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Analysing Antennas with Artificial Electromagnetic Structures for Advanced Performance in Communication System Architectures

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Abstract

Research into antennas along with artificial electromagnetic designs, such as metamaterials and metasurfaces, has attracted substantial interest in recent communication systems. The unique electromagnetic properties manifested in these engineered materials are missing in natural materials, leading to better antenna performance in various ways. The purpose of this investigation is to evaluate the design and implementation of these fake structures in order to improve antenna efficiency, bandwidth, directionality, and size reductions. Metamaterial-based antennas permit remarkable management of electromagnetic waves, facilitating the manipulation of wave propagation, polarization, and radiation patterns. This end result results in higher signal strength, decreased interference, and improved power efficiency, particularly important in high-frequency communication networks such as 5G and 6G. Also, the ability to design efficient and lightweight antennas that preserve performance will be important for tomorrow's communication systems, covering satellite communications, the Internet of Things (IoT), and wearable devices. The specific goal of this study is to address these artificial electromagnetic structures used for various communication environments, with specific questions pertinent to fabrication, scalability, and integration of these structures within the present systems. Integration of these advanced materials into the antenna system can significantly enhance the wireless communication significantly, forming the foundation of much improved, adaptable and robust communication systems in the years to come.

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Introduction

New advancement in wireless communication has revolutionized the design of antennas. Not surprisingly, as the need for higher performance small form factor devices rises, engineers are now adopting artificial magnetic problems to try and achieve the impossible. Such revolutionary physical substances as metamaterials now transform the possibilities of designing antennas, providing an ability to influence the character of electromagnetic waves and improve crucial parameters, including bandwidth and isolation. This article is focused to explore fascinating subject of novel antenna designs employing artificial electromagnetic conducting structures. IIt gives an insight on the basic concepts and their implementation in development of advanced antenna elements. It also describes ways of improving the performance of antennas and briefly goes over the main aspects like the ability to alter the resonant frequency and minimise the size of the antenna. Which leads us to the final section of the book that gives practical information as to how these innovative antennas can be built and measured in this first-ever book that presents a comprehensive overview of a progressive field that is revolutionizing wireless applications.[1-4]

Fundamentals of Artificial Electromagnetic Structures

The development of artificial electromagnetic structures, primarily metamaterials, has dramatically transformed antenna design due to its characteristics that are not available in nature. These materials have remarkably high electromagnetic properties, which originate in the size of the materials on the nanoscale level rather than in their composition. This new strategy generated new opportunities for regulation of electromagnetic waves, expanding the perspectives for more progress in wireless communication devices and antenna.

Types of Metamaterials

Metamaterials can be classified into several categories based on their electromagnetic properties:

1. Single Negative (SNG) Materials: These are epsilon negative (ENG) which have negative permittivity or mu negative (MNG) which has negative permeability.
2. Double Negative (DNG) Materials: These are also referred to as left handed materials (LHM), these materials possess both negative permittivity and permeability.
3. Double Positive (DPS) Materials: These have positive values of permittivity and permeability.
4. Zero Index Metamaterials (ZIM): These materials either have low permittivity or permeability, which ranges near to zero.

In general the three classes of metamaterials provide a unique advantage in altering the electromagnetic properties of an antenna depending on its use. Properties ad Characteristics, particularly metamaterials, have revolutionized antenna design by offering unique properties not found in nature. These synthetic materials exhibit extraordinary electromagnetic characteristics, stemming from their nanoscale structuring rather than their chemical composition. This innovative approach has opened up new possibilities in controlling electromagnetic waves, leading to significant advancements in wireless communication and antenna performance.

Properties and Characteristics

Metamaterials are thus characterized by unique properties that stem from their structures, which are constructed deliberately. Some key characteristics include:

Negative Refraction: This makes it possible to exercise immense control over the management of electromagnetic waves resulting in formation of special super lenses with sub-wavelength resolution.

Tailored Electromagnetic Properties: The possible to let permittivity and permeability be adjustable allows for various degrees of wave control and engagement.

Subwavelength Resolution: Meta materials can interact with the waves at dimensions less than the size of a wavelength of the specified electromagnetic wave, resulting in better antenna sizing.

Dispersion Control: Another important parameter of metamaterials is the frequency dependency which depending on the application affects bandwidth in case of antenna.

Anisotropy and Bianisotropy: They point control of EM waves in a particular direction and affect the radiation pattern of an antenna.This has implications on the radiation pattern of an antenna.

Applications in Antenna Design

The unique properties of metamaterials have led to numerous innovative applications in antenna design:

1. Bandwidth Enhancement: Inspirited by metamaterials, the improved parasitic antennas can successfully solve one of the significant problems in the design of the antennas, namely ultrawide bandwidth.
2. Miniaturization: This paper also shows that through the use of the subwavelength properties of metamaterials, an engineer is able to design electrically small antennas and still achieve optimized performance.
3. Gain Improvement: Metamaterial structures may help to increase antenna gain resulting in more directive and efficient antennas.
4. Frequency Reconfigurability: The difficulty in designing compact metamaterial-based antennas is tied to the dispersive characteristics of filters, where it is possible to achieve frequency-tunable operation.
5. Polarization Control: Metamaterials used in antennas have better control of polarization of the waves passing through thereby improving signal quality in areas of wireless communication.
6. Isolation Enhancement: Metamaterials apply in multiple input multiple output (MIMO) where they decrease signal coupling between the antenna factors which enhance the entire system performance.

Of them one particular type of application can be stated, namely the use of what are known as Artificial Magnetic Conductors which work in analogous way to the external perfect Magnetic Conductors which are in fact not real. These circuits have been implemented are being successfully integrated into the design of antennas that facilitates transmission between the antennas and increase RFID detection ranges. The incorporation of metamaterials in antenna structures have, therefore, ushered in groundbreaking improvements in handling of core issues including size miniaturization, performance boost, and selective operational frequencies. These enhancements have particularly rendered the metamaterial based antennas desirable for use in radar applications, wireless communications and sensing. With advancing research in this area, even more, possibilities can be seen whereby metamaterials can bring a greater set of advancements in the design of antennas and wireless communications. Electromagnetic properties can now be designed at the nanoscale, so even more efficient, compact and versatile antennas can be expected to be developed in the future.[5-7]

Design Principles of Innovative Antennas

It is clear that when designing new and complex antennas made from artificial electromagnetic structures, several parameters must be taken into account in order to obtain the best results. Section 3 discusses some of the factors designers use to design modern and efficient antennas that can fulfill their intended functions.

Substrate Selection

For this reason, the substrate has a potential to affect the built-in antennas in different ways as shown above. Regarding emerging approaches in designing the antenna, the engineers are considering using the engineered substrates having spatiometamaterial electromagnetic characteristics. These substrates can significantly enhance the performance of metasurface antennas by enabling the control of the direction of the electromagnetic waves (Table 1).

A potentials one is direct manufacturing using Space Filling Curves (SFC) for microwave application additively manufactured engineered substrates. These SFC substrates offer several advantages:

Expanded design space: So, by changing the local substrate permittivity and using SFCs in combination with printed dimensions of conductive patches, designers can bring the range of achievable surface impedances forward significantly.

Increased gain: An important application of the SFC-substrate is the exploitation of the increased design space for the improved gain of a metasurface antenna for the given size.

Rapid fabrication: Production of these SFC substrates has been eased by the advanced manufacturing systems like the nScrypt 3Dn-300 which can fabricate these substrates in a short time.

Patch Geometry Optimization

Radiation characteristics of an antenna patch are also influenced by the shape of the patch. In reality, originality when designing antennas may involve the use of complicated patches and several shapes. For instance, the 'Flower Metamaterial Antenna looks like the center of a flower with petals.

Key considerations for patch geometry optimization include:

Multiband operation: When the geometry of the patch is well selected, the operation of antennas is effective at multiple bands and hence making them flexible.

Miniaturization: This kind of patch shapes can allow achieving size miniaturization without affecting the efficiency of the radiator, which is specifically important for applications where space is a limiting factor.

Bandwidth enhancement: The designs can be optimized to render more bandwidth, which goes to solve one of the central issies of the designs of the antennas.

Radiation pattern control: To enhance directivity and gain, certain configuration features may be made to patch elements so as to form the desired radiation pattern.

Table 1. Designs for Specific Bands

Frequency Band	Antenna Type Suitable	Common Applications	Design Considerations
HF (3 - 30 MHz)	Dipole, Yagi-Uda	Amateur radio, shortwave	Requires longer elements
VHF (30 - 300 MHz)	Log-Periodic, Yagi-Uda	TV broadcasting, FM radio	Compact design needed for urban areas
UHF (300 MHz - 3 GHz)	Patch, Microstrip	Cellular, Wi-Fi, GPS	Miniaturization and bandwidth optimization
SHF (3 - 30 GHz)	Parabolic, Phased Array	Radar, satellite communication	High-gain, focused patterns required
EHF (30 - 300 GHz)	Horn, Parabolic	Terahertz communication, 6G	Precision design, high-frequency loss mitigation

Feed Mechanism

Another area that is affected by the feed mechanism is the impedance matching and therefore the performance of the antenna. Consequently, in modern develop novel design of the antenna, engineers have been investigating a number of feeding techniques with respect to the weaknesses observed previously.

One of the discussed solutions is the use of a modified co-planar waveguide (CPW) feed. This feeding mechanism offers several advantages:

Lower losses: CPW feeds are found to have much lower losses than microstrip lines if directly deposited on high resistivity silicon substrates.

Reduced sensitivity: They are not as dependent on bulk parameter specifications, for instance carrier concentration.

Improved impedance matching: Feed line width and distance from feed line to ground can be varied to get the feed line impedance to match the antenna's input.

Compatibility with on-chip designs: CPW feeds are much preferred for integrated on chip antennas for incorporation on silicon based technologies.

Substrate thickness, dielectric constant etc., are known parameters when designing a feed mechanism, and preferred operating frequency. For example, in a high resistivity silicon microstrip design, a 300-μm thick wafer may be used with CPW feed line on a higher metal level above thin layer of silicon dioxide. With these design principles in mind, engineers can design new antennas that would achieve better performances than present off-the-shelf ones: substrate selection, patch geometry optimization, and feed mechanism. These advanced designs have promise for the evolution of wireless communication systems to yield higher efficiency and

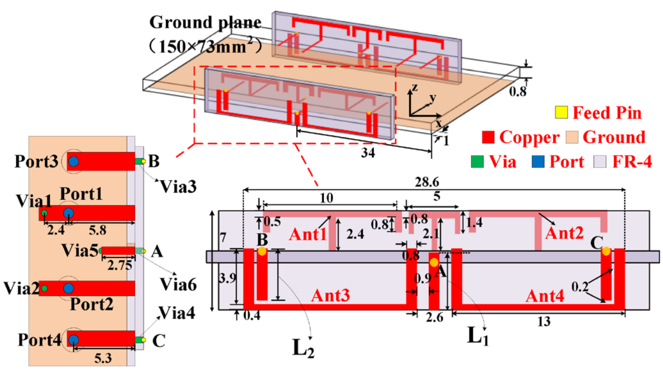

Fig. 1. Advanced design of antenna with aid of artificial electromagnetic structures

miniaturized equipment in numerous applications.[8]

Metamaterial-Inspired Antenna Elements

Metamaterial-inspired antenna elements have emerged as an innovative concept drawing from the idea of small antennas that can provide superior performance and reduced sizes. These novel architectures utilize the rather unique electromagnetic properties of metamaterials in ensuring that communication systems that have been_ wireless_ for a long time are not constrained.

Split Ring Resonators

This research focuses on metamaterial inspired Antennas with particular attention to the most basic structures of Split Ring Resonators (SRRs). After their introduction by Pendry in 1999, SRRs incorporated into a periodic lattice have become one of the most frequent components of metamaterials because in the vicinity of the SRR resonance frequency, they produce negative effective magnetic permeability of the medium. Consequently, a typical SRR configuration includes two concentric annular ring, having gaps in the inner and outer surfaces with opposite directions. This geometry enables SRRs to couple with resonant wavelengths larger than their size, thus offering possibilities of shrinking antennas. Key parameters of an SRR include:

- Outer radius (R): 3.6 mm
- Inner radius (r): 2.5 mm
- Ring width (w): 0.2 mm
- Gap between rings (t): 0.9 mm

SRRs have had a significant impact on antenna design, enabling:

Electrically small antennas: SRR-based antennas can work at λ/10 or even λ/40 if the wavelength as compared with λ/2 conventional antennas.

Increased radiated power: The power radiated by electrically small dipole antennas can be improved significantly by encapsulating an antenna with a layer of DNG material.

Natural impedance matching: The DNG material is realizable as a matching network for the antenna, to reduce the amount of reactance and increase efficiency..

Complementary Split Ring Resonators

A related structure is the Complementary Split Ring Resonators (CSRRs) which are similar to SRRs but provide more advantages to antenna designers. CSRRs work not only for the loading purpose but also for the radiator as a result less number of antennas could be design in compact manner efficiently.

A notable example is the T-complementary split-ring resonator (T-CSRR) antenna, which demonstrates:

Compact size: The latter variety can have significantly smaller radiators thus having close to 74% smaller circuit dimension than the typical half-wavelength slot antenna, and about 50% less than a T-shaped monopole antenna.

Reasonable gain: As a result, a T-CSRR antenna employed alone can offer a gain of 3.1 dBi as well as competitive slot antennas.

Array configurations: Using multiple geometries of T-CSRR configurations to createParallel 1 × 4 T-CSRR antenna arrays offer gains as high as 9 dBi at 2.45 GHz for potential high gain applications.

Current trends in development of CSRR have enabled near perfect designs that can be very useful in ambient power harvesting. These novel CSRR designs exhibit:

- High absorption efficiency: Efficiencies of up to 99% in the specific carrier frequencies within the S-and C bands.
- Polarization insensitivity: Quite a stable response within the variation of the angles of incidence.
- Compact size: Slightly less in size than previous designs but considerably more efficient.

Electric-LC Resonators

Another type of metamaterial-inspired antenna antennas is known as Electric-LC (ELC) resonators have attracted interest in recent years. These structures are intended to have pronounced electric resonances that should enhance magnetic resonances of SRRs.

ELC resonators offer several advantages in antenna design:

Frequency tunability: It has also been noticed that ELC structure resonate at frequencies which can be easily controlled by the geometric dimensions of the designed antenna.

Multiband operation: A number of ELC resonators may be consequently incorporated within an antenna structure with each resonator tuned to a different operating frequency range.

Enhanced bandwidth: Because the frequency selection is flexible with ELC resonators, wideband or even ultra-wideband antennas can be produced by designing the resonators in an appropriate way.

The integration of these metamaterial-inspired elements such as SRRs, CSRRs, and ELC resonators in the antenna designs have illuminated the way to some advanced forms of compact and efficient antennas. These structures could provide solutions to the major problems facing wireless communication systems including size reduction, wide bandwidth and isolation problems in MIMO systems. With continues development of research in this area, enhanced and more complex metamaterial inspired antenna elements are likely to bebrought to light promising innovative and high-performance antennas for future generation wireless communication systems.[9]

Performance Enhancement Techniques

Antennas proposed using artificial electromagnetic structures have been useful in the evolution of antennas. These techniques have helped the engineers to overcome some of the traditional barriers in engineering and thus has improved most of the Paradigm Key Performance indicators. This section explores three crucial aspects of performance enhancement: solution techniques can be divided into bandwidth increase techniques, gain up techniques, and downsizing techniques.

Bandwidth Improvement

Increasing bandwidth has remained a key concern in antenna design especially for systems intending to operate on multiple frequency bands in wireless communication systems. In this respect, antennas inspired in metamaterial have shown remarkable capacity. An approach seen and explains how bandwidth can be increased, at the same time mututal coupling reduced thru the use of split ring resonators (SRRs). The enhancement of bandwidth using the integration of CSRRs has been considered successful in this study. These structures serve not only as loading members but also as radiators resulting in small, efficient antennas. For example, T-complementary split-ring resonator (T-CSRR) antennas have been realized to have reasonable gains of 3.1 dBi using a compact size (Table 2).

Modern innovations in CSRR design have produced structures which exhibit extremely high coupling coefficients within the operating frequencies to be used therefore acting as efficient ambient power harvesting structures. All these new CSRR designs shown in Fig.2 offer resonant absorption efficiency as high as 99% at a few selected S&C band frequencies, and angular variation insensitivity to the plane of polarization.

Gain Enhancement

Table 2. Testing Methods

Test Type	Description	Testing Equipment	Purpose
Network Analyzer Test	Measures impedance and return loss	Vector Network Analyzer (VNA)	Ensures impedance matching and minimal signal reflection
Anechoic Chamber Test	Tests radiation pattern and gain	Anechoic Chamber, Antenna Positioner	Visualizes antenna radiation characteristics
Field Strength Test	Measures the strength of the radiated field	Field Strength Meter	Determines effective range and coverage
Near-Field Scanning	Examines the near-field behavior	Near-Field Scanner	Optimizes antenna for near-field applications
Temperature/Humidity Testing	Measures performance under different conditions	Environmental Chamber	Ensures antenna durability and reliability in harsh environments

Enhancing the gain of the antenna has been a great endeavour, particularly for those antennas that will be working in the near field of the human body. Several techniques have been developed to address this issue:

1. Metamaterial (MTM) superstrates: The gain enhancement results obtained with the usage of MTM with low-refractive index, zero-refractive index, and high-refractive index have been significant.
2. Electromagnetic band gap (EBG) and frequency selective surfaces (FSS): These structures have been used to make antennas as superstrates so as to enhance its antenna gain.
3. Grounded MTM: This approach has been shown to improve gain significantly for planar antennas when placed above the plane of the antenna.
4. μ-very-large (MVL) property: This characteristic of MTM has been used in the improvement of the gain of the electric sources.

For instance, the application of these methods provides about 3 dB of the gain enhancement with an SAR of 0.405 W/kg (1 g tissue). This approach shows the feasibility of achieving both gain and SAR control, which is highly influenced by biomedical antenna applications.

Miniaturization Methods

Since the usage of compact wireless portable devices is a trend, miniaturization of antennas is one such important parameter that deserves critical attention. Several methods have been developed to reduce antenna size without compromising performance:

1. CSRR loading: Such an approach has been effective in achieving reduced size particle. For example, CSRR enabled the reduction of the size by 55.17%, with the antenna working in the 2.34GHz instead of 4.8GHz.
2. Space Filling Curves (SFC): Such structures have been combined to synthesize additively manufactured engine ered substrates where the electromagnetic wave interactions and the effective gain for the antenna size of the metasurface used have been further enhanced.
3. Patch geometry optimization: The geometries of the patch have been made more intricate as seen in the "Flower Metamaterial Antenna" in order to achieve both multiband operation and miniaturization.
4. Substrate engineering: Engineered substrates having electromagnetic characteristics change within the substrate volume are the basis for development of compact antennas with higher characteristics.

These PER performance enhancement techniques have greatly transformed the procedures used in creating efficient and compact antennas for different uses. The study in this areas equally promises future innovation in metamaterial based antenna elements, with additional possibility of even more complex and more advanced technical antenna for future fourth generation wireless communication systems.[10]

Fabrication and Measurement Considerations

Designing and characterizing modern forms of antennas in artificial electromagnetic structures demands much attention to some specific features. All these properties have significant implications in making wireless communication system antenna to be precise and accurate.

Prototyping Techniques

Some of the most significant changes in the design of prototyping of antennas are brought by the additive manufacturing system. New manufacturing technologies like the nScrypt 3Dn-300 system makes it possible to print engineered substrates for electromagnetic wave with varying amplitudes in short time. Actually, this capability has opened new design opportunities for the metasurface antennas to control the directives of an EM wave and for obtaining more gain than required per unit size of the antenna.

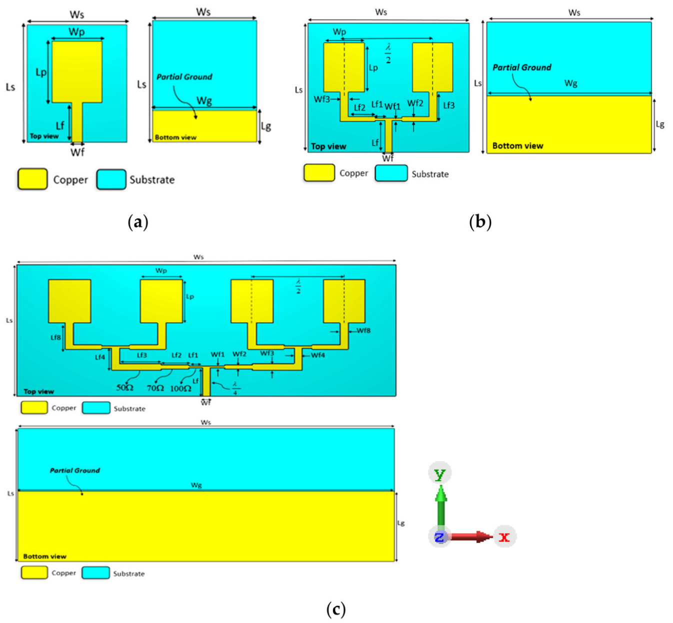

Fig. 2. Fabrication and Measurement Considerations

One innovation includes applying Space Filling Curves (SFC) manufacturing technology to generate engineered substrates through microwave additive manufacturing systems. These SFC substrates offer several advantages, including:

1. The design space available for realizing a gamut of surface impedances is widened.
2. To achieve higher gain it has been observed that for a specific size of the metasurface antenna, larger values of metasurface gain can be obtained.
3. Fast prototyping, thereby, reducing the number of operations.

In fact, for metamaterial-inspired antennas including SRR or CSRRs, the geometrical size of the resonator structures should have high fabrication tolerance. To create structures having such strict dimensional precision, photolithography or electron beam lithography techniques may be used.2 Testing and Characterizationes the use of Space Filling Curves (SFC) to create additively manufactured engineered substrates for microwave applications. These SFC substrates offer several advantages, including:

1. Expanded design space for achieving a wide range of surface impedances
2. Increased gain for a given metasurface antenna size
3. Rapid fabrication, streamlining the production process

For metamaterial-inspired antennas, such as those using split ring resonators (SRRs) or complementary split ring resonators (CSRRs), precise fabrication of the resonator structures is crucial. Techniques like photolithography or electron beam lithography may be employed to achieve the required accuracy in the fabrication of these sub-wavelength structures.

Testing and Characterization

It has been ascertained that the performance of the designed antenna needs to be first tested and characterised in order to confirm the effectiveness of the design. Key parameters that need to be measured include:

1. Return loss: This parameter shows the quality of the match between the antenna's feed line and the antenna; this normally is measured by the VNA.
2. Radiation pattern: The 3-D radiation pattern of the antenna could be measured in an anechoic chamber using some specific measuring instrument.
3. Gain: Antenna gain can be calculated with the use of gain transfer technique, three antenna technique among others.
4. Bandwidth: The range of frequencies that the antenna is effective can also be deduced from return loss measurements.
5. Efficiency: Presentation of gain and directivity data can be used with radiation efficiency.

For antennas designed to be placed close to the human body, farfield pattern is not sufficient information; instead, SAR is of great importance. One particular experimental verification turned up approximately 3 dB of gain enhancement, and a SAR value 0.405 W/kg, for the 1g of tissue, a potential for conduction of both gain and SAR in biomedical applications of antennas were also demonstrated by metamaterial techniques [11]-[12].

Performance Validation

The second aspect of the staged measurement process is performance validation where the results were compared with modeled, emulated and expected performance. This process may include:

1. Electromagnetic simulations: By applying experiments aimed at modeling of the antenna's behavior through the use of the selected software tools as well as the comparison of the obtained results with the actual measurements.

2. Impedance matching verification: Guaranteeing the fact that the input impedance of the fabricated antenna is a match to the specified design within the operation frequency range.
3. Bandwidth verification: Verifying that the required bandwidth of the antenna is achieved or is above the required design rate.
4. Gain and radiation pattern analysis: Looking at Fig.10, it can easily be seen that measured patterns closely match the simulated one to check the directionality factor and thus the gain of the antenna.
5. Efficiency calculations: To evaluate directly the radiation efficiency of the antenna, using the measured values of gain and directivity.

This may be true for metamaterial-inspired antennas, where further steps may be required to ensure that the required EM properties are truly present. For example, NZRI superstrates and AMC surfaces that are geometrically optimized for desired electromagnetic response may warrant unconventional characterization methods.

Therefore, the material and measurement challenges for complex new antennas based on metamaterials are a higher level of fabrication methodology, sophisticated characterization techniques, and rigorous assessment of performance. These are some of the necessary procedures that have to be followed to guarantee that the fabricated antennas are correct to specifications and are capable of performing efficiently in accordance to their designed wireless communication applications.

Conclusion

Novel developments in the sector of artificial electromagnetic structures have great impact on the design of antenna and push the horizon of wire0less communication systems. It can be noted that incorporation of these new materials and methods affects vital parameters such as the bandwidth, gain and the size of the required antennas which in turn allows for the development of lighter and more effective antennas. Innovations with the help of metamaterials like split ring resonators, and their complementary structures have made it into what is fast becoming the next generation of innovative antenna structures. When planning for the future, the use of artificial electromagnetic structures for antenna design seems promising and full of future. Ongoing research in this area will further develop new, improved and high performance antennas for future wireless applications. As improved the fabrication technology and performance authentication methodology, the functionally advanced these prominent attractive antennas to come as electro-magnetic revolution of wireless application device system both in mass consumption use and in the scientific biomedical and aerospace specific areas are highly affirmative.

References

1. Radavaram, S. and Pour, M., 2021. A wideband coplanar L-strip fed rectangular patch antenna. IEEE Antennas and Wireless Propagation Letters, 20(9), pp.1779-1783.
2. Cicchetti, R., Faraone, A., Miozzi, E., Ravanelli, R. and Testa, O., 2016. A high-gain mushroom-shaped dielectric resonator antenna for wideband wireless applications. IEEE Transactions on Antennas and Propagation, 64(7), pp.2848-2861.
3. Edwards, Terry. “Semiconductor technology trends for phased array antenna power amplifiers.” In 2006 European Radar Conference, pp. 269-272. IEEE, 2006.
4. Alnahwi, F.M., Abdulhasan, K.M. and Islam, N.E., 2015. An ultrawideband to dual-band switchable antenna design for wireless communication applications. IEEE Antennas and wireless propagation letters, 14, pp.1685-1688.
5. Sato, G., 1991. A secret story about the Yagi antenna. IEEE Antennas & Propagation Magazine, 33(3), pp.7-18.
6. Zhang, T., Li, R., Jin, G., Wei, G. and Tentzeris, M.M., 2011. A novel multiband planar antenna for GSM/UMTS/LTE/Zigbee/RFID mobile devices. IEEE Transactions on Antennas and Propagation, 59(11), pp.4209-4214.
7. Steensma, B., van de Moortele, P.F., Ertürk, A., Grant, A., Adriany, G., Luijten, P., Klomp, D., van den Berg, N., Metzger, G. and Raaijmakers, A., 2020. Introduction of the snake antenna array: geometry optimization of a sinusoidal dipole antenna for 10.5 T body imaging with lower peak SAR. Magnetic resonance in medicine, 84(5), pp.2885-2896.
8. Zheng, J., Ala-Laurinaho, J. and Räisänen, A.V., 2019. On the one-antenna gain measurement method in probe station environment at mm-wave frequencies. IEEE Transactions on Instrumentation and Measurement, 68(11), pp.4510-4517.
9. Zhang, Z., Iskander, M.F., Langer, J.C. and Mathews, J., 2005. Dual-band WLAN dipole antenna using an internal matching circuit. IEEE Transactions on Antennas and Propagation, 53(5), pp.1813-1818.
10. Abreu, P., Aglietta, M., Ahlers, M., Ahn, E.J., Albuquerque, I.F.D.M., Allard, D., Allekotte, I., Allen, J., Allison, P., Almela, A. and Castillo, J.A., 2012. Antennas for the detection of radio emission pulses from cosmic-ray induced air showers at the Pierre Auger Observatory. Journal of Instrumentation, 7(10), p.P10011.
11. Ge, L. and Luk, K.M., 2012. A wideband magneto-electric dipole antenna. IEEE Transactions on Antennas and Propagation, 60(11), pp.4987-4991.
12. Asili, M., Chen, P., Hood, A.Z., Purser, A., Hulsey, R., Johnson, L., Ganesan, A.V., Demirci, U. and Topsakal, E., 2015. Flexible microwave antenna applicator for chemo-thermotherapy of the breast. IEEE Antennas and Wireless Propagation Letters, 14, pp.1778-1781.