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Reconfigurable Metamaterial-Loaded Vivaldi Antennas for Biomedical Microwave Imaging: A Review

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ABSTRACT: Vivaldi antennas loaded with metamaterials are currently being utilized in the form of reconfigurable metamaterial-loaded Vivaldi antennas, representing a promising class of antennas in advanced biomedical imaging and sensing applications. The design is an enhancement of the naturally ultra-wideband and high-directivity Vivaldi structure with the miniaturization and field enhancement properties of metamaterial inclusions. Frequency, polarization, and radiation pattern are some of the key features of biomedical diagnostics that can be dynamically reconfigured using tuneable elements like P-I-N diode, varactors, and graphene-based switches. This paper will give a summary of recent findings related to the design, analysis, and uses of reconfigurable metamaterial-loaded Vivaldi antennas in the field of biomedical imaging, especially in the determination of tumours and tissue characterization in noninvasive systems. The discussion notes the development of metamaterial integration methods, reconfigurable mechanisms, choice of substrate materials, and their influence on the measure of antenna performance like gain, bandwidth, and Specific Absorption Rate (SAR). Moreover, fabrication strategies, experimental validation of the use of tissue phantoms, and performance comparison with the traditional antennas are tackled. The future research outlooks have been given at the end of the paper, highlighting compact and low-SAR and optically-controlled antenna architectures of the next-generation biomedical imaging systems.

1. INTRODUCTION

Microwave-based biomedical imaging systems are one of the newest and brightest replacements to such traditional diagnostic instruments as MRI and CT scans. These systems depend on high-performance antennas with the ability to produce wideband electromagnetic fields to identify dielectric differences between the healthy tissues and malignant tissue. Vivaldi antenna with Ultra-Wideband (UWB), constant gain, and directive radiation has become one of the most appropriate antennas to be used in biomedical imaging and sensing devices [1].

Antennas loaded with metamaterials have attracted great interest over recent years since they can be used to increase the gain of an antenna, suppress surface waves, and reduce the amount of backward radiation that an antenna emits to the human tissues. Such artificial structures as Split-Ring Resonators (SRRs), Complementary SRRs (CSRRs), and H-shaped resonators can have negative permittivity and permeability, which allows for focusing the field and minimizing it [2, 3]. Also, the reconfigurable nature of components, including PIN diodes, varactors, or graphene layers, makes the antenna dynamically tunable in both frequency and radiation pattern so that it can adjust to different biomedical imaging conditions in real time [4, 5].

The reconfigurable Vivaldi antenna loaded with metamaterials (RMVA) has been used successfully in the microwave frequency (1–10 GHz), which can be used to detect the location of breast tumours, monitor brain strokes, and characterise tissue in noninvasive ways. The dielectric properties of tissues, like the return loss, bandwidth, gain, and Specific Absorption Rate (SAR), have a great effect on the performance of the antenna when it is used in proximity to biological tissues [6]. Thus, the design should be such that it would have high radiation, impedance matching, and SAR compliant with international standards, including IEEE C95.1, ICNIRP [7], etc.

The most common uses of reconfigurable Vivaldi antennas in biomedical imaging are also demonstrated in Fig. 1, where an array of antennas is a UWB imaging array around the biological phantom to generate high-resolution dielectric maps. A summary of potential biomedical [8] applications of such antennas is provided in Table 1, highlighting their use in tumour localization, dielectric contrast imaging, and microwave tomography [9, 10].

To achieve optimal imaging accuracy, these antennas are designed to be compact, lightweight, conformal, and biocompatible. Additionally, high-frequency substrates, such as Rogers RT5880, Taconic TLY-5, or FR-4 (for low-cost prototypes), are typically used due to their low dielectric loss and mechanical stability [11]. The metamaterial loading assists in reducing the overall antenna size while maintaining a wide impedance bandwidth, and the reconfigurable elements allow adaptability under different imaging environments and tissue dielectric variations [12].

Nevertheless, a number of challenges remain. The lossy dielectric media may lead to frequency detuning, loss of gain [13], and increment in SAR in the proximity of biological tissues. Furthermore, fabrication accuracy and matching in array systems have a great impact on the imaging performance [14]. In

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TABLE 1. Summary of biomedical imaging applications of reconfigurable metamaterial-loaded Vivaldi antennas.

Application Area	Operating Band (GHz)	Reconfigurability Type	Outcome
Breast tumour detection	2–8	Optical/Graphene-based	Improved imaging depth and localization
Brain imaging	3–10	Varactor-tuned	Enhanced dielectric contrast detection
Tissue characterization	1–6	PIN diode switching	Adaptive imaging capability
Portable medical scanners	2.4/5.8	Hybrid (optical + electrical)	Multi-modal imaging flexibility

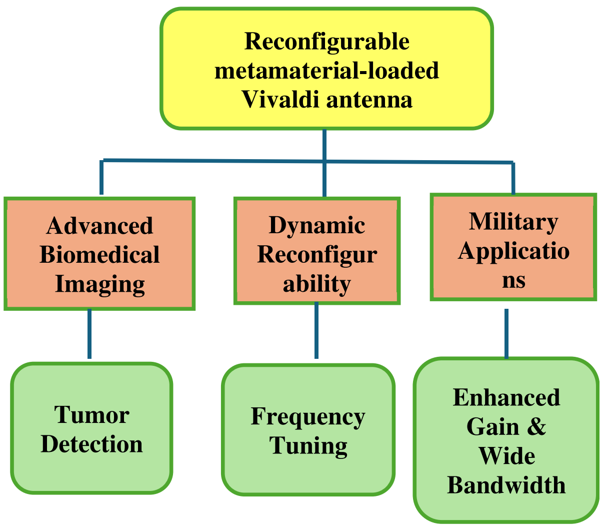

FIGURE 1. Photograph of a representative reconfigurable metamaterial-loaded Vivaldi antenna prototype reported in the literature, illustrating an experimental measurement setup using a vector network analyzer (VNA). The antenna is fabricated on a Rogers RO4003C substrate ($\varepsilon_r = 3.55$, thickness $= 1.6$ mm) with typical overall dimensions on the order of several tens of millimeters. The referenced study reports an ultra-wideband impedance response satisfying $|S_{11}| < -10$ dB over a wide frequency range within the microwave imaging band. Detailed S-parameter responses and radiation characteristics are provided in the original publication.

this way, contemporary designs aim at the realization of the tapered slot geometry, loading of the aperture, and switching network configuration in order to attain compactness as well as efficiency.

Over the past ten years, several types of studies have shown the possibility of the metamaterial- and graphene-loaded Vivaldi antennas in biomedical imaging [15, 16]. These designs with great gain (up to 9–12 dBi), bandwidth ($>$ 6 GHz), and SAR reduction ($>$ 50%), confirm their applicability to microwave imaging systems.

This review paper aims to present and discuss the recent developments in the design, fabrication, and application of reconfigurable metamaterial-loaded Vivaldi antenna to biomedical imaging, as illustrated in Fig. 1 [13]. Also, the paper highlights the importance of the metamaterial integration, frequency/pattern reconfigurability, and safety assessment (SAR) in the form of simulation and experimental validation [17].

The remainder of this work is structured in the following way. Section 2 talks about the development of Vivaldi antenna design and how it can be adapted to biomedical systems [18]. Section 3 is dedicated to the metamaterial integration methods of bandwidth and gain enhancement.

In Section 4, the reconfigurability methods, such as optical and graphene-based tuning methods, are introduced. Section 5 puts emphasis on biomedical imaging applications and SAR assessment in multilayer tissue phantoms. In Section 6, fabrication techniques and measurement arrangements during the development of antennas prototypes are discussed. Lastly, the article ends with the outlook of the future trends and research issues of reconfigurable metamaterial-based biomedical antennas in Section 7 [19, 20].

1.1. Novelty and Contribution of This Review

Unlike existing review articles that primarily address either conventional Vivaldi antennas or metamaterial-enhanced antennas in a general context, this review specifically focuses on reconfigurable metamaterial-loaded Vivaldi antennas (RMVAs) for biomedical microwave imaging applications. The manuscript presents a unified and structured synthesis of metamaterial integration strategies, reconfigurable mechanisms — including varactor diodes, PIN diodes, and graphene-based approaches — and their combined influence on key imaging-related antenna performance metrics, such as bandwidth, resolution, penetration depth, and SAR.

Furthermore, this review emphasizes comparative performance analysis under biomedical imaging conditions by systematically compiling and interpreting reported simulated and experimental results from the literature. Rather than merely summarizing prior work, the manuscript critically discusses reported performance trends, practical limitations, and biomedical relevance, with particular attention to imaging adaptability and SAR compliance. By explicitly linking antenna reconfigurability with adaptive imaging capability and safety considerations, this work offers a focused perspective that is not comprehensively addressed in existing reviews.

2. DESIRABLE CHARACTERISTICS AND CRITICAL DESIGN CHALLENGES

In recent times, reconfigurable Vivaldi antennas loaded with metamaterials have been receiving more and more attention because of the many capabilities that they have in biomedical imaging, radar sensing, and adaptive wireless systems. These antennas are developed to be highly functional within complex biological applications and are available with high gain, wide frequency response, and tunability to provide real-time medical diagnostics.

New electromagnetic features generated by incorporating metamaterial inclusions and reconfigurable components include beam focusing, gain boosting, SAR, and signal-to-noise ratio, which are of great interest in noninvasive tissue imaging and tumour localization [21].

The features and design attributes that are desirable in all the biomedical imaging antennas are: compactness, biocompatibility [14], low SAR, high radiation efficiency, and real-time adaptability. The subsections that follow are an overview of the main design issues that have been faced when developing RMVA [22].

2.1. Substrate and Metamaterial Selection

The electromagnetic performance of the Vivaldi antenna is greatly determined by the substrate and the composition of the metamaterial used. In biomedical imaging, the antenna will be used in close proximity to the human tissue, necessitating low-loss dielectric materials, including Rogers RT5880 [23].

In the meantime, SRRs, CSRRs, or H-shaped resonators are used in metamaterial unit cells in order to enhance the effective refractive index and dissipate backward radiation [16]. These materials are selected and arranged carefully so as to attain a high imaging resolution and compliance to electromagnetic safety [24].

2.2. Human Tissue Interaction

The interaction of the antenna with the biological tissues is one of the most important design issues. Human tissues have frequency-dependent complex permittivity and conductivity, changing the distribution of the electromagnetic field of antennas. The antenna undergoes resonant frequency shift, with impedance mismatching, and loss of gain, when it is put in proximity or contact with the body [25].

This detuning effect is more pronounced in the microwave range due to the high dielectric constant of skin and fat layers. Therefore, accurate bioelectromagnetic modelling using Computer Simulation Technology (CST) or High Frequency Structure Simulator (HFSS) with realistic tissue phantoms is essential for reliable antenna performance prediction and SAR evaluation [26].

2.3. Specific Absorption Rate (SAR) Considerations

SAR measures the rate at which electromagnetic energy is absorbed per unit mass of human tissue and is expressed in W/kg. High SAR levels can cause thermal stress and safety concerns. According to IEEE C95.1 and ICNIRP guidelines, the SAR limit for localized exposure is 1.6 W/kg averaged over 1 g of tissue and 2.0 W/kg averaged over 10 g of tissue [27]. In RMVAs, metamaterial loading and High-Impedance Surfaces (HISs) are employed to minimize backward radiation and confine electromagnetic energy in the forward direction. Proper impedance matching and field shaping help achieve SAR values well below regulatory limits, making these antennas safe for prolonged biomedical imaging [28].

2.4. Geometrical Variation and Fabrication Tolerance

The Vivaldi antenna geometry, along with exponential taper, aperture slot, and metamaterial structure, is important in the determination of the performance. Nonetheless, fabrication errors, bending of substrates, and errors in alignment may result in performance differences in terms of frequency variations and loss of gain [21].

In biomedical applications [25], mechanical flexibility and structural stability are important, where conformal deposition is performed on curved surfaces or on tissue phantoms, and conforming the deposition is important. Therefore, the substrate thickness and dielectric uniformity should be controlled with the greatest accuracy as they determine the radiation behaviour during the physical deformation process.

2.5. Environmental Effects and Biomedical Conditions

The dielectric constant of the substrate and inclusions made of a metamaterial can be greatly influenced by environmental parameters, like temperature, humidity, and body moisture. Human tissues are wet and lossy, which means changes in ambient humidity, or perspiration may result in impedance mismatch and resonance drift [14]. One solution to this weakness is to cover the antenna with biocompatible encapsulation layers or waterproof coatings (e.g., silicone or pdms layers) to ensure consistent performance during imaging [28, 29].

2.6. Reconfigurability Complexity and Control Mechanism

Biasing and additional control complexity is also provided by the inclusion of configurable elements like photodiodes, varactors, or graphene-based layers [30]. Furthermore, the integration of graphene or photoconductive layers requires precise fabrication [31] and thermal control to ensure predictable tunability. The challenge lies in achieving multi-band or beam-steerable operation without compromising the antenna's bandwidth or radiation efficiency [32].

2.7. Summary of Design Requirements

Among other challenges mentioned above, there are a number of common requirements when designing RMVAs to use biomedical imaging:

1. The antenna must be wearable or phantom-based medical imaging, small, lightweight, and conformal.
2. It should not change its impedance and gain during bending or mechanical stress.
3. The antenna design must be such that it would have a low backward radiation of the antenna and SAR that complies with the IEEE/ICNIRP standards.
4. The system should embrace real-time frequency or pattern reconfigurability, without the increment of fabrication complexities.
5. The materials employed must be biocompatible, low-loss, and thermally stable during operation.

TABLE 2. Summary of the most commonly used substrate materials for RMVAs and their corresponding dielectric.

Substrate Material	Relative Permittivity (ε_r)	Loss Tangent (tanδ)	Thickness (mm)	Frequency Range (GHz)	Remarks/Application Relevance
Rogers RT5880	2.2	0.0009	0.787–1.575	2–12	Low-loss substrate; suitable for UWB
Taconic TLY-5	2.17	0.0009	1.27	3–10	Stable dielectric; ideal for multilayer RMVA designs
Rogers RO4350B	3.48	0.0037	0.762–1.524	2–8	Balanced cost and performance for compact imaging setups
Duroid 6010	10.2	0.0023	1.27	1–5	High-ε_r for antenna miniaturization and metamaterial loading

3. MATERIAL SELECTION FOR RECONFIGURABLE METAMATERIAL-LOADED VIVALDI ANTENNAS

The antenna materials used in the conventional microstrip or horn antenna designs might not be appropriate in biomedical imaging antennas, particularly when they are used in an area close to human tissues. Such antennas require biocompatible, low-loss, thermally stable substances capable of providing safe and efficient electromagnetic operation in bio-environments.

To mitigate these issues, high-frequency substrates, metamaterial inclusions, and new conductive coatings, including graphene, will be employed to increase gain, bandwidth, and SAR compliance [25, 32].

The materials on which the substrates are fabricated are based on dielectric constant, loss tangent, thermal stability, and biocompatibility, whereas the conductive layers are based on electrical conductivity, smooth surface, and possibility of reconfigurability [23].

The first important step involves finding the best substrate material that can support metamaterial unit cells and reconfigurable layers; then, it is essential to select an appropriate conductive coating or sheet (copper, silver, or graphene) on the radiating part. With proper selection of materials, the gain, bandwidth, and SAR are high, and at the same time, the patient safety and comfort are maintained during imaging experiments [33, 34].

3.1. Non-Conductive Materials

The non-conductive (substrate) materials incorporated in RMVAs are crucial in the electromagnetic response of the antennas and the interactions of the antennas with the human tissue. These substrates should have low thermal expansion, low dielectric loss, and low thermal expansion with human tissue.

Such substrates have to be of low dielectric loss, low thermal expansion, and constant permittivity with a broad frequency response to ensure maximum accuracy and reproducibility of imaging [7]. Besides electromagnetic performance, biocompatibility and mechanical flexibility are also necessary, especially when the antenna is incorporated in wearable and contact-based biomedical systems.

Rogers RT5880, Taconic TLY-5, and Rogers RO4350B are these materials [25], which are highly used because of their low loss tangent and constant dielectric characteristics. Conformal biomedical imaging configurations are also finding increased popularity with flexible polymerisations, such as Polydimethylsiloxane (PDMS) and biocompatible composite, as discussed in Table 2 [28].

The characterization of the dielectric properties of these substrates in the operating frequency range (1–10 GHz) before designing the antenna is required. This is to provide that the HFSS or CST electromagnetic simulation is an accurate representation of a real-world behaviour.

3.2. Conductive Materials

The radiating elements, feed lines, and ground planes of all antennas must be made of conductive materials. In the case of RMVAs, the efficiency, the distribution of current over the surface, and thermal stability during operation depend on the conductive material.

Traditional conductors' copper is often used, although graphene and silver nanoparticle coatings and transparency in optically activated films are used more often in biomedical applications to allow reconfigurability [35].

The conductivity (σ) of these materials, measured in Siemens per meter (S/m), directly affects radiation efficiency and power dissipation. The following equation expresses the relation among conductivity (σ), surface resistivity (ρ), and film thickness (τ):

$$\sigma = \frac{1}{(\rho \times \tau)}$$

Graphene films have the benefit of electrically and optically tunable surface conductivity and are therefore applicable to

TABLE 3. Summary of the commonly employed conductive materials in RMVA designs and their relevant characteristics.

Conductive Material	Electrical Conductivity (S/m)	Type	Key Characteristics	Application in RMVA
Copper (Cu)	5.8×10^7	Metal	High conductivity, easy fabrication	Radiating layer, feedline
Silver Nanoparticle Film	4.1×10^7	Metal Ink	Printable, flexible	Conformal and flexible antennas
Graphene Sheet	Variable (10^3–10^5)	2D Material	Transparent, low loss	Frequency-tuneable imaging
ITO Film	1×10^5	Semiconductor	Transparent, low loss	Biomedical sensor arrays
Photoconductive Layer (Si-based)	1×10^2–10^4	Semiconductor	Light-activated, high-speed switching	Optical reconfigurability control

adaptive biomedical imaging systems in RMVAs. From Table 3, there are other common materials, such as silver-plated copper, ITO (Indium Tin Oxide) used as a transparent biomedical sensor material, and photodiode-integrated metallic layers as optical switching material [30].

4. METAMATERIAL STRUCTURES AND INTEGRATION TECHNIQUES

Metamaterials are man-made engineered materials, which have never been observed in nature to possess electromagnetic characteristics, including negative permittivity and negative permeability.

These special properties have been extensively applied to improve the performance of the antennas in gain, bandwidth, miniaturization, and radiation efficiency [5].

In reconfigurable metamaterial-loaded Vivaldi antenna lines (RMVAs), metamaterial designs have been placed tactically in the aperture, slot, or substrate layers to enhance the confinement of the fields and to reduce backward radiation to biological tissues.

Electromagnetic Band Gap (EBG), Artificial Magnetic Conductors (AMCs), Split Ring Resonators (SRRs), Complementary Split Ring Resonators (CSRRs), and SRRs can be very useful in improving the electromagnetic field distribution to obtain high imaging resolution and low Specific Absorption Rates (SAR) [7]. Fig. 2 illustrates the typical integration locations of metamaterial units within a Vivaldi antenna.

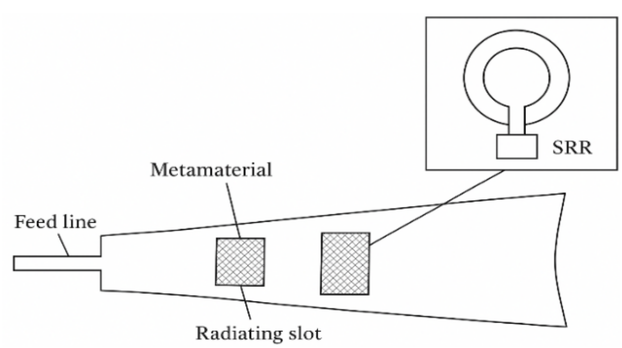

FIGURE 2. Integration of metamaterials into a Vivaldi antenna.

4.1. Split Ring Resonator (SRR) and Complementary SRR (CSRR) Loading

The two most frequent metamaterial inclusions used to realise miniaturization and gain enhancement are SRR and CSRR. SRRs, when positioned on top of the tapered slot or aperture of the Vivaldi antenna, form local resonance fields that increase or decrease current confinement and decrease propagation of surface waves. It results in a highly focused beam and enhanced directivity, which is crucial in biomedical imaging [22]. The step-by-step evolution of the proposed multiple-input multiple-output (MIMO) antenna configuration, including the integration of the frequency selective surface (FSS) structure, is presented in Fig. 4.

4.2. Electromagnetic Band Gap (EBG) and High Impedance Surface (HIS)

The EBG and HIS designs serve as surface-wave suppressors and thus enhance radiation efficiency and reduce the back lobes towards the human body. The periodic layout of the EBG unit cells below the ground plane of the Vivaldi antennas forms a stopband, which stops undesired coupling among the various components in imaging arrays [36]. The geometry and dispersion characteristics of the EBG decoupling structure are depicted in Fig. 7, confirming its stopband behavior in the operating frequency range.

This design guarantees low mutual coupling, which is important in multi-antenna biomedical imaging systems, e.g., in microwave tomography. Moreover, HIS structures serve as in-phase reflectors, which increase the forward radiation and gain of the antennas without being complex [37].

4.3. H-Shaped and SRR-CSRR Hybrid Metamaterials

H-shaped resonant systems in a hybrid design with SRR-CSRR composites provide a broadband response and retain the strengths of H-shaped and SRR-CSRR design types. These units offer negative permittivity with negative permeability simultaneously, and it further increases the electromagnetic energy concentration of the aperture region. This configuration, therefore, offers better gain and bandwidth of the antennas without dramatic size requirements, including in biomedical

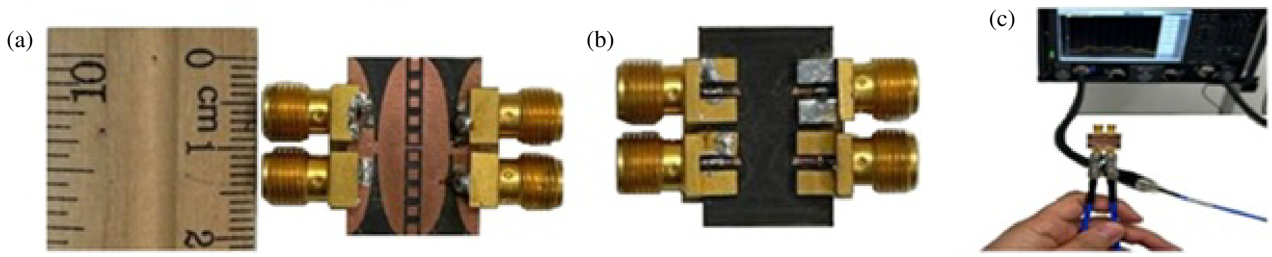

FIGURE 3. Fabricated prototype of a reconfigurable metamaterial-loaded Vivaldi antenna used as a representative example in the reviewed literature: (a) top view, (b) bottom view, and (c) vector network analyzer (VNA) measurement setup. The antenna is fabricated on a Rogers RT5880 substrate ($\varepsilon_r = 2.2$, thickness $= 1.575$ mm) with overall dimensions of approximately 60 mm $\times$ 50 mm. The measured reflection coefficient confirms ultra-wideband operation with $|S_{11}| < -10$ dB over the frequency range reported in the corresponding reference [13].

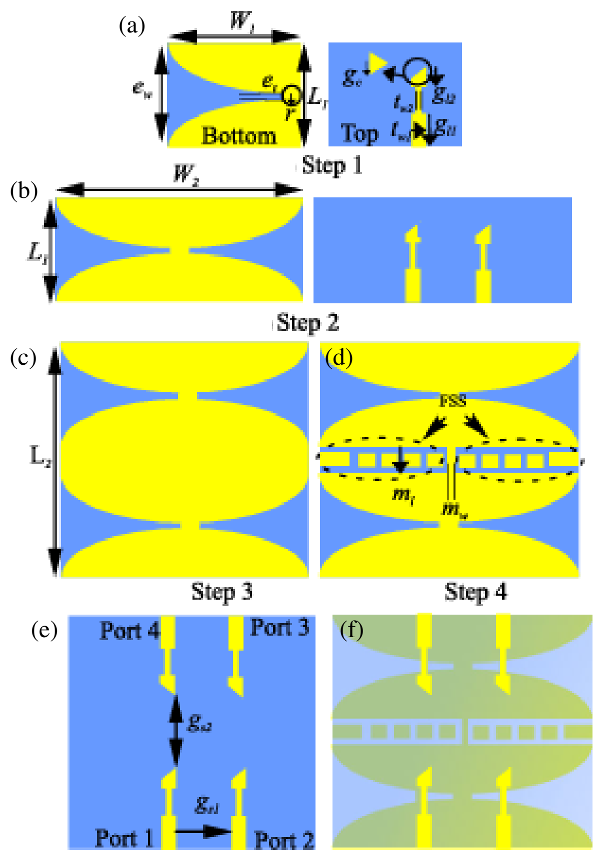

FIGURE 4. Proposed MIMO antenna design steps, (a) single element, (b) two elements, (c) four elements without FSS, (d) proposed final four elements with FSS, (e) inter-element spacing, and (f) perspective view of the design [4].

imaging in a deep-tissue scan in 2–8 GHz frequency bands [38].

4.4. Graphene-Based Metasurfaces for Reconfigurability

Dynamically reconfigurability of the antenna structure is introduced with the introduction of graphene layers or graphene-based metasurfaces. Graphene tuneable surface conductivity enables the adjustment of the resonance frequency and beam direction in real time through the use of optical or electrical bias [6]. These metamaterial Vivaldi antennas with graphene

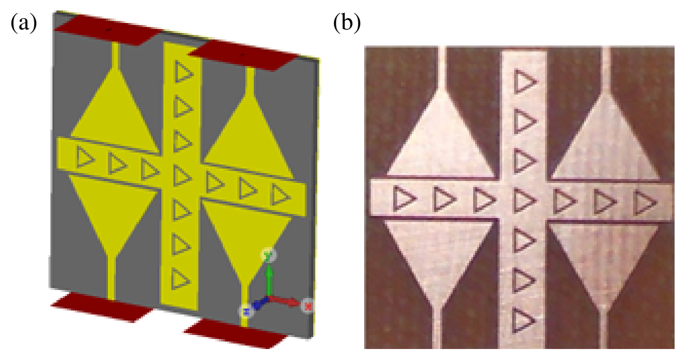

FIGURE 5. Simulation layout of the 2 $\times$ 2 antenna arrays loaded with an EBG decoupling structure, (b) photograph of the fabricated array (top side) [39].

have the potential to be frequency agile at 3–10 GHz and beam steerable to $\pm 30°$ as they can be used in adaptive biomedical imaging systems as well as in variable target depths.

4.5. Metamaterial-Integrated Reconfigurable Design Considerations

In the implementation of metamaterials into reconfigurable antennas, a number of design requirements have to be considered: Unit cell dimension and periodicity have to be optimized, so that the metamaterial resonance should not exceed the operating frequency. The compatibility between the substrate and metamaterial inclusions is very important to escape mechanical stress or dielectric mismatch.

5. BIOMEDICAL IMAGING APPLICATIONS AND SAR ANALYSIS

Reconfigurable metamaterial-loaded Vivaldi antennas (RMVAs) have become an extremely promising solution to non-invasive biomedical diagnostics through microwave imaging. This technology has unique benefits that are high spatial resolution, deep tissue penetration, and low ionizing energy, which are appropriate in identifying tumours, physiological changes, and defining the dielectric properties of tissues [32]. The imaging mechanism, system setup, and safety assessment through Specific Absorption Rate (SAR) are addressed in detail in this section.

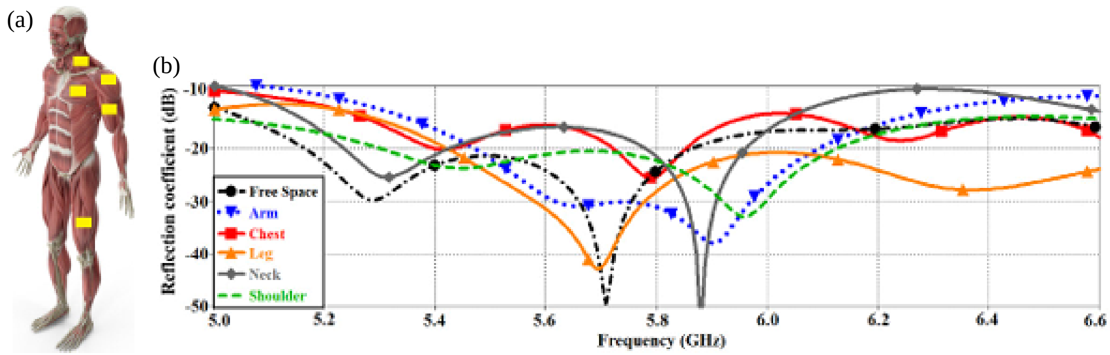

FIGURE 6. Evaluation of the antenna arrays' performance when they are mounted on the human body, (a) array placed at different locations on the human model, (b) on-body loading effect on the array's reflection-coefficient [40].

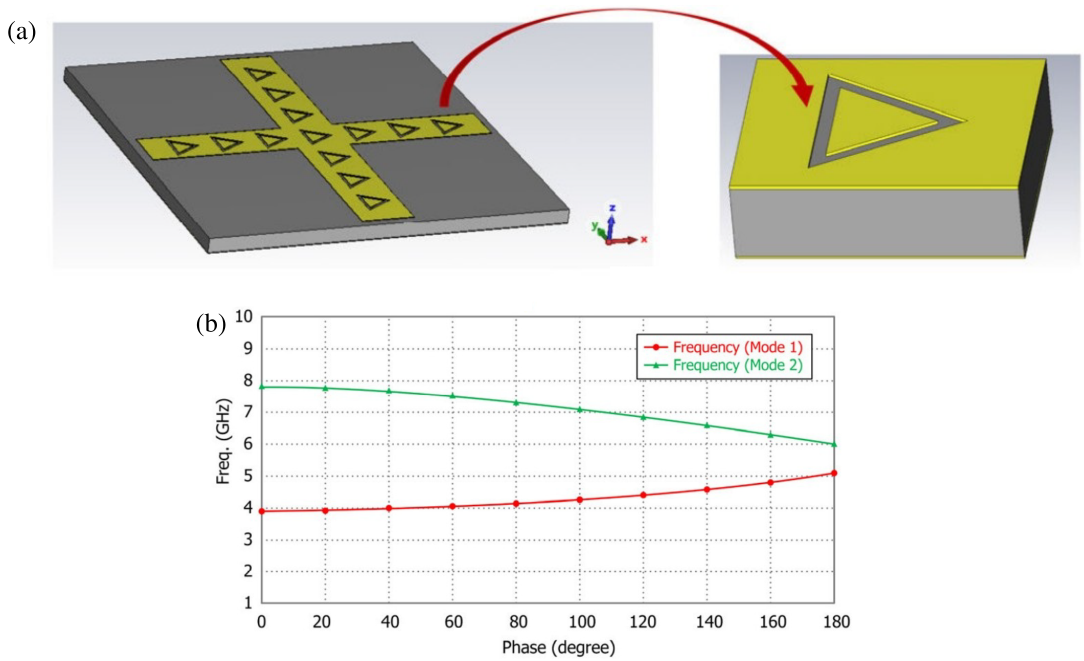

FIGURE 7. (a) The proposed EBG decoupling structure, and (b) dispersion diagram of the EBG structure obtained by CST microwave studio [41].

5.1. Microwave Biomedical Imaging Principle

The concept of microwave imaging is based on the fact that various biological tissues have dissimilar dielectric constants and conductivities at microwave frequency. A higher water content and permittivity are common to malignant tissues, including tumors, which leads to greater scattering of incident electromagnetic waves [3]. The experimental microwave imaging setup employing a tissue-equivalent phantom and a Vivaldi antenna array is shown in Fig. 9.

The prototype shown in Fig. 3 is included to illustrate typical fabrication and measurement practices reported for RMVAs, rather than to present new experimental results in this work.

As per Table 4, the metamaterial-integrated Vivaldi antenna provides improved radiation directivity and reduced coupling between antenna elements. Moreover, the application of the EBG-backed substrates or graphene reduces the back radiation, thus making the levels of the SAR lower during imaging. The simulated and fabricated EBG-loaded antenna arrays used for mutual-coupling reduction are shown in Fig. 5.

The scattered fields from healthy and cancerous tissues are captured, processed, and reconstructed into an image using algorithms such as Delay-and-Sum (DAS) or Time Reversal (TR) techniques.

5.2. Experimental Setup and Phantom Model

The experimental configuration generally consists of a pair or array of Vivaldi antennas arranged around a biocompatible tissue phantom. Each antenna transmits and receives signals in a multistate manner, and the collected signals are processed for image reconstruction. The phantom mimics human tissue properties using materials such as agar, glycerine, and deionized water to replicate the dielectric constants of skin, fat, and muscle layers [43]. The on-body performance degradation and loading effects of antenna arrays under different human body placements are illustrated in Fig. 6, highlighting variations in the reflection coefficient due to tissue proximity.

TABLE 4. Summary of metamaterial configurations and their effects on reconfigurable Vivaldi antennas.

Metamaterial Structure	Integration Location	Electromagnetic Property	Effect on Antenna Performance	Biomedical Benefit
SRR (Split Ring Resonator)	Near slot/ aperture	Negative μ	Improves gain, reduces size	High imaging resolution
CSRR (Complementary SRR)	Ground plane/ substrate	Negative ε	Enhances bandwidthimpedance matching	Better tissue contrast
EBG/HIS	Ground plane array	Surface-wave suppression	Reduces backward radiation, increases efficiency	Low SAR, safer operation
H-shaped resonator	Aperture edge	Dual-band resonance	Expands frequency range	Multi-modal imaging
SRR-CSRR Hybrid	Slot and substrate	Double-negative (DNG)	Boosts gain and bandwidth	Deeper tissue penetration
Graphene met surface	Radiating slot/ aperture	Tunable conductivity	Enables frequency and pattern reconfigurability	Adaptive imaging depth

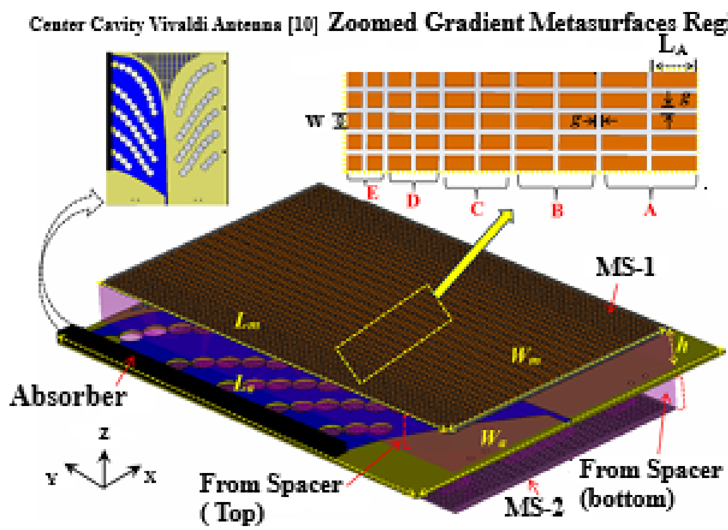

FIGURE 8. 3-D schematic diagram of the multilayer Vivaldi antenna [42]. (For better visibility of the metasurfaces layers, foam spacers are made transparent in pink colour).

5.3. Reconfigurability Effects on Biomedical Imaging Performance

The reconfigurability characteristics discussed in this section are derived from representative simulation and experimental studies reported in the literature on reconfigurable metamaterial-loaded Vivaldi antennas. This review does not present new tuning or beam-steering measurements; rather, it summarizes commonly reported trends related to frequency agility, radiation-pattern reconfiguration, and adaptive near-field behavior enabled by varactor diodes, PIN diodes, and graphene-based tuning mechanisms under biomedical imaging conditions. A three-dimensional multilayer configuration of the metamaterial-integrated Vivaldi antenna is illustrated in Fig. 8.

Reported RMVA implementations demonstrate frequency reconfiguration through the electrical biasing of varactors or PIN diodes, as well as optical or electrostatic tuning of graphene-based metasurfaces. Depending on the antenna geometry and metamaterial configuration, resonance shifts ranging from several hundred megahertz to multiple gigahertz within the 3–10 GHz band have been reported. Such frequency agility enables adaptive imaging for tissues with varying dielectric properties.

5.4. Methods and Data Sources for Performance Comparison

This review does not present new experimental or simulation results; instead, it provides a structured comparison of representative reconfigurable metamaterial-loaded Vivaldi antenna (RMVA) designs reported in the recent literature. The performance metrics discussed in this section are extracted from peer-reviewed simulation and experimental studies conducted under biomedical microwave imaging scenarios. The objective is to synthesize reported findings in a consistent manner and highlight general performance trends associated with metamaterial

TABLE 5. Comparative performance metrics of conventional Vivaldi antennas and reconfigurable metamaterial-loaded Vivaldi antennas (RMVAs) reported in representative biomedical imaging studies.

Parameter	Conventional Vivaldi	Metamaterial-Loaded RMVA
Operational Bandwidth (GHz)	3.1–10.6	2.8–11.2
Peak Gain (dBi)	6.4	8.9
SAR (W/kg, 1 g average)	1.52	0.84
Image Resolution (mm)	7.5	3.2
Field Focusing (Near-field)	Moderate	Strong
Tissue Penetration Depth (cm)	4.1	6.8

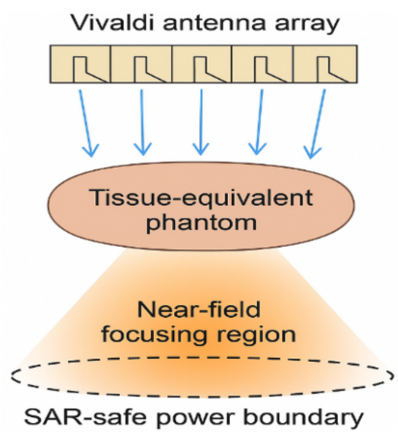

FIGURE 9. Illustration of the typical experimental setup for biomedical imaging using a metamaterial-based Vivaldi antenna array, where a tissue-equivalent phantom is positioned in front of the antenna array.

integration and reconfigurable mechanisms, rather than to evaluate a single antenna configuration.

In the surveyed studies, antenna performance was predominantly analysed using full-wave electromagnetic solvers such as CST Microwave Studio and ANSYS HFSS, which are widely used for ultra-wideband antenna modeling in lossy biological environments. These tools were employed to assess impedance matching, radiation characteristics, near-field behavior, and Specific Absorption Rate (SAR) under free-space and tissue-loaded conditions. Biomedical relevance was ensured through the use of tissue-equivalent phantoms, including homogeneous and multilayer models representing skin, fat, and muscle tissues with frequency-dependent dielectric properties across the 1–10 GHz range. Imaging performance was commonly evaluated using reconstruction techniques such as Delay-and-Sum (DAS) and Time Reversal (TR), with reported imaging resolution, penetration depth, and tumour detectability derived from reconstructed images or point-spread analyses provided in the original studies. The comparative metrics summarized in Table 5 — including bandwidth, gain, SAR, imaging resolution, and penetration depth — are therefore compiled from studies that explicitly reported these quantities under controlled simulation or experimental conditions, enabling a meaningful comparison of relative performance trends across different RMVA designs.

5.5. Specific Absorption Rate (SAR) Evaluation

When the antennas are kept in proximity to the biological tissue, a fraction of the emitted electromagnetic energy is reabsorbed by the body. This absorbance is measured in the SAR, defined as:

$$\mathrm{SAR} = \frac{\sigma(|\mathrm{E}|^2)}{\rho}$$

where σ is the electrical conductivity (S/m), E the electric field intensity (V/m), and ρ the tissue density (kg/m^3).

According to IEEE C95.1 and ICNIRP standards, the permissible SAR limits are: 1.6 W/kg averaged over 1 g of tissue (IEEE); 2.0 W/kg averaged over 10 g of tissue (ICNIRP).

In the RMVA model introduced, ground material structure and metamaterial layers serve the role of a shield, and they backscatter the radiation used in opposite directions to the tissue to keep the SAR well below these regulatory levels.

Using the methodology and data sources described in the preceding subsection, Table 5 summarizes representative performance metrics of conventional and metamaterial-loaded Vivaldi antennas reported in biomedical imaging literature.

The values listed in this table are compiled from previously published simulation and experimental studies reported in the referenced literature. SAR values correspond to 1 g averaged tissue models evaluated under IEEE C95.1 guidelines using numerical solvers (CST/HFSS). Imaging resolution is derived from reconstructed images or reported point-spread analyses. Tissue penetration depth is defined as the maximum depth at which a detectable dielectric contrast ($\geqslant -6$ dB relative to background) is reported in phantom-based imaging studies. Minor variations may occur due to differences in antenna geometry, phantom composition, antenna-to-phantom spacing, and imaging configuration.

5.6. Discussion and Safety Considerations

Based on Table 5, it can be observed that the proposed RMVA has a significant decrease in SAR, which guarantees patient safety and also yields better imaging clarity. The high near-field focusing potential facilitates the resolution and accuracy of the deep-seated tumours.

Moreover, the reconfigurability of graphene is tuned and dynamically controlled so that the radiation properties of the antennas are optimized to achieve the imaging of tissues of various depths. The above features render the RMVA an eligible solution to real-time biomedical diagnostic systems, e.g., breast cancer detection, brain imaging, and cardiac monitoring.

5.7. Challenges and Open Issues in RMVA-Based Biomedical Imaging

Despite the significant progress reported for reconfigurable metamaterial-loaded Vivaldi antennas, several technical and practical challenges remain before widespread clinical adoption can be achieved. Fabrication tolerances of metamaterial unit cells and reconfigurable elements can lead to performance deviations, particularly at higher frequencies, where small dimensional variations cause noticeable resonance shifts.

The long-term reliability and repeatability of graphene-based and optically controlled reconfiguration mechanisms also remain open issues, especially under continuous biasing and in humid or lossy biomedical environments. In addition, accurate bias-network integration without disturbing antenna radiation characteristics continues to be a nontrivial design challenge.

From an application perspective, most reported imaging validations are limited to simplified or homogeneous tissue phantoms. Translating RMVA-based imaging systems to realistic, heterogeneous human tissue models and clinical environments introduces additional challenges related to calibration, motion artifacts, and system-level complexity. Addressing these limitations will be essential for transitioning RMVAs from laboratory prototypes to clinically viable diagnostic tools.

6. APPLICATIONS AND FUTURE SCOPE

The combination of metamaterials and reconfigurable mechanisms with Vivaldi antenna architectures has greatly extended its use beyond conventional radar and communication systems. RMVAs are ideal devices in the biomedical imaging, industry sensing, and high-resolution short-range communication systems because of their ultra-wideband functionality, high directivity, and field-focusing feature. This part is a summary of some of the most important applications of the present and the possible future directions of research.

6.1. Biomedical Imaging Applications

Noninvasive biomedical imaging, particularly breast cancer detection, brain activity monitoring, and tissue dielectric characterization, represents some of the most common applications of RMVAs [44, 45]. The various metamaterials and Vivaldi designs boost the near-field concentrations, enabling low-contrast dielectric anomalies to be observed in biological tissues.

Split-Ring Resonators (SRR) and Electromagnetic Bandgap (EBG) are mathematically manufactured metamaterial unit cells that serve the purpose of concentrating the field, enhancing the imaging contrast and spatial resolution. Also, tunable layers of graphene and photodiode switches allow operating frequency and radiation direction to be changed dynamically to different imaging depths of objects or tissue types [46].

Recently, in phantom models, metamaterial-loaded Vivaldi arrays have been shown to have imaging resolutions as small as 2 mm and have been found to enable early-stage tumour detection. Their low SAR and conformal design are the factors that make them highly applicable in continuous diagnostic monitoring [47].

6.2. Industrial and Sensing Applications

In other fields outside the biomedical sector, RMVAs have demonstrated super promises in nondestructive testing (NDT), ground-penetrating radar (GPR), and object localization. Reconfigurable antennas also have the beam steering and high penetration depth that make the detection of the subsurface defects, cracks, and material inhomogeneities easy.

As an example, GPR systems have adopted metamaterial-backed Vivaldi antennas to detect underground utilities in underground structures at a depth of 50 cm without much interference [2]. In a similar manner, reconfigurable Vivaldi arrays have been used in monitoring the health of concrete and composite materials with a structural health monitoring using their ultra-wideband capabilities to image internal defects.

6.3. Communication and IoT Integration

RMVAs are also considered in short-range ultra-wideband (UWB) communication and Internet of Things (IoT) networks. They are reconfigurable, in high gain, and small, thus suitable for body-centric communication and wireless power transfer (WPT) applications [22].

These antennas have a built-in dynamic change of frequency and direction to steer a beam to ensure stable connectivity of IoT medical devices, including wearable biosensors, smart implants, and remote health care monitors, by incorporating graphene or varactor diodes. The frequency agile nature of RMVAs provides an improved communication reliability in dense RF conditions, which is in line with the future 6G and body-area network policies [48–50].

7. CONCLUSION

Recent advancements in the creation of reconfigurable metamaterial-loaded Vivaldi antennas (RMVAs) have created new possibilities to attain high-performance, compact and safe antenna systems to be used in biomedical imaging and sensing. This review has presented a focused and critical synthesis of reconfigurable metamaterial-loaded Vivaldi antennas, highlighting how reconfigurability and metamaterial integration jointly influence biomedical imaging performance and SAR compliance. The review has given the overall discussion of the available literature, including the material selection, design issues, strategies of metamaterial integration, fabrication process, and measurement technique. This is verified by the synthesis of recent papers that show the inclusion of metamaterial unit cells, i.e., SRR, CSRR, EBG, and AMC structures, increases the gain, bandwidth, as well as field-focusing capacity of the traditional Vivaldi antennas without incurring a high Specific Absorption Rate (SAR) that could not satisfy the biomedical safety requirements.

Moreover, RMVAs enable the dynamic control of operating frequency and radiation patterns through the use of graphene layers, photodiodes, and varactor diodes, allowing adaptive imaging across multiple frequencies and tissue depths, making them especially useful to noninvasive diagnostic systems, including breast tumor localization and brain scanning, as well as tissue dielectric profiling.

In the reviewed literature, we also find that flexible and biocompatible substrates, like PDMS, Rogers RT5880, and polyimide, have made wearable and implantable antenna designs without being affected by the electromagnetic performance. The new technologies in fabrication, such as inkjet printing, laser nexus manufacturing, and 3D additive manufacturing, have further boosted the process of transitioning to viable medical and industrial applications.

The combination of machine-learning-assisted control, AI-assisted images reconstruction, and optically reconfigurable in the future can have fully autonomous and intelligent imaging systems. On the whole, the RMVAs are an innovative leap towards the future of electromagnetically adaptive antenna systems that define a transition between the traditional microwave engineering and the upcoming smart biomedical systems.

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