National Journal of Antennas and Propagation, ISSN: 2582-2659 Vol. 6, No. 2, 2024 (pp. 9-16)

RESEARCH ARTICLE

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Integrated Dielectric Resonator Antenna to Traditional Antenna for Better Bandwidth and Gain

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KEYWORDS:
These include:
Antenna gain;
Bandwidth enhancement;
Dielectric resonator antennas;
Hybrid antenna design;
Wideband communication systems.

ARTICLE HISTORY:

Received	10.05.2024
Revised	15.07.2024
Accepted	17.08.2024

DOI:
https://doi.org/10.31838/NJAP/06.02.02

Abstract

The integration of dielectric resonator antennas (DRAs) with conventional antennas appears to be a suitable technique for enhancing bandwidth and gain in present day communication systems. The dielectric resonators themselves are low loss materials in the microwave frequency range, possessing properties which improve the performance of antennas. Combined with a more traditional antenna, the patch or dipole, for instance, the capability of the two antennas together simply enhances the features of the two separate sources. DRAs can enhance efficiency, yield wider bandwidth, and optimize radiation patterns compared to conventional antennas, which offer tested structures of consistently performing their tasks. This combination makes it possible to design small-sized, high-gain efficient antennas, mainly suitable for applications, which demand a wide operating frequency range, including the 5G, satellite communication technologies, radars, etc. Further, DRAs enable reduction of conductor losses while improving gain and efficiency, especially when operating at higher frequencies. It also provides a higher degree of freedom in designing the antenna, because the performance can be optimized to meet certain needs like compact size or being multiband. As the requirements for new generation of complex communication systems with high-gain and wideband antennas continue to increase, this research creates a new concept to integrate the dielectric resonators and conventional antennas.

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How to cite this article: Rai HT, Mu GW, Lu RQ. Integrated Dielectric Resonator Antenna to Traditional Antenna for Better Bandwidth and Gain. National Journal of Antennas and Propagation, Vol. 6, No. 2, 2024 (pp. 9-16).

Dielectric Resonator and Conventional Antenna Integration

Another remarkable invention in wireless communication system is dielectric resonator antennas, which present size reduction and efficiency. These compact devices take advantage of the dielectric constant and relative permittivity associated with various materials to realize high director antenna gain and accurate selector resonant frequency. The necessity for higher network performance in the contemporary world has spurred researchers to incorporate dielectric resonator antennas with the conventional antennas to improve the capacity of the resultant systems. Incorporation of dielectric resonator and conventional antenna elements presents the new visions of polarization characteristics and enhanced circular polarization. This integration enables us to optimize and achieve high gain plus bandwidth frequency with reference to antenna parameters. This article explains the basic working principle of DRA, introduces different kinds of dielectric materials and fabrication methods, and discusses how to realize higher gain in integrated designs. Further, it illustrates how feeding networks to these hybrid antennas are designed and points out usages of such antennas in advanced communications systems .[1-3]

DRA Basics and Conventional Antenna Integration

DRA Operating Principles

The dielectric resonator antenna (DRA) is a three dimensional structure that utilizes dielectric material as the resonator for efficient radiation. These antennas use the radiating mode of a dielectric resonator to transform a guided wave to an unguided wave or RF signal. The basic idea of a DRAs is farther similar to that of Cavity resonators where radio waves 'oscillate back and forth' in the resonator forming what is called standing waves (Table 1).[4]

Table 1. Antenna Materials and Their Properties

Material	Conductivity (S/m)	Weight (g/cm³)	Corrosion Resistance	Applications
Copper	5.96×10^7	8.96	Moderate	Common for most antennas
Aluminum	3.77×10^7	2.7	High	Lightweight antennas
Gold	4.10×10^7	19.32	Excellent	High-performance antennas
Silver	6.30×10^7	10.49	Poor	High-conductivity applications
Steel	1×10^6	7.85	Moderate	Structural components

Typically, the size of a DRA is inversely proportional to the square root of the product of the free space wavelength at the resonance frequency λ0 and the relative permittivity εr of the material used in the construction of the radiating structure. This relationship enable large amount of size reduction by selecting materials with high dielectric constants which make the DRAs unique for compact designs and array system interfaces. DRAs can be fabricated in different forms in particular cylindrical, rectangular as well as conical forms. The rectangular DRA position control for instance has enhanced design freedom because it has three geometric independent parameters. This shape also yields relatively small cross polarizations compared to the cylindrical form. The usable range of DRAs shrinks as the dielectric constant of the material increases and beyond the resonant frequency, the decrease in current results in the ability to fine-tune the present level of current by varying the next pump opposed to a large abrupt change.[5]

Benefits of Integration

The incorporation of dielectric resonator antennas into conventional designs of the antennas offers a number of benefits. This potentiates the general system abilities and also creates new opportunities to fine-tune the parameters of antennas. Some key benefits include:

1. Improved Efficiency: Consequently, DRAs do not suffer from losses via conduction, provided the elements are properly excited; their radiation efficiency is high. This feature becomes you more important at higher frequencies where regular metal antennas can suffer heavy loses.
2. Compact Size: Miniaturization of antenna elements is conveniently possible based on the use of materials with high dielectric constants. This is especially important in array configurations where they're is little space to provide individual antenna.
3. Bandwidth Control: It is clear that the impedance bandwidth of DRAs can be tuned by varying the dimensions and the properties of the resonators carefully. Such flexibility can let designers conducting antennas with either a narrow bandwidth and a wide bandwidth according to different applications.
4. Polarization Versatility: Complementation with conventional antennas permits optimizing polarization characteristics in DRAs. This capability is especially valuable with the goal of attaining circular polarization, commonly used in today's communications facilities.
5. Feeding Flexibility: Performed by DRAs, these couplings can present straightforward coupling schemes to any transmission line employed at microwave or millimeter-wave frequencies. This makes them suitable for integration to various planar technologies and it is easier to optimize coupling by adjusting the positions..

Design Challenges

While the integration of DRAs with conventional antennas offers numerous benefits, it also presents several design challenges that need to be addressed:

1. Material Selection: The selection of the proper dielectric material having the desired permittivity and small loss tangent is of importance. Originally high permittivity ceramics and good quality factors were employed, but now materials such as PVC and PCBs are being considered.
2. Fabrication Techniques: The actual processes of manufacturing DRAs, at least at millimeter-wave frequencies, are difficult mainly due to the small size of the structures. For high frequency analogues, it is difficult to mount them accurately on printed circuit boards as in the 3D printed approaches or machinings with hard ceramic materials.
3. Alignment Issues: The alignment is crucial when incorporating DRA array elements with PCBs with feeding networks included. Shunt and series misalignments reduce antenna performance and create disparate characteristics in the transmission lines.
4. Bandwidth Limitations: Even though DRAs allow for

bandwidth control to be adjustable, the ability to achieve desired, ultra-wide bandwidth alongside with other beneficial characteristics can be a problem. To overcome this problem, different methods have been proposed including the stacked organization or the perforated structures.

5. Feeding Network Design: The formation of feeding network convenient to provide adequate amounts of power to the DRA, to deliver adequate excitation while at the same time passing through minimal amounts of loss and owning the right radiation features, must be planned and enhanced.
6. Integration with Existing Systems: Integrating DRAs into already used and implemented antenna systems could offset the original designs and the processes of manufacturing, which is a time-consuming and expensive activity.

Solving these problems is usually a question of exchanging one parameter for another, for example, size, bandwidth, or efficiency. In the future developments of the research in this field, new materials for DRA structures, fabrication techniques for their implementation and new methodologies in the designs of the integrated DRA systems will have to be developed to overcome these limitations to the maximum.[6]

MATERIALS AND FABRICATION TECHNIQUES

The kind of dielectric materials and fabrication methods used is of paramount importance in the creation of DRAs and the interface with regular antenna systems. This section looks at the most important characteristics of the choice of materials, methods of manufacturing, and the interaction with PCB technology.

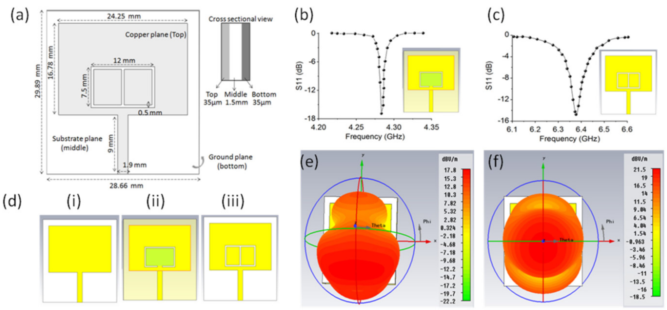


Fig. 1: Materials and Fabrication Techniques

Dielectric Material Selection

Different dielectric material selection poses a great influence on the performance of DRAs. Earlier ceramic materials with higher permittivity and quality factors varying from 20/2000 were used. However, dealing with recent innovations, this issue has resulted in a new focus upon comparatively elastic material. The relative permittivity (εr) of the material forms a major parameter to decide the overall size and efficiency of the DRA. The size of a DRA depends on a parameter related to λ0/√εr, where λ0 is free space wavelength for the resonant frequency. This relationship lets for large amount of size reduction if high dielectric constant materials are to be selected; EAMs are thus favorable for compact designs and array configurations. In particular, materials with a high relative permittivity, εr ≈ 10-100 are used for miniaturization. Nonetheless, the impedance bandwidth is inversely related to the relative permittivity of the dielectric resonator. Consequently the use of materials with very high dielectric constants leads to the design of antennas with narrow bandwidth. In recent years plastics material like polyvinyl chloride (PVC) and printed circuit board (PCB) laminates have been used frequently. These materials present specific advantages in regards to the fabrication and adaptation into existing PCB technologies. For example, microwave-grade laminates like Rogers 6010 or 3010 with higher dielectric constant are employed as carriers for the DRAs in the SI based designs.

Manufacturing Methods

The construction of DRAs utilizes different methods, which depend on the selected material, as well other parameters of the required antenna. Some common methods include:

1. Extrusion and Cutting: Bundles of cylindrical or rectangular prism ceramic rods are extruded into bars, thereafter sliced into the necessary length as embodied by the engineering models.
2. Machining and Punching: For other products such as, PVC and PCB laminates, the use of machining and punching is necessary for shaping the DRA to the required size and shape.
3. 3D Printing: This new method has many advantages for DRA fabrication such as high speed prototyping, design of complex and unprocessable shapes and high εr materials.
4. Lithography: As it has been pointed out, this method is especially effective when it comes to generating accurate patterns and structures specially in DRA designs made of PCB material.
5. Multilayer PCB Process: This method is used to build DRA arrays with feed incorporated into the perfectly metallized substrate hence giving Substrate integrated DRAs..

Integration with PCB Technology

The combination of DRAs with PCB technology has created numerous opportunities for antenna design and fabrication. Some key aspects of this integration include:

1. Feeding Network Design: Component side fed DRAs can be fed using several transmission line coupling methods used in PCB based circuits. Such techniques are direct microstrip feed, extended microstrip line, coaxial feed and stripline feed with capacitive feed.
2. Substrate-Integrated DRAs: To overcome the problems of alignment particularly at millimeter wave frequencies substrate integrated DRAs have been fabricated. These designs employ the multilayer PCB process for building DRA arrays with integrated feeds.
3. Co-fabrication: End-fire DRAs can be co-designed with the feeding network on a single substrate, avoiding two different assembly procedures.
4. Selective Copper Plating: By using 3D positioning, the deposition of selective copper plating on the DRA can be utilized in the construction of feed networks, matching structures or grounds.

Based on the combination of DRAs and PCB technology, researchers have achieved new compact and low cost antennas for the modern communication systems. It not only helps to realise such manufacturing outcomes but also contribute to the improvement of the performance and stability of the antenna systems.[7-9]

GAIN ENHANCEMENT STRATEGIES

For better performance in wireless communication system, there is need to increase the gain of dielectric resonator antennas (DRAs). Different methods have been used in order to improve the gain of DRAs to ensure that they meet the requirements of highly directive applications. This section analyses some of the most fruitful approaches for amplifying DRA gain.

Shaping the Dielectric Resonator

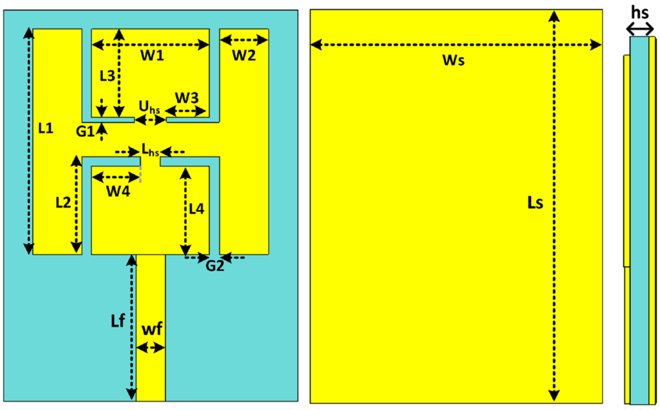
One of the methods to increase gain of a DRA is through the appropriate design of the dielectric resonator in terms of the shape that it is molded into. In this way, adjusting the geometry of the resonator has impact on the radiation pattern and leads to higher directivity of the antenna. For example, there are successful experiments utilizing systems of multiple DRAs in multi-segment configurations or stacked configurations to enhance gain. Computer simulation of two rectangular DRAs with high relative permittivity values, εr = 38 and 80, stacked has been said to allow the radiation of a gain of 6.2 dBi at 1.5 GHz. This technique exploits the physical link between the size of the DRA and its dielectric constant in order to achieve more compact designs with better gain performance. The other method is when other structures are incorporated into the DRA. For example, the rectangular DRA used in conjunction with the surface-mounted short horn (SMSH) shows considerable gain enhancements. This integration of both dielectric resonator and horn structure aims to attain the strengths of the two without the weaknesses observed earlier.2 Multiple Mode Excitations gain of a DRA is through careful shaping of the dielectric resonator. By modifying the geometry of the resonator, designers can optimize the radiation pattern and improve the antenna's directivity. For instance, using multi-segment DRAs or stacked configurations has shown promising results in gain enhancement. Stacking two rectangular DRAs with high relative permittivity values (εr = 38 and 80) has been reported to achieve a gain of 6.2 dBi at 1.5 GHz. This technique takes advantage of the relationship between the DRA size and its dielectric constant, allowing for compact designs with improved gain characteristics. Another method involves integrating additional structures with the DRA. For example, combining a rectangular DRA with a surface-mounted short horn (SMSH) has demonstrated significant gain improvements. This hybrid approach leverages the benefits of both the dielectric resonator and the horn structure to enhance the overall antenna performance.

Excitation of Multiple Modes

Operation of multiple modes within a single DRA has proved to be an efficient approach to gain boosting and multiband operation. This approach enables the distribution of multiple modes of excitation at the same time – the odd- and even- order modes that can offer better prospect for the performance of an antenna at different bands. One of the presented techniques employs an offset-slot feed and an E-coupling scheme to select a series of inherent modes in a rectangular DRA. The position of the slot and the length of the slot have a significant impact on selective frequency response where the designer can decide which mode to excite or simply tune the performance of the antenna. In particular, controlling the operating mode, and specifically, HIM excitation is known to yield high DRA gain. This technique is successfully increases the electrical area of the antenna thus obtained better gain ratios to the size of the physical structure is not increased. For example, gain increases of up to 5 dBi have been noted for some investigations when higher-order modes of operation have been employed as against basic mode operation. One of them is an H-shaped DRA with a trapezoidal conformal feed where stable radiation patterns and increased gain owing to higher order mode excitation were demonstrated. In order to achieve the broad bandwidth for operation while still preventing the loss of the higher gain of the DRA, the structure may be shielded by multiple layers, thus forming a multistage transformation.

Use of Metamaterials

Metamaterials; artificial composite structures formed purely from human fabrication with extraordinary electromagnetic characteristics, have been demonstrated to have the possibility to improve the functioning of DRAs. These engineered materials can be employed to design FSS and EBG structures that are essentially important to enhance the antenna gain and minimize coupling between antennas inside the array (Figure 2).



(a) (b) (c)

Fig. 2: Gain Enhancement Strategies

By way of example, FSS superstrates may serve, for instance, as high, reflective surfaces and they can enhance the directivity and in turn, the gain of the antenna. A substantial degree of gain enhancement especially in mm-wave has been realised through proper design of the FSS structure and the proper positioning of the FSS at a suitable height above the DRA.

Another work showed an H-SRR that when the DRA is place together with one × three arrays of hexagonal-shaped split-ring resonator (H-SRR) unit cell, the mutual coupling is significantly reduced to 30dB while the antenna performance is not affected. This approach succeeded in improving numerous other important factors including ECC and CCL in addition to the gain.

The use of metamaterial based solutions allows the possibility to influence the radiated wave through phase front control and maximum efficiency as described by Huygen's principle. Thus, exciting both electric and magnetic surface currents, they will allow unidirectional scattering and increase the gain and directiveness of the antenna.

These developments have shown that incorporation of metamaterials to DRAs will enhance the capabilities of the later and make the later even more appropriate for new wireless communication systems such as 5G.

Feeding Network Design for Integrated Systems (Table 2)

The design of feeding networks has a key importance in the incorporation of dielectric resonator antennas DRA with normal antenna systems. The feeding network design outlines the flow of feeding and guarantees optimum performance and efficient gains avoiding losses. This section discusses feeding network design in terms of impedance matching approach, bandwidth improvement methods, and approaches towards minimizing losses.

Impedance Matching Techniques

To increase the power transfer into the feeder from the feeding network and between the feeder and the antenna, impedance matching is critical. In DRAs, it is also possible to make impedance matching in numerous methods as a way of improving its performance. Filter circuits one of the methods that is applied in the system includes the use of circuits that are designed to offer

Table 2: Antenna Types and Applications

Antenna Type	Frequency Range	Primary Application	Characteristics
Dipole Antenna	3 kHz - 300 GHz	Broadcasting, TV, Radio	Simple design, omnidirectional
Yagi-Uda Antenna	30 MHz - 3 GHz	TV reception, HAM Radio	Directional, high gain
Parabolic Antenna	1 GHz - 300 GHz	Satellite, Radar	High directionality, used for long-distance
Microstrip Antenna	1 GHz - 100 GHz	Mobile communication, GPS	Low-profile, lightweight
Helical Antenna	30 MHz - 8 GHz	Satellite communication, GPS	Circular polarization

a particular amount of impedance at the transmission frequency. They are used as impedance matching circuits because impedance as found in feedline must match with the input impedance at the input port of the antenna. Another effective method is the use of transmission line stubs. These stubs can be used as shunt types as shunt capacitor stubs or shunt inductive stubs. Because it is possible to accurately model the stub length and their position, this technique comes beneficial for multi-band DRA system where one gets higher selectivity as well as broader bandwidth. Thus, more cumbersome antenna configurations that require a series fed as well as a corporate fed approach can be powered equally with the help of the hybrid feeding network. This method provides a more controlled means to excite individual antenna elements to the overall improvement of the system.

Bandwidth Enhancement Methods

The bandwidth can be increased by a better design of physical structures of DRAs, which can be important for contemporary communication systems implemented with broad working frequencies. This paper describes several beneficial designs one of which is the proximity-coupled feeding scheme. According to this technique, the radiating patch is fed by the open-end microstrip which is etched on a different layer. This they can manipulate the feed line position around the patch in order to realize correct coupling and hence the widening of the antenna frequency. The other technique relates to aperture-coupled feeding in which the radiating patch is excited via a slot inserted in the ground plane. This technique also enables a good physical separation of feed network from the radiating element and consequently gives better bandwidth and lesser spurious radiation. To achieve higher bandwidth, designers can use elements of parasitic nature, further. By placing unequal parasitic patches close to the driven patch connected at the radiating edge wider bandwidths can be realized. This method stands a great chance to depict bandwidths up to 20%.

Minimizing Losses

Minimizing losses in the feeding network is crucial for maintaining high antenna efficiency. Traditional corporate-feeding networks often suffer from high losses due to multiple power dividers and spurious radiation. To address this issue, novel feeding techniques have been developed that avoid such losses while maintaining uniform excitation to array elements. One promising approach is based on exciting standing waves using discrete metallic patches. This method has demonstrated remarkable efficiency improvements compared to standard microstrip lines or dielectric image guide (DIG) feeds. In some cases, radiation efficiency of up to 93% has been achieved, which is equal to the array element efficiency, confirming that the feeding method does not introduce additional losses. To further minimize losses, careful consideration must be given to the physical layout of the feeding network. Designers should aim to keep signal paths as short as possible and use high-quality coaxial cables or waveguides for connections. For instance, waveguide diplexers connected through high-precision waveguide flanges can offer minimal loss and high isolation. By implementing these strategies in feeding network design, engineers can significantly enhance the performance of integrated DRA systems, achieving higher gain, wider bandwidth, and improved efficiency. These advancements make DRAs increasingly suitable for a wide range of applications in modern communication systems, including those requiring circular polarization and precise control over resonant frequency.

Applications in Modern Communication Systems

The integration of dielectric resonator antennas (DRAs) with conventional antenna systems has opened up new possibilities in various fields of modern communication. These hybrid antenna designs offer enhanced performance, making them suitable for a wide range of applications.

5G and mm-Wave Communications

The advent of fifth-generation (5G) technology has brought about a paradigm shift in wireless communications. DRAs play a crucial role in this domain, particularly in millimeter-wave (mm-wave) spectrum applications. The mm-wave bands, including 28 GHz, 38 GHz, 60 GHz, and E-band (71-76 and 81-86 GHz), are key enabling technologies for 5G communications.

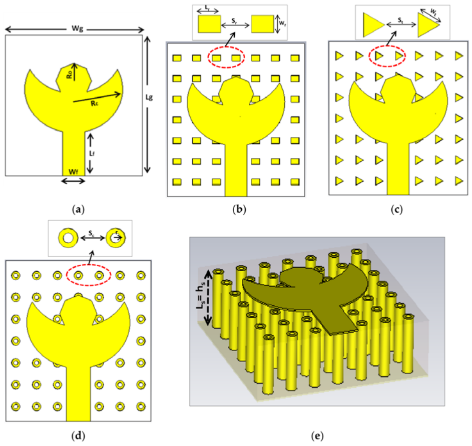


Fig. 3. Applications in Modern Communication Systems

Thus, a significant number of current DRAs with MIMO applications were shown to be successful in performing 5G. Such systems can improve the data rates within given power and bandwidth constraints. Such systems are implemented in printed inverted F-antenna (PIFA) system with three elements: the element of 5G wireless communications at the frequency of 28GHz and bandwidth of 807MHz. A similar work is 4 × 4 dual-band MIMO antenna at 28 and 38 GHz bands with operation bands of 14.3% and 5.26% at both the frequencies. Applying DRAs in mm-wave assists in overcoming the high path loss associated with the mm-wave frequency band. Use of the antenna arrays enables the designers to realize better gain and directivity, both of which are important for extending range of signal. In addition to this, DRAs are smaller in the proposed frequencies enlarging their applicability in small devices and base stations.

Satellite and Radar Systems

DRAs have been applied broadly in satellite communication systems and radar systems. Due to their high radiation efficiency, small size and the capability to work at the high frequencies, the mentioned applications are suited for them. DRAs are employed in L-, S-, C-, X-, Ku-, and Ka bands in satellite communications. For example, Beyond Gravity is well-known and reputable antennas manufacturer that has been providing DRAs for satellite purposes more than fifty years. Their antennas are applied in different segments of use, some of which are; Telecom, Telemetry and Command (TT&C), Data Downlink (DDL), and Inter Satellite Links (ISL). These antennas possess natural advantages over their counterparts with regard to power-handling capability and radiation pattern. DRAs find special use in radar systems because of the high gain and fine tuning of the desired resonant frequency. This makes them perfect for the use in cases where the targets to be detected and followed are quite precise.

IoT and Wearable Devices

The Internet of Things (IoT) and wearable devices are the other frontiers where the DRAs have been making more solutions commonly. Due to compactness ad high efficiency it is possible to incorporate DRAs in small portable devices. In case of wearable IoT care systems, DRAs can be implemented in the gadgets that capture the individual physiological signs including pulse rate, blood pressure and temperature among others. These wearable devices can also incorporate DRAs and then upload the information to other central stations for processing. This makes possible health status surveillance/ supervision, which is good in elderly / geriatric care and in chronic ailments. The incorporation of DRAs in such devices enables the interface to convey information effectively and enables the device to be compact enough so that the end-users can tolerate and accept its presence. Therefore, owing to high gain and polarization characteristics along with frequency band flexibility, DRA forms an important part of today's communication technologies. Starting from 5G and satellite communication to IoT and wearable devices DRA never ceases to throw the impossible into the realm of the possible in the realm of wireless communication.

CONCLUSION

It describes the effect arising out of use of dielectric resonator antennas in union with standard antenna structures on the wireless communication systems in the contemporary world. This combination results in staggeringly improved measures of gain, polarization, and size of the antennae. Such developments make integrated DRA systems even more appropriate to satisfy the strict needs of the sophisticated technologies such as the fifth generation of wireless networks or 5G, satellites and IoT devices. That said, the advancement of research in this field has seen significant increase in development of new materials, fabrication techniques and design methods. These advancement should be expected to further stretch the current 'frontiers' of possible innovations in the antenna technology thus offer more opportunities for enhancing wireless communications systems. It is expected that the continual advancement of DRA integration will always be central to the development of the communication technology in terms of speed, coverage and reliability of above mentioned applications.

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