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Developments And Difficulties in RFM Energy Harvesting Antenna Design and Rectifying Circuits

Abstract: **-** Energy-efficient, battery-free technologies are becoming more and more necessary as smart devices proliferate. These technologies are necessary to support IoT devices in Industry 4.0 and 5G networks, which demand minimal maintenance and sustainable operation. A carbon-free future is supported by integrating radio frequency (RF) energy harvesting with IoT and 5G technologies, which allows for real-time data collection, lowers maintenance costs, and boosts productivity. With an emphasis on low-energy device powering and far-field wireless power transfer, this overview examines the difficulties and developments in RF energy harvesting. It focuses on enhancing diode nonlinearity design while examining downsizing, circular polarization, fabrication problems, and efficiency using the metamaterial-inspired antenna. In this study, important parts such antennas, rectifiers, and impedance matching networks are examined, and their uses in biomedical and Internet of Things devices are assessed. The evaluation ends with suggestions for future.The demand for battery-free, energy-efficient solutions is rising as smart devices proliferate.

Keywords: RFM, IOT, Wireless Power Transmission, Design of an Antenna.

I.INTRODUCTION

Wireless sensors and electronic devices are essential for wearable technology, implants, sports monitoring, healthcare, and environmental sensing. Conventional batteries' limitations, such as their short lifespans and difficulty in replacing them in many use situations, restrict their widespread usage. Reliability and sustainability in energy supply techniques are essential for the long-term viability of Internet of Things (IoT) devices. Even though operational efficiency has been improved by methods like data aggregation and sleep scheduling, there is still a growing need for wireless energy harvesting (WEH) systems that can capture far-field radio frequency (RF) energy. RF energy harvesting can help a number of unique IoT applications. To enable constant connectivity in smart homes, RF energy can power wireless sensors and gadgets.

RF energy harvesting has been the subject of recent research. Nonetheless, most surveys focus primarily on particular facets of rectenna circuit design. The scope of reviews must be expanded in order to fully understand new developments in radio frequency technology, such as antenna arrays, artificial intelligence-assisted antenna design, and metamaterials. Current trends and future directions for RF energy-gathering devices and circuits have been examined in surveys. With an emphasis on antenna arrays, impedance networks, and rectifiers, these evaluations highlight strategies and tactics to raise the RF-to-DC conversion efficiency of rectenna systems. However, in these surveys and methods to improve the RF-to-DC conversion efficiency of rectenna systems, the use of metamaterials and artificial intelligence in rectenna design is still mainly unexplored.

However, important subjects like artificial intelligence, rectifiers, and the vital cooperation between the antenna, impedance matching network, and rectifiers were not included in their study. To enhance the design of

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reconfigurable antennas, these topics need more research. The wider idea of RF energy scavenging was not covered in a prior review, which concentrated on using CMOS RF-DC rectifiers for a wide power dynamic range. Few studies have thoroughly examined all of the major contemporary technologies, including metamaterial-inspired antenna designs, Schottky diodes, rectennas, and power generated in RFEH design, despite the large body of research on RF energy harvesting and associated technology. Although these studies offer insightful information, they frequently concentrate on particular elements, ignoring the more comprehensive integration of related developments.

This paper's remaining sections are arranged as follows: In energy harvesting techniques are discussed with an emphasis on the development of wireless power transfer (WPT) and radio frequency transmission. With a focus on enhancing bandwidth, gain, and radiation patterns, looks at important antenna technology characteristics. Impedance matching networks and related issues are covered.

II.LITERATURESURVEY

In 1819, Hans Christian Oersted made the discovery that electric currents produce magnetic fields, establishing the connection between the two. Future advancements in electromagnetism and contemporary technologies were made possible by this finding. Ampere's Law and Faraday's Law are two important theoretical developments that were influenced by Oersted's research.

James Clerk Maxwell expanded on these ideas in 1864 with the introduction of Maxwell's Equations, which significantly improved our knowledge of how electric and magnetic fields interact. His work from 1873 emphasized how these forces are interrelated, paving the way for subsequent technological advancements like wireless power transmission (WPT).

Heinrich Hertz used sophisticated equipment to send electricity over short distances in 1888, offering the first empirical evidence of electromagnetic waves. This was a major turning point in the study of electromagnetic waves. Hertz served as an inspiration for Nikola Tesla, who created alternating current (AC) systems that transformed the way power was distributed. The foundation for contemporary WPT technology was established by Tesla's efforts, particularly his remedies for coil overheating. His well-known Tesla coil experiment from 1899 proved that wireless energy transmission was feasible.

The goal of Tesla's latter experiments, which took place between 1899 and 1901, was to wirelessly transfer electrical energy over great distances. These attempts were, however, limited by the capabilities of the technology at the time. When W.C. Brown used microwaves to successfully power a helicopter in 1964, it was a significant advancement in WPT. The JPL Goldstone Facility later, in 1975

III.ENERGY HARVESTING SYSTEM

Solar energy is a sustainable choice for outdoor applications since it uses photovoltaic cells to turn sunlight into electrical power. With average conversion rates of about 8%, its effectiveness is contingent upon the length and intensity of sunshine. Utilizing the thermoelectric effect, thermal energy harvesters take advantage of temperature variations. Although they have poorer conversion efficiency, these systems power gadgets like smartwatches and health monitors.

Wind energy harvesters provide a clean and renewable power source by employing turbines to turn wind into electricity. Nonetheless, the efficiency of wind flow is severely hampered by its erratic nature. Mechanical energy harvesters use piezoelectric, electromagnetic, and electrostatic processes to capture motion and vibrational energy. These devices use industrial vibrations or physical activity like walking to generate energy.

RF energy harvesting has become more popular as wireless communication technologies, such as 5G networks and the Internet of Things, have grown in popularity. In order to get high energy transfer efficiencies—which frequently surpass 80% near-field radio frequency harvesters employ specialized sources. Receiving signals from far-off sources, like cellular towers, far-field radio frequency harvesters transform them into useful electricity using rectifier circuits. This technique's power density and efficiency are highly dependent on the source output power and signal propagation distance.

In Table 1, these energy harvesting techniques are compared based on their power density, availability, features, efficiency, applications, and related advantages and disadvantages. Finding the best energy source for a certain application is made easier by this thorough comparison.

Modern uses for RF energy harvesting include wearables, biomedical devices, Industry 5.0, and the Internet of Things. In smart factories, it provides consistent, dependable power to sensors and communication equipment, lowering maintenance costs and boosting adaptability. IoT devices don't need to replace their batteries very often. RF energy harvesting is used in biomedical implants to increase device dependability and patient comfort.

Utilizing accessible radio frequency signals, wearables can benefit from small, light power sources. RF energy harvesting's spectrum of applications is further expanded by its application to smart homes, environmental monitoring, and agricultural sensors.

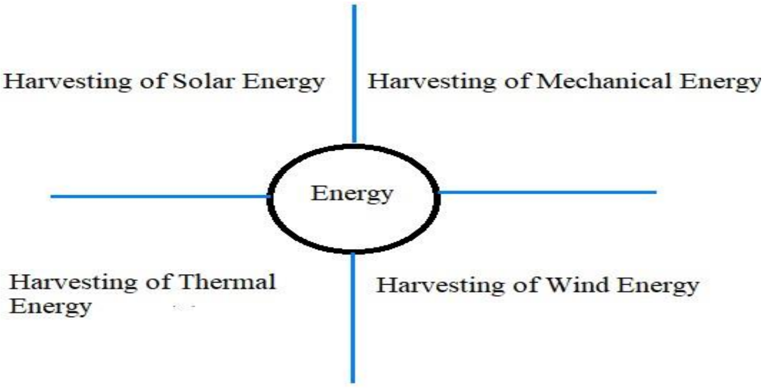

Fig.3.1. Different Energy Harvesting System

IV.DESIGN OF ANTENNA

In order to transform electrical impulses into electromagnetic waves and vice versa, radio frequency (RF) energy harvesting depends on antennas. Antennas, which vary in design depending on frequency, application, and signal qualities, are essential to devices like satellite systems, TVs, radios, and cell phones. In order to improve power transfer and reduce signal reflections, impedance matching is a crucial difficulty in rectenna design. For RF energy harvesting (RFEH) and wireless power transfer (WPT) to operate at their best, antenna gain, bandwidth, and polarization are essential. Increasing directivity does not always result in better energy capture, even when high-gain antennas are helpful for RF energy harvesting. Effective power recovery from various sources requires the proper ratio of bandwidth to gain. Multiband antennas produce power more effectively, while wideband antennas capture power over several frequencies.

Antenna gain gauges how well power is transmitted or received in a certain direction. For RF energy harvesting, high-gain antennas are necessary, but they work best when the energy source is known. In certain situations, a well-designed antenna can achieve moderate gain. Antennas' polarization, beamwidth, pattern, and shape all affect how effective they are. While unidirectional antennas are better suited for long-distance transmission, omnidirectional antennas are best when the direction of incoming waves is unknown. For better reception, dual linearly polarized antennas minimize polarization mismatch, whereas circularly polarized antennas absorb energy from numerous polarizations.

Monopole antennas are versatile for circular polarization and are frequently utilized in RFID and mobile communications systems.Spiral antennas work well in radar and wideband communications for circular polarization and broadband coverage. Because of their high gain and directionality, yagi-uda antennas are appropriate for targeted energy harvesting and point-to-point communications. Horn antennas are effective for high-frequency energy harvesting and support circular polarization; they are frequently used in satellite and microwave communications. Slot antennas are small and appropriate for integrated circuits and RFID. When combined with circularly polarized feed horns, parabolic reflector antennas provide incredibly high gain for satellite communications and long-distance wireless power transmission.The Coyote Optimization Algorithm was used to create a multiband microstrip patch antenna that was optimized for cellular and LoRa WAN frequencies, resulting in a peak gain of 3.94 dBi. Developed for energy harvesting at 2.4 GHz and 5.8 GHz, a dual-band receiver antenna achieved RF-DC conversion efficiency of 63% and 54.8%, respectively.

A tiny antenna that uses the GSM-900, UTMS2100, and TD-LTE bands was created for small devices in order to overcome the limitations of miniaturization. In order to increase the efficiency of RF energy harvesting, multiband and broadband antennas, including self-complementary slot and patch designs, have been developed to match rectifier impedance at 2.45 GHz. In RF-DC conversion, a triple-band differential antenna that targets frequencies between 2.1 GHz and 3.8 GHz achieved maximum efficiencies of 53% and above 59% efficiency at −10 dBm. With an RF-to-DC conversion ratio of up to 78%, fractal-based antennas are perfect for small energy harvesting devices.

Wearable and mobile technologies, where compact form factors are essential, continue to face significant challenges in terms of miniaturization. Although high-gain antennas work well for harvesting radio frequency energy, their size may restrict their application in portable systems. Environmental elements including air conditions and signal interference can affect how efficiently energy is harvested, particularly in crowded metropolitan settings where multipath interference is prevalent. Improving long-distance power transmission requires antennas to be designed to withstand these circumstances. Concerns about manufacturing costs also arise when scaling high-performance antennas for more extensive uses, such as wireless sensor systems and Internet of Things networks. A thorough analysis of several multiband and broadband antenna designs for rectenna applications is provided.

4.1. RECTENNA DESIGN USING ANTENNA ARRAYS

Antenna arrays perform better than single rectennas in RF energy harvesting (RFEH) and wireless power transfer (WPT) for larger power requirements by enhancing gain, beam steering, and interference suppression. Element spacing, excitation phase, and amplitude all affect how well they work; larger arrays increase DC combiner efficiency. Maximizing RF capture is the goal of recent designs such as printed Yagi [, square patch, and dielectric resonator arrays. By increasing beam widths and lowering coupling effects, arrays increase efficiency. While some arrays utilize separate rectifiers for each antenna, others send RF power to a single rectifier. Retarder integration is still difficult despite improvements. Multi-element designs and ferrite cores reduce coupling and preserve multiband performance. 2G, 3G, and 4G bands are covered by arrays with baffles and reflectors that maximize cross-polarization and gain.

A quasi-Yagi array that is tailored for RFEH operates at 2.3–2.63 GHz on a Rogers 5880 substrate (0.762 mm thick, relative permittivity 2.2). It has a peak gain of 8.7 dBi and a 25% RF-to-DC conversion efficiency at 2.45 GHz due to its small size (26 mm by 190.5 mm) . A stacked microstrip patch array with a peak gain of 7.8 dBi at 3.5 GHz is developed on a 1.6 mm FR4 substrate (relative permittivity 4.4) and works between 3.3 and 3.9 GHz.

Designed on a 1.6 mm FR4 substrate, the MIMO rectangular patch array functions at 2.32 GHz and 2.8 GHz. The MIMO arrangement enhances signal reception and diversity even with its comparatively modest gain (−10.13 dBi) [70]. Operating frequencies for a dipole antenna array on a Rogers 4350 substrate (0.8 mm thick, permittivity 3.48) are 0.76–0.88 GHz, 1.9–2.7 GHz, and 3.3–3.9 GHz. It achieves efficiencies of 57%, 49.5%, and 60.44% with gains of 6.9 dBi at 0.76 GHz and up to 10.6 dBi at 3.6 GHz, respectively.

A ferrite-loaded substrate (1.0 mm thick, permittivity 15, permeability 1000) is used to create an antenna system with reflectors and subarrays that operates between 1.7 and 2.7 GHz. Its maximum gain is 8.9 dBi, and its coverage area is 380 mm by 350 mm. Designed on a Rogers 4350 substrate (0.8 mm thick, permittivity 3.48), a unidirectional four-patch array works at 2.45 GHz with an efficiency of 81.5% and a peak gain of 12.7 dBi.

Operating at 0.69–0.96 GHz and 1.7–2.7 GHz, respectively, is a two-element lower band and five-element upper band array on a FR4 substrate. With an efficiency of 35% and 45% across the bands, this array, which has a peak gain of 14.65 dBi, is 43 mm x 43 mm . Reaching a peak gain of 8.5 dBi and 22% efficiency at 2.45 GHz, a square patch array offers omnidirectional coverage between 1.65 and 2.76 GHz . A twelve-element Vivaldi array with peak gains of up to 4.33 dBi and efficiency above 60% is constructed on a Rogers RT6002 substrate (0.5 mm thick, permittivity 6.15). It operates at 1.7–1.8 GHz and 2.1–2.7 GHz.

4.2. REDUCED SIZE OF ANTENNAS THROUGH DESIGN INSPIRED BY METAMATERIALS

Metamaterials like mu-negative (MNG), epsilon-negative (ENG), and double-negative (DNG) materials have been included into designs by researchers, leading to notable advancements in antenna miniaturization. These materials enable antennas to retain or enhance performance while decreasing size because of their tailored electromagnetic properties. Metamaterials accomplish this by producing in-phase currents and resonant behaviours, which enhance radiation efficiency and allow for compact designs.

To further optimize compactness and performance, split-ring resonator (SRR/CSRR) cells and RLC resonant structures aid in fine-tuning antenna properties. Meta surfaces and Frequency Selective Surfaces (FSSs) combined with composite right/left-hand (CRLH) unit cells improve antenna performance by altering the distribution of electromagnetic fields surrounding the antenna, which reduces physical dimensions without compromising bandwidth or gain.

The capacity of metamaterials to change the effective wavelength of the electromagnetic waves interacting with the antenna is the main basis for the mechanics of miniaturization. The size of a conventional antenna usually varies with the operating wavelength; larger antennas are needed for longer wavelengths. Metamaterials efficiently compress the wavelength within the material by adding negative permittivity (ε) or permeability (μ), enabling antennas to function at the same frequency while being physically smaller. This is especially helpful for consumer electronics, where space is at premium and small, effective antennas are essential.

To support both on- and off-body communications, for example, a small, dual-band metamaterial antenna for body-centric wireless communication is miniaturized by using a circular patch for unidirectional patterns and a zeroth-order loop for omnidirectional radiation. A quarter-wave shorted patch antenna and a T-shaped probe dipole can be combined thanks to the use of metamaterials to boost substrate permeability. This greatly reduces the size of the antenna without sacrificing performance. A modified split-ring resonator (MSRR) on a Rogers 5870 substrate (0.762 mm thick with a permittivity of 2.33), this design runs in the frequency range of 1.7–2.67 GHz. With an efficiency of 45% and a peak gain of 8.51 dBi, the antenna has dimensions of $0.55\lambda0\times0.363\lambda0$.

A GPS antenna array featuring mu-negative (MNG) metamaterials and broadside coupled split-ring resonators (BC-SRRs) demonstrates how metamaterials are especially helpful in dual-band antennas. Performance is improved and the antenna footprint is decreased thanks to this design's reduction of mutual coupling in the L band. In this case, using metamaterials not only increases radiation efficiency but also drastically reduces the antenna's total size, making it more appropriate for small systems. In conclusion, by changing the way electromagnetic waves propagate, the use of metamaterials into antenna design allows for a significant reduction in size. The metamaterial's effective wavelength can be compressed, allowing antennas to be smaller without sacrificing performance or efficiency. This invention is essential for creating small antennas for wearable technology, wireless energy harvesting, and the Internet of Things applications with high performance requirements and space limitations.

4.3. ANTENNA CIRCULAR POLARIZATION USING DESIGN INSPIRED BY METAMATERIALS

Depending on how the electric field is oriented, antenna polarization—which can be either linear or circular—has a direct impact on how well RF energy harvesting devices work. Because it enables antennas to receive signals from many orientations and reduces polarization mismatches that frequently arise in dynamic situations, circular polarization is especially advantageous in radio frequency (RF) systems. Particularly in systems vulnerable to multipath interference or quickly shifting signal directions, this leads to more reliable signal reception. When the transmitter and reception antennas are properly oriented, cross-polarization losses—which happen when the antennas' electric fields are not aligned—are reduced.

Because they allow for more compact and high-performing antenna designs, metamaterial structures are essential for improving circular polarization. Antennas can maintain or even enhance gain thanks to metamaterials.

For example, a metamaterial-loaded cavity antenna that operates in the 9.7 GHz to 10.27 GHz frequency range uses Rogers RT6010 and Rogers 5880 substrates with thicknesses of 0.635 mm and 0.762 mm, respectively, and permittivities of 6.15 and 2.2. With a peak gain of 14.1 dBi, this design attains an efficiency of 6.0% and a bandwidth of 74.1%. Higher efficiency and gain are made possible by the metamaterials in this arrangement, which greatly improve the antenna's circular polarization performance.

A FR4 substrate with a thickness of 1.0 mm and a permittivity of 3.5 is used to create an electromagnetic bandgap (EBG) structure that functions at two different frequencies: 12.5 GHz and 14.2 GHz. With a total efficiency of 47.7%, this structure produces gains of 6.0 dBi and 4.3 dBi, respectively. At these frequencies, the overall gain is between 23.1 and 24.4 dBi. By enhancing circular polarization and controlling electromagnetic wave propagation, an EBG structure makes the design appropriate for high-frequency applications. Split-ring resonators (SRRs) and other metamaterial components of the EBG structure help to effectively manipulate electromagnetic fields, enabling better polarization control.

One frequency-agile near-field resonator antenna design that uses parasitic components on a Rogers 5880 substrate with a permittivity of 2.2 and a thickness of 0.762 mm is another. This antenna achieves an efficiency of 3.92% and a gain of 5.92 dBi when operating at 1.39 GHz. While maintaining steady circular polarization, the antenna may dynamically adjust to various operating frequencies thanks to the parasitic elements. This layout demonstrates how well metamaterials work to produce flexible, high-performing antennas for RF energy harvesting devices.

V. IMPEDANCE MATCHING NETWORK OF ANTENNA AND RECTIFIER

An important topic of research in almost every area of electronics is impedance matching. In applications where signal transmission is critical, such as communication and energy harvesting, effective termination is necessary for reducing reflections and preserving signal integrity. Impedance mismatch in an RF network result in power being reflected back to the source from the boundary. This reflection does not convey energy to the load; rather, it produces a standing wave.

The nonlinear nature of diodes and transistors causes the impedance to vary with frequency in rectifiers that use them. It is challenging to fit a typical 50-ohm antenna to an RF-DC rectifier because of this variation. This impedance mismatch causes an electrical signal to reflect, which is represented by the reflection coefficient equation

$$y = S11 = S22 = \frac{Zrect - Zant}{Zrect + Zant}$$

It is frequently called the reflection coefficient or the $S11$ parameter. Here, Zrect stands for the impedance of the rectifier, which is represented as $R1$+$X1$, and Zant for the antenna, which is written as $R2$+$X2$. Furthermore, the antenna impedance's complex conjugate is denoted by Zant. In all cases, the reflection coefficient Y is equal to or less than 1.

L, T, and π-matching networks are often utilized impedance matching circuits in radio frequency energy harvesting (RFEH) systems. These circuits match the load impedance at a desired frequency by arranging inductors and capacitors in L, T, and π forms.

The distributed impedance matching technique can also be used to match impedance for antennas. This method uses stubs, tapered lines, baluns, active components, single- and multi-section quarter-wave transformers, and other structural modifications to the antenna. The distributed impedance matching technique's primary benefit is that it eliminates the need to modify the radiating structure's geometry. This simplifies the design process because the matching network has no effect on the antenna's radiation efficiency. This approach, however, makes the antenna larger, which makes it less suitable for real-world array systems. Furthermore, the matching network's additional circuitry can result in higher spurious radiation losses, which would lower system efficiency.

The extremely low and fluctuating input power levels present special difficulties for the impedance matching network (IMN). The nonlinear load impedance of the rectifier, which changes in response to the power received by the antenna, serves as the input to the IMN. The source impedance of the IMN, which is not always 50 ohms, is provided by the antenna in the meantime. As a result, the IMN may not function at its best at different power levels and must be built for a particular level of received power.

VI.DESIGN OF RECTIFIER FOR WIRELESS POWER TRANSFER/ENERGY SCAVENGING SYSTEM

Rectifiers transform radio frequency (RF) signals into direct current (DC) signals for use in radio frequency energy harvesting (RFEH) systems. The low power density of RF waves and ineffective harvesting circuits are the primary challenges in RFEH technology. Multiband and broadband rectifiers (BBRs) have been designed to increase the output DC power.However, changes in ambient electromagnetic (EM) radiation can affect rectifiers' performance.

Several techniques are used in rectifier design to lessen the impact of input power fluctuations. Topology, operating frequency (broadband, single band, or multiband), impedance matching, combiner type, feeding antenna, and power level (low, medium/high power, or wide input power dynamic range) are some of the criteria that determine the classification of rectifiers**.**

Sensitivity, power conversion efficiency, and power dynamic range are some metrics that can be used to evaluate a rectifier's performance. The quantity of input power required to generate a 1 V DC output at the anticipated load is known as sensitivity. As these variables alter, the rectifier's efficiency may decrease, mostly as a result of the circuit's Schottky diode or CMOS's nonlinearity. The rectifier's input impedance may be impacted by changes in RF input power and frequency, leading to mismatches that lower power conversion efficiency. Resolving these problems is essential to guaranteeing reliable RFEH system activation and performance in real-world applications.

VII.EFFICIENCY OF POWER HARVESTING AND CONVERSION IN FAR-FIELD RECTENNA

Since they transform ambient radio frequency energy into DC power and enable low-power devices to function in situations where traditional power sources are impractical or unavailable, antennas are essential parts of far-field radio frequency energy harvesting (RFEH) systems. The power gathered by rectennas and the challenges of optimizing power utilization are the main topics of this section, whereas earlier sections covered the design and operation of antennas and rectifiers in RFEH systems.

For applications like satellite communications, medical implants, and remote sensors, where minimizing power loss is necessary for extended operation, far-field rectennas must effectively absorb energy transmitted over long distances.

The power usage of popular sensors and electronic equipment, from RF transmission at sub-μW levels to GPS receiver chips at 15 mW. Rectennas in far-field RF energy harvesting (RFEH) systems need to provide sufficient power to sustain these devices. RF harvesting is difficult with high-demand components like GPS chips and standby cell phones, but energy harvesting applications are better suited for lower-power sensors like temperature, pressure, humidity, and accelerometers, which use 0.32 mW to 27 µW. This illustrates how RFEH systems can power low-energy devices, especially in sensor networks and the Internet of Things.

VIII.CONCLUSION

This analysis concludes by highlighting the vital role that rectenna technology plays in developing 5G and IoT systems, which require low-maintenance and sustainable solutions. In order to facilitate real-time data collection and help create a future free of carbon emissions, RF energy harvesting is essential. The following are the main obstacles: Rectifier Performance: When handling a wide variety of frequencies, existing rectifiers are inefficient since they are usually optimized for restricted frequency bands. Changes in load and input power can also impair performance.

Antenna downsizing: While necessary for small devices, antenna downsizing frequently results in decreased efficiency and performance. There are other difficulties in achieving effective circular polarization in decreased form factors.

Research should concentrate on improving miniaturization while preserving performance, which includes creating novel materials and designs that increase productivity.

Enhance Impedance Correspondence: Build sophisticated impedance matching networks that can adapt to variations in frequency and power levels on the fly. It might be beneficial to use machine learning techniques for real-time optimization.

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