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AMC-Based Miniaturized Waveguide With Reconfigurable Pass-Bands Below Cut-Off Frequency and Quasi-TEM Mode

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ABSTRACT This work introduces an innovative miniaturized transverse electromagnetic (TEM) waveguide design, which is 60% smaller than conventional metal waveguides. The proposed waveguide offers two distinct electronically reconfigurable passbands well below the cutoff frequency. This has been achieved by using sidewalls composed of reconfigurable artificial magnetic conductors (AMC), optimized to operate at 3.51 GHz and 4.37 GHz. By replacing the metal sidewalls with an AMC structure, a TEM mode can be sustained within the confined space enclosed by the waveguide structure, which otherwise would not exist in a conventional metal waveguide. This eliminates typical cut-off frequency constraints that limit the size of conventional waveguides, thereby enabling a significant miniaturization of the waveguide design. The work also proposes a reconfigurable AMC design whose operating frequency can be dynamically adjusted by applying or removing a direct current (DC) bias across the integrated PIN diodes. Additionally, this work utilizes 3D printing technology to fabricate a functional waveguide, highlighting the design's compactness, cost-effectiveness, versatility, and fast prototyping capabilities for a wide range of microwave applications. This study therefore demonstrates the potential of using reconfigurable AMCs for compact and versatile waveguide designs that can be 3D-printed for various practical use cases and modern microwave applications.

INDEX TERMS Artificial magnetic conductor (AMC), transverse electromagnetic (TEM) mode, waveguide miniaturization, metaguide.

I. INTRODUCTION

ARTIFICIAL magnetic conductors (AMCs) have emerged as a significant area of research in surface electromagnetics and microwave engineering due to their ability to exhibit properties of theoretically ideal, but non-existent, perfect magnetic conductors (PMCs). PMCs are not known to occur naturally as free-moving magnetic charges have not yet been discovered in nature [1]. Consequently, the non-existence of natural PMCs has spurred a widespread interest in the development of engineered surfaces such as AMCs that can mimic the properties of PMC materials and be used in various applications [2]. Over the years,

electromagnetic engineers have explored various methods and materials to realize AMCs, with some notable advancements in the existing literature [2], [3], [4]. Unlike perfect electric conductors (PECs), which fully reflect incident waves with a reflection phase shift of 180°, AMCs reflect incident waves with a phase shift of 0°, and suppress surface wave propagation for both transverse electric (TE) and transverse magnetic (TM) modes. However, due to the resonant nature of most AMC realizations, the zero phase reflection property is only observed at a specific point in the frequency spectrum [5], [6]. In practical applications, the effective bandwidth of an AMC is usually considered

within the $+90^\circ$ to -90° range on either side of the central frequency [5]. This allows the AMCs to function as a PMC equivalent within this band, benefiting several areas and applications such as low-profile antennas, specific absorption rate (SAR) reduction in wearable antennas, symmetric E-plane and H-plane beams in horn antennas, reduced mutual coupling between array elements, miniaturized waveguides with quasi-TEM wave propagation [7], [8], [9], [10], [11], [12], [13], [14].

Over the years, a variety of AMC structures have been investigated, each with their unique attributes and drawbacks. The uniplanar photonic bandgap (UC-PBG) type AMCs comprise of an array of metallic patches separated by a small gap and placed over a grounded dielectric substrate. While UC-PBG-based AMCs are easy to fabricate and analyze, they suffer from limited bandwidth, higher design complexity, and their performance is highly sensitive to the angle of incident waves restricting their applications [15]. Another popular AMC realization is the mushroom-type AMC introduced by Sievenpiper et al. in [5], which consists of an array of metallic patches connected to the ground plane through vias. This design improves the bandwidth and angular stability compared to the UC-PBG realizations, however, their fabrication process is complex and expensive due to the necessity of many vias. Moreover, both of these approaches have a continuous PEC-based ground plane, making the design bulky and also causing image and scattering-induced currents at the back of the structure, increasing the risk of surface waves [16]. An alternative approach that can get rid of this PEC-based ground plane has been proposed by Erentok et al. in [6] and is known as the volumetric realization of an AMC using a capacitively loaded loop (CLL) structure. Although this approach gets rid of the image currents, it is extremely sensitive to fabrication anomalies, offers a narrow band of operation, and is highly sensitive to the alignment of the structure with the E-field vector of the impinging electromagnetic waves. Therefore, it can be said that each AMC structure comes with its unique challenges, necessitating trade-offs between ease of fabrication, operational bandwidth, angular stability, and efficiency. Overcoming these challenges requires a careful balancing act between the design complexity, fabrication feasibility, and performance requirements [17], [18].

As advances continue in the field of AMCs, new design principles and fabrication techniques are constantly being evaluated to enhance their potential use and applications. The integration of theoretical knowledge and real-world application in the development of these engineered surfaces keeps opening up new avenues for the potential use of AMC-based devices in the future. One such application in which AMC surfaces find use is the realization of a quasi-Transverse Electromagnetic (quasi-TEM) waveguide [19]. A conventional waveguide, which is made of a single, hollow conductor, does not have any transverse voltage gradient and hence cannot support TEM mode. However, if the sidewalls of the waveguide are instead made using

an AMC structure, which can act as an insulator, the required voltage gradient can be created to support the TEM mode. Since the TEM mode is cutoff-less, with its propagation constant being real and linear at all frequencies, the waveguide's lateral size is no longer constrained by the operating frequency. In this type of structure, the phase velocity tends to approach the speed of light in free space with a near-uniform E-field distribution within the waveguide structure at specific frequency points. Consequently, such a waveguide can either be used for aperture enhancement or waveguide miniaturization depending on the application requirements. The work proposed in [3] by Yang et al. uses a UC-PBG-based structure to design the AMC sidewalls for such a waveguide. Although this design offers TEM mode, the operating frequency is not reconfigurable, thereby limiting the use to a narrow frequency band. Moreover, the EBG structures are more suitable for far-field operation and when used in near-field operation can cause diffraction and act as parasitic elements. Hence, waveguide miniaturization cannot be achieved effectively using this approach. The work proposed in [4] by Marqués et al. has used a sub-wavelength split ring resonator (SRR) structure placed inside the hollow waveguide to achieve a passband below the waveguide cut-off frequency. Though this design offers waveguide miniaturization, the construction is complicated requiring the placement of a structure in the middle of the waveguide which might not be suitable for various applications requiring a simple and robust design. This approach also achieves single-band operation and does not offer the versatility of frequency reconfiguration. Another work, proposed in [12] by Shahvarpour and Caloz uses a grounded ferrite slab placed in a perpendicular bias field to provide a PMC boundary at the sidewalls. Although this approach offers a homogeneous AMC structure with tunable operating frequency (by varying the bias field) and miniaturization, it is extremely bulky and complicated to fabricate due to the requirement of a bias field, and thus might not be suitable for various applications requiring compactness.

A. RESEARCH PROBLEM AND OBJECTIVES

Modern waveguide technology faces the challenge of achieving significant miniaturization while maintaining high performance and reconfigurability, especially at sub-6GHz frequencies. Traditional waveguides are physically constrained by their cut-off frequencies, limiting their use in compact systems. Although previous approaches have attempted to address these limitations, a solution integrating miniaturization, reconfigurability, and cost-effective fabrication has been elusive.

This work proposes a compact, AMC-based waveguide with dual reconfigurable pass-bands below the cut-off frequency, utilizing modern fabrication techniques. This innovative design combines metamaterial-inspired reconfigurable AMC technology with modern 3D printing, facilitating the creation of compact, versatile, and high-performance waveguides.

Algorithm 1 Research Method for AMC-Based Miniaturized Waveguide

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1: TheoreticalModeling:
2: function THEORETICALMODELING
3:   Develop a theoretical model of AMC-based miniaturized waveguide
4:   Model waveguide as an array of parallel resonant LC circuits
5:   for each circuit in waveguide do
6:     Calculate surface impedance ( $Z_s$ ) using the ratio of tangential electric ( $E_t$ )
       and magnetic ( $H_t$ ) fields
7:   end for
8:   Ensure  $Z_s$  achieves in-phase reflection similar to PMC
9: end function
10: DesignOptimization:
11: function DESIGNOPTIMIZATION
12:   Optimize geometric parameters of AMC unit cells
13:   for each unit cell in AMC do
14:     Set dimensions and placement of copper patches and vias
15:     Optimize for dual-band operation at 3.51 GHz and 4.37 GHz
16:   end for
17:   Use PCB manufacturing techniques to fabricate AMC unit cells
18: end function
19: Fabrication:
20: function FABRICATION
21:   Fabricate waveguide housing and structural components
22:   Fabricate waveguide housing using 3D printing technology
23:   for each unit cell in AMC do
24:     Integrate unit cell into the waveguide structure
25:   end for
26:   Make sidewalls using optimized AMC designs
27: end function
28: ExperimentalValidation:
29: function EXPERIMENTALVALIDATION
30:   Test prototype using a vector network analyzer (VNA)
31:   Measure transmission characteristics with VNA
32:   Analyze transmission coefficient ( $S_{21}$ )
33:   Analyze E-field and H-field distributions
34:   Confirm quasi-TEM mode propagation
35:   Confirm effectiveness of AMC sidewalls
36: end function
37: AnalysisandComparison:
38: function ANALYSISANDCOMPARISON
39:   Compare experimental results with theoretical predictions and previous studies
40:   Compare experimental results with theoretical predictions
41:   Compare experimental results with previous studies
42:   Analyze bandwidth, reconfigurability, and power handling capabilities
43:   Ensure design meets identified requirements
44: end function
45: function RESEARCHMETHOD
46:   THEORETICALMODELING
47:   DESIGNOPTIMIZATION
48:   FABRICATION
49:   EXPERIMENTALVALIDATION
50:   ANALYSISANDCOMPARISON
51: end function
52: RESEARCHMETHOD

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The work exploits the benefits of Transverse Electromagnetic (TEM) waveguides, achieving a size reduction of 60% compared to traditional all-metal waveguides. With AMC sidewalls functioning at 3.51 GHz and 4.37 GHz and integrated PIN diodes, the waveguide can dynamically adjust its operational frequency while supporting TEM mode propagation within a lightweight structure. This makes it ideal for microwave applications where space is limited.

Furthermore, the methodology used in this work encompasses theoretical modelling, design optimization, and experimental validation along with comparisons with existing designs detailing each step in Algorithm 1. This research thus bridges theoretical and practical aspects, advancing the potential of AMC-based waveguides.

II. METAMATERIALS INSPIRED ARTIFICIAL MAGNETIC CONDUCTORS: A THEORETICAL INSIGHT

Metamaterials are artificially engineered materials that can exhibit properties not found in naturally occurring materials. Metasurfaces, essentially the two-dimensional (2D) version of metamaterials, can precisely manipulate electromagnetic waves in unique ways [17]. Although their applications are vast, their potential as artificial magnetic conductors (AMCs) is particularly notable [20], [21].

The design of a metamaterial-inspired AMC involves creating an array of parallel resonant LC circuits. These circuits exhibit high impedance at a specific resonance frequency ($\omega_0 = 1/\sqrt{LC}$), blocking the flow of surface currents and allowing manipulation of the artificial surface for desired frequencies. Modern printed circuit board (PCB) manufacturing enables the creation of these 2D geometric configurations, which act as parallel resonant LC circuits offering high impedance to surface currents, thereby mimicking the behaviour of a perfect magnetic conductor (PMC) [16].

Central to the interaction between electromagnetic waves and the surface of a material is the concept of surface impedance Z_s . This impedance is defined by the ratio of tangential electric and magnetic fields:

$$Z_s = \frac{E_t}{H_t} \quad (1)$$

where E_t and H_t represent the tangential electric and magnetic fields, respectively. The operational principle of an AMC revolves around achieving an in-phase reflection, similar to a PMC, which requires the surface impedance to meet specific criteria:

$$\text{Re}(Z_s) \approx 0 \quad \text{and} \quad \text{Im}(Z_s) > 0 \quad (2)$$

The surface impedance Z_s can be related to the intrinsic impedance of the metamaterial ζ and the angle of incidence θ_i :

$$Z_s = \zeta \cdot \cos(\theta_i) \quad (3)$$

The intrinsic impedance ζ is defined as:

$$\zeta = \sqrt{\frac{\mu}{\epsilon}} \quad (4)$$

where μ is the permeability and ϵ is the permittivity of the metamaterial. Designing an effective AMC requires precise control of ϵ and μ , often through structures like split-ring resonators or electric LC resonators, ensuring that the surface impedance conditions are met [6], [21]. This understanding allows the engineering of metamaterials to exhibit AMC properties, extending their applications in modern electromagnetic systems.

III. DESIGN AND FABRICATION OF THE MINIATURIZED WAVEGUIDE

A. EVOLUTION IN AMC DESIGN: RECONFIGURABLE UNIT CELL

The ever-growing demand for agile and versatile microwave components has shined a spotlight on the importance of adaptability in modern electromagnetic designs. AMCs have thus emerged as an influential paradigm in this evolution, offering the ability to craft unique electromagnetic responses in a compact form factor [16]. However, while AMCs have proven to be invaluable in various applications, their static and highly resonant nature has often restricted their potential use in dynamic environments. By adding the principle of reconfigurability into the AMC design, one can possibly, overcome some of the traditional limitations and open up various new possibilities. Among several methods available to achieve this, the incorporation of semiconductor components stands out due to their simplicity, low cost, and ease of fabrication. By controlling the state of these semiconductor components, the electromagnetic properties of the AMC unit cell can be dynamically adjusted, thus tailoring the AMC response based on the needs of the application. This work delves deep into this novel idea, exploring the nuances of a reconfigurable AMC design using PIN diodes, and exploring the realm of such adaptable AMC designs.

In the design of periodic surfaces, a unit cell serves as the fundamental building block of the entire structure. This unit cell is arranged within a 2D lattice in such a manner that the collective effect of these unit cells can engineer certain electromagnetic characteristics at a macroscopic level. This research proposes a novel unit cell design capable of exhibiting AMC properties in two distinct frequency bands. The reconfiguration of the unit cell to operate in these two frequency bands is achieved by either applying or removing a direct current (DC) bias across the four PIN diodes, as shown in Fig. 1.

The design of the AMC-based miniaturized waveguide begins with the concept of replacing traditional metal sidewalls with artificial magnetic conductor (AMC) sidewalls to support a quasi-TEM mode. The unit cell has been designed using a multilayered printed circuit board (PCB) layout comprising two layers of Rogers RO4360G2® substrates sandwiched between three layers of copper metal, as shown in Fig. 1(c). Both RO4360G2® layers measure 1.52 mm in thickness and possess a dielectric constant (ϵ_r) of 6.15 with a loss tangent ($\tan \delta$) of 0.0038, while the three copper layers have a thickness of 0.0175 mm. The top copper layer connects to the bottom copper layer through four vias (VIA_1) present near the edge of the unit cell, while the middle copper layer connects to the bottom copper layer using a centrally located via (VIA_2). The comprehensive construction of the reconfigurable unit cell is illustrated in Fig. 1, with its final design parameters being $P_{EY} = 1.66$ mm, $P_{EX} = 0.25$ mm, $D_{Ui} = 18.2$ mm, $X_{UO} = 23$ mm, and $X_{Ui} = 18.2$ mm. Geometric parameters are optimized to achieve dual-band operation at 3.51 GHz and 4.37 GHz.

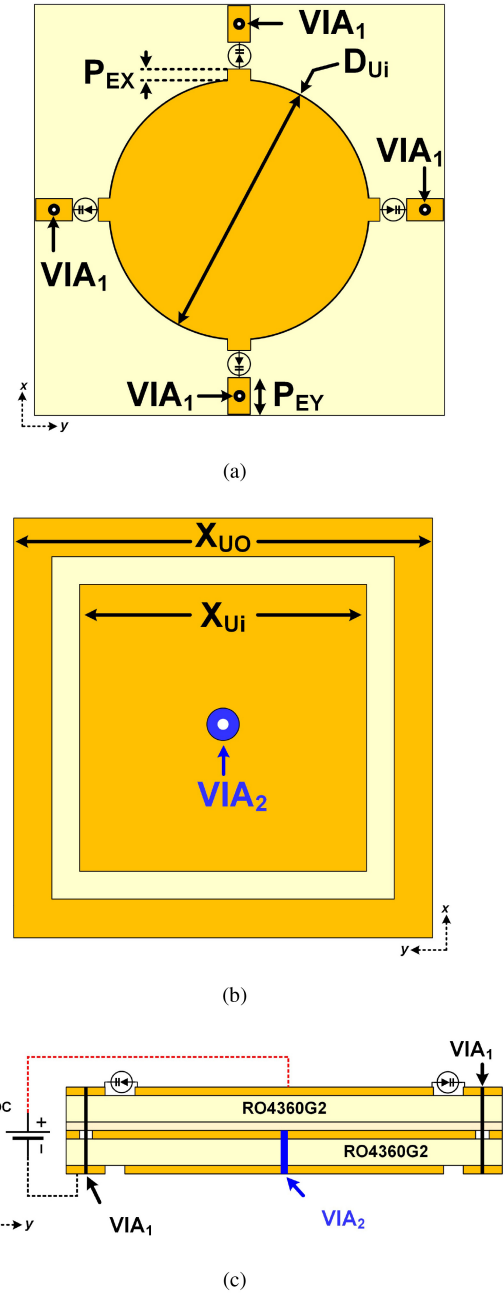


FIGURE 1. Design of the reconfigurable AMC unit cell proposed in this work. (a) Front view. (b) Back view and (c) Side view with DC biasing.

Reconfigurability is introduced through PIN diodes, allowing electronic switching of operating frequencies via DC biasing. The unique reflection phase characteristics of the proposed unit cell have been depicted in Fig. 2 and summarized in Table 1. To obtain these reflection phase characteristics, a full-wave finite element method (FEM) has been used within the CST Design Studio Suite®. The unit cell has dual-band functionality, operating as an AMC in two distinct frequency bands centred around 3.51 GHz and 4.37 GHz as presented in Fig. 2. The frequency band over which it can be considered as an AMC falls within the reflection

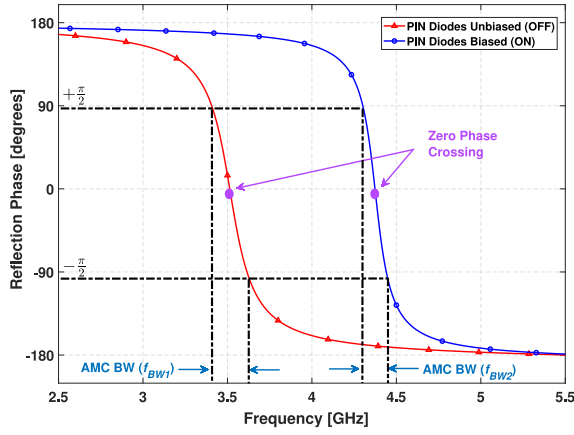


FIGURE 2. Spectra of the reflection phase characteristics of the proposed unit cell for varying reverse bias voltage levels.

TABLE 1. Summary of operation of the reconfigurable AMC unit cell.

Operating Frequency band (GHz)	Zero Phase Crossing (GHz)	AMC bandwidth (MHz)	Unit cell status	
			PIN diodes OFF	PIN diodes ON
f_{BW1} (3.40-3.61)	3.51	210	AMC	PEC
f_{BW2} (4.30-4.44)	4.37	140	PEC	AMC

phase $\pm \frac{\pi}{2}$ as it is within this band that the magnitude of the surface impedance exceeds the free space impedance and the image currents are in-phase [5]. Therefore, the unit cell can be considered to behave as an AMC over a bandwidth of 210 MHz (f_{BW1}) and 140 MHz (f_{BW2}), in the two respective bands of operation. This showcases a significant contribution of this work towards reconfigurable AMC designs and the potential of its diverse applications. Evident from the presented results, the unit cell's responsiveness to the biasing state of the PIN diodes offers a dynamic control mechanism to switch between the two bands of operation. When the PIN diodes are unbiased, the unit cell offers AMC properties within f_{BW1} and when the PIN diodes are biased, the unit cell behaves as an AMC within f_{BW2} . This tunable AMC functionality, achieved through simple diode biasing, highlights an innovative approach to reconfigurable AMCs, lending flexibility as well as adaptability to the proposed design. Such advances not only push the boundaries of AMC designs but also pave the way for more intricate and application-specific electromagnetic solutions using AMCs, making it an important accomplishment of this study.

B. CHALLENGES IN PARAMETER-BASED RECONFIGURABILITY

The quest for achieving reconfigurability in metamaterial-inspired designs often hinges on the ability to manipulate their geometric parameters. Such a pivotal parameter in the context of the proposed AMC design is the radius D_{ui} of the circular patch, as shown in Fig. 1(a). Varying D_{ui} directly impacts the resonance frequency of the structure, thereby

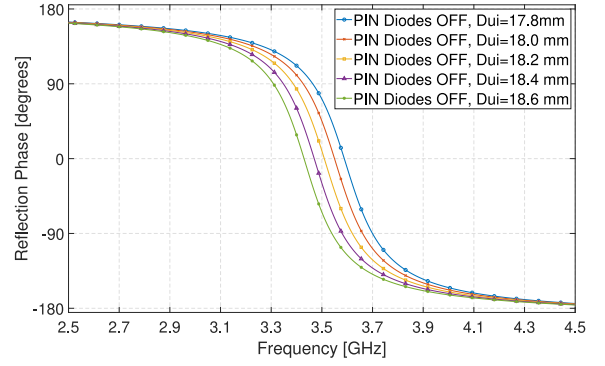


FIGURE 3. Analysis of the reflection phase characteristics spectra of the proposed unit cell as a function of varying D_{ui} .

allowing the structure to be further tuned at the design stage to suit various applications that might require a further change of the operating frequency. As shown in Fig. 3, alterations in D_{ui} can result in further changes in the resonance frequency of the AMC, making it operational anywhere between 3.3 GHz and 3.7 GHz. This heightened sensitivity also highlights the precision required in designing and fabricating such metamaterial-inspired designs, especially when aiming for a specific operational frequency. While the ability to change resonance frequency through mere parameter adjustments like D_{ui} offers flexibility, it also brings forth challenges in maintaining consistent performance across varied configurations. The aforementioned sensitivity necessitates rigorous simulations and precise control during both the design and fabrication processes to ensure a desired outcome.

A further layer of versatility is introduced by integrating active elements such as PIN diodes in the AMC structure. While they offer dynamic reconfigurability, they also interact with the inherent characteristics of the AMC design. Therefore, balancing these static (geometric) and dynamic (active element-induced) elements for reconfigurability remains a challenging endeavour but, if done correctly, holds the promise of highly adaptable and tunable AMCs.

C. RECONFIGURABLE MINIATURIZED WAVEGUIDE

Rectangular waveguides are one of the most basic guiding structures in electromagnetics and have been used in various microwave, antenna and satellite applications for decades. Though a substantial amount of work has been done on the miniaturisation of planar guiding structures, there are several applications where the use of waveguides is preferred over planar guiding structures, e.g., feed-network for large antenna arrays, multi-frequency interlaced antenna arrays etc. On several occasions, for such kinds of applications, there could be many open-ended radiators, each having a different band of operation, cramped into a common space. This gives rise to a practical requirement for having a compact and miniaturised waveguide [14].

A standard waveguide is made up entirely of PEC walls with its transversal dimension $\geq \frac{\lambda}{2}$ so that the field

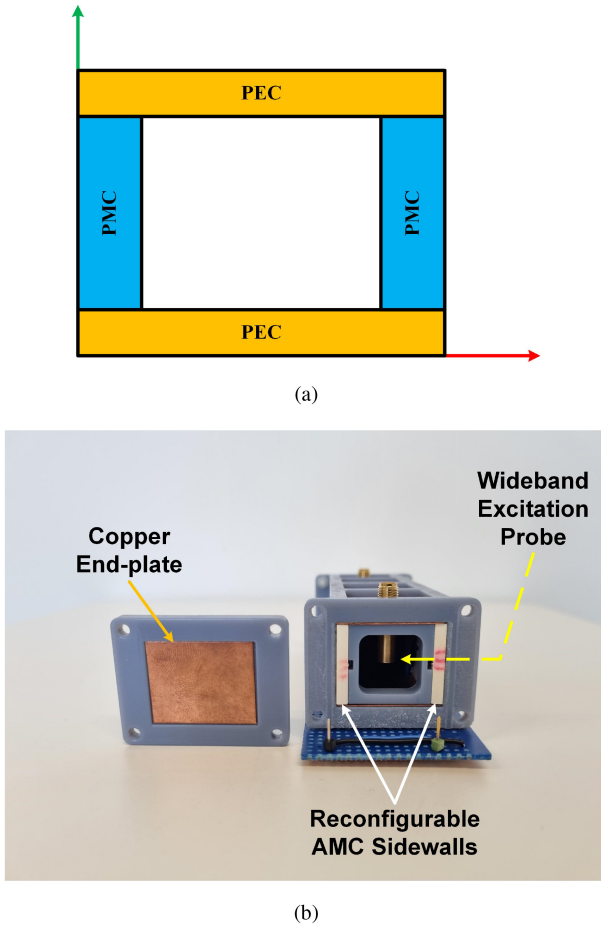


FIGURE 4. Fully enclosed waveguide design. (a) Theoretical representation of the enclosed PEC-PMC waveguide. (b) The fabricated fully-enclosed waveguide with wideband excitation probe and Copper end-plate.

distribution can satisfy the boundary conditions needed for the propagation of the electromagnetic waves [19]. Such waveguides cannot support TEM mode as the transverse voltage gradient of a single-conductor transmission system is zero. However, if the sidewalls are made up of AMC material, then TEM propagation might be possible as AMC walls can act as insulators between the horizontal PEC walls thereby providing the required voltage gradient to support TEM mode. As the TEM mode does not have a cut-off frequency, this could potentially result in a waveguide whose lateral size is no longer constrained to be $\geq \frac{\lambda}{2}$ and thus could be miniaturized [12], [13]. The design and construction of such a miniaturized waveguide prototype using commercially available components, PCB manufacturing, and 3D printing techniques are explained in this section.

As depicted in Fig. 4, the proposed miniaturized waveguide has been designed by inserting sidewalls on either side of the waveguide made up of the reconfigurable AMC unit cell discussed in Section III-A. Several AMC unit cells have been placed along the length of the waveguide structure thereby acting as a PMC boundary as represented in Fig. 4(a). The two AMC sidewalls have an air gap of $A = 23.5$ mm between them and have been enclosed from

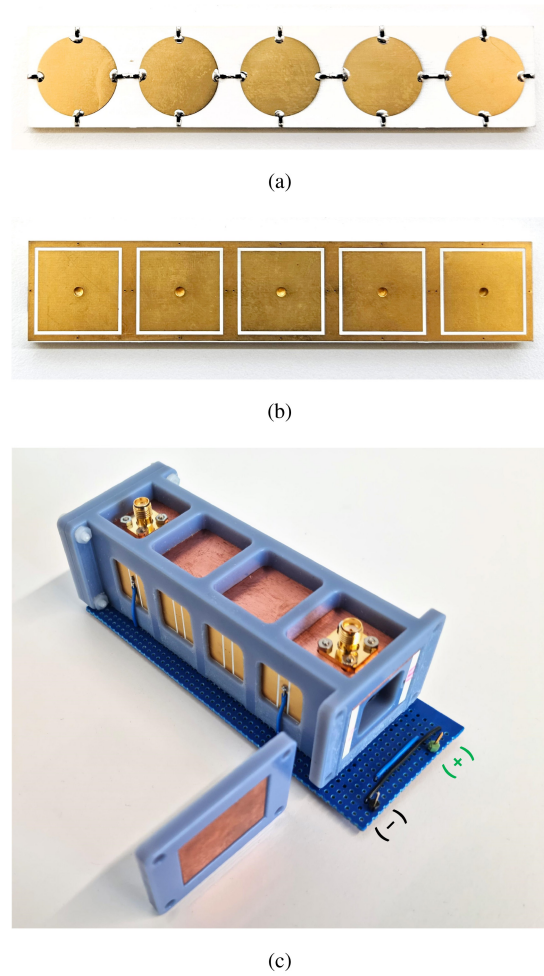


FIGURE 5. Fabricated components using PCB fabrication and 3D printing techniques. (a) The inner side of the AMC sidewall. (b) The outer side of the AMC sidewall. (c) Fully assembled miniaturized waveguide structure.

the top and bottom sides using copper plates acting as PEC. To ensure a fully enclosed design, careful design and precise assembly are essential. This is to prevent any electromagnetic leakage that could degrade the performance of the waveguide. The design of the enclosure begins with the AMC sidewalls, which must fit precisely within the waveguide structure. These sidewalls should be continuous and without gaps to ensure proper electromagnetic confinement. The top and bottom plates of the waveguide are made of high-conductivity materials such as copper, which should have tight contact with the sidewalls to prevent leakage. The complete assembly has been enclosed in a precisely fabricated 3D-printed cage which houses the waveguide assembly tightly and securely preventing any leakage. The ends of the waveguide are sealed with conductive Copper End-plates that have been screwed tightly on both ends of the waveguide, ensuring that the electromagnetic waves are contained within the structure. The AMC sidewalls along with the fully fabricated miniaturized waveguide have been presented in Fig. 5. The 3D printed cage has been fabricated using a material called “VeroBlue-RGD840” and can be seen

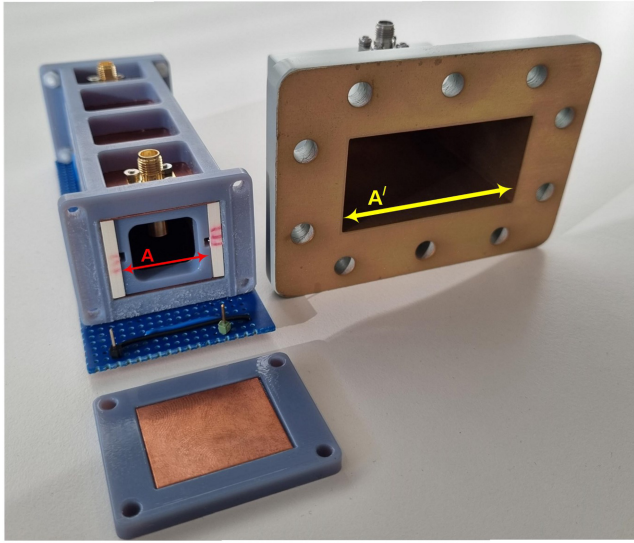


FIGURE 6. Fabricated reconfigurable miniaturized waveguide (lateral width $A = 23.5$ mm) compared with a standard WR229 waveguide (lateral width $A' = 58.1$ mm).

housing the TEM waveguide structure as shown in Fig. 5(c) giving the waveguide robustness and stability.

The fabricated design of the proposed miniaturized waveguide has been compared to a standard waveguide in Fig. 4. Both of these waveguides offer a high transmission coefficient at 3.55 GHz and 4.4 GHz but while the standard WR-229 waveguide has a lateral gap of $A' = 58.1$ mm between its sidewalls, the proposed miniaturized waveguide has a lateral gap of $A = 23.5$ mm. This makes the proposed miniaturized waveguide $\approx 60\%$ smaller in lateral dimension compared to a standard WR-229 waveguide. This innovative design provides practical solutions for various applications where space and performance are critical. In satellite communication, the compact waveguide can be integrated into small satellites or payloads, enhancing communication capabilities without adding significant weight or size. For portable radar systems, the miniaturized waveguide allows for more compact and mobile radar units, improving ease of deployment and operation. In adaptive communication systems, the dual-band and reconfigurable features enable dynamic frequency management and better spectrum utilization, essential for modern, flexible communication networks. Additionally, in high-power transmitters, the waveguide's ability to handle significant power levels while maintaining performance ensures reliable and efficient signal transmission. By overcoming traditional limitations in size, performance, and production complexity, this work paves the way for future advancements in versatile and efficient communication devices.

IV. RESULTS AND DISCUSSIONS

The fully fabricated prototype of the proposed miniaturised waveguide design was tested and measured at the University of Surrey, U.K., using a Rohde & Schwarz® ZVA67 vector

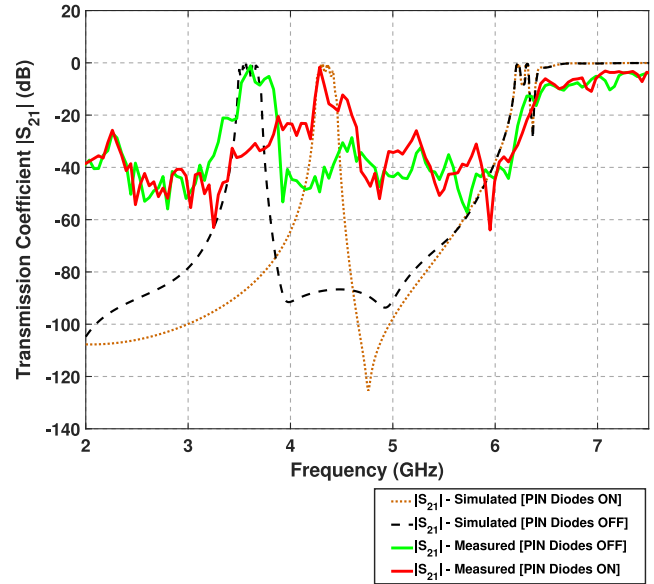


FIGURE 7. Spectra characteristic of the power transmission coefficient ($|S_{21}|$) for the proposed miniaturized waveguide, comparing both measurement and simulation results, and highlighting an additional pass-band below the cutoff frequency when operating in PMC mode.

TABLE 2. Summary of the measured results of the fabricated miniaturized waveguide.

Operating Mode	Centre Frequency (in GHz)	Pass Band (in GHz)	Peak Transmission (S_{21})	PIN Diodes Status
AMC_{F1}	3.6 GHz	3.51 – 3.83 GHz	−1.1 dB	Unbiased
AMC_{F1}	4.3 GHz	4.26 – 4.35 GHz	−1.6 dB	Biased

network analyzer (VNA) and validates several key achievements. The measured power transmission characteristics of this waveguide are presented in Fig. 5 and have been summarised in Table 2. The accuracy and robustness of the presented design have been effectively validated through a comparative analysis of both numerical and experimental results, particularly focusing on the transmission spectra. The setup utilized two wideband excitation probes inserted at the far ends of the miniaturized waveguide to measure the transmission power spectra. The observed transmission characteristics resonate with the theoretical predictions for the behaviour of the waveguide when the PIN diodes are toggled between their “ON” and “OFF” states. Notably, when the waveguide is in its AMC mode, the transmission spectrum reveals a pass band located much below the standard cutoff frequency. The peak transmission for these pass-bands is identified to be -1.1 dB when operated at 3.55 GHz in the AMC_{F1} mode and -1.6 dB when operated at 4.4 GHz in the AMC_{F2} mode. This is an enhancement of 50–60 dB when compared with a standard metal waveguide of similar dimensions operating in this frequency range. These results clearly show that the waveguide offers two separate pass-bands below the standard cut-off frequency which can be easily reconfigured by controlling the biasing of the

TABLE 3. Comparison of the proposed miniaturised waveguide with other designs reported in the existing literature.

Metrics for Comparison	[3]	[4]	[12]	[13]	This work
PMC Realization method	UC-PBG	Split-Ring Resonator	Grounded Ferrite with static Magnetic bias	Grounded Ferrite with static Magnetic bias	Reconfigurable Artificial Magnetic Conductor
Operating frequency (GHz)	9.5 – 10.4	6.0	3.37	5.20	3.51 – 3.83 4.26 – 4.35
Waveguide miniaturization	No	Yes ($0.12\lambda_0$)	Yes ($0.25\lambda_0$)	Yes ($0.26\lambda_0$)	Yes ($0.27\lambda_0$ & $0.33\lambda_0$)
Fabrication Technique/Material	PCB	PCB	Ferrite slab	Ferrite Slab	PCB+3D Printing
TEM/quasi-TEM mode	Yes	Yes	Yes	Yes	Yes
TEM pass band(s)	Above cut-off	Below cut-off	Below cut-off	Below cut-off	Below cut-off
Peak Transmission Co-efficient ($ S_{21} $)	—	≤ -12 dB*	-1 dB	-1dB	-1.1 & -1.6 dB
Frequency Reconfigurability	No	No	No	No	Yes

*Value estimated from numerical data reported in the literature.

PIN diodes. This operating region aligns with the inherent operational PMC bandwidth of the unit cell discussed in Section III-A and integrates into this waveguide design. At frequencies above 6.38 GHz, the lateral size of the proposed waveguide becomes comparable to $\frac{\lambda}{2}$ and therefore the structure starts behaving as a standard waveguide thus allowing frequencies above 6.38 GHz to propagate through the structure and hence a continuous pass band can be observed above 6.38 GHz as shown in Fig. 5. These observations and results underline a significant achievement of this work which is a reinforcement of the theoretical concept of eliminating the cutoff frequency for a waveguide constructed with sidewalls made up of a PMC boundary.

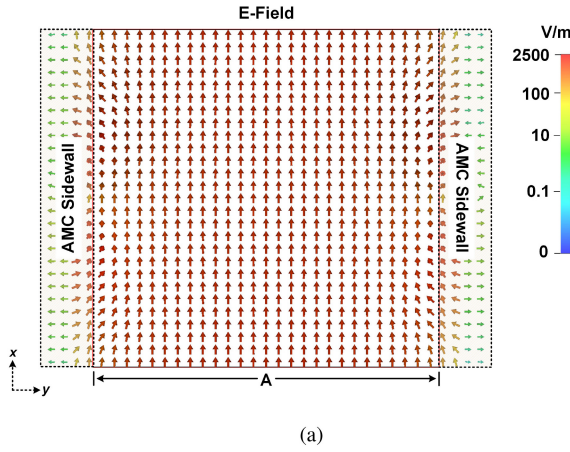
Several potential solutions can enhance the bandwidth of the proposed AMC-based miniaturized waveguide. Optimizing the AMC unit cell design by incorporating broadband structures, such as fractal patterns or multi-resonant configurations, can provide a wider operational bandwidth. Introducing multiple layers of AMCs with different resonant frequencies can also broaden the bandwidth. Furthermore, incorporating advanced low-loss dielectric materials can reduce loss and improve performance. Tuning and reconfigurability strategies, such as replacing PIN diodes with varactor diodes or using electrically tunable materials like liquid crystals, can dynamically adjust resonant frequencies. Advanced fabrication techniques, such as micromachining, can create finer features and reduce parasitic effects. Additionally, machine learning techniques can optimize design configurations to enhance bandwidth. Implementing these strategies can significantly increase the bandwidth of the proposed waveguide, expanding its applicability and performance in various microwave and millimeter-wave applications.

The electric (E) and magnetic (H) field distributions of the proposed miniaturized waveguide, while operating in AMC_{F1} and AMC_{F2} frequency bands, have been presented in Fig. 8 and Fig. 9, respectively. The E-field distribution results presented in Fig. 8(c) and Fig. 9(c) show a comparative analysis of a standard metallic waveguide, an ideal TEM waveguide and the proposed AMC waveguide. It can be

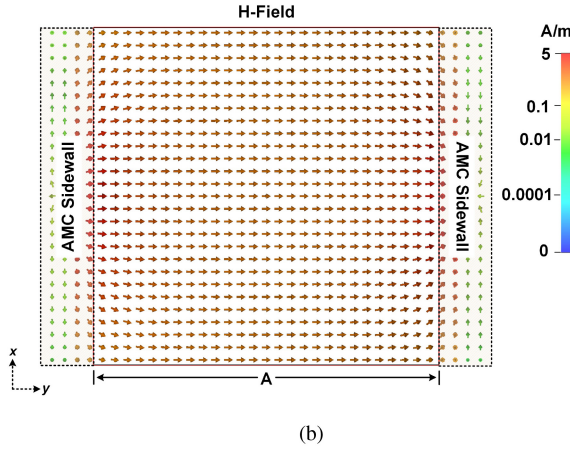
observed that the proposed AMC waveguide has an almost uniform E-field distribution that is quite close to an ideal PMC waveguide with marginal deviations near the sidewalls. This further demonstrates the existence of quasi-TEM mode propagation through the miniaturized waveguide while it is operating near the frequency of zero-phase crossing of the unit cell, which is in stark contrast to the sinusoidal distribution of a standard PEC waveguide.

To illustrate the advantages of the proposed design, a comparative study has been performed considering some of the pivotal designs present in the existing literature and has been encapsulated in Table 3. The design presented by Yang et al. offers a higher bandwidth and utilizes cost-effective PCB fabrication techniques, but lacks frequency reconfiguration and miniaturization [3]. The design presented by Marques et al. offers miniaturization, but due to the requirement to insert the SRR slab in the middle of the waveguide, the construction becomes complicated and it also does not offer a high transmission coefficient [4]. The design presented by Shahvarpour et al., which utilizes sidewalls made up of ferrite material offers miniaturization as well as a high transmission coefficient but uses a very bulky technique of placing the waveguide in the presence of a static magnetic field which might not be practical for various applications [12], [13]. On the other hand, the proposed design not only offers a higher overall bandwidth by using reconfigurable AMC sidewalls but also offers miniaturization while maintaining a high transmission coefficient and ease of fabrication by utilising cost-effective fabrication techniques such as PCB manufacturing and 3D printing. This comparative study underscores the distinctive edge that the proposed design holds not only in terms of performance but also in terms of compactness and ease of fabrication.

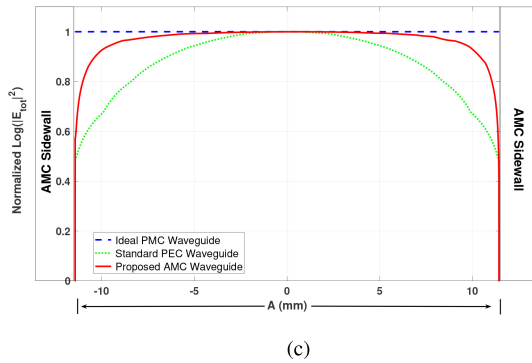
The proposed AMC-based miniaturized waveguide demonstrates a balanced approach to fabrication by leveraging both standard PCB manufacturing and advanced 3D printing techniques. Despite the multi-layered structure of the AMC unit cells, the fabrication process is streamlined through the use of well-established, cost-effective, and



(a)

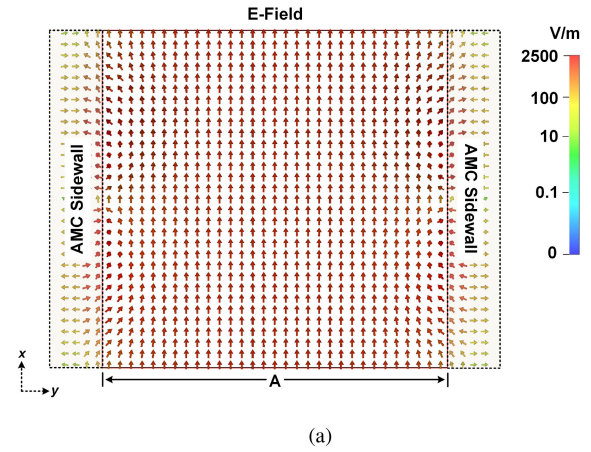


(b)

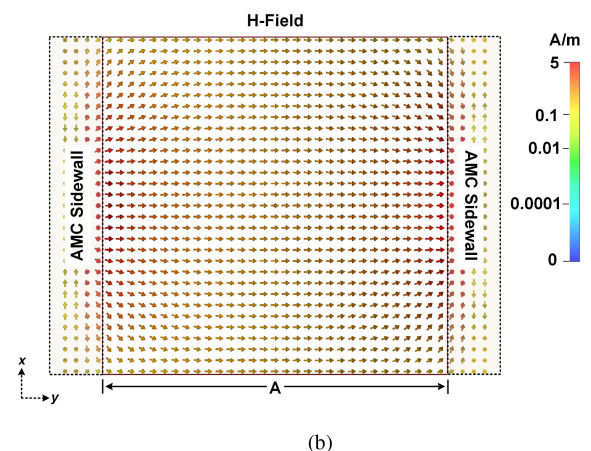


(c)

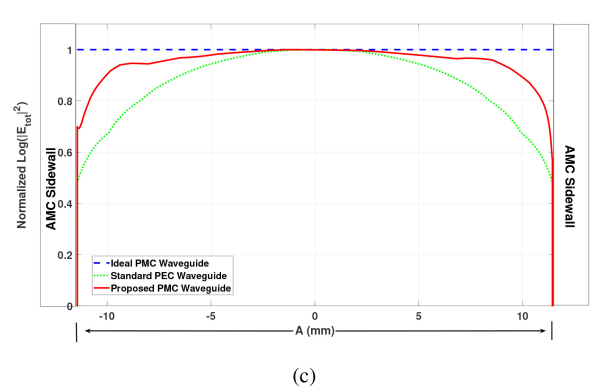
FIGURE 8. Cross-sectional field distribution of the miniaturized waveguide at 3.6 GHz. (a) Vectorial E-field distribution in PMC mode. (b) Vectorial H-field distribution in PMC mode. (c) E-field comparison between the miniaturized waveguide in PMC mode, an ideal PMC waveguide and a standard PEC waveguide.



(a)



(b)



(c)

FIGURE 9. Cross-sectional field distribution of the miniaturized waveguide at 4.3 GHz. (a) Vectorial E-field distribution in PMC mode. (b) Vectorial H-field distribution in PMC mode. (c) E-field comparison between the miniaturized waveguide in PMC mode, an ideal PMC waveguide, and a standard PEC waveguide.

widely accessible PCB techniques. These methods contrast sharply with more complex and less accessible fabrication processes such as microfabrication or cleanroom procedures required for other advanced electromagnetic structures. The assembly of our design is simplified through automated PCB alignment and bonding procedures, ensuring high reliability and reducing the need for precise manual alignment inherent in methods using split-ring resonators (SRRs) or photonic bandgap (PBG) structures. Additionally, the

structural components of the waveguide are fabricated using 3D printing technology, which allows for rapid prototyping and customization without the necessity of complex moulds or tooling. This stands in contrast to traditional machining or milling of metallic waveguide structures, which can be both time-consuming and costly. Compared to conventional metallic waveguides, which require specialized equipment and skilled labour, and EBG or SRR-based structures,

which involve intricate lithography and etching processes, our approach is significantly simpler and more scalable. Furthermore, ferrite-based designs, like those proposed by Shahvarpour and Caloz [12], involve bulky materials and the application of static magnetic fields, complicating the fabrication and limiting practicality. Our method's high reproducibility and scalability, facilitated by PCB production and 3D printing, ensure consistent quality and ease of design adjustments, making it superior in manufacturability compared to other advanced methods. This comprehensive combination of precision and ease of fabrication highlights the innovative nature and practicality of our waveguide design.

A. SUMMARY OF OBJECTIVES VS RESULTS

The objectives for the results achieved in this work focus on miniaturizing the standard waveguide without compromising on the performance, scalability, and applicability across various domains. The various objectives corresponding to each major result are articulated below:

1) TEM MODE OF OPERATION

To excite TEM mode inside the waveguide which does not exist in conventional, all-metal, waveguides. This is due to the absence of a transverse voltage gradient in a single conductor waveguide. The benefit of a TEM mode is that it is cutoff-less, with its propagation constant being real and linear at all frequencies. Hence the waveguide's lateral size is no longer constrained by the operating frequency leading the way for miniaturization.

2) RECONFIGURABLE PASS-BANDS

To demonstrate the capability of the proposed waveguide to offer dual reconfigurable pass-bands significantly below the standard cutoff frequency, thereby enhancing the waveguide's versatility and applicability in different frequency ranges.

3) PMC MODE PERFORMANCE

To validate the theoretical concept of creating a pass-band below the conventional cutoff frequency, thereby overcoming traditional size limitations through an innovative technique.

4) HIGH TRANSMISSION COEFFICIENT

To achieve superior transmission performance, indicated by high transmission coefficient of -1.1 dB and -1.6 dB at 3.55 GHz and 4.4 GHz respectively, thus demonstrating the waveguide's performance in practical applications.

5) FABRICATION SIMPLICITY AND SCALABILITY

To ensure cost-effective and scalable fabrication using PCB and 3D printing techniques, making complex designs easier to produce, thus enhancing manufacturing and scalability.

6) INTEGRATION INTO MODERN SYSTEMS

To miniaturize the conventional waveguide making it easier to incorporate it in modern communication and radar systems, ensuring their effective performance in complex and space constraint environments.

B. FUTURE DIRECTIONS FOR AMC-BASED MINIATURIZED WAVEGUIDE DEVELOPMENT

The promising results obtained from the development of the AMC-based miniaturized waveguide open several avenues for future research and development. Future efforts can focus on the following areas:

1) BANDWIDTH OPTIMIZATION

Enhance the operation of the AMC structures by incorporating advanced designs, such as multi-resonant configurations, fractal patterns, and broadband AMC architectures, to achieve wider operational bandwidths suitable for diverse applications.

2) MATERIAL IMPROVEMENTS

Explore alternative materials with superior electromagnetic properties, like low-loss dielectrics and metamaterials. Materials with higher dielectric constants and lower loss tangents could improve the waveguide's efficiency and operational range.

3) RECONFIGURABILITY ENHANCEMENTS

Increase the reconfigurability of AMC structures by integrating varactor diodes or other tunable components. This can allow for continuous and dynamic frequency tuning, making waveguides adaptable for real-time operations in future 5G and 6G systems.

4) ADVANCED FABRICATION TECHNIQUES

Utilize micromachining, laser lithography, and novel 3D printing materials to achieve higher precision and scalability in waveguide production, reducing parasitic effects and thereby enhancing performance.

5) SYSTEM INTEGRATION

Focus on incorporating miniaturized waveguides into modern communication and radar systems, including adaptive antenna arrays and integrated photonic circuits. Study their performance in complex electromagnetic environments and interactions with other system components.

6) THERMAL MANAGEMENT SOLUTIONS

Develop efficient cooling strategies, like heat sinks and forced air cooling, to handle higher power levels without impairing waveguide performance.

7) SIMULATION AND MACHINE LEARNING

Leverage advanced simulation tools and machine learning algorithms to optimize design and predict performance. Machine learning can streamline the optimization process by identifying optimal design parameters for enhanced bandwidth and efficiency.

8) FIELD TESTING

Conduct comprehensive field tests in collaboration with industry partners to validate waveguide performance in practical settings, gathering data under various conditions.

By targeting these areas, this research aims to elevate AMC-based miniaturized waveguides, making them more versatile, efficient, and adaptable for contemporary microwave technologies. This can potentially advance next-generation communication systems, radar technologies, and integrated photonic circuits, aligning with the evolving needs of the industry.

V. CONCLUSION

This work proposes a novel and innovative TEM waveguide design that is significantly smaller than standard waveguides and utilizes cost-effective fabrication methods, such as standard PCB fabrication and 3D printing, to showcase a working prototype. The fabricated miniaturized TEM waveguide is 60% smaller than a standard waveguide operating at the same frequency. The design successfully incorporates reconfigurable artificial magnetic conductors (AMCs) as sidewalls, which can operate at two distinct frequency bands centred at 3.51 GHz and 4.37 GHz. By introducing AMCs as sidewalls in the waveguide, the design emulates the presence of perfect magnetic conductor (PMC) boundary conditions, enabling the miniaturized waveguide to sustain a quasi-TEM mode. This is an experimental validation of the concept that a waveguide can support TEM modes if a voltage gradient can be created between its two horizontal walls. The experimental results demonstrate that the TEM mode is virtually cut-off less, allowing for pass bands to exist much below the cut-off frequency where the sidewalls act as AMCs. These pass bands are observed between 3.51–3.83 GHz and 4.26–4.35 GHz with peak transmission coefficients ($|S_{21}|$) of -1.1 dB and -1.6 dB, respectively. Furthermore, the E-field and H-field distributions across the lateral cross-section of the proposed TEM waveguide confirm the presence of quasi-TEM mode propagation within the miniaturized waveguide structure. These measured pass bands fall well within the $n77/n78/n79$ frequency bands of the 5G NR, making this design suitable for 5G and beyond applications.

Furthermore, future work will focus on optimizing the reconfigurable AMC structures to enhance its operational bandwidth and frequency reconfigurability. Exploring alternative materials and fabrication techniques could further improve the waveguide's performance and integration capabilities. Investigating the application of this miniaturized waveguide design in complex electromagnetic environments and its potential use in advanced communication systems will also be a key area of exploration. By bridging theoretical insights with practical implementations, this work sets the stage for developing advanced waveguide solutions that can meet the evolving demands of modern microwave technologies, especially in the sub-6GHz range.

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