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Material Selection for Optimized Antenna Performance: A Comprehensive Analysis

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Abstract

The performance of antennas is heavily influenced by the choice of materials used in their design. This work presents a comprehensive analysis of various materials and their properties relevant to antenna applications, focusing on parameters such as dielectric constant, conductivity, magnetic permeability, and thermal stability. The interplay between these properties significantly affects the efficiency, bandwidth, gain, and impedance matching of the antenna. This study explores materials such as metals, ceramics, and composites, alongside advanced materials like meta-materials and graphene. Special attention is given to low-loss substrates and conductors to minimize energy dissipation and improve radiation efficiency. Additionally, the thermal and mechanical properties of materials are examined for their role in maintaining performance stability in diverse environmental conditions. The analysis serves as a guide for selecting optimal materials for specific antenna applications, including wireless communication, satellite, and radar systems, offering insights into trade-offs between electrical performance and structural integrity.

Keywords: Meta-materials, PCB material, composite, metals, nano-particles, dielectrics

INTRODUCTION

The selection of materials plays a pivotal role in the design and optimization of antennas, directly influencing parameters such as efficiency, bandwidth, and size. For instance, in microstrip patch antennas, the choice of substrate material significantly affects performance. A study analyzing different substrate materials for microstrip patch antennas operating at 5.8 GHz found that varying the design structure from a rectangular patch to an E-shaped structure, along with appropriate substrate selection, can lead to optimized performance.

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Advancements in materials like graphene and carbon nanotubes have opened new avenues for antenna design, especially in the terahertz (THz) frequency range. Graphene, for example, has been identified as a promising candidate for nanoantenna design due to its superior performance in terms of miniaturization, directivity, and radiation efficiency. Studies have shown that by dynamically adjusting the surface conductivity of graphene, it is possible to enhance antenna performance, achieving high directivity and stable impedance.

Additionally, the use of magnetic materials as substrates has been proposed to overcome challenges such as the platform effect caused by conducting ground planes. Research indicates that employing magnetic thin films can enhance the radiation efficiency of planar antennas. For instance, a study demonstrated that a planar antenna backed by a FeGaB thin film achieved a radiation efficiency of 25%.

In conclusion, critical performance parameters in antenna design are impacted by the careful selection and optimization of materials. Ongoing research continues to explore various materials and configurations to achieve optimized antenna performance across different applications.

LITERATURE REVIEW

In their research on wearable antennas, Wang *et al*. showed that, in contrast to conventional metallic materials like copper, aluminium and nickel, nanoscale entities such as varied dimensions nanoparticles, have better physical, electrochemical, and performance properties (Figure 1) [1]. These characteristics greatly increase the possibility of creating long-lasting electronic composites. Singh *et al*. proposed antenna designs with various materials and analyzed them [2]. Deepthy *et al*. have analyzed of substrate materials in microstrip antenna for biomedical applications [3, 4]. The concept of Antenna Materials Development in Automotive Radars is discussed by Konishi *et al*. [5]. Whittaker *et al*. presented an overview of the most recent developments which includes information on three-dimensional printing materials and techniques for antennas and materials [6]. Equivalent Circuits for Microwave Metamaterial Planar Components is presented by Marcelli *et al*. [7]. Rahman *et al*. evaluate the preparation of a new flexible antenna for microwave applications based on sol-gel produced MgxCa (0.9-x) Zn0.10Fe_2O_4 nanoparticle [8]. This study's work is broken down into two phases: metals and alloys. Ramli *et al.* designed and analyzed antenna on the cotton substrate, which has a dielectric constant $\varepsilon r=1.58$ with a thickness of 0.27 mm [18]. Kumar SA (2018) designed textile antenna materials for wearable applications [9]. Ansal *et al*. have analyzed antenna with different substrate materials with various thicknesses [10]. With this literature survey, it is proposed that high conductivity materials with low loss tangent are to be used for designing antennas required for the applications [9].

METHODOLOGY

Antenna materials play a pivotal role in determining the performance parameters of antennas, including radiation efficiency, frequency response, and bandwidth. Electrical characteristics including conductivity, permittivity, and permeability are affected by the material selection. Thermal properties like conductivity, heat capacity and curie temperature; and conductive materials, dielectrics, and metamaterials are the primary categories investigated in antenna research [11].

Traditional Conductive Materials

Early antennas were predominantly made from metals like copper, aluminium, and silver due to their high electrical conductivity, which minimizes resistance and maximizes radiation efficiency. Commonly used because of its high conductivity and ease of manufacturing, copper is ideal for reducing loss and

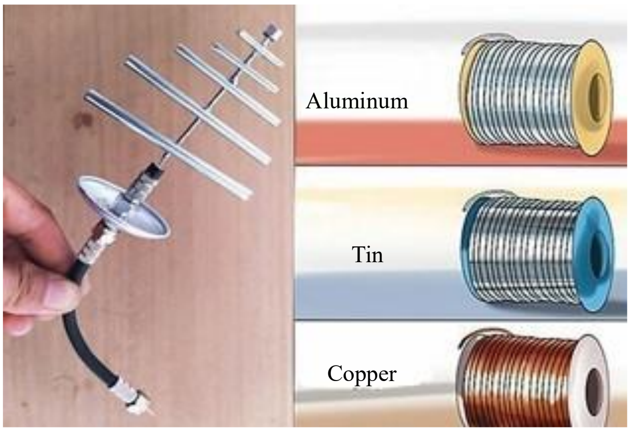

Figure 1. Different materials like Al, Tin, and Cu.

achieving better radiation efficiency. Studies show that copper remains a cost-effective option, though issues like oxidation affect its long-term performance. Aluminium antennas are lighter and less expensive than copper, but they are less conductive. Nonetheless, they are appropriate for mobile and aircraft applications due to their lightweight nature.

Dielectric Materials and Substrates

Dielectric materials are frequently used in microstrip and patch antennas to form substrates, which affect the antenna's resonant frequency, impedance matching, and radiation pattern [12]. A low-cost, widely used dielectric substrate in printed circuit board (PCB)-based antennas, FR-4 offers reasonable performance for applications that do not require high precision. Its efficiency at higher frequencies is constrained by its relatively high loss tangent. High performance dielectric substrates such as Rogers RT/duroid are preferred for high-frequency applications [13]. Although they are more expensive, they offer excellent stability and low loss, which makes them appropriate for specific uses like satellite communication and radar.

Advanced Materials

New materials like composites, metamaterials, and conductive polymers are revolutionizing antenna design by offering unique properties that overcome traditional material limitations [14].

Metamaterials are artificially engineered materials, which exhibit unique electromagnetic properties not found in nature (Figure 2) [8]. Research on metamaterials demonstrates their ability to create compact, highly efficient antennas with enhanced directivity and bandwidth. They are particularly helpful in applications where multi-frequency operation and space limitations are important factors.

Graphene is a promising material for future antenna design (Figure 3). Because of its electrically adjustable characteristics, graphene is perfect for applications needing flexibility and small size. It is highly conductive and has shown potential in terahertz frequencies [15].

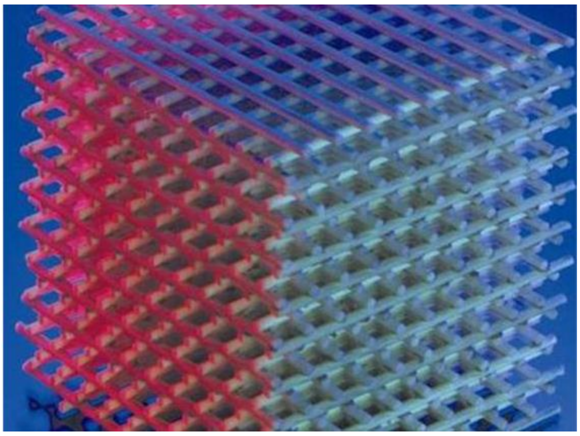

Figure 2. Metamaterials.

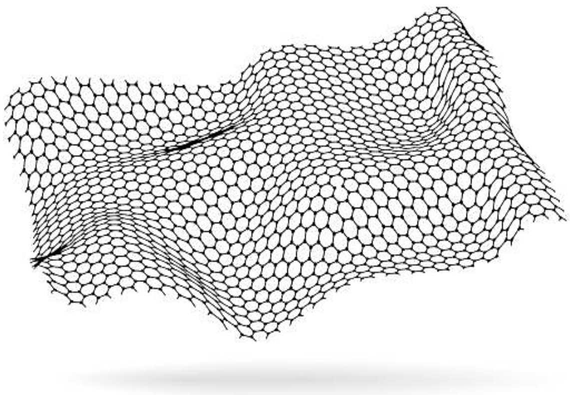

Figure 3. Grapheme net.

Figure 4. Conductive polymer sheet.

Conductive Polymers are lightweight, flexible, and conductive (Figure 4) [16]. Polymers are being investigated for wearable and flexible antennas [17], particularly in the realm of Internet of Things (IoT) and wearable technology [18]. These materials offer a trade-off between conductivity and flexibility, making them suitable for certain niche applications.

Emerging Trends in Antenna Materials

Flexible and wearable antennas: With the advent of flexible electronics, materials like textile-based composites and conductive inks are gaining popularity. These antennas are designed for body-worn applications such as health monitoring, where flexibility, low weight, and biocompatibility are crucial.

Sustainable materials: Recent efforts have focused on the use of biodegradable and eco-friendly materials for antenna fabrication, driven by increasing environmental concerns. Materials like cellulose and other biopolymers are being explored for single-use or disposable antennas.

Low loss conductors for antenna design include copper, graphene, and silver nanoparticle ink. Due to its great conductivity, copper transmits radio waves with very little loss. Graphene is another metallic liquid with lower loss than EGaIn and mercury metallic liquid antennas. Silver nanoparticle ink is used as a conductive material with high electrical conductivity and low rate of oxide formation [19].

Low-loss substrates are materials with low dielectric loss and dispersion that are used in high-frequency applications. They are important for the development of components and systems that work in millimeter-wave and terahertz (THz) regions, where signals can be attenuated by water, oxygen, and other gases. Here is an example of low-loss substrate, Polytetrafluoroethylene (PTFE) shown in Figure 5.

Figure 5. PTFE material.

CHALLENGES AND FUTURE PROSPECTS

Even with these developments, problems like striking the perfect balance between cost and performance still exist. The high cost of high-performance materials like graphene and metamaterials prevents their widespread use. Moreover, integrating these materials into mass production processes presents technical challenges [4]. Furthermore, making sure the materials' resistance to temperature and humidity variations, among other environmental conditions, is a major consideration with long-term deployment.

The future of antenna materials lies in the exploration of hybrid materials, combining the best properties of conductive metals, dielectrics, and metamaterials to achieve more efficient, versatile, and compact antennas. The following methods are used for materials, material selection, material characterization, antenna design, simulation and optimization, antenna fabrication and measurement (Figure 6) [20]. The materials used for antenna design include metals, alloys, metamaterials, and substrates.

1. *Metals and alloys:* Due to their excellent conductivity and versatility in shaping, copper and aluminium are frequently utilized materials. An example of alloys is stainless steel. Any member of the alloy steel family that typically contains 10–30% chromium is called stainless steel. Together with its low carbon concentration, chromium offers exceptional heat and corrosion resistance.
2. *Metamaterials:* These artificial materials can be used to improve antenna performance, such as by increasing bandwidth, power gain, and reducing RCS.
3. *Substrates:* An important part of the antenna, the substrate, affects how well the antenna radiates. When selecting a substrate, the dielectric constant, stiffness, thickness, and loss tangent should all be considered.
4. *Radomes:* An integral part of modern antenna designs, radomes must perform reliably in all environments and over the life of the product.

CASE STUDY

In case of wearable antenna, that are integrated with textile materials can be implemented in medical and telecommunications applications. The advantages of that antenna are lightweight, low-cost fabrications, reduced form of factors, and the ability to fit the non-planar surface will open more possibilities for future applications. However, the materials for the antenna design such as conductive materials and substrate with high conductivity such as silver with a conductivity of 6.30×107 S/m and low dielectric constant, respectively, are preferred.

In case of FR-4, 1.575 mm for RT-5880 and 1.58 mm for TLC-30 have been chosen to carry out this work with the relative permittivity of 4.3, 2.2, and 3, respectively. The antennas' performances in terms of reflection coefficient, voltage standing wave ratio (VSWR), bandwidth, gain, and efficiency performance is good using CST Microwave studio [21].

The Role of Electronics in Antenna

Since it can affect the antenna's performance quality, antenna material is one of the most crucial aspects of antenna design. The ability of materials to conduct electricity is known as conductivity, and the electrical characteristics of materials are taken into consideration while choosing antenna materials.

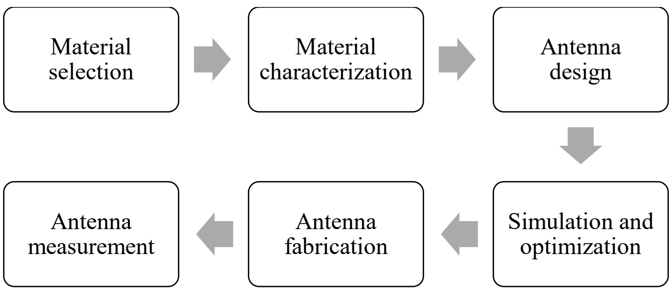

Figure 6. Flow chart of material methods for antennas.

Multi-channel devices are often preferred because they reduce power consumption and increase antenna performance. However, low-power gadgets frequently result in losses and weaken the antenna's signal. The type of material used in antenna design is also related to the electrical properties of the antenna, i.e. its ability to radiate electromagnetic signals. Radio waves can travel through copper without any loss since it is a highly conductive metal. It is the most widely utilized material for antenna construction since it can also radiate signals with good efficiency. Other materials sometimes used in antennas include aluminium, iron, and brass metals. These materials are frequently chosen when cost is an issue since they can transfer signals with a respectable level of efficiency despite having poorer conductivity than copper. To create alloys with better qualities, copper is frequently combined with other metals like nickel, zinc, or tin. Because they improve performance and lower losses, these alloys are frequently found in antennas. These alloys can occasionally be altered to maximize the antenna's performance for use. Additionally, alloys are favored because they last longer than pure copper antennas and are more corrosion resistant. A few of the material's characteristics determine which material is used to make the antenna. Electrical conductivity is one of the most crucial characteristics of the materials used to build antennas. Because of their low strength and great electrical conductivity, metals are typically selected based on their electrical characteristics. Because of their superior electrical qualities, metals like copper, aluminium, and silver are frequently employed in antenna designs. Because of its excellent electrical conductivity, low energy, and capacity to absorb and scatter radio radiation, copper is the ideal material for antennas.

Aluminium's strong electrical conductivity, low strength, and capacity to absorb and spread radio waves make it a preferred material for antenna building. Due to its high electrical conductivity, low resistance, and capacity to absorb and scatter radio energy, silver is another material that is frequently used in antenna designs. Because of its superior electrical qualities, copper clad aluminium (CCA) is a material that is frequently utilized in antenna building.

Because of its exceptional electrical qualities and capacity to both absorb and conduct radio frequency energy, copper clad steel (CCS) is another alloy that is frequently utilized in antenna building. Its effectiveness also depends on efficiency. The antenna's shape, the kind of antenna elements it uses, and its placement are all significant variables that might impact its performance. By carefully choosing the materials used in Good Antenna, performance can be guaranteed by antenna designers.

Alloys such as brass and iron are also used in antenna construction due to their excellent electrical properties. Alloys are favored over other materials due to their superior strength to weight ratio and increased resistance to corrosion. The electrical properties of the equipment also affect the performance of the antenna, so it is important to ensure that the antenna is designed to optimize the fire electricity of the equipment. By understanding the electrical properties of the material, the best performing antennas can be designed.

Comparing the conductivity and electrical strength of different alloys is an important step in antenna fabrication. Because of their superior electrical strength and conductivity, alloys are favored. Different metals are combined to form metals that have different electrical properties than individual metals. The type of alloy used in antenna fabrication depends on the antenna application. For instance, due to their great electrical performance and low strength, copper-nickel alloys are frequently utilized in the production of antennas. Aluminium alloys are frequently used in antenna construction due to their ductility, which facilitates shaping. For uses like radio and television transmission, this enables the antenna to send and receive signals at high frequencies. Excellent electrical qualities are also possessed by the alloys used in the production of antennas. For applications like radio and television transmission, these parts enable the antenna to send and receive stronger signals.

Manufacturers are also now experimenting with ceramic materials that are lighter than traditional metals and can be used to create larger antennas. For example, manufacturers can now use 3D printing technology to create more efficient antennas with fewer parts. This makes the antenna more efficient and requires less energy and materials to make it. This has led to the development of new devices that are more efficient and can transmit signals better over longer distances. The best electronic materials to assist boost antenna performance are still being sought for by manufacturers. The efficiency and effectiveness of antennas have increased with the development of new materials and technologies. Manufacturers will be able to provide antennas with improved electrical qualities and features as new materials and technologies advance, satisfying the demands of consumers. Metamaterials are a class of such artificial composite structures whose physical properties are different, like structural behavior of materials which have negative permeability and permittivity values, they are different, innovative and unique from natural materials and hence widely used in antenna design and microwave applications. The broad notion that an artificial structure made up of well-designed and manufactured elementary cells or arrays has unique resonance and propagation qualities is the foundation for metamaterial components and antennas. In contrast to regular materials, metamaterials have simultaneous negative values of the dielectric constant and magnetic permeability. For a metamaterial response, single elements, periodic, or quasi-periodic structures may be appropriate.

Fused Filament Fabrication

Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are the two most often utilized materials in fused filament fabrication (FFF). Simple off-the-shelf printers can easily print these. Rather than their electromagnetic characteristics, the filaments are made for their physical characteristics. ABS has a relative permittivity, εr, of 2.69 and a loss tangent, $\tan\delta$, of 0.012, while PLA has an εr of 2.7 and a $\tan\delta$ of 0.008 measured at 1 MHz [3]. Additionally, Table 1 represents the list of materials with their properties.

RESULTS

An antenna with copper as a conducting material and a substrate with a lower dielectric constant is better suited to produce higher gain and directivity with lower return loss, according to the findings of research and simulation employing RT Duroid, Bakelite, and Taconic materials. Figure 7 shows the design of microstrip antenna and its materials. The metal component is a ground and copper microstrip patch. In between them is the dielectric substrate. Figure 5 display different materials in PTFE.

Table 1. List of materials with properties.

Materials	Dielectric constant/ Permittivity	Conductivity	Magnetic permeability	Loss tangent	Thermal stability
Copper	Infinite	High	1	0.015	More stable
Aluminium	Infinite	High	1	0.0002	Thermally unstable
Silver	Infinite	High	0.99998	0.99998	Stable but depends
Ceramic glass	5–10	1.38 W/(m.K)	0.375	0.001	Good thermal stability
Air	1	Poor	1	0	Less
FR4 epoxy [22]	4.4	Between 0.25 and 0.4 W/m.K	1	0.02	–40 to 130°C
RT Duroid, composite	2.2	1.44 W/m.K	0.002796	0.0009	Excellent
Rogers	2.33	Dielectric	6	0.0012	Excellent
Benzocyclo butane	2.6	Dielectric	NA		Depends
Bakelite	4.8	0.976645 W/m.K	6.5	0.022	Cu, Al
Taconic RF-35	10	10–12 W/m.K	NA	0.0035	Cu, Al
Metamaterials	Negative permittivity, <0–2.7	Exceptional	Negative permeability, <0	Low dielectric loss	Stable
Graphene metallic liquid	9.3203	Exceptional	Impermeable material	Low	Depends

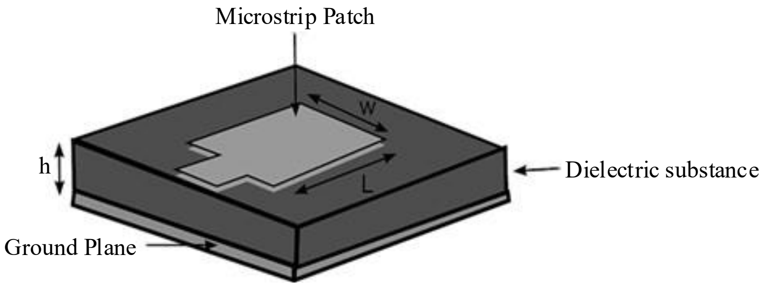

Figure 7. The required materials for microstrip antenna-metal for patch and ground, dielectric for insulation between patch and ground.

Table 2. Comparative statistics of materials and properties.

Properties	Copper	Aluminium	Tin
Electrical ratings	Has lower electrical resistance, voltage drop, and power loss	Medium	0.020
Current capacity	More	Medium	Less
Weight	Heavy	Lighter	0.007
Cost	High	Cheaper	0.003
Conductivity	99%	62%	0.041
Environment sustainability	Possible	Can be recycled	0.047
Strength	Stronger	Lesser	Less
Expansion	Less expansion	Less	Medium

Small items are removed by applying linked component labeling to the resulting image, which depicts text detection using a second set of criteria that removes all objects with an area of less than 300 pixels^2 and a filled area of less than 500 pixels^2. Tin, copper (Cu), and aluminium (Al) are comparable in the following ways:

According to experimental studies, copper is the most favored material for antennas because of its outstanding radiation and conductivity properties. Due to its excellent conductivity, copper can transmit radio waves with little loss [23]. Table 2 shows the comparative statistics of materials and properties.

CONCLUSION

This project discusses the materials used in antenna design. To sum up, a critical stage in guaranteeing optimum performance and functionality in antenna design is material analysis. Several key considerations arise from this analysis: By taking the conductivity and losses, the choice of conductive materials significantly impacts the efficiency of an antenna. High-conductivity metals, such as copper, aluminium, and silver, are ideal for minimizing resistive losses, enhancing the radiation efficiency of the antenna. The materials used for substrates or dielectrics should have low dielectric losses and stable permittivity over the operating frequency range. Low-loss dielectric materials such as Teflon, FR4, or Rogers laminates ensure minimal signal attenuation, thus improving overall performance. Materials must be chosen based on environmental conditions the antenna will face (e.g., temperature, humidity, corrosion). Corrosion-resistant materials such as stainless steel or coated metals can increase how long outside antennas last. For applications involving mobility or aerospace where weight restrictions are crucial, lightweight materials like composites or aluminium may be preferred. Additionally, these materials make handling and integration simpler. The cost of materials and ease of manufacturing also play a role. While exotic materials like graphene or carbon nanotubes may offer superior properties, their high cost may limit their application to specialized use cases. With advances in materials science, new materials such as metamaterials, flexible substrates, and 3D-printed conductive materials offer novel opportunities for antenna design, enabling miniaturization, improved flexibility, and integration into non-traditional environments. By carefully balancing these material properties, designers can optimize the performance, durability, and cost-efficiency of antennas for various applications, from consumer electronics to aerospace systems. The selection of antenna materials is critical to optimizing performance, with traditional metals like copper still dominating low-cost designs. However, the growing demand for antennas with enhanced flexibility, high-frequency performance, and environmental sustainability is driving research into advanced materials such as metamaterials, graphene, and conductive polymers. The literature suggests that future innovations in antenna materials will likely focus on balancing cost, performance, and adaptability to meet the needs of emerging technologies like 5G, IoT, and wearable electronics.

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REFERENCES

1. Wang C, Zhang N, Liu C, Ma B, Zhang K, Li R, Wang Q, Zhang S. New advances in antenna design toward wearable devices based on nanomaterials. Biosensors. 2024 Jan 10; 14(1): 35.
2. Singh K, Dhayal M, Dwivedi S. Design and analysis of ultra-wideband microstrip patch antenna with various conductive materials for terahertz gap. Discover Appl Sci. 2024 Apr 25; 6(5): 224.
3. Deepthy GS, Nesasudha M. Analysis of substrate materials in microstrip antenna for biomedical applications. Mater Today: Proc. 2023 Jan 26.
4. Kaur G, Singh A, Mittal D, Kaur A, Panday P, Sidhu E. Performance analysis of conductive patch materials for the design and fabrication of microstrip patch antennas. In 2017 IEEE Progress In Electromagnetics Research Symposium-Spring (PIERS). 2017 May 22; 502–508.
5. Konishi J, Choi HW, Wei Q. Antenna materials development in automotive radars. In 2023 IEEE International Workshop on Antenna Technology (iWAT). 2023 May 15; 1–3.
6. Whittaker T, Zhang S, Powell A, Stevens CJ, Vardaxoglou JY, Whittow W. 3D Printing Materials and Techniques for Antennas and Metamaterials: A survey of the latest advances. IEEE Antennas Propag Mag. 2022 Dec 26; 65(3): 10–20.
7. Marcelli R. Equivalent Circuits for Microwave Metamaterial Planar Components. Sensors. 2024 Mar 29; 24(7): 2212.
8. Rahman MA, Islam MT, Hossain A, Singh MJ, Albadran SM, Soliman MS, Samsuzzaman M. Preparation of new flexible antenna based on sol–gel synthesized MgxCa (0.9-x) Zn0. 10Fe2O4 nanoparticle for microwave imaging applications. J Mater Res Technol. 2022 Sep 1; 20: 3579–91.
9. Kumar SA, Shanmuganantham T. Design and performance of textile antenna for wearable applications. Trans Electr Electron Mater. 2018 Oct; 19(5): 352–5.
10. Ansal KA, Kumar AS, Baby SM. Comparative analysis of CPW fed antenna with different substrate material with varying thickness. Mater Today: Proc. 2021 Jan 1; 37: 257–64.
11. Tan KG, Ahmed S, Hamdi A, Ming CX, Abdulwasie K, Hossain F, Peng C, Basarudin H, Rahmat MK, Thiruchelvam V. FR-4 substrate based modified ultawideband antenna with gain enhancement for wireless applications. J Eng Sci Technol Rev. 2019 Jul 1;12(4):108–12.
12. Ramli N, Noor SK, Khalifa T, Abd Rahman NH. Design and performance analysis of different dielectric substrate based microstrip patch antenna for 5G applications. Int J Adv Comput Sci Appl. 2020; 11(8): 77–83.
13. Correas-Serrano D, Gomez-Diaz JS. Graphene-based antennas for terahertz systems: A review. arXiv preprint arXiv:1704.00371. 2017 Apr 2.
14. Zahedi A, Liyanapathirana R, Thiyagarajan K. Biodegradable and Renewable Antennas for Green IoT Sensors: A Review. IEEE Access. 2024 Dec 11; 12: 189749–189775.
15. Salonen P, Rahmat-Samii Y, Schaffrath M, Kivikoski M. Effect of textile materials on wearable antenna performance: A case study of GPS antennas. In IEEE Antennas and Propagation Society Symposium, 2004. 2004 Jun 20; 1: 459–462.

16. Singh R, Arora M, Dubey YM, Kumar V, Sahu G. RT/Duroid 5880-based Hook slotted multi frequency low profile patch antenna for WBAN applications. Mater Today: Proc. 2020 Jan 1; 30: 28–34.
17. Al-Haddad MA, Jamel N, Nordin AN. Flexible antenna: a review of design, materials, fabrication, and applications. In J Phys: Conf Ser. IOP Publishing. 2021 May 1; 1878(1): 012068.
18. Fei ZC, Ramli N, Jethi PL, Sanossi TK, Abd Rahman NH. Performance analysis of rectangular microstrip patch antenna with different substrate material at 2.4 GHz for WLAN applications. In 2021 IEEE 7th International Conference on Space Science and Communication (IconSpace). 2021 Nov 23; 46–49.
19. Ali U, Ullah S, Kamal B, Matekovits L, Altaf A. Design, analysis and applications of wearable antennas: A review. IEEE Access. 2023;11:14458–86. doi:10.1109/ACCESS.2023.3243292.
20. Tan CS, Wee FH, Yew BS, Veeraperumal V. UWB Microstrip Patch Antenna for Dielectric Material Measurement System. In 2024 IEEE 1st International Conference on Communication Engineering and Emerging Technologies (ICoCET). 2024 Sep 2; 1–4.
21. Uganya G, Bommi RM, Kinol AM. Comparative Analysis of Microstrip Patch Antenna with Different Slots and Substrate Materials. In 2023 IEEE 4th International Conference on Electronics and Sustainable Communication Systems (ICESC). 2023 Jul 6; 125–131.
22. Krzysztofik WJ, Cao TN. Metamaterials in application to improve antenna parameters. In: Canet-Ferrer J, editor. Metamaterials and Metasurfaces. London (UK): IntechOpen; 2018. p. 63. doi: http://dx.doi.org/10.5772/intechopen.80636.
23. Eralp ME, Cakir O, Civi ÖA, Unalan HE, Baktur R. Transparent Conductive Nanowire Antennas-Material Preparation, Characterization, and Notes on Antenna Design. In 2024 IEEE International Symposium on Antennas and Propagation and INC/USNC-URSI Radio Science Meeting (AP-S/INC-USNC-URSI). 2024 Jul 14; 2701–2702.

