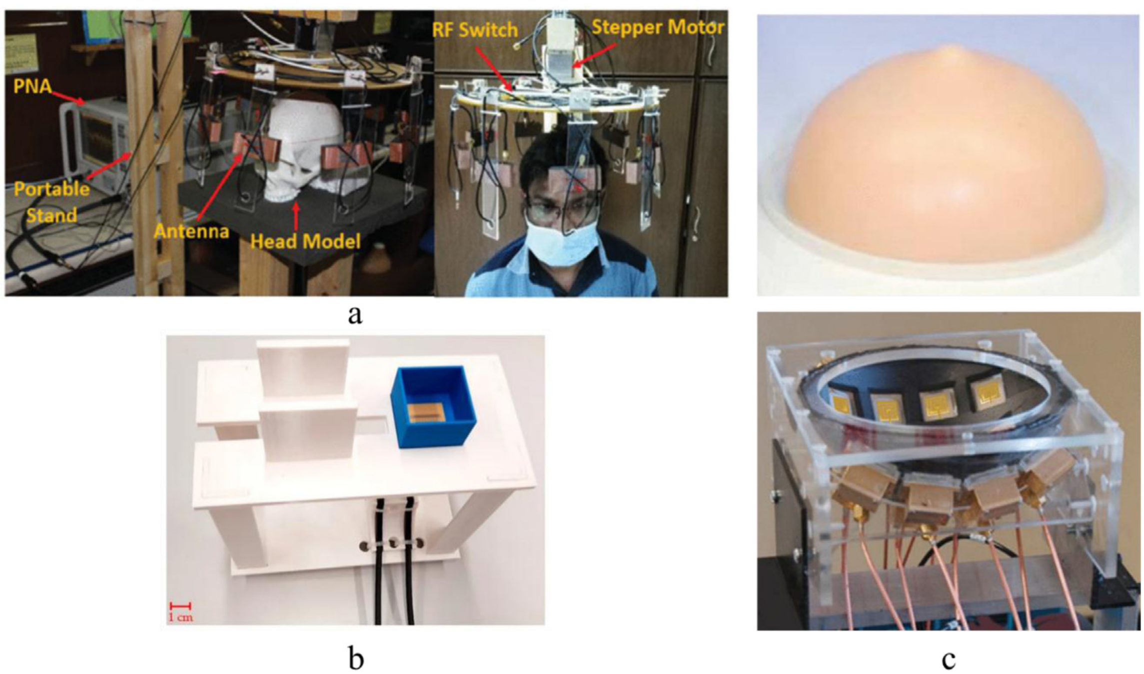


Fig. 7. (a) Experimental setup of a portable head imaging system with an array of metamaterial loaded 3D antennas around a head phantom (left) and around a human head (right) [45]. (b) A custom 3D printed holder for a metamaterial microwave sensor and small phantom samples for non-invasively measuring blood glucose levels [79]. (c) A standard breast phantom (top) for testing a prototype for microwave breast imaging using a metamaterial-inspired antenna array (bottom) [42].

interest. The designed and simulated unit cell patterns are then embedded in various substrates and bonded into stacks using special bonding films or molding techniques.

Metamaterial integration into sensing devices such as body imaging has been researched and experimentally validated by [26]. Metasurface-enhanced antennas for microwave imaging are depicted in Figures 5 and 6. In particular, in Figure 5a metasurface is attached in front of a triangular antenna comprising an inner metallic pattern between two high dielectric substrates Rogers 3010TM substrates [26]. In Figure 6 a few common unit cell patterns are presented, such as the SRRs (Fig. 6a) and Jerusalem cross patterns (Fig. 6b). These are typical patterns used for both metamaterials and metasurfaces design.

6 Discussion on phantom preparation

An important step towards the development of metamaterial-based devices, metasurfaces, and antennas for biomedical applications is the experimental verification and testing of the developed setups. To achieve this, tissue-mimicking phantoms for RF, microwave, and mm-wave frequencies are used. Phantoms are meant to replicate the EMC properties of actual tissue and, thus, present the same response to an EM excitation. For instance, near-field metamaterial antennas are assessed in the presence of a specific biological tissue, or a wearable metamaterial absorber is initially trialed using a human-like phantom.

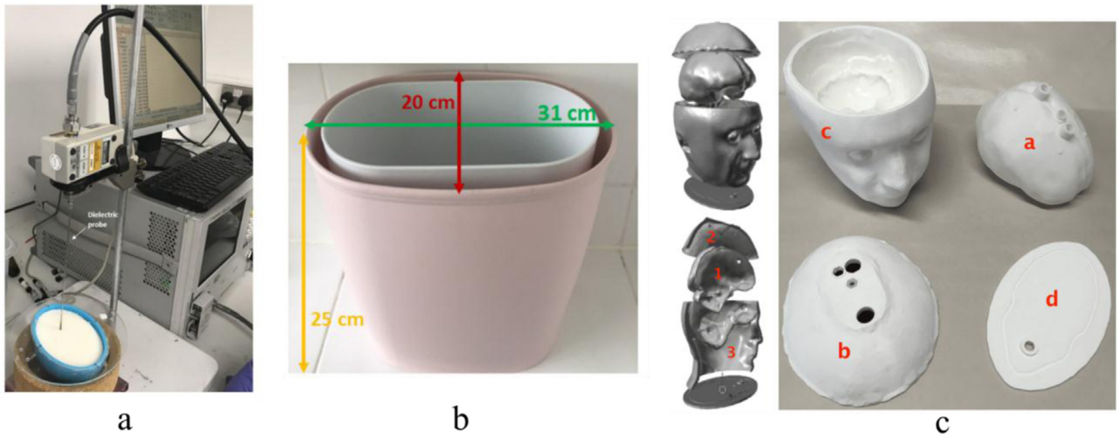


Fig. 8. (a) Properties measurements with an open-ended coaxial probe by Keysight of an ellipsoid brain phantom [77]. (b) Containers to form a simple two-layer chest phantom for microwave lung lesion detection [80]. (c) Multi-layer with significant anatomical detail mold to be filled with liquid tissue phantoms to simulate the human brain [81].

In [45], the authors initially tested an array of metamaterial-loaded directional 3D antennas on a head phantom (Fig. 7a), while in [42] a standard breast phantom was used for microwave imaging with a metamaterial-inspired antenna array (Fig. 7c). Figure 7b shows the experimental setup of a phantom holder to non-invasively access blood glucose levels with a metamaterial microwave sensor [79].

Depending on the desired complexity level, some phantoms are either rudimentary (fewer components/elements/average composites) or realistic ones that include multiple tissues and external-internal structuring. The simple phantoms are based on molds of simple shapes, such as an ellipsoid for modeling the human head [77] or a cylindrical box for modeling the human chest [80] (Figs. 8a, 8b), while the more realistic ones are designed by additive manufacturing from STL files derived from MRI scans [81], [82] (Fig. 8c). The molds to hold the phantom mixtures are usually 3D printed structures made by Acrylonitrile Butadiene Styrene (ABS) and high impact polystyrene (HIPS) that exhibits $\varepsilon_r \approx 2.6$ and $\varepsilon_r \approx 2.4$ respectively at microwave and mm-wave frequencies with low losses [83]. Phantoms are grouped into three main categories based on their composition: a) gel-like phantoms [77,84,85], b) liquid phantoms [81,86] and c) solid phantoms [82]. The gel-like phantoms are synthetically created by mixing appropriate liquid and solid constituents following specific fabrication procedures. The underlying principles for choosing these constituents include:

- Incorporating liquids (such as water, glycerol, or oil) with varying dielectric properties in a mixture to achieve the desired properties.
- Introducing components that ensure uniformity in the mixture, such as surfactants.
- Including gelation agents to solidify the mixture, like gelatin or agar.

These materials are mixed and processed under specific sets of instructions, such as sequence, temperature and mixing speed and they are subsequently poured into molds and left to solidify. The main advantage of these phantoms is that, after solidification, the molds can be removed for not affecting the experimental measurements and the performance of the DUT, although they have short life span as their dielectric properties change over time [87]. Generally, gel-like phantoms offer a wide range of dielectric properties, geometric complexity, and low-cost fabrication, but the respective construction process lacks high control of the desired properties and has low repeatability.

Likewise, liquid phantoms consist of combinations and solutions of the identical liquid constituents found in the preceding group of phantoms, except for substances that induce gelation (such as gelatin or agar). In this scenario, the intention is to prevent the formation of solidified structures. Utilizing these phantoms enables more precise manipulation of their characteristics and facilitates measurements within them. For example, embedding implantable antennas to test their performance or receivers to calculate SAR is considerably more attainable. However, the respective containers or 3D-printed molds are not removable and must also possess significant thickness and waterproof properties, which can dramatically impact the accuracy of the measurement results. This is a considerable challenge, especially for realistic phantoms with multiple tissues that necessitate an equal number of thick wall separators.

Finally, solid phantoms are made by adding high-index solid powders into low-index polymers, such as polyurethane resin, graphite, and carbon black. The dielectric resin formed by this mixture is poured into a mold for curing, and subsequently, the solid phantom is removed from the mold [82]. While this approach yields solid phantoms that are durable and consistent over an extended lifespan, it necessitates specialized materials and can be challenging to produce due to the viscous nature of the resin. Lossy silicon-carbon-based mixtures are also used for various commercially available phantoms, in order to match the CTIA OTA certification standard "Test Plan for Wireless Device Over-the-Air Performance", as the head (SAM-V4.5BS) or chest (CHEST-P10) phantom by SPEAG, Switzerland [88].

7 Discussion and conclusions

The previous sections discussed how biomedical metamaterials are used in the low EM spectrum for enhancement of the antenna characteristics (Sect. 2), clinical imaging improvement (Sect. 3), or protection from EM radiation (Sect. 4). Generally, although metamaterials (and their 2D sibling, metasurfaces) play an auxiliary role in the development of clinical devices, they allow new degrees of freedom in engineering both the near and far field EM effects via material (or artificial material) composites. Indeed, metamaterials enable a promising route for enhancing the antenna performance metrics. Biomedical imaging greatly benefits from these metamaterial approaches in many ways, such as increased isolation between the elements, SNR improvement and field localization. Metamaterial absorbers have great potential for EM protection due to their exceptional and tunable performance and low-profile features. The incorporation of metamaterials in EM diagnostic and therapeutic tools, as well as in wearable and implantable components, could serve as the determining factor in advancing a device from the prototype stage to practical real-life applications. However, design and development challenges remain to be addressed. For instance, extreme miniaturization on antennas may significantly decrease their efficiency or the addition of extra substrates and superstrates on planar antennas will increase the volume of the final setup. Additionally, materials with very high permittivity and low ohmic and dielectric losses are highly desired for RF biomedical applications but very difficult to develop and use. Similarly, an ideal bio-protection absorber should simultaneously provide polarization-insensitive absorptivity for various angles of incidence, mechanical flexibility, and good heat isolation from the attached object.

Electrically compact and highly efficient Huygens antennas could be recommended as strong candidates for a range of EM biomedical applications. Their versatility is evident in various designs already conceived, exhibiting characteristics such as CP and being proposed for applications in RF and microwave domains [89,90]. Active metasurfaces, which integrate components like varactors, and Huygens' metasurfaces—a novel concept employed to reshape EM radiation into a desired form while maintaining an extremely thin profile—may also serve as promising candidates for biomedical applications. [91,92]. Additionally, the inverse design approaches are emerging as the way forward both in metamaterial design and implementation, where physically unintuitive designs can deliver enhanced functionalities. In other words, inverse-designed metamaterials can be a promising avenue for future research endeavors. Lastly, both metamaterial and phantom composition domains could benefit since additive and subtractive processes are commonly used to implement both composites. Hence, knowledge of metamaterial composition can facilitate the phantom composition and vice versa.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The data is available upon request (Dimitrios C. Tzarouchis, e.mail: dtzarouc@gmail.com).

Author contribution statement

DCT conceived, initiated and organized idea of the article. DCT and MT co-authored all sections. IS and DR curated section 5 and 6 and KD the section 4. All authors edited the article. The text was grammatically refined using Grammarly.

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