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Survey of Synergistic Advances in Photonic Bandgap-Based Wireless Antennas: Review and Applications

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Abstract— This paper gives an elaborate overview of the latest advances in energy-based antennas in the period between 1987 and 2026 [1][2]. In this regard, the paper focuses on the basic principles of photonic bandgap (PBG) structures and the different design methods that can be used in combination with different antennas.[3][4]. In addition, this paper highlights the latest developments in the technology of antenna design utilising PBG material in combination with the modern devices of wireless communication systems, such as IoT technology, mm-wave communication, terahertz systems, as well as the future 5G and 6G systems [12]. In addition, the paper emphasises the main advantages of designing PBG antennas, as well as existing limitations and further perspectives in this sphere of scientific research and development. This paper concentrates on the issue of scaling of the PBG patterning technologies, combined with the appropriate substrates.

Keyword— Photonic bandgap structures, PBG antennas, 5G communication, 6G networks, microstrip antenna, dielectric resonator antenna, CST simulation.

I. INTRODUCTION

Photonic Bandgap (PBGs) and Electromagnetic Bandgap (EBGs), are two structures from among the innovative technologies that have come to revolutionise antenna design, providing a level of manipulation of electromagnetic waves' propagation through artificially designed periodic structures never seen before. Such technologies make use of engineered band gaps to reduce unwanted radiation **[5]**. Antenna designers have recently begun to make progress with PhC technology that overcome many of the classical limitations (bandwidth, size, gain, etc.) of current planar antennas **[6]**. As we outlined earlier, PBG structures essentially add another dimension to the designer’s toolkit by introducing an engineered dispersion characteristic which results in frequency bands around some natural frequencies for which electromagnetic waves cannot propagate. Photonic bandgap (PBG) structures have been shown to enhance the efficiency and reliability of a range of antennas, such as horn antennas, dielectric rod antennas, metasurface antennas and leaky-wave antennas. These technological advances suggest that PBG-based antenna technology is evolving as well as finding new applications. in certain frequency bands but forbidding them in others **[7]**.Unlike traditional antenna design approaches that rely solely on geometric manipulation and substrate engineering, PBG structures introduce an additional design dimension through engineered dispersion characteristics **[8]**. problems. emergence of frequency bands around some natural frequencies in which electromagnetic waves cannot propagate, i.e., they block some frequency ranges. (PBG) structures enhance antenna efficiency and reliability. antennas, dielectric rod antennas, metasurface antennas, leaky-wave antennas, and horn antennas. advances in PBG-based antenna technology, highlighting design evolution and emerging applications.

II. DESIGN EVOLUTION

A. Early Development and Fundamental Architectures

Initially, antenna development involved early studies on mushroom-type EBG structures consisting of metal patches connected to a ground plane by vias **[9]**. Such designs worked effectively to suppress surface waves by tailoring the reflection phase states. The introduction of the uni-planar compact PBG (UC-PBG) structure in **[9]** was a significant advancement since it eliminated the necessity for vias without compromising performance. The early implementations focused on microwave band microstrip patch antennas where the PBG substrates were shown to increase impedance matching and gain without changing the size. The initial researches utilized two-dimensional photonic crystal slabs with periodic arrangements of cylindrical air holes **[10]**. These structures showed frequency-dependent features for selective guiding and localization of waves. It was demonstrated that tuning of lattice spacing, hole radius and periodicity can lead to full photonic bandgaps in the desired frequency ranges **[11]**.

Photonic bandgap (PBG) materials are periodic architecture structures that affect electromagnetic propagation through constructive and destructive interference to create certain bands over which the transmission is blocked in order to fabricate such PBGs. The bandgap frequency is largely controlled by the lattice periodicity, dielectric constant and unit-cell geometry.

B. Foundational Approaches to PBG Antennas

For initial designs of PBG antennas, the main concern was to decrease surface wave loss of microstrip antennas. After that,The periodic ground features then have been introduced to enhance the radiation efficiency of the microstrip antennas, and their impact for a first time was rather not so obvious. the improved behaviour of new PBG structures to force them to reach their best possible performance. Overall behaviour. There are several examples, for instance:

a) Reflect array antennas for millimetre-wave communication **[13]** : Reflect array antennas mix the idea of a parabolicreflector with the logic of a phased array. You can think of them as a flat panel that carries passive or tunable cells, these the individual cells of a reflect array apply a phase shift to the incoming wave. Once the required phase map of the individual cells has been designed, the reflected wavefront is very directive. After refocusing towards bettering overall performance of antenna layout, today there are numerous examples of various designs of periodic structures of ground planes used in antenna construction, for instance: reflect arrays are gaining interest because they can offer a large number of reflector cells which can be realized as passive or active elements and provide high gain, are low in profile and light in weight.

i) High gain and directivity that can look similar to parabolic dishes.
ii) Low profile height together with low weight, allowing for a very compact housing for user-friendly devices.
iii) Beam steering, by employing tunable elements such as MEMS, liquid crystals, or varactors.
iv) The fact that the antenna can be cost-effectively fabricated compared to fully electronically steered phased arrays.

b) Metasurface antennas for beam shaping **[14]**: Metasurface antennas use engineered subwavelength structures to sort of steerto steer electromagnetic waves in very specific ways and to sort out special tasks such as for example the so-called beam shaping (focusing, etc.). As mentioned already before antennas of that kind are ideal for 5G communications as well as for satellite communications and also for use in so-called passive as well as in active radars. Metasurface antennas for beam shaping: Metasurface antennas steer electromagnetic waves with subwavelength structures. The apertures phase distribution can be controlled to form and steer a beam, focusing it, steering it or even forming multiple beams. These high flexibility antennas could be very appropriate for 5G, satellite communications, or even for some kind of radar systems when a controlled radiation pattern is needed. These devices have specific applications, 5G, satellites and also military radar which typically have very specific radiation patterns which need to be controlled.

c) Leaky-wave antennas for beam scanning **[15]**: Leaky-wave antennas are guided antennas which are designed to leak energy in a specific direction. Their main characteristic is that the radiation beam scans while increasing the frequency. The scanning of the main beam is achieved without mechanical movement, and this kind of antenna is very useful for real-time beam steering in millimeter-wave communications, for automotive radar and for imaging systems. Leaky-wave antennas emit radiation in a continuous fashion along the structure and thus are used to design antennas which allow main beam steering by changing the frequency of operation. In order to allow real time beam steering, applications like millimetre-wave communication, automotive radar, and imaging systems need such leaky-wave type antennas. frequency. So the scanning happens without mechanical motion. Applications are for instance the millimeter-wave communications as well as the automotive radar and the imaging applications.
communications, automotive radar, and imaging systems.

d) Dielectric rod antennas with harmonic suppression **[16]**: Dielectric rod antennas use low-loss dielectric materials to support surface waves that radiate efficiently at the rod’s end. Incorporating PBG or EBG structures around the rod suppresses higher-order harmonics, ensuring clean radiation patterns, improved efficiency, and reduced interference. They are widely used in satellite communication and high-frequency microwave links.

III. PBG ANTENNA DESIGN METHODOLOGIES

A. Unit Cell Design:

The design process begins with a PBG unit cell, which determines the electromagnetic bandgap characteristics.
Key parameters included in this design are:
a)Periodicity (p) b)Rod diameter or slot widthc)Dielectric constant d)Height of the structure.

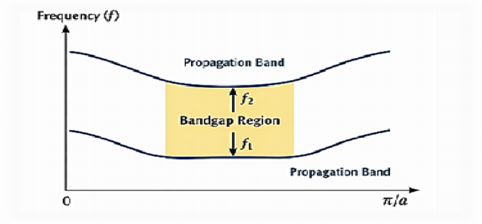


Fig 1: Dispersion diagrams showing bandgap frequencies for PBG antennas.

The x-axis shows the wave vector (β), ranging from 0 to π/a, where $a$is the lattice period. The y-axis represents the frequency (f) of electromagnetic waves. The blue curves indicate propagation bands, where waves can travel through the periodic structure. The yellow shaded region between frequencies $f_1$and $f_2$is the bandgap region, where no propagation occurs. This is the frequency range that suppresses surface waves. The vertical arrow marks the bandgap width, which determines how effectively the structure isolates unwanted mode. The analysis of bandgap characteristics is analysed using simulation tools such as:

a) CST Microwave Studiob) HFSSc)COMSOL Multiphysics

B. Types of PBG Structures Used in Antennas [9]

a). Electromagnetic Bandgap (EBG) Structures: Periodic metallic or dielectric surfaces used to suppress surface waves.
b). Photonic Crystal:Dielectric periodic lattices used for high-frequency electromagnetic control.
c) Meta-surfaces:Two-dimensional artificial materials that manipulate electromagnetic waves.
d).Mushroom-Type EBG:This is the most useful PBG structure used in antenna ground planes.

C. Work Flow for PBG Antenna Design

The workflow shows the development process of an antenna in single steps [18]. geometry and lattice design, simulation setup, bandgap analysis, performance evaluation, optimization, fabrication, and testing and integration. The testing and integration of the antenna is followed by feedback, which in return is used for revising the requirements for future designs. Feedback loops from testing to requirements analysis are common in modern PBG antenna research.

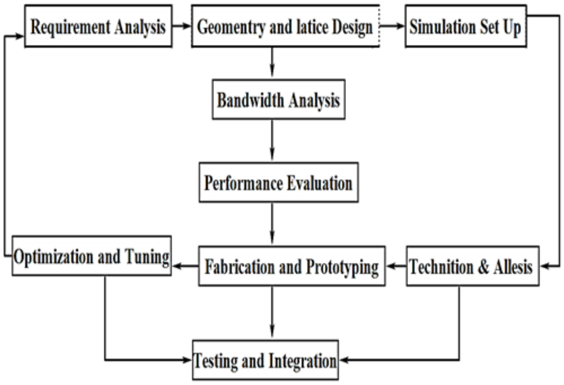


Fig. 2. Photonic Band Gap Antenna workflow

D. Flow chart for designing PBG Antenna using CST software

Fig. 2 shows the step by step design of a PBG antenna using CST Microwave Studio **[27]**. First, the design requirements are defined. Then, the geometry and the lattice are modelled. The simulation setup is then defined using frequency solver, time solver and eigenmode solver to obtain the results. These results are then used to perform the bandgap analysis to define the suppression regions. Then, the performance of the antenna is evaluated. After that, the design is optimized and refined. The final step involves fabrication and prototyping of the design. The design is then tested and integrated to complete the design.

The workflow is iterative in nature and involves several refinements until a high quality and reliable design is obtained.

Fig.3: Photonic Band Gap antenna designing flow diagram using CST software

a) Design starts from needs analysis. The first thing that needs to be done in designing includes choosing the frequency band on which design is to be made, like 5G, THz, and mm-wave bands. Other things that need to be analyzed are gain, bandwidth, directivity, and EMI rejection. It must also be remembered that one needs to choose an application domain, where design can be used, e.g., IoT applications, biomedical applications, and aerospace engineering.

b) The next step in designing would include geometry and lattices. This can be done through the selection of a specific type of lattice, such as woodpile, kagome, hexagonal, and mushroom lattice. Dimensions and periodicity of unit cells as well as defect locations can be selected. This design process requires modeling with CST, keeping things simple if not absolutely accurate.

c) Simulation Setup: This is where you define your simulation setup for the study of the antenna's electromagnetic characteristics. It includes using appropriate solvers such as Frequency Domain Solver (FD), Time Domain Solver (TD), and Eigenmode Solver (EM). Appropriate boundary conditions and excitations should be defined. Set up the field monitors to observe radiation patterns and S-parameters.

d) Band Gap Analysis: From the above findings, we can determine the frequency range that causes the blocking of the electromagnetic waves. Using the eigenvalue method, plot the dispersion diagram. Band gaps can easily be observed from f_1 to f_2 (f_1-f_2). Surface waves are no longer supported on this structure. Modes are seen at areas of sharp cutoffs.

e). Performance Evaluation: Begin by assessing the performance of the antenna using simulated data. Gain figures can be used to measure the performance with regard to bandwidth. The directivity is used to illustrate the effectiveness of the antenna. Polarization accuracy is validated through simulation. Begin with optimizing parameters separately before adjusting timing and structure to suit improved efficiency. Afterward, adjustments to structure enhance performance. Changes in spacing come after analysing the results from previous steps. Ultimately, accuracy is enhanced by optimizing parameters based on feedback from previous steps.

f). Optimisation and Tuning: This involves making changes to spacing of lattice points and dielectric permittivity of the materials used. Subsequently, make modifications to the shapes of imperfections, relating to behaviour changes. Every modification involves changing a single parameter at a time, observing results without predicting effects. Optimizations of multiple objectives can be done using CST's optimizer or artificial intelligence-based algorithms.

IV. CLASSIFICATION AND PERFORMANCE CHARACTERISTICS

A. Primary Design Categories

PBG structures can be categorized under three fundamental dimensional types of structures, each having its own distinct advantage for application in antennas **[5].**

The first dimensional PBG structures rely on stacked layers of varying dielectric constant that enable wavelength-scale control of properties in one direction only **[19]**. 1D PBG structures have shown considerable promise in increasing bandwidth and gain in microstrip patch antenna, with improvements of over 40% in bandwidth recorded **[20]**. The most popular 2D photonic crystal structure with antenna applications consists of periodic holes arranged in the air medium**[10]**. Furthermore, the 2D lattice allows control of the wave propagation along the plane of the antenna, allowing more effective surface wave suppression and higher radiation efficiency **[21]**. In terms of implementation in 3D space, however, the PBGs suffer from fabrication challenges that restrict their usage in commercial antenna arrays **[22]**

B. Key Performance Indicators and Comparison

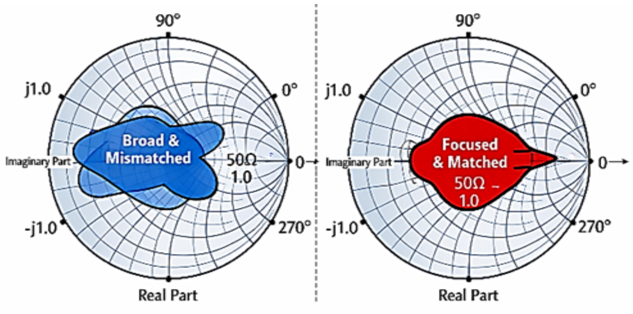
The use of PBGs results in noticeable improvements in key performance indicators for antennas. Effective surface wave suppression is possible in a range up to 65%, depending on proper design optimizations **[23]**. Gain enhancement may be up to 2 – 8dB depending on the structure and frequency used, although in specialized cases, gains up to 10dB were reported **[24]**. Mutual coupling in MIMO array antennas has shown considerable improvement due to embedded EBG decoupling elements, which result in isolation improvement of up to -10dB to -34dB **[25]**. The bandwidth enhancement in antennas using PBG structures can be realized using various mechanisms, such as the effect of a slow wave, optimizing the impedance match or manipulating modes **[26]**. Comparisons have shown that the antennas incorporating the use of PBGs significantly outperform those without them.

C. Antenna Structure Integration

The process of implementing PBG structures can be done via different techniques. First, ground plane is used to stop any surface wave propagation and reduce rear unwanted signals. The application is efficient since it increases performance and minimizes interference in a configuration with multiple adjacent antennas. It is usually understated until elements are spaced very closely – there will be less crosstalk between them. Everything follows naturally: cleaner output is achieved where it is needed. Improved efficiency occurs automatically with the inclusion of this element underneath **[9].**This step is responsible for the energy flow control, as well as amplifying the power. Energy distribution is controlled via the creation of a narrow central beam. Antenna is surrounded by a repeating structure which prevents the formation of stray signals due to creating an area where frequencies are not allowed. There is less side emission as the additional paths are blocked. Cleaned output signal results from such an operation. Control over shape is performed internally, without any additional components involved. Inside the insulation material, there is an element that controls the movement of the signal while eliminating unnecessary frequencies.

D. Performance Enhancement Techniques Using PBG Structures

a) Gain Enhancement: PBG structures mitigate surface wave propagation and re-radiate the energy into the main lobe which leads to typical gain improvement is 2–5 dB depending on structure.



Before PBG **After PBG**

Fig.4: Antenna Gain Pattern with and without PBG Substrate

The blue contour is a much larger mismatched impedance area than the one seen for post PBG, meaning the transfer of energy through surface waves becomes less efficient. Pre PBG is similar to the red contour and is the smaller matched lobe around the centre region at an impedance of 50 Ω.

b) Bandwidth Improvement: Resonant cavities and meta-surface superstrates increase the effective aperture of antennas, thereby improving bandwidth.

c) Harmonic Suppression: Higher order harmonics may be suppressed by using Photonic crystals. This enhances the performance of antennas and reduces interference effects.

d) Mutual Coupling Reduction: By applying PBG structures to antenna arrays, mutual coupling between antenna elements may be decreased.

E. Result Analysis of PBG Antenna Structure

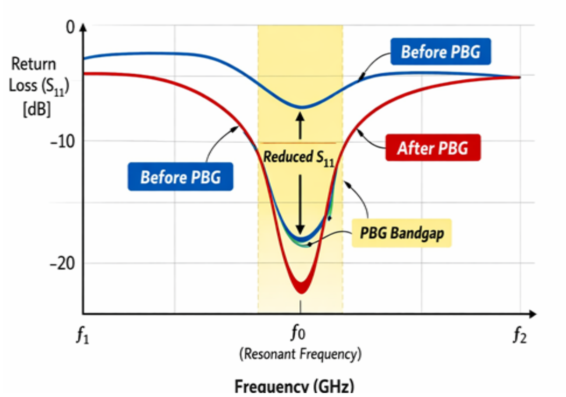


Fig.5:Return loss(S11) and Frequency Plot

Figure 5 (After and Before PBG) indicates that the PBG structure suppresses unwanted waves,provides stronger radiation and better antenna performance at the resonant frequency.

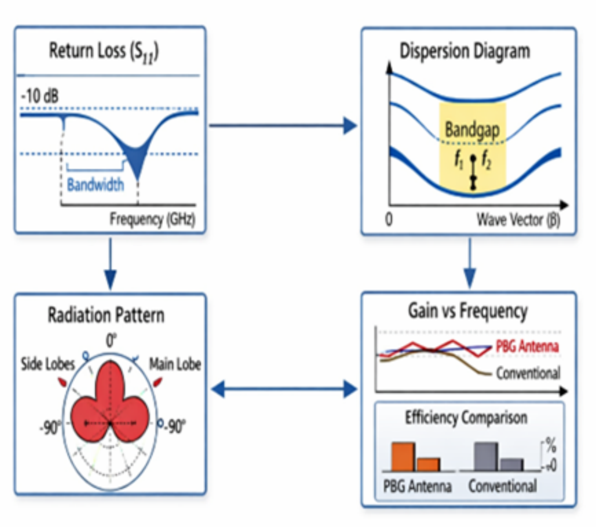


Fig.6: Result analysis of PBG antenna structure

Figure 6 confirms that performance can be improved by adding a PBG structure. This is evidenced by several figures: the S_{11} plot shows wider impedance matching with a lower surface resonance below −10 dB; from the dispersion diagram we can see where the bandgap lies to eliminate surface waves; the reduced side lobes and enhanced main-lobe in the radiation pattern plot lead to higher directivity; and the gain and efficiency plots show 2–5 dB increase in gain and 10–20 % increase in radiation efficiency over a conventional antenna. Overall the PBG design affords wider bandwidth, improved matching and better radiation characteristics.

V. APPLICATIONS IN NEXT-GENERATION WIRELESS SYSTEMS

A. 5G and mm-Wave Systems

Dual-band operation allows support for both sub-6GHz and mmWave bands. Wide bandwidth allows for high-speed data transfer as well as low latency. High gain and efficiency allows surface waves to be suppressed. Compact design is suitable for smartphones, sensor nodes, smartwatches, and other wearables.

IoT and robotics devices can use these antennas efficiently in low-power, space-constrained applications. There will be significant advantages in having reliable high-frequency connections for headsets and multimedia equipment. The PBG antenna has a wide reflective area and poor impedance matching ($S_{11} \approx -10$ dB). The antenna is suitable for functioning in the mentioned range of frequencies utilized by millimeter-wave communication systems. Reconfigurable electromagnetic bandgap arrays **[28]** and multifunctional millimeter-wave designs **[29]** have been proposed for sub-6 GHz and mm-wave 5G applications. Zakeri et al. **[30]** demonstrated enhanced gain in radio-over-fibre systems.

B. Terahertz and 6G Communication

Jornet et al. **[31]** emphasized ultra-fast PBG-based lenses and meta-surfaces **[32]** provide high directivity and imaging capabilities Advanced PBG structures enable antenna operation at extremely high frequencies required for light speed communication. High-speed wireless links enable ultra-fast data transfer in THz communication networks. Imaging and sensing are used in medical imaging, security scanning, and non-destructive testing. Satellite and deep-space communication provide low-loss, high-gain antennas for THz bands. A few examples are as follows:

a) Spectroscopy – Supports precise material characterization and chemical detection.
b) IoT and robotics – Compact THz antennas for short-range, high-capacity links, such as those used in robotic control units, environmental sensors, and connected industrial machinery.
c) Industrial automation – THz sensing for quality control and monitoring.

C. Aerospace, Satellite, and Radar Systems

Safety radar antennas and shaped-pattern reflect arrays **[37]** illustrate PBG's role in aerospace safety and satellite communication. High-gain PBG antennas are suitable for radar systems and airborne communication. Aircraft communication requires high-gain, low-loss antennas for secure air-to-ground and inter-aircraft links.Satellite systems require compact, efficient antennas for space communication and navigation. Radar performance is enhanced in terms of resolution and detection by suppressing surface waves and side lobes.Antennas required for sky link technologies where reliable communication with earth stations to track weather stations and earth observations are needed. Défense refers to surveillance radars, trackers, and guidance for missile systems operating in HF bands.

D. Biomedical and Wearable Devices

These applications of skin like antennas combined with smart materials are medical body monitoring **[35]**. The flexible antennas for these biomedical applications **[36]** can utilize PBG integration to allow less interference and miniaturized integration. These applications include: a) Diagnostic Scanning – Higher resolution and accuracy for tissue scanning and biological signal collection. b) On-body Networking – Maintain connection to wearable devices and smart clothing. c)Implant communication – Allow higher data transmission for pacemakers and brain implants. d) Biochemical monitoring – Support sensors for glucose, (hydration and vital signs) Radiation control – Control of leakage and safe operation near human tissue.

E. Multibeam and Holographic Metasurfaces Integrating

A PBG arrangement is effective to decouple adjacent meta-atoms. This suppresses localized near-field cross-talk to ensure that each pixel performs exactly as the holographic algorithm intends. This reduces the phase errors, and cleans up coverage pattern. Multi-beam operation was realized by Lian et al. **[33]** by integrating Luneburg lenses with stacked horns, while Nguyen and Byun **[38]** proposed honeycomb-shaped holographic Metasurface antennas substrates and boundaries address fundamental hardware constraints such as surface-wave loss and profile thickness. The PBG lattice is applied as an isolating wall. The lateral substrate modes are suppressed, thus limiting the energy to the active feed line. This enables the developers to pack multiple feed networks together with tight spacing and at the same time achieve high port-to-port isolation, for clean independent beam shapes. Instead of letting energy escape horizontally through the board, the PBG forces trapped energy back upward into free space. This directly increases the radiation efficiency and enables multibeam antennas to scan at wide, low-elevation angles without losing signal strength.Maximizes Efficiency **[23]**: Converts wasted surface wave energy to useful radiated power. Cleans up beam shapes Reduces sidelobes Prevents multiport interference Enables Planar Profiles: Replaces bulky, heavy 3D metallic shielding structures with a lightweight, flat, etched PCB pattern.

TABLE 1
ADVANTAGES OF PBG STRUCTURES IN ANTENNA DESIGN

Feature	Improvement
Surface wave suppression	Higher efficiency
Radiationcontrol	Higher gain
Harmonic suppression	Reduced interference
Bandwidth Enhancement	Wideband performance
Mutual Coupling reduction	Better antenna array performance

VI. ANTENNA MINIATURIZATION AND SIZE REDUCTION TECHNIQUES

A. Miniaturization Mechanisms Through PBG Integration

Band gap structures allow for antenna miniaturization by taking advantage of electromagnetic characteristics that allow a decrease in electrical wavelengths and frequency. MPCs show slow wave behaviour that allows for minimal reflection when an air-crystal interface is encountered. This makes possible an antenna that can be miniaturized up to 25-30 times its actual size without any loss in radiating efficiency **[40]**. The phenomenon on of slow waves results from the low speed at which waves travel in these structures. Antenna with slotted ground plane combined with photonic crystal principles achieve 50% antenna size reduction while preserving working range and gain characteristics **[41]**. Miniaturized RFID reader antennas based on composite right-/left-handed (CRLH) negative order resonance achieve size reduction through first-resonance (-1st mode) operation, producing compact antennas with efficiency exceeding conventional designs **[42][44]**. Split-ring resonator arrays embedded in low-permittivity dielectric substrates achieve miniaturization factors as high as 25.54 times compared to high-permittivity dielectric resonator antennas without significant performance degradation **[43]**.

B. Bandwidth Enhancement In Combination With Miniaturization

Another important innovation in PBG antenna design is the ability to simultaneously realize the antenna's small size and wide operating bandwidth, which were previously regarded as mutually exclusive goals. The implementation of reactive impedance surface (RIS) in conjunction with polarization converter metasurfaces allows obtaining 22.3% wider signal matching bandwidth along with 78.9% volume reduction **[45]**. Slotted patch antenna designed using PBG substrate materials exhibits wide bandwidth beyond 213.75% with left-handed metamaterial loading **[46].** Multiplicity of cavity and resonator structures utilizing PBG concept results in quad-resonances, thus providing 33.86% fractional bandwidth and maximum realized gain of 7.97 dBi**[47].**The multiplicity principle for resonances due to hybrid cavities allows creating several impedance maxima, thus increasing operating bandwidth without any additional size limitations. Antennas implemented with PBG concept and having corrugated ground structure allow realizing 43.8% antenna size reduction within 5.8 GHz ISM band **[48].**

C. Material Innovations for PBG-Based Antennas.

Modern implementations of PBG antennas rely on complex materials other than simple FR-4 or Roger’s substrates. Three-dimensional printing of photonic crystals based on alumina ceramics and other materials is possible for accurate control over lattices shapes and materials which were not achievable before through conventional technology **[54]**. Composite photonic crystals combined with Maxwell Garnett theory of small flat patch antennas results in enhanced permittivity due to use of fumed silica combined with RT-Duroid dielectric substrate materials providing maximum gains at C-band, X-band and Ku-band equal to 13.89 dB **[53]**. Quantum dots-based photonic structures are applied in silicon photonics to provide enhanced natural light emission as well as high mode confinement at frequencies below terahertz [49]. Inexpensive artificial dielectric resonant antennas based on three-dimensional printing microwave materials combine conductive and dielectric filaments of equal fusing temperature which allow tuning of their effective permittivity and permeability in very wide range **[50]**. Graphene-based photonic materials represent next generation solutions which provide tunability and reduced losses compared to conventional metal-based structures.

D. Manufacturing and Integration Advances

The advent of modern fabrication techniques has made it possible to create exact PBG structures. In fact, 3D printing allows the quick and effective construction of prototypes for intricate designs of photonic crystal geometries, especially useful in terahertz applications, where traditional machining turns out to be very expensive **[51]**. Inkjet and aerosol jet printing technologies ensure an easy and convenient method of facilitating direct patterning of engineered material patterns on flat surfaces, thus allowing compatibility with traditional microelectronics **[52]**. Screen-printing approaches have helped in the realization of photonic bandgap antennas that use conductive inks printed onto cotton polyester substrates, useful for the integration of these devices into wearables for medical purposes **[53]**. The use of laser direct structuring and micromachining techniques is helpful for micron-scale precision in creating PBG structures, necessary in the case of millimeter-wave and terahertz applications where features get close to the wavelengths of operation.

VII. PERFORMANCE ANALYSIS AND COMPARISONS

A. Quantitative Performance Improvements

Various comparisons show significant and substantial benefits from PBG-based antenna designs. Gains of up to 3.5 dB with peaks above 10 dB have been reported for various types and frequency ranges of antennas **[24]**. The bandwidth improvement ratio averages 45% and has been found to exceed 100% through advanced PBG material design **[46]**. Effectiveness in surface wave suppression, which is among the main advantages offered by PBG, results in 65% reduction through optimization of the lattice parameters **[26]**. Effective reduction of mutual coupling between closely spaced antennas has been reported to range from -10 dB to -60 dB with the help of metamaterial EBG decoupling mechanisms **[25]**. Miniaturization results averaging 35% and reaching 89% have been reported **[55]**.

B. Reliability and Environmental Tests

There have been exhaustive studies on the environmental robustness of PBG-based antennas regarding various temperaturerages, humidity levels, and bends suitable for practical application purposes. The transparent EBG-backed wearable antennas cancontinue to operate optimally even after undergoing deformation, experiencing gain differences of only 1.55 dBi over the expected body bends **[56]**. SAR studies always reveal consistent reductions of more than 95% of SAR through the use of EBG backing,with observed values going as low as 0.0859W/kg, far below regulated maximums **[57]**. The two emerging design needs foron body devices include frequency stability and detuning robustness. EBG-backed antennas display outstanding frequency detuning immunity, with measured results indicating that there was less than 3% frequency shift in the curved body areas,compared to the 15-20% experienced by equivalent conventional antennas **[58]**.

C. Prospective Research Pathways

Future Research Directions for PBG antenna design will be:

a) AI optimization: Optimization techniques utilizing computers will be employed for the determination of the best PBG lattices using bandwidth, gain, and EMI reduction as criteria. Predicting performance trade-offs will be achieved accurately without using extensive prototyping.

b) 6G and ultrahigh frequency links:PBGs will find application for very fast speed devices like wireless and sensing applications **[60],[31],[32]**. Design photonic crystal antennas with meta surfaces to achieve miniaturized terahertz antennas.

c) Topological photonic structures: Design novel techniques on topological photonic insulator structures using spin-photonics to get leaky waves resistant to manufacturing defects **[35],[29],[62]**. Look into the possibilities that exist in kagome and honeycomb lattice structures and how they can be used in the control of polarization states and multi-beam applications.

d) 3D Printing/Additive Manufacturing: Design novel dielectric material using 3D printing for high-frequency PBG antennas **[63],[64]**.

e) Compact and wearable applications: Miniature PBG antennas for medical sensing applications and wearable electronics **[65]**. Emphasis will be put on flexible materials that are able to retain bandgap characteristics even when bent.

f) Improved Reconfigurable and Adaptive Arrays Improvement in the performance of the smart EBG photonic array by utilizing the tunable bandgap properties of beam steering. The frequency flexibility above the Ka-band frequencies can be achieved through the use of liquid crystal-based phase shifters **[62].**

g)Hybrid Metasurface-EBG Structures:Hybrid metasurface structures using metallo-dielectric groove gap waveguides **[66]**, **[67]** with PBG lattices for improved electromagnetic interference (EMI) protection.

Explore Fabry–Perot resonator arrays **[68]**, incorporating PBG layers for excellent directivity. Research in Quantum and Optical Communication focuses on photonic dimers and nanorod lattices **[69]** for quantum communication networks.

VIII. ADVANCING TECHNOLOGIES AND OUTLOOK AHEAD

A. *Smart Pathways in Topological Photonics*

Light antenna structures will play a vital role in future antennas due to quantum mechanical properties exhibited by photons for manipulating electromagnetic waves in ways never before seen. Using reciprocal PTI metasurfaces, it is possible to develop a novel way of generating a radiation process with the ability to control its impedance automatically within the entire photonic insulator bandgap region **[70]**. These structures are able to produce leaky-wave radiation and orbital angular momentum beams using edge modes, making it possible to create entirely new types of antennas. Antennas that are capable of reconfigurable photonic bandgap using PIN diode technology are used in cognitive radio for frequency and radiation pattern changes. Time-varying metasurfaces create momentum bandgaps for surface waves as well as free-space waves at the same time, resulting in the amplification phenomenon of waves within bandgaps **[71]**.

B. *Integration with 6G Systems and Beyond*

Terabit wireless demands antenna capabilities beyond current 5G capabilities, with focus on sub-terahertz and submillimeter waves, massive MIMO arrays, and combined sensing-communication functions. Phototunable topological photonics achieve 160 Gbps waveguide operation with on-chip cavity-based demultiplexing without crosstalk **[72]**. These systems leverage Silicon Valley photonic crystal topological properties to create defect-free optical waveguides and efficient couplers suitable for heterogeneous integration with RF frontends. Photonic antenna systems employing multi-beam antennas using photonic quasi-optic methods provide efficient coverage in large geographical regions at low cost and small size, which is critical to applications in satellite and ground backhauls **[73]**. Photonic all-dielectric horn antennas made by 3D printing provide an effective solution using millimeter-wave technology with gain levels between 10.6-13.9 dBi between frequencies of 25-27 GHz **[74]**. This places photonic bandgap technology as a key enabling technology platform for 6G requirements.

C. *Integration with Artificial Intelligence and Machine Learning*

The use of ML model based on photonic bandgap theory has emerged to be a very promising solution to such highly complex multi-parameter design landscapes. The training of ML algorithms on simulation results obtained through EM computations of thousands of photonic bandgap designs helps in quick identification of optimised design based on the desired specifications [40]. Design of beam scanning array antenna for 5G communication using millimeter wave frequency and multi-configurable beamformer technology can be optimized with the use of CNN based approach **[75].**By using the different techniques, we have been successful in optimizing the multi-port wavelength division multiplexers **[76]**.

D. *Uses and Development Directions of PBG Antennas (with CST)*

Future applications of PBG antenna structures will be in emerging in 5G/6G ,THz and Satellite systems.

Fig.7: Future applications of PBG Antenna

These are ideas that will be explored using techniques like beam forming, harmonics suppression, and metasurface integration. a) Parametric Optimization Using AI/Machine Learning Leverage the parametric sweep and optimization functionalities of CST to train machine learning models that will optimize lattice parameters, defect locations, and substrates properties. Optimize bandwidth and gain while minimizing surface wave loss.

b) Investigation of 6G & Terahertz bands Investigate photonic crystal and metasurface antennas using CST simulation tool at terahertz bands. Verify dispersion diagrams and behaviour of bandgaps useful for ultrafast communications and sensing. Example: Use CST eigenmode solver to investigate epsilon-mu-near-zero photonic crystals**[77]**.c). Topological Photonic Structures: Model spin PTI and kagome lattices **[36]**, **[78], [79]** using CST to investigate leaky-wave radiation robustness. Utilize CST field monitors to observe edge states and ensure defect tolerance to manufacturing errors). 3D Printing and Materials Research Load CST with CAD models of 3D-printed dielectric lattices **[34]**, **[32], [80]** for simulation validation. Investigate the impact of anisotropy and loss tangent on materials for guiding practical fabrication's). Biomedical and Wearable Devices Model flexible substrates in CST to examine effects of strain on PBG properties **[35]**. Make use of CST's bio-tissue library in simulations to test SAR (Specific Absorption Rate) compatibility for biomedical applications. Reconfigurable/Adaptive Arrays. Introduce tunable EBG arrays **[28]** in CST incorporating either varactor diode elements or liquid crystal phase shifters **[15]**. Perform time domain analysis to demonstrate dynamic beam steering and (frequency agility capabilities) Hybrid Metasurface-EBG Design Integrate groove gap waveguides **[66], [67]** with Fabry-Perot resonator arrays **[11]** within CST to study polarization purity and electromagnetic interference reduction capabilities. Apply CST's S-parameter simulation feature to quantify coupling and isolation.i) Quantum and Optical Integration: Expand CST simulations into optical frequencies and examine nanorod dimers **[69]** and photonic metasurfaces.

IX. CHALLENGES, LIMITATIONS, AND RESEARCH GAPS

A. *Technical Challenges and Performance Trade-offs*

Although considerable progress has been made, there are some technological limitations in PBG antennas that hinder their adoption in the future. First, robustness sensitivity is very important in implementing the sub-THz and Thz PBG antennas, which requires high tolerance levels in the order of ±5% of the feature dimensions, hence lowering the feasibility of manufacturing **[22]**. Secondly, dispersion effects in photonic crystals and their frequency dependency limit their suitability for ultra-wideband operations; hence, some dispersion engineering is necessary or even frequency band restrictions. Thirdly, low radiation efficiency, especially at very high frequencies, is an observed problem in some cases, where efficiency drop by over 50% **[72]**.

B. *Integration Complexity and System-Level Issues*

The employment of PBG antennas into transceivers, PDN, and the cooling system gives rise to some other issues that cannot be characterized using antenna parameters. The phenomenon of mutual coupling for the MIMO configuration made up of closely located PBG antennas poses certain problems, although these have been successfully addressed when creating PBG antennas **[81]**. Frequency tuning techniques applied during the design of tunable PBG antennas produce a few additional drawbacks which partially neutralize the benefits provided by this innovative approach. There are no established criteria for evaluating PBG antennas, thus making any comparison of the results presented in scientific literature impossible **[52]**.

X. INDUSTRIAL APPLICATIONS AND COMMERCIAL DEPLOYMENT STATUS

A. *Telecommunication Infrastructure*

Telecom deployment is increasingly making use of PBG antennas for both 5G base stations that need to accommodate multi-band operations and MIMO architectures. Small-cell base stations commercially deploy patch antennas integrated with EBG technology, capable of delivering gain of 12 dBi and isolation of -25dB between the antenna elements, allowing dense urban deployment **[83]**. Backhaul antennas with PBG structures can simultaneously operate on different frequency bands ranging from sub-6GHz up to mm-wave bands, without compromising performance.

B. *Consumer Electronics and Wearables*

Consumer device implementations have started incorporating photonic bandgap concepts through integrated antenna modules combining metamaterial layers with conventional patch radiators **[56]**. Smartwatch and fitness tracker antennas utilizing uniplanar compact EBG structures achieve multiband capability with form factors compatible with consumer device aesthetics and comfort requirements. EBG-based medical implants have also become quite common, where clinical trials have shown their performance as well as biocompatibility **[58]**.

C. Military and Space Applications

PBG-based antennas in aerospace provide compact implementation due to the constraints on size and weight **[84]**.In satellites, PBG substrates in the antenna improve gain and hence enable lower transmit power, resulting in a reduced weight, power consumption, and costs. Military use PBG antennas for beam steering and spectrum agile operations in the electromagnetic environment.

XI. CONCLUSION AND FUTURE OUTLOOK

Innovation in photonics' field of study has resulted in a dramatic shift in wireless antenna design, which has made the simultaneous realization of seemingly incompatible goals, including miniaturization, widening bandwidth, increasing gain, and overall downsizing, possible **[20]**. The development from 2006 to 2026 suggests not only a steady growth in number of publications and applications, but also a transition from theoretical research to practical use in the context of 5G technology, portable devices, and special cases like terahertz communication systems **[52]**.

Using modern materials, especially 3D printed ones and composite materials, was instrumental in overcoming previous limitations, thus enabling cost-efficient production, which is important for mass production. In light of possible uses of modern photonics, the optimization opportunities provided by artificial intelligence and their potential application in future generations of wireless technology, especially 6G systems, it can be concluded that photonic bandgap antennas may very well be in the early stages of development even after two decades since the first appearance.

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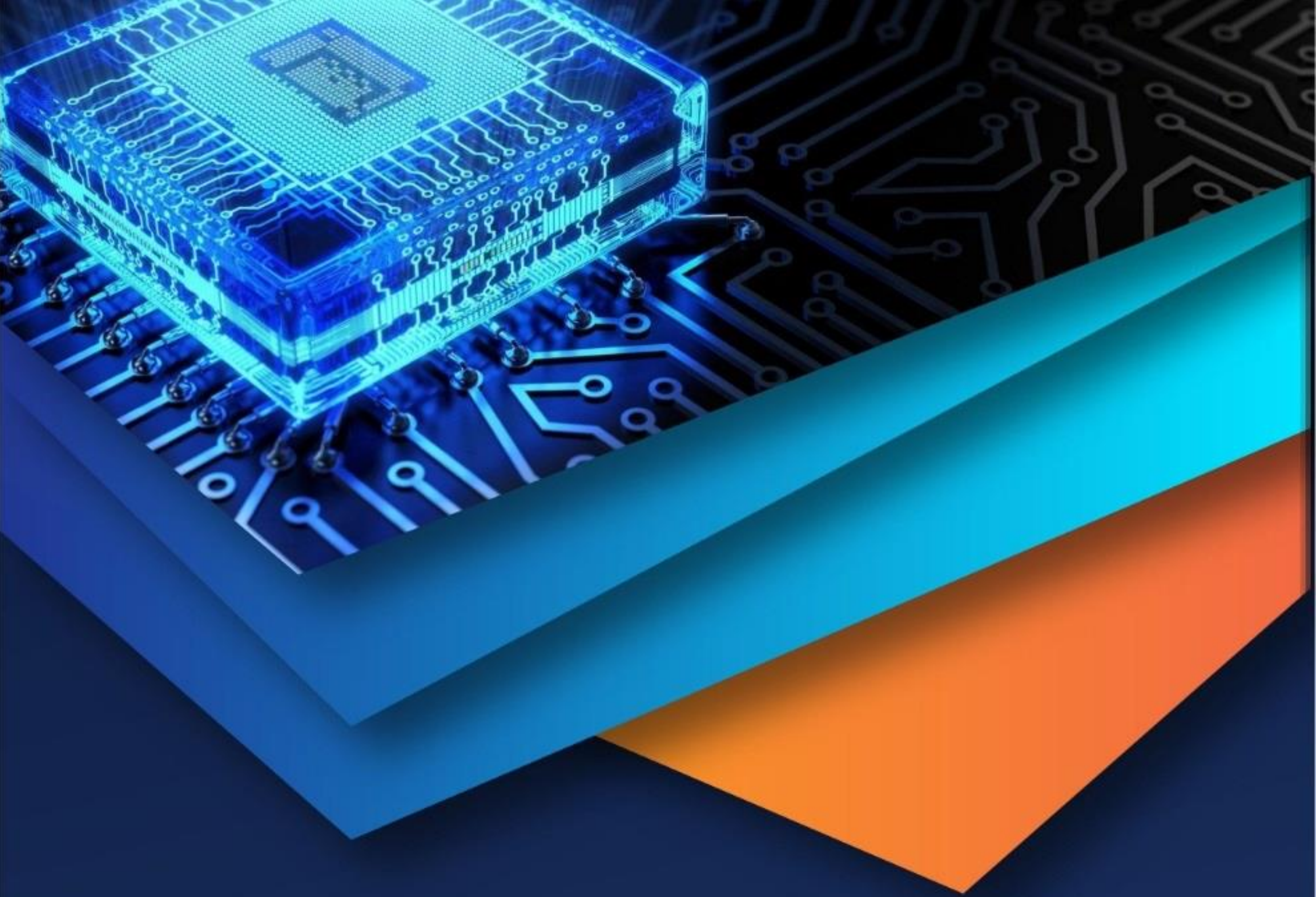

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