Multi-Band Resonant Photonic Crystal Antenna for 5G Applications

Nila Bagheri[1], Emanuel Teixeira[2], Fernando J. Velez[3], Jon M. Peha[4]
[1,2,3]Instituto de Telecomunicações – DEM, Universidade da Beira Interior, Faculdade de Engenharia, Covilhã, Portugal
[1]nila.bagheri@ubi.pt, [2]emanuelt@ubi.pt, [3]fjv@ubi.pt

[4]Dept. of Electrical and Computer Engineering, Dept. of Engineering & Public Policy, Carnegie Mellon University,
Pittsburgh, PA, USA
peha@cmu.edu

***Abstract*—Extended reality (XR) is bridging the gap between virtual and real-world interactions enabling users to interact in realistic virtual worlds, removing physical obstacles, and establishing shared areas that promote greater comprehension and teamwork. The growing demand for high-frequency 5G communication systems supporting these new applications motivates the need of compact and efficient antennas capable of operating at millimeter-wave frequency bands. This work explores how the use of photonic crystals leverages the properties of a multi-band antenna operating within the 27.81 GHz and 41.93 GHz resonant bands. The High-Frequency Structure Simulation (HFSS) software is utilized in this paper to outline a comprehensive design and modeling approach for the proposed microstrip patch antenna.The design process involves optimizing the geometry and periodicity of the photonic crystal structure to obtain resonant modes at the desired frequency bands by exploiting its bandgap properties, whilst enabling high quality resonances within the targeted frequency bands. The electromagnetic simulations and numerical analysis results demonstrate that the designed multi-band photonic crystals-based antenna achieves a gain of 9.61 dBi. The resonant modes exhibit high quality factors, resulting in improved radiation efficiency. The proposed photonic crystal-based antenna compact size, high gain, and multiple resonant bands make it suitable for a wide range of applications, including next-generation wireless communication systems supporting XR, radar systems, or satellite communications in the upper frequency bands.**

***Index Terms*—Photonic Crystal Antenna, Multi-Band Resonance, 5G Communication, Millimeter-Wave Bands, High Gain.**

I. INTRODUCTION

The continuous evolution of wireless communication technology networks are integral to the seamless integration of immersive experiences in Extended Reality (XR), [1]. XR, encompassing Augmented Reality (AR), [2], Virtual Reality (VR), [3], and mixed reality (MR), [4], merge physical and digital environments to create captivating and interactive experiences. XR denotes the seamless fusion of the virtual environment with the physical world [5]. These applications cover a diverse range of sectors, including entertainment, education, and training. As the demand for high data throughput and low-latency connectivity grows, the development of specialized antennas become crucial to meet the unique requirements of XR devices. Virtual Reality (VR) is designed to deliver a fully engaging encounter within a simulated environment, whereas AR is focused on integrating virtual elements into the real world. Mixed Reality (MR) represents an evolving paradigm aiming to establish a cohesive environment with seamless interactions between the physical and virtual realms. Beyond these fundamental concepts, the roots of XR can be traced back to the 1960s with the introduction of diverse VR and AR devices, such as the Sensorama VR machine [6] and Sword of Damocles AR machine [7]. The continuous advancement of computer and simulation technologies over time has winned the progress of VR and AR. With the increasing portability of today's devices, end-users (UEs) can now partake in a more immersive experience.

XR finds extensive application not only in consumer entertainment, including cultural performances, exhibitions, films, and live events, but is also progressively making inroads into vertical sectors such as medical care, education, and industry [8], [9]. Experiencing considerable success, smart wearables, [10], [11], [12], [13], and [14], have become pivotal in reshaping applications within the health sector, fitness regimens, and industrial environments. Their versatile functionality overcomes conventional boundaries, positioning them as necessary tools for improving personal well-being, fueling fitness routines, and optimizing productivity in various industrial applications. Integration of conformal antennas has found practical application in smart devices, particularly in smart watches [15], [16], [17], [18] smart phones, [19], [20], [21], [22], [23], [24], solar panels [25], [26].

This paper introduces a state-of-the-art multi-band photonic crystals-based antenna designed to operate at 41.93 GHz and 27.81 GHz frequency bands, aligning with the millimeter-wave band ideal for 5G communication.

The focus on XR applications, such as AR and VR,

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bring out the antenna significance in enabling immersive and responsive experiences. As XR devices rely on robust and high-performance communication systems, the proposed antenna, with its multi-band resonance and high gain presents a compelling solution that addresses the connectivity challenges associated with XR technology. With its seamless transformation of telecommunications, XR offers a dynamic, multisensory platform that surpasses the constraints of conventional technologies.This evolution goes beyond simple communication, guiding users into fully immersive virtual environments that eliminate physical barriers and provide communal areas that foster improved understanding and cooperative working. In this challenging context, the deployment and strategic design of effective millimeter-wave band antennas is critical to the effectiveness of XR experiences. Antennas are essential elements of the XR ecosystem that allow wireless signals to be transmitted and received in a variety of settings and at different distances. Their crucial function guarantees the dependability and superior communication that pedestrians with smart gadgets and integrated infrastructure components require. XR is well-positioned to gain from increased data speeds, decreased latency, and enhanced dependability as 5G networks develop and wireless communication technologies progress. Slot antennas stand out as a planar antenna configuration widely used for various wireless communication applications due to their compact size, low profile, and ease of integration with printed circuit boards. This becomes particularly important while navigating the complex world of XR communication, as flexibility and adaptation are critical. Slot antenna antennas meet the challenges of a transforming telecom industry ecosystem by increasing the efficiency of XR systems while functioning in the 26.2-28.5 GHz and 40-44 GHz frequency bands. As such, the combination of XR with cutting-edge antenna technologies set the stage for dependable wireless communication, smooth connectivity, and immersive experiences will revolutionize the fundamental structure of a globally interconnected world.

The combination of XR and cutting-edge antenna technology marks a revolutionary period in which the distinctions between the actual and virtual worlds become increasingly hazy, opening up numerous opportunities for improved connectedness, cooperation, and invention. Antennas play an important role in maintaining a reliable and smooth communication infrastructure as XR continues to gain importance. Beyond conventional boundaries, the design takes into account the particular requirements of XR applications. To provide users participating in XR experiences with consistent and dependable connectivity, antennas must be able to handle the complexity of a variety of environments, from metropolitan landscapes to isolated places.

Besides, the collaborative nature of XR, which emphasizes shared areas and interaction, making antenna efficiency and dependability even more crucial. Novel, more efficient antennas make XR work by shaping the wireless signals needed to build attractive virtual worlds.

The potential of XR is further enhanced by the predicted increase in data rates, reduction in latency, and enhanced reliability, making it an essential facilitator across diverse sectors, encompassing e-commerce, entertainment, healthcare, and education. Future-focused, ongoing research into patch antennas and other cutting-edge solutions allows for maximizing XR experiences. With their improved radiation characteristics and multi-band operation, these antennas leverage the transformation potential of XR in the telecommunications sectors whilst becoming a seamless part of our daily lives, blending the real and virtual worlds. To explore the rest of this paper, the following sections are organized as: Section II explores the integration of photonic crystal-enhanced antennas for enhanced performance, with a specific emphasis on the future prospects and implications of photonic crystal-enhanced antennas in XR communications. Section III addresses aspects of antenna design and includes performance analysis (by emphasizing key findings and implications). The return loss plot for dual resonance bands, radiation pattern plot, and gain plot are examined, together with the 3D radiation pattern. Section IV introduces our antenna, showcasing its compact design, 5G performance, and potential for advancing communication technologies and XR experiences. Finally, Section V not only presents the conclusions and summarizes the findings of the work, by providing an overview of the key contributions, but also briefly presents proposals for future research.

II. Integration of Photonic Crystal-Enhanced Antennas for Enhanced Performance

The integration of photonic crystals plays a significant part in optimizing signal quality for XR communications and effective signal propagation, whilst contributing to reducing interference and ensuring a stable and reliable communication link. The incorporation of photonic crystals into antenna designs not only enhances signal quality but also enables the creation of compact and efficient antennas, contributing to the miniaturization of XR devices without compromising the performance. Moreover, the simplified communication architecture facilitated by photonic crystals-enhanced antennas contributes to latency reduction in XR applications, essential for real-time life experiences. Lower latency ensures the seamless integration of virtual and augmented elements into the user real-world environment. Additionally, this integration enhances energy efficiency, a critical factor for wearable XR devices. Photonic crystal antennas, with their specialized designs, minimize energy consumption, while photonic crystals contribute to reducing signal losses, resulting in more energy efficient XR communications. These advancements emphasize the transformative potential of integrating photonic crystal-enhanced conformal antennas, offering a holistic enhancement to XR telecommunication experiences.

The integration of photonic crystal-enhanced antennas shows significant promise for the future of XR telecommunication. This section explores potential pathways for further advancements, including the exploration of novel materials, advanced manufacturing techniques, and enhanced signal processing algorithms. Additionally, the impact of these integrated

Fig. 1. XR telecommunication system showcasing enhanced performance for immersive experiences in various applications.

antennas on the broader XR ecosystem, considering applications in healthcare, education, and industry, will be thoroughly examined. By forecasting the pathway for the development of this type of antennas, we aim to provide valuable insights into the long-term evolution of XR communications.

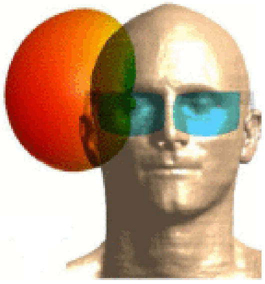

Fig. 2. Utilizing antenna technology for smart glasses: enhancing connectivity and performance for a smarter vision experience.

III. ANTENNA DESIGN AND PERFORMANCE ANALYSIS

The integration of the photonic crystals into the design of the antenna enhances the manipulation of electromagnetic waves. The resonant band, coupled with a considerable gain increase, enhances the performance of the antenna in amplifying transmitted signal strength, whilst also improving signal reception. To enhance antenna directivity and efficiency while preventing substrate surface path loss, we chose a photonic crystal substrate over the conventional substrate [27].

Whilst seeking optimal antenna performance, the choice of substrate materials are fundamental. In this study, the substrate selected was RT/Duroid 5880, known for its high performance and reliability, providing an acceptable appropriate foundation solution for the antenna structure. Copper, chosen for its excellent conductivity, was employed in crafting the patch antenna with a thickness of 35 μm. This precise selection of materials aims to enhance the overall efficiency and responsiveness of the antenna, ensuring seamless integration into XR communication systems.Detailed information about the antenna geometry is presented in Fig. 3.

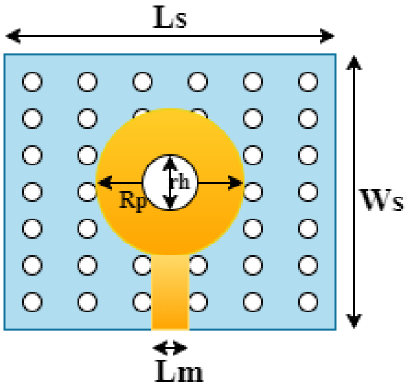

Fig. 3. Antenna geometry: Configuration of antenna based photonic crystal.

The primary design goal has been to ensure that the antenna resonant bands precisely occur at 27.81 GHz and 41.93 GHz, aligning perfectly with the frequency bands required for XR communications. Throughout the design process, factors such as radiation patterns, polarization, and form factors have been carefully considered. This comprehensive approach ensures that the antenna not only meets stringent technical specifications but also aligns harmoniously with the unique demands of XR experiences. One can learn that to use Photonic Band Gap (PBG) in antenna design is important and significantly influences the performance of antennas in telecommunication. PBG refers to a range of frequencies at which the propagation of electromagnetic waves, such as light or radio waves, is prohibited or strongly inhibited within a certain material or structure. Table I. provides a comprehensive overview of size parameters.

TABLE I
SIZE PARAMETERS TABLE: DETAILING THE DIMENSION AND SPECIFICATION OF KEY PARAMETERS.

Parameter	Value (μm)
Ls	7320
Ws	6120
Rp	1720
Lm	745
rh	300

Fundamental aspects like the improvement in the radiation pattern, return loss plot, and gain plot highlight the effectiveness of our multi-band antenna in XR communications, showcasing the advantages of integrating photonic crystals in its design and fabrication. It is a step toward creating antennas that perform better and contribute to improved XR experiences.

The return loss plot, as represented in Fig. 4, is a crucial chart to understand the photonic crystal antenna resonance characteristics. The presence of two distinct resonance bands at specific frequencies, such as 27.81 GHz and 41.93 GHz, aligns with the targeted frequency requirements of XR communications.

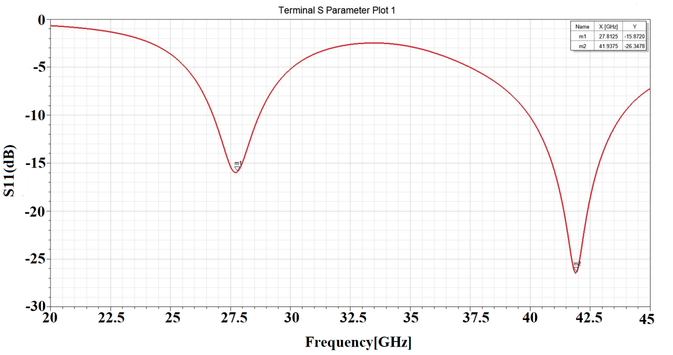

Fig. 4. Return Loss Plot illustrating dual resonance bands in photonic crystal antenna.

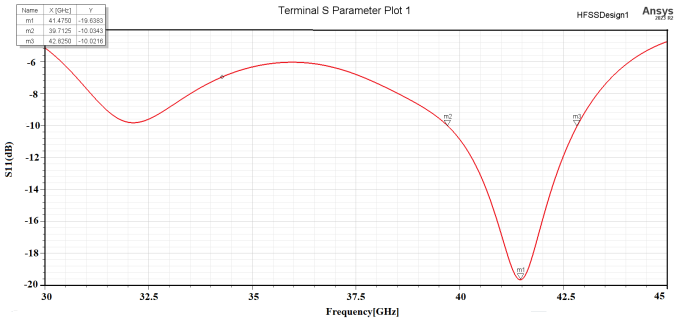

Fig. 5. Return Loss Plot illustrating a resonance band in an antenna without photonic crystal substrate.

Fig. 5, illustrated the return loss of antenna without photonic crystal substrate, showcasing a distinct resonance band, by a notable reduction in antenna bandwidth. This representation emphasizes the influence of the absence of a photonic crystal on the performance characteristics of the antenna. It is noteworthy that the bandwidth of this antenna is 3.11 GHz, with the resonance band occurring at 41.47 GHz.

The radiation pattern, as shown in Fig. 6, illustrates the directional capabilities of our photonic crystal-enhanced antenna. This pattern showcases the antenna capability to centralize and direct signals.

Fig. 7, illustrated the antenna gain plot without photonic crystal, indicating a value of 4.92 dB. In comparison, Fig. 8, representing the antenna gain plot with photonic crystal, demonstrates a noticeable decrease in gain for the antenna without a photonic crystal. In addition, the use of the photonic crystal enhances the antenna's directionality, contributing to the observed higher gain. The design consists of a photonic crystal optimizes the antenna ability to concentrate its radiation in specific directions, resulting in a more efficient and focused signal transmission. This notable improvement in gain and directional characteristics underline the significant impact of integrating photonic crystal into the antenna design. It provides valuable insights for antenna optimization, emphasizing the potential for enhanced performance in applications where superior gain and directional accuracy are important.

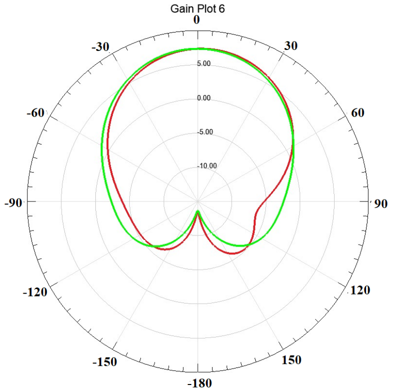

Fig. 6. Radiation Pattern Plot: Demonstrating the concentrated and precise signal direction of our designed photonic crystal-enhanced antenna.

The gain plot, as shown in Fig. 8, provided a quantitative measure of the antenna's ability to amplify signal strength. The antenna gain is 7.36 dB, confirming its efficiency in enhancing the power and effectiveness of signal transmission and reception. In the case of XR communication, a higher gain is important for achieving reliability.

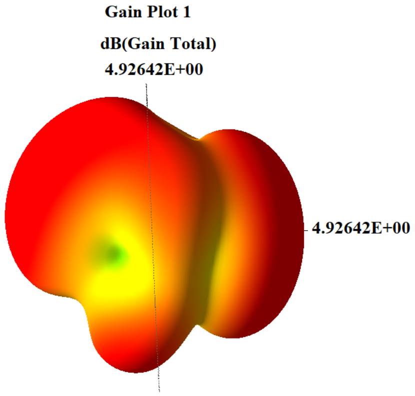

Fig. 7. Efficiency Comparison: Illustrating antenna gain, highlighting the impact of the photonic crystal for enhanced performance.

Including the 3D radiation pattern of the antenna in the analysis improves our understanding of signal behavior, antenna design engineers use this visual insight to enhance antenna design for optimal performance, as demonstrated in Figure 9. The real-world application of the 3D pattern provides valuable insights, supporting informed decision-making during the antenna design and deployment.

Table II, presented a comparison of antenna parameters between the proposed design in this study and those reported in previous studies. As is apparent from the table, the proposed antenna showcases a broader bandwidth and higher gain compared to the antennas reported in previous studies, further exhibiting the distinctive feature of dual resonance bands.

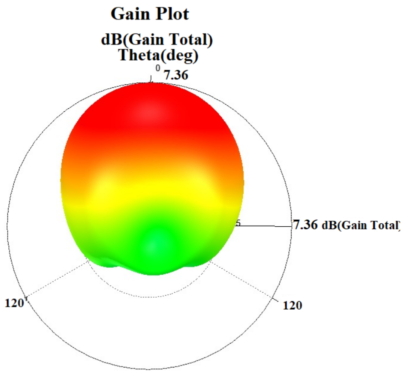

Fig. 8. Gain Plot: Showcasing the photonic crystal antenna efficiency

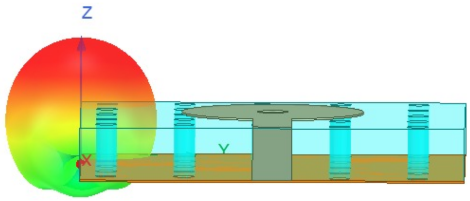

Fig. 9. Integrating the 3D radiation pattern atop the antenna in the analysis.

In recent years, the field of computational electromagnetic modeling (CEM) has seen the emergence of diverse numerical methods, categorized into differential and integral equation approaches. These methods include the green function method, finite integration techniques (FIT), finite element method (FEM), method of moments (MoM), finite-difference time-domain (FDTD), and others. Our chosen software for this study is HFSS, which relies on the FEM for calculations.Within the realm of antenna design, FEM acts as a powerful tool for simulating and optimizing performance. It aids researchers and engineers in understanding how antennas interact with electromagnetic fields and physical structures, leading to improved designs and enhanced overall performance. FEM is instrumental in solving Maxwell's equations, describing the behavior of electric and magnetic fields in the presence of physical boundaries. The process involves dividing the domain into finite elements, assigning electromagnetic properties, and applying numerical techniques to solve the resulting equations. These elements subdivide the domain into sub-domains (mesh), adopting shapes such as triangles or quadrangles for two-dimensional problems and prisms, hexahedra, or tetrahedra for three-dimensional problems. This enables accurate modeling and analysis of electromagnetic phenomena, covering antenna characteristics like gain, radiation pattern, and impedance. FEM utilizes finite elements to discretize the structure into smaller subsections, optimizing the solution for electric and magnetic fields. Conversely, FIT discretizes both space and time using a mesh for spatial sampling and a time step for temporal sampling. Both FEM and FIT play significant roles in simulating electromagnetic phenomena and improving antenna designs.

TABLE II
COMPARISON IS CONDUCTED BETWEEN THE ANTENNA PARAMETERS PRESENTED AND THOSE REPORTED IN PREVIOUS STUDIES.

Methods	f GHz	Gain (dB)	S_{11} (dB)	B.W (GHz)	Reference No.
FEM (HFSS)	28	5.35	-20.59	2.8	[28]
FEM (HFSS)	28.3	2.60	-21.11	-	[29]
FEM (HFSS)	28.04	5.87	-13.83	0.180	[30]
FEM (HFSS)	24.81	6.16	-13.5	-	[31]
FIT (CST)	28.20	5.20	-20.03	2.100	[32]
FEM (HFSS)	27.81 41.93	7.36	-15.87 -26.34	6.3	This Work

IV. STATEMENT OF NOVELTY

The proposed antenna in this study, with its compact size, performs exceptionally well in 5G wireless communication applications, providing high radiation performance with a bandwidth of approximately 6.3 GHz and a gain of 7.36 dB. The multi-resonant capability, coupled with high gain, positions it as a promising solution for next-generation communication systems. Photonic crystals significantly enhance antenna performance by enabling efficient wave control and resonance at smaller dimensions, resulting in compact, high-performing antennas. Their manipulation of effective characteristics are pivotal in achieving exceptional performance without compromising efficiency. In the realm of high-performing antennas, efficiency, directivity, wide bandwidth, high gain, and compact design are critical characteristics. To further enhance antenna performance and achieve compact size, we opted for a photonic crystal substrate instead of a conventional uniform substrate. This choice effectively prevents substrate surface path loss, resulting in improved antenna directivity and efficiency. As mentioned in the text, the difference between the diagrams of the antennas with and without photonic crystal substrate clearly shows the advantages of the former ones. As a consequence, this work provides valuable insights to discussions about the convergence between photonics and communications technologies, aiding in the enhancement of XR experiences characterized by their intrinsic reliability and efficiency toward and a harmonious fusion of radiation technology and innovation.

V. CONCLUSION

Antennas designed for XR applications must have specific attributes to ensure optimal performance. These characteristics include precise directional capabilities and high efficiency in energy conversion for effective transmission and reception, compact size for seamless integration into XR devices, wide bandwidth to support diverse communication frequencies, reliability through consistent and stable connectivity, compatibility with specific XR communication technologies, and higher antenna gain to enhance overall signal quality and reception. The photonic crystal-enhanced antenna presented in this paper represents an applicable contribution to millimeter-wave communications. The characteristics of this device, including resonant band coverage at 27.81 GHz and 41.93 GHz with a gain of 9.61 dBi, highlight its suitability for next-generation communication requirements. The integration of photonic crystals into the design of antennas for beyond 5G applications play an essential role in manipulating electromagnetic waves, whilst leading to improved signal propagation and management. The proposed antenna features an effective size reduction, high directivity, and high gain play a pivotal role in enhancing signal quality, reducing latency, and improving energy efficiency in XR devices. The system support for XR experiences, diverse XR applications in fields such as medical care, education, and industry, and its real-world integration features demonstrate its versatility and adaptability. The integration of photonic crystals into antenna designs further enhances the system performance for XR applications. Improved signal quality, customized antenna designs for XR devices, reduced latency, and enhanced energy efficiency collectively contributes to an organized communication infrastructure. This integration not only ensures stability and reliability in real-time communication but also facilitates the miniaturization of XR devices without compromising performance. Essentially, the combined application of photonic crystals and conformal antennas presented in this work hold great promise for revolutionizing XR communications. In the future, we aim to integrate antenna-based photonic crystals, MIMO technology, and beamforming techniques into XR communications.

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