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Millimeter-Wave Broadband Antenna: A Review and Current State of the Art

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Abstract - **A broadband antenna can transmit and receive radio signals across a broad frequency spectrum. The use of broadband millimeter-wave (mmWave) band antennas has garnered significant interest in wireless communication research. As a result, this type of antenna finds applications in television, radio broadcasting, and radar communication. The millimeter-wave broadband antenna covers an extensive range of frequencies, leading to distinct design methodologies for such structures. The primary focus of this manuscript is to present a comprehensive overview of the recent developments in millimeter-wave antenna design, encompassing an in-depth analysis of the working principles of broadband antennas and their associated design characteristics. This review aims to shed light on the challenging path for antenna researchers and the potential enhancements achievable through broadband antenna technologies. Various applications, including enhanced wireless communication, high-definition and ultra-high-definition multimedia, and security signal intelligence, necessitate high data rates and significantly greater bandwidth. Consequently, a substantial demand for millimeter-wave broadband antennas can cater to these requirements.**

Keywords: **millimeter-wave, broadband antenna, frequency spectrum, material selection, metamaterial, half-power beam-width**.

I. Introduction

In modern wireless transmission systems, millimeter-wave technologies are emerging as a solution to provide high-data-rate communications. Millimeter-wave communication systems utilize broadband antennas with high-gain characteristics to achieve high-speed data communications and counteract the path loss between transmitters and receivers. The short wavelengths of mm-wave frequencies offer significant spatial processing gains, enabling the use of numerous antenna elements that theoretically compensate for isotropic path loss. Integrating multiple antennas in millimeter-wave systems brings various implementation and computation challenges; however, the anticipated performance gains are readily attainable.

Millimeter-wave communication faces challenges such as atmospheric absorption and propagation losses due to its high frequency, resulting in reduced transmission distances. To address this issue, solutions involve employing transmitters with higher-power, antennas with increased gain, and receivers with enhanced sensitivity to extend the communication range of the system.

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Considering the costs and durability of millimeter-wave communication systems, incorporating high-gain antennas presents a cost-effective approach to improve the communication range [1–2]. Fig.1. illustrates the necessity of millimeter-wave antennas in this modern era.

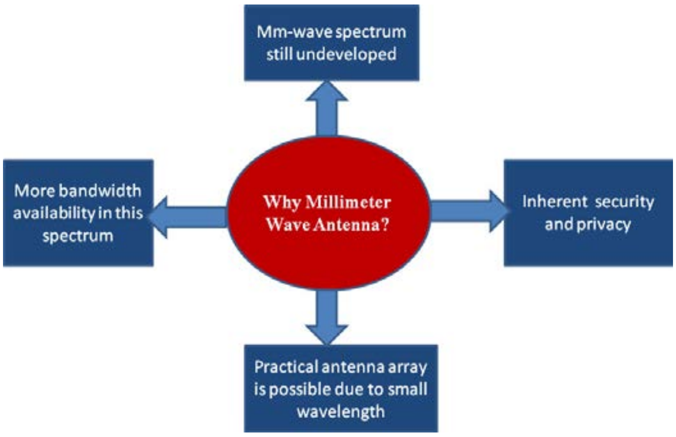


Fig.1. Need of Millimeter wave Antenna

A compact system-on-chip-based antenna is utilized in a biosensor to enhance the detection and monitoring of breast cancer cells. This antenna extends the operational range within the millimeter-wave spectrum. Millimeter waves have the capability to reflect off the human body, conceal objects, and even penetrate common clothing materials, making them effective for detecting explosives on individuals. To achieve efficient detection of concealed objects in both active and passive personnel screening systems, it is essential that clothing remains relatively transparent at the system's operating frequency. Therefore, a thin layer of dielectric material is commonly incorporated into fabrics. The thickness of these materials within the millimeter-wave band's wavelength is intentionally kept significantly smaller.

In August 2016, students at New York University detected millimeter waves at 14 different locations. While communicating in the E-Band with a power output of less than 1 watt, they observed that the millimeter waves traveled approximately 10 kilometers in southwest Virginia, achieving a download speed of 5 Gbit/s. Fujitsu Laboratories Ltd in Japan reported advancements in a millimeter-wave signal generator based on CMOS technology. This millimeter-wave generator is capable of efficiently modulating a wide range of frequencies, specifically from 76 to 81.

In February 2017, NEC Corporation in Japan, in collaboration with the B.T. Group, E.E. Limited, and U.K. operators, partnered with the University of Salford to conduct extensive testing. The main objective was to assess the performance of critical mobile backhaul utilizing millimeter-wave technology for 4G and 5G systems. This collaboration aimed to achieve a high level of accuracy and understanding for various contemporary applications, including the medical market, remote sensing, building automation, and factories.

In May 2017, Apple Inc. in the United States submitted an application to research new 5G millimeter-wave wireless communication technology. The objective was to improve bandwidth, accuracy, and speed in wireless cellular connections. This application included a request for an experimental license to achieve high cellular link performance in multipath and direct signal paths at central base stations using millimeter-wave spectrum.

In 2017, Mie Fujitsu Semiconductor Limited (MIFS) and Hiroshima University announced advancements in a low-power 5G millimeter-wave device. They developed an antenna based on MIFS technology for an operating frequency range of 79 GHz to 105 GHz. This antenna is employed to enhance the safety of future vehicles. [3–5].

This manuscript presents the design and comparison of various structures for broadband communication. The primary focus is to provide a comprehensive review of broadband millimeter-wave antennas. The manuscript is organized to offer foundational insights into the design and working principles of these antennas. The initial part of the manuscript delves into a detailed explanation of mathematical analysis, dispersion characteristics, and feeding mechanisms.

Subsequently, the design considerations based on meta-materials, fractal structures, multimode designs, broadband antenna arrays, and specialized broadband antennas are discussed in the following section. This discussion includes a parametric comparison with other antennas used in millimeter-wave broadband techniques.

Additionally, the manuscript addresses the future prospects of broadband antennas and identifies potential challenges. The paper's structure is methodically divided into sections, each covering detailed design methodologies and working principles of millimeter-wave broadband antennas. The first section elaborates on the working principle and mathematical analysis of broadband antennas.

The second section explores various design configurations for millimeter-wave broadband antennas. The final section compares this review with recent studies on broadband millimeter-wave antennas, summarizing the future prospects and recent developments in millimeter-wave antennas, thereby concluding the manuscript.

II. Broadband Antenna

A. Millimeter Wave Broadband Antenna Working Principle

An antenna is classified as a broadband antenna when its pattern and impedance remain significantly consistent over an octave or more in the frequency range. In such an antenna, the physical dimensions of the structure do not change abruptly; instead, a smooth boundary material condition is applied to achieve broadband characteristics. A crucial principle of broadband antennas is their self-scaling behavior. In the case of broadband antennas, most radiation occurs within an active region near the antenna's circumference, which is typically equivalent to one wavelength or half wavelength in width. The Rumsey principle asserts that an antenna's scaling property exhibits broadband characteristics if the antenna's shape is entirely determined by its angle [6].

The following sections explain the working principles of different millimeter-wave broadband antennas. This exploration will provide insights into achieving antennas' broadband characteristics.

1) Log Periodic Antenna

The electrical properties of the log-periodic antenna vary logarithmically as a periodic function of the operating frequency. An increase in the number of connected elements in the antenna design improves the bandwidth and frequency response of the system.

Working Principle**-** A log-periodic antenna primarily operates within its active region rather than throughout the entire structure. When the elements' length is smaller than their resonant length, a magnitude of current flows in this area, causing a shift in the device voltage and resulting in slight backward radiation due to high capacitive impedance. When the element length matches the wavelength, the current is at its maximum (active region) and in phase with the supplied voltage. This active region provides maximum radiation, with the apex being the location for the highest frequency. For intermediate frequencies, the active area shifts toward the middle, and for lower frequencies, it moves toward the largest elements. The active region is most extended when the minimum frequency is considered [7–8].

2) Spiral Antenna

The spiral antenna is a self-complementary structure known for its frequency-independent performance over a broad bandwidth. Due to its high performance and compact form factor, it finds widespread use in the communication sector.

Working Principle**:** The broadband characteristic of the spiral antenna is attributed to its constant input impedance and its ability to maintain a VSWR (Voltage Standing Wave Ratio) below 2:1 over a wide operating frequency range. The two-arm Archimedean planar spiral and the two-arm equiangular spiral are the most commonly used types of spiral antennas. The equiangular spiral is designed to be truly self-complementary, as the spiral radius follows a logarithmic dependency on the rotation angle. In contrast, the Archimedean spiral, while not strictly frequency-independent due to its linear expansion rate, exhibits electrical properties very similar to those of the equiangular spiral. Furthermore, the Archimedean spiral is often preferred for its ease of manufacturing [9–10].

3) Leaky Wave Broadband Antenna

A leaky wave antenna is designed based on a unique technique involving a leaky grounded coplanar waveguide (GCPW), which comprises a metallic strip and a prism.

Working Mechanism**:** This antenna system generates leaky wave (fixed beam) radiation, which is then transferred to the prism and subsequently radiated through the metallic strip transition. The design produces fixed beam radiation due to the non-dispersive nature of the GCPW, simplifying the design and fabrication process. The reported bandwidth of this antenna exceeds 33%, with an operating frequency range extending from 28.8 GHz to over 40 GHz. An innovative approach introduces an eight-port planar design for a leaky-wave antenna (LWA), which operates using a frequency-dependent beam-steering technique. The leaky wave antenna holds significant promise for cost-effective three-dimensional space beam scanning applications [11-12].

4) Vivaldi Antenna

The Vivaldi antenna is an essential example of a broadband antenna. The tapering design of the antenna is seen in Fig.2. (a).

Working Principle- An open space in the antenna is excited via a feed line and is usually terminated by a coaxial or a sector-shaped area. The electromagnetic waves are connected to an exponentially tapered design pattern through slot lines. The central part of the Vivaldi antenna is the tapered slot that resembles a two-dimensional exponential horn antenna. Usually, λ/4 strip lines are used to short-circuit the design, thus enhancing the antenna's operating frequency range and bandwidth. For broadband impedance matching, the circular sector with the strip line is designed on the second layer of the printed circuit board [13–14]. Fig.2. (b) shows the radiation pattern of the antenna.

5) Biconical Antenna

The biconical design uses a thicker wire over a simple dipole, easily enhancing the antenna's bandwidth.

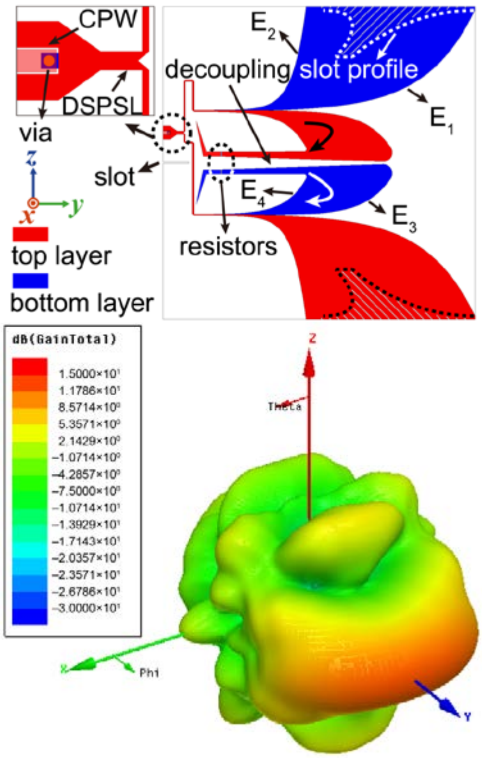


Fig.2. (a)Broadband Vivaldi Antenna and (b) Radiation Pattern of Vivaldi Antenna (Reprinted with permission from [14])

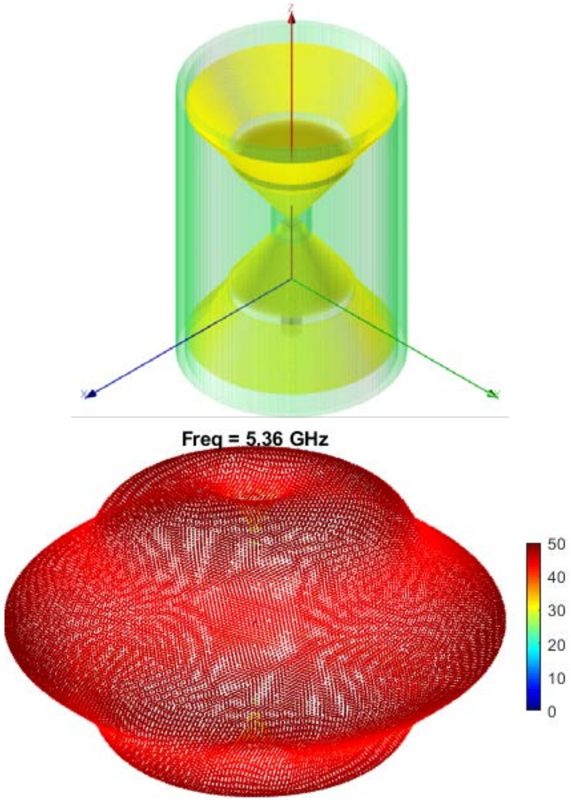


Fig.3. Broadband Biconical Antenna and Radiation Pattern of the Biconical Antenna (Reprinted with permission from [16])

Working Principle**:** The concept of a wired structure is further extended as a flared conductor to form a biconical structure to increase the bandwidth. The antenna is shown in Fig.3. A complex input impedance is developed due to the standing wave ending towards the cones. A part of the energy is reflected, resulting in energy storage. A portion of the wave is radiated when the outgoing spherical wave reaches a maximum radius perpendicular to the axis than close to the cones. As the uniform transmission line acts as a guide for traveling plane waves similarly, the biconical antenna acts as a guide for traveling outgoing spherical waves [15–16]. The radiation pattern of the antenna is shown in Fig.3.

B. Mathematical Analysis of Millimeter Broadband Antenna and Its Dispersion Characteristic

Dispersion characteristic is an essential parameter in designing a broadband antenna. Return loss and antenna efficiency are the conventional parameters defining an antenna's narrow band characteristic.
Let the surface curvature of the antenna be –

$$r = F(\theta, \phi). \tag{1}$$

where r is the surface distance and $r'$is the scaled value of surface distance.

$$r' = KF(\theta, \phi). \tag{2}$$

Both terminals of the broadband antenna are assumed to be close to the origin and θ is 0 and π to make it symmetrical along the axis

$$KF(\theta,\phi) = F(\theta,\phi + C). \tag{3}$$

K represents a scaling factor by which the antenna is scaled from the original frequency. The original and the scaled structure are identical as well as congruent. And thus, to achieve congruency, the scaled structure is rotated by an angle C dependent on the scaling factor K.

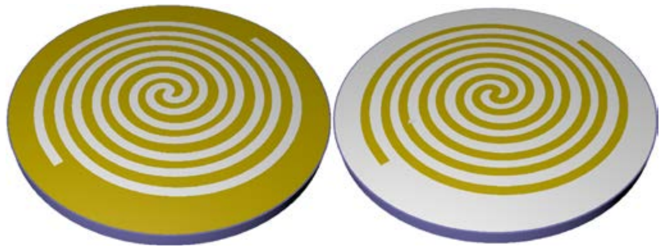


Fig.4. Broadband Spiral Antenna analysis(Reprinted with permission from [17])

$$\frac{d}{dC}\,[KF(\theta,\phi)] = \frac{dK}{dC}\,F(\theta,\phi) = \frac{\partial}{\partial C}\,[F(\theta,\phi + C)]$$
$$= \frac{\partial}{\partial(\phi + C)}\,[F(\theta,\phi + C)].$$
$$\frac{d}{d\phi}\,[KF(\theta,\phi)] = K\,\frac{\partial F(\theta,\phi)}{\partial\phi} = \frac{\partial}{\partial\phi}\,[F(\theta,\phi + C)] \tag{4}$$
$$= \frac{\partial}{\partial(\phi + C)}\,[F(\theta,\phi + C)].$$

For physical congruency, the electrical parameters of the original and the scaled antenna should have superimposing properties at all the operating frequencies. And thus, to obtain such property, a functional representation of $F(\theta,\phi)$ is obtained. The mathematical analysis of the antenna is done by taking Fig.4. as a reference.

$$\frac{dK}{dC}\,F(\theta,\phi) = K\,\frac{\partial F(\theta,\phi)}{\partial\phi}.$$
$$\frac{1}{K}\frac{dK}{dC} = \frac{1}{r}\frac{\partial r}{\partial\phi}\,\left[\text{using } r = F(\theta,\phi)\right]. \tag{5}$$

From equation (4) and equation (5) it is concluded that the radiation pattern of the broadband antenna is azimuthally rotated by an angle C.

$$r = F(\theta,\phi) = e^{a} f(\theta).$$
$$a = \frac{1}{K}\frac{dK}{dC}. \tag{6}$$

$f(\theta)$ is an arbitrary function, and from the above equations, it is seen that the broadband antenna parameters are independent of θ,ϕ and the general solution of the antenna is dependent on the surface distance $r = F(\theta,\phi)$.All the equations (1-8) used in this mathematical analysis describe the broadband antenna and thus, the design of a broadband antenna is dependent on surface equation and is independent of its frequency [17–18].

The broadband antenna transmits distorted pulses, and thus, dispersion parameters such as group delay, fidelity factor, and transfer function are used to determine the performance of such antennas. A proper transmission/reception setup is built to calculate the dispersion characteristic of the broadband antenna. The dispersion characteristic of the broadband antenna in the frequency domain is directly related to the transmitted spectrum $S_t(f)$ group delay and transfer function (S_{21}) and the received signal spectrum $S_r(f)$ is mathematically given as

$$S_r(f) = S_{21}(f)\cdot S_t(f). \tag{7}$$

The transfer function of the phase and magnitude distortion determines the dispersion of the received signal. The group delay parameter defines the phase distortion and is represented as $d\phi/df$where ϕ is the phase of $S_{21}(f)$.

For linearity in phase and constant group delay is a must. The fidelity factor (F) of the transmitting and receiving signal shows the validation of the induction of the amount of pulse distortion in a broadband antenna and is defined as-

$$F = \max_{\tau} \frac{\int_{-\infty}^{+\infty} S_t(t)\; S_r(t-\tau)\, dt}{\sqrt{\int_{-\infty}^{+\infty} |S_r(t)|^2\, dt.\;\; \int_{-\infty}^{+\infty} |S_r(t)|^2\, dt}}. \tag{8}$$

The spectrum similarity between any two communicating signals is defined by the fidelity factor (F). It is unity when the two signals are congruent to each other. Without any severe distortion, the antenna can communicate well if the group delay varies around 3.4ns, fluctuating almost 0.6ns for the complete operating frequency range. Thus, the distortion in the signal and the fidelity factor defines the dispersion characteristic of a broadband antenna [19–20].

C. Feeding Mechanism of Broadband Antenna

The feedline transfers energy from the source to the structure in a broadband antenna. The impedance of the transmission line for the broadband antenna is generally 50Ω.

The maximum power transfer theorem is utilized to obtain a broadband characteristic, and power excitation through the feedline is done at a point of 50Ω impedance for full input power.

Fig.5. shows the antenna model with T-slot and CPW as a feed.

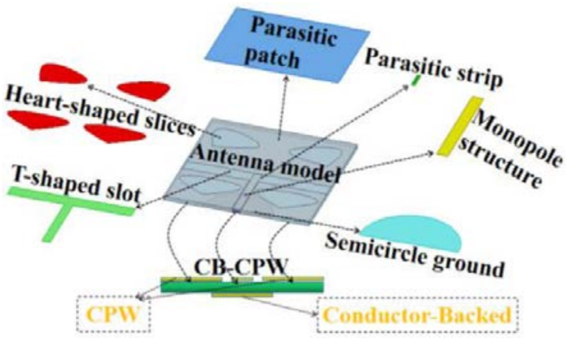


Fig.5. Feeding Techniques of Broadband Antenna (Reprinted with permission from[21])

Various feeding techniques fulfill this condition and can be used to design broadband antennae. A microstrip tapered feed line is adopted for perfect impedance matching and is inserted into an antenna port. The antenna port is a sector where the feedline is inserted to allocate the input signal properly. Both sides of the substrate use two metallic bending lines in such feed. A coplanar waveguide is preferred over a microstrip feedline to make a broadband antenna compatible with integrated microwave circuits.

In a fractal broadband antenna structure, implementing a microstrip line with exponential tapering is done to excite the antenna. An exponential form factor is introduced between the radiator and the feedline for an increment in the impedance bandwidth of the antenna. The broadband antenna design uses a stepped connection structure between a tapered radiator and stripline, significantly improving the impedance bandwidth and thus enhancing the broadband parameters [22–26].

In the case of broadband impedance transition from 50 Ω to 80 Ω, a tapered microstrip line, and a slot line are used to feed a radiator, and even it increases the directivity of the antenna. To conveniently match 50Ω impedance over a broadband range, a microstrip feed line is switched to a symmetric double-sided slot line. A balun structure with electromagnetic antenna coupling between the slot line and the microstrip design is introduced for an unbalanced signal to a balanced signal transition. A Gaussian sinusoidal modulated tapered slot feedline and a bending feedline structure are employed for a broadband antenna design to upgrade the antenna's broadband performance and compact the antenna. A multi-layered substrate structure is recommended to attain a broadband characteristic of an antenna, and substrate integrated waveguide is utilized as feed-in such antenna design [27–28].

Table 1 shows the comparison of feeding techniques of millimeter wave antenna.

D. Substrate Material Selection for Millimeter Wave Broadband Antenna Design

The selection of a dielectric substrate plays a crucial role in the design of broadband millimeter-wave antennas. Several critical characteristics of a substrate, such as permittivity, surface wave production, loss tangent, dispersion constant, temperature range, elastic stability, mechanical strength, anisotropic properties, weight, and cost, must be carefully considered before initiating antenna design. One of the most commonly used dielectric substrates in the design of millimeter-wave broadband antennas is polyethylene terephthalate (PET), which has a dielectric constant of 3.2 and a dissipation factor of 0.002. PET also finds applications as a nanocomposite material in emerging millimeter-wave technologies. Another popular choice for a dielectric substrate, known for its flexibility, is polydimethylsiloxane (PDMS), with a dielectric constant of 2.7 and a dissipation factor of 0.0012.

PDMS is a superior substrate option for millimeter-wave antenna design. Both PET and PDMS are widely utilized in broadband antenna design due to their low dielectric constants, high gain performance, and suitability for high-frequency operation [29].

For lower millimeter-wave operating frequency, an FR-4 substrate with a dielectric constant 4.4 is designed to design the compact grid array antenna. The efficiency and gain of such substrate-used antenna design are 66.0% and 14.4 dBi, respectively. Usually, to design an antenna with an operating frequency of 25.0–30.0 GHz, the Nelco N9000 as a PCB with ε of 2.2 and a loss tangent of 0.0009 is used, which provides a gain of 18.52 dBi and an isolation level of almost greater than 12.7 dB [30].

TABLE 1
COMPARISON OF FEEDING TECHNIQUES OF MILLIMETER WAVE ANTENNA

Ref.	Antenna	Freq (GHz)	Substrate	Size (λ_0 in mm)	B.W (%)	F.T	Gain (dB)	Fab Tech	Design Specification
[22]	Microstrip Antenna	32	RT Duroid 5880	1×1×0.2	17%	Coaxial back feed	7.8	LTCC	Low backward radiation
[23]	Fabry Perot Cavity Antenna	56	Rogers RT5880	1.5×1×0.08	17.8%	Coplanar Waveguide	21	PCB	High Gain performance with low side lobes
[24]	Magneto-Electric Dipole Antenna	30	RT Duroid	N/A	62%	Asymmetrical substrate integrated coaxial line	6.2	PCB	Wide bandwidth and superior radiation characteristics
[25]	Air filled slot antenna	60	Silicon layer	1.5×1×0.025	2.17%	SIW	3.21	LTCC	Conical beam is realized
[26]	Leaky wave antenna	35	ROGERS 6002	4×4× 0.25	14.9%	GCPW-SIW	12	Integrated RFIC	Low cost

* B.W= Bandwidth (GHz), F.T= Feeding Technique, Fab Tech= Fabrication Technique, GCPW=Grounded coplanar waveguide, RFIC= Radio frequency integrated circuit

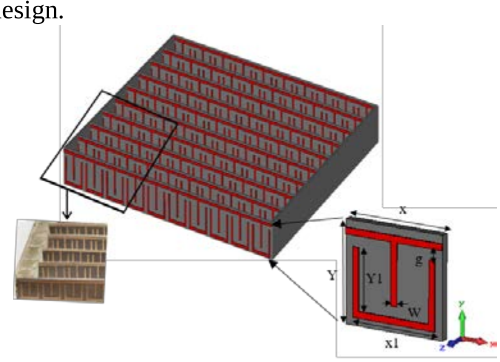
The frequency selective surface (FSS) superstrate is selected to provide a low-profile broadband feature with a high antenna efficiency. Such an antenna design has a high gain with an efficiency of more than 90.0% [31].

An antenna with RT/Duroid 5880 as a microstrip line feeds a substrate, providing proper matching with enhanced bandwidth and ease of fabrication. The size of the Rogers 5880 substrate used is 5.8 × 1.5 mm^2 with a thickness of 0.254 mm. This design achieves a gain of almost 7 dB and an isolation more significant than 16 dB in the millimeter-wave frequency range. Another option to increase the gain of the millimeter-wave antenna multi-layered structure is designed. An antenna with an operating frequency of 40.0–50.0 GHz uses Rogers 5880 substrate with a thickness of 0.508 mm, which provides between 7.3 and 12.5 dBi[32].

III. Design Configuration of Broadband Millimeter Wave Antenna

A. Metamaterial Based Broadband Antenna

A meta-material is an artificial synthetic material with negative refractive index property not found in a natural substance. A meta-material is considered a dispersion engineering material as the phase response of the device is controlled by it. Two fundamental approaches are considered to design broadband antennas using meta-material, i.e., the transmission line approach and the resonance approach. A transmission line approach is a non-resonant approach based on transmission line theory. It provides design tools with low loss for a large operating frequency range. A split rings resonator, a thin wire, or a complementary resonator are mainly used in the resonance approach, leading to a lossy circuit. An anisotropic zero-indexed meta-material is synthesized to enhance the gain and radiation properties of a broadband antenna[33–35]. Fig.6 (a) and (b) shows the metamaterial-based antenna array and planar antenna design. An anisotropic inhomogeneous artificial material and a high indexed meta-material are used to achieve the broadband characteristic of an antenna. The design of an antenna using meta-material significantly impacts the dimension of the structure. The metamaterial has a high permeability value, i.e., $\mu_r >> 1$, which substantially reduces the size of the broadband antenna without the use of a high permittivity substrate, and it even enhances the gain, radiated power level, and bandwidth of the design.



(a)

(b)

Fig.6. Metamaterial Based Broadband Antenna (a) Metamaterial based Antenna Array and (b) Metamaterial based Antenna (Reprinted with permission from[33–34])

TABLE 2
COMPARISON OF METAMATERIAL BASED BROADBAND AND MILLIMETER – WAVE ANTENNA

Ref.	Antenna	Freq (GHz)	Substrate (ε_r)	Size (λ_0 in mm)	B.W (%)	F.T	Gain (dB)	Fab Tech	Design Specification
[36]	MIMO	28	Single mu Metamaterial (MNG)	0.5×0.25×0.025	22.2	Transmission Line	12.4	PCB	Near zero for permittivity, permeability
[37]	Aperture Antenna	290	2.2	13.63×13.63×2.25	34.4	Stripline	-	LTCC	Terahertz Band
[38]	Antenna Array	60	2.33	5×7×1.4	16.3	SIW	18	LTCC	High Gain
[39]	MIMO	24	2	1×1×0.04	23.4	Inset feed	11	PCB	5G System

* B.W= Bandwidth (GHz), F.T= Feeding Technique, Fab Tech= Fabrication Technique, PCB=Printed Circuit Board, LTCC= Low temperature Co-Fired ceramic

The meta-material is a radiating component in developing multiple compact-sized communication systems. Meta-material units are essential in gain enhancement in a non-resonant frequency band. If the meta-material cell length is reduced, the gain is also decremented at lower and higher frequencies.

When the cell length increases, the gain is increased drastically over a non-resonant frequency band. Fig.6 (a) and (b) show the metamaterial-based broadband antenna, and Table 2 shows the comparison table of different metamaterial-based Broadband millimeter Wave antennas. For a broadband antenna's radiation pattern improvement, a parallel meta-material is used, which acts as a phase shifting and thus enhances the overall working of the antenna. For a broadband imaging application, a combination of a meta-material unit with CSRR (circular split ring resonator) is recommended [36–39].

B. Fractal Based Broadband Antenna

A non-predefined repeated structure is called a fractal structure. In contrast with the traditional Euclidean antenna, the fractal antenna shows an effective manner of space occupancy, thus minimizing the broadband antenna's size. A Koch curve structure is a basic fractal design termed an initiator of the structure [40–41].

The design is converted into three equal segments. For the first iteration, the middle segment is replaced by two similar segments of the same length, and such iteration is called a generator [*ko*]. Generation of successive iterations uses the smaller ascending bumps, and theta is identified for different iterations of the Koch fractal shape. The fractal slot edge suppresses the E-field in the surroundings and interfaces its metal edges, thus making the medium softer [42–43]. The fractal designed at the edges of the structure discards the E-field trapping and thus enhances the antenna's gain over an entire broadband frequency range. Fig.7 shows the fractal design of the millimeter wave broadband antenna, and Fig.8 shows the antenna radiation pattern [44–45].

The consecutive iteration of the fractal design reduces the cut-off frequency at a lower range and thus increases the bandwidth of the structure.

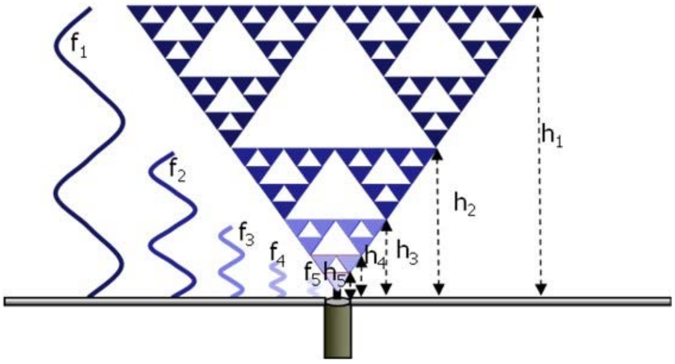


Fig.7. Fractal Broadband Antenna Design (Reprinted with permission from[44])

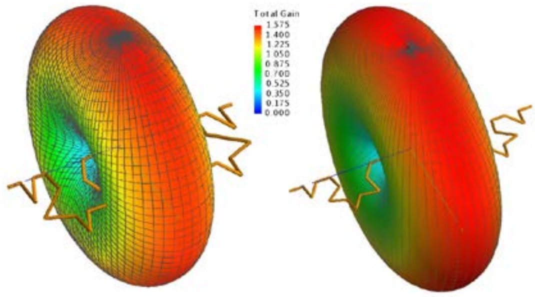


Fig.8. Fractal Broadband Antenna Radiation Pattern (Reprinted with permission from[45])

A fractal structure enhances the antenna parameters without occupying a sizeable geometrical dimension. Table 3 compares the fractal-based broadband millimeter wave antenna [46–47].

TABLE 3
COMPARISON OF FRACTAL BROADBAND AND MILLIMETER WAVE ANTENNA

Ref.	Antenna	Freq (GHz)	Substrate	Size (λ_0 in mm)	B.W (%)	F.T	Gain (dB)	Fab Tech	Design Specification
[42]	Snow Flake Array	28	2.2	0.8×0.2×0.02	13.43%	SIW	10.12	PCB	Dual Beam
[43]	Fractal EBG	28	Polyester fabric	0.95×0.95×0.045	40%	CPW	15	PCB	Wearable Antenna
[46]	Koch Fractal	100	2.2	6.66×6.66×0.26	89.99%	Microstrip	11.6	PCB	Security System

* B.W= Bandwidth (GHz), F.T= Feeding Technique, Fab Tech= Fabrication Technique

C. Unbalanced and Balanced Broadband Structure

The Antipodal Vivaldi structure is an actual example of a broadband antenna. The unbalanced antipodal form shows a degraded performance and poor polarization characteristics, rectified by a balanced antipodal Vivaldi antenna (BAVA). It is a three-layered structure in which the outer layers act as the ground layer, and the middle-structured layer is a conductor. A substrate separates these three layers. A dielectric material Through this balanced structure is an equipoise between a ground and a conductor plane. These forces current to flow in a different path on the layers and thus enhances the antenna's performance.

This balancing design provides an elongated substrate with the loaded slot, which changes the beam squint and thus increases the end-fire performance, giving a higher front-to-back ratio. To make a broadband antenna compact, a coagulation patch is introduced in between the two flares of the BAVA [48–49].

The tapered design of the antenna consists of a tapered slot line open-ended structure. The electric field at the slots is tightly bound and starts decaying rapidly as it moves away from the slots. As the width of the slot is increased, the characteristic impedance and the guided wavelength also increase. The radiation mechanism of the tapered slot Vivaldi antenna is based on the behavior of the slot, i.e., when the wavelength is less than $0.4\lambda_0$, which is the free space wavelength of an antenna, and if the wavelength exceeds this limitation. The tapered slots no longer behave as a transmission line and thus enhance the structure's radiation pattern. The tapering shape decides the application of the antenna design. Vivaldi antenna is a surface-type antenna in which the radiation occurs through the exponential flare.

The exponential flare of the tapered antenna regulates the radiation and the antenna pattern, and it is observed that the waves experience a tight bond at the start point of the flare, and the bond becomes weaker as the wave moves away from the originating point and thus radiates properly. The profile selection determines the half-power beam width (HPBW) and the antenna bandwidth. On increasing the radius of curvature of the Vivaldi antenna, the HPBW in the E-plane is reduced.

The antenna's bandwidth is inversely proportional to the radius of the Vivaldi antenna and exponential profile. The feed design is the critical factor limiting the bandwidth of the tapered antenna. Stub over a micro-strip feed is also used to optimize the antenna's behavior and match the frequency over a wider bandwidth [50–52]. Table 4 is a comparison of unbalanced and balanced broadband millimeter wave antenna.

D. Multimode Broadband Antenna

Mode control is the new technique for designing a broadband antenna. A multimode broadband antenna is designed by fitting a meander line into a twisted loop traditional structure. Keeping the aperture size of the design constant, the shifting of the resonant mode at a lower frequency is done, which facilitates the bandwidth and miniaturization of the antenna. Now for second mode movement at high operating frequency and with an acceptable impedance match, the embedding of twisted strips inserted into the coupling area of the structure is done. A loop-dipole is driven, and due to strong coupling, the other dipole, when coupled, acts as a resonator or a parasitic antenna element. Thus, the large bandwidth or impedance matching due to multiple resonances is attained.

A new resonance pattern is established at a high working frequency by introducing a parasitic polarization element and is checked by varying the linear area of the parasitic element. Modifying the parasitic element allows the lower-ordered resonance modes to operate at a low working frequency. Now they combine with the higher-ordered mode, and thus, bandwidth is extended to a large extent. The current path of the antenna design determines the system's first mode, while the coupling region adjustment between crossed loop-dipoles gives the second mode description [53–54]. Either altering the antenna's coupling gap width W_c or the loop-dipole L_p length can simultaneously influence the two resonant modes, with a degraded bandwidth exhibited.

TABLE 4
COMPARISON OF UNBALANCES AND BALANCES BROADBAND MILLIMETER – WAVE ANTENNA

Ref.	Antenna	Freq (GHz)	Substrate	Size (λ_0 in mm)	B.W (%)	F.T	Gain (dB)	Fab Tech	Design Specification
[50]	Vivaldi	30	Graphene	0.6×0.6×0.02	16.6	Microstrip	8.1	PCB	Reconfigurable
[51]	AVA Array	24	2.2	6.11×2.93×0.08	15.3	Power divider network	12	PCB	Based on Anisotropic Metasurface
[52]	Antipodal Septum Antenna	60	2.2	1×1×0.02	40	Rectangular Waveguide	10.2	PCB	High Gain

* B.W= Bandwidth (GHz), F.T= Feeding Technique, Fab Tech= Fabrication Technique, AVA= Antipodal Vivaldi Antenna

E. Special Broadband Antenna

1) Microstrip Patch with U-Slot

Embedding different types of slots on the radiating patch enhances the bandwidth characteristic of an antenna. A U-slot patch antenna is proposed, which gives a better bandwidth, impedance matching, and gain. The shape of the patch also plays a vital role in determining the antenna's operating frequency. A U-slot is introduced on the antenna patch, which is symmetrical to the microstrip feed and thus helps obtain a symmetrical radiation pattern. The proposed antenna is a two-layer structure with Teflon as a dielectric permittivity (ε_r=2.2). U-slot is made on the lower layer of the Teflon substrate, which is coupled with the antenna's ground. The top layer is designed with a circular patch, enhancing the structure's isolation. A ground feeds the antenna-backed coplanar waveguide (GBCW) and covers the 60GHz band. The area of the core of the antenna is $0.6\lambda_0 \times 0.6\lambda_0$ with a bandwidth of 10 GHz operating at frequencies 57.2 GHz to 67.3 GHz. The gain of the given antenna is 8 dBi. The feed's position is selected so that it is close to the null voltage point for the fundamental modes [55–57]. The U-slot excites the adjacent resonance modes, which are in the vicinity of the fundamental frequency f_0, thus enhancing the proposed antenna's bandwidth.

2) Microstrip Patch with E-Slot

When etched on the patch surface, the E-shaped longitudinal slot creates a change in the E-field distribution of the adjacent resonance mode without affecting the dominant TM mode. E-slot helps in tuning the resonance frequencies of the two adjacent ways, which provide an impedance matching over a broader range and thus enhance the system's bandwidth. The placement of the transverse E-slot on the patch determines the current distribution over the antenna, the radiation pattern on the E-plane and H-plane, and the suppression of undesirable modes to reduce the cross-polarization. The functioning of the proposed antenna over the Ku band and the bandwidth achieved is around 45.4%, with an efficiency of more than 85%. The length of the E-slot is used to excite the broadside radiation pattern of two different modes, and the frequencies are tuned so that they are close to each other and provide a broadband performance. The substrate used is a two-layer Taconic TYL with ε_r=2.2 and a thickness of 0.508 mm, and roger material with ε_r=3.4 and a thickness of 0.1mm is used to connect the two substrate layers. The antenna size is $0.46\ \lambda_0 \times 0.70\ \lambda_0$ at 37.5 GHz with a peak gain of 8.5 dB [58–59] .

3) Microstrip Patch with Ring-Slot

Ring slots on the patch play a vital role in exciting the hybrid mode of the structure. Using a post vias, a cylindrical cavity is designed on the substrate. Four ring slots, which acts as a radiating element, is etched on the cylindrical cavity. The radius of the ring decides the modes excited on a feed, the bandwidth, and the operating frequency of an antenna.

Fig.9 shows the ring slot broadband antenna design [60].

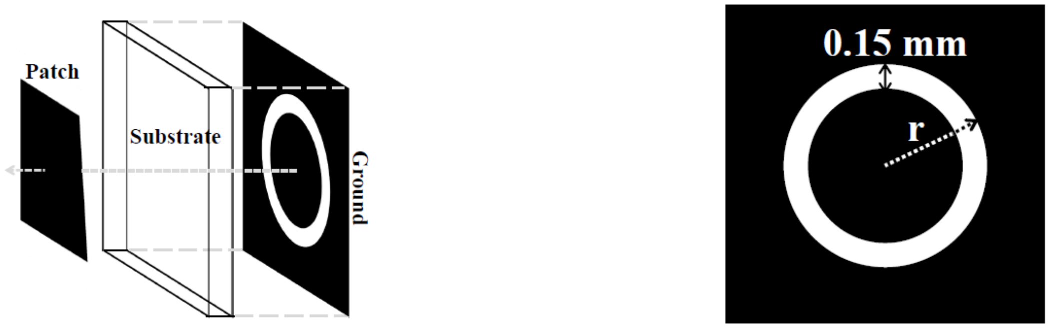
The substrate used to design the proposed antenna is Rogers 5880 with ε_r=2.2, and the thickness of the substrate is taken as 0.787 mm. The loaded ring slot determines the cut-off frequency alteration and the patch's electric field distribution.

Due to these slots, the TM and hybrid modes are shifted to higher frequencies, then combine to enhance the antenna's bandwidth. The operating frequency is from 25 GHz to 29.5 GHz. The maximum peak gain of the antenna is 13 dB [61–62]. Table 5 is the comparison of different microstrip patch broadband millimeter wave antennas.

TABLE 5
COMPARISON OF MICROSTRIP PATCH BROADBAND AND MILLIMETER – WAVE ANTENNA

Ref.	Antenna	Freq (GHz)	Substrate	Sizen (λ_0 in mm)	B.W (%)	F.T	Gain (dB)	Fab Tech	Design Specification
[55]	Compact Patch	26	RT Duroid 5880	10×4×0.8	68.6	Single strip line	15	PCB	5G
[59]	Symmetric E-Patch	37.5	RT Duroid 5880	0.46×0.70×0.076	45.4	CPW	8.5	PCB	K-band application
[57]	Dirac Leaky wave	28	Rogers RO4003	6×4×0.75	38.5	SIW waveguide	15.8	PCB	Modal analysis
[58]	Switched Beam	60	ROGERS CuClad 217	24×12×3	18.4	Micro-stripline	16	PCB	Main beam is switchable
[61]	Narrow beam	28	Rogers RT5880	0.25× 0.25× 0.075	35.5	RF connector	10.7	PCB	High gain

* B.W= Bandwidth (GHz), F.T= Feeding Technique, Fab Tech= Fabrication Technique, CPW=Coplanar waveguide, SIW=Substrate Integrated Waveguide



(a) (b)

Fig. 9. (a) and (b) Ring Slot Broadband Antenna Design (Reprinted with permission from[60])

4) Lens Antenna

The lens antenna design is suitable for achieving high gain in mm-wave antenna technology. The technology used in such a method is a waveguide lens which uses waveguide elements as a refractive and dispersive honeycomb media. To enhance the bandwidth of the lens, a zoning technique is applied. Here the waveguide elements are truncated so that the modulo 2π distribution in the aperture can be achieved. Thus, the bandwidth of the lens is enhanced. The diameter used for designing the lens is 24mm for 55 GHz operation. The drawback of the waveguide lens technique is that the honeycomb media is not precise, and a variation in the refractive index is noticed, which distorts the phase distribution of the aperture and thus produces high-side lobes.

A homogenous dielectric lens is introduced to overcome the waveguide technique's drawback. In this technique, the outer surface of the lens also serves as a radome. The main concept in this technology is a dual-frequency feed that keeps the phase distribution of the aperture constant and is capable of millimeter-wave frequency operation. The disadvantage of this lens design technique is that designing the lens for lower frequencies of operation is practically impossible as the larger dimension of diameter of the lens is needed, which increases the overall weight of the antenna.

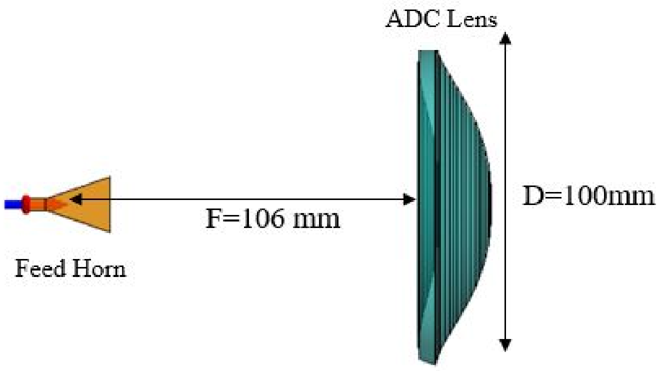


Fig.10. Lens Broadband Millimeter-wave Antenna Design (Reprinted with permission from [63])

Another class of lens antenna design is the inhomogeneous index of refraction on the dielectric lens of the antenna. For the effective refractive index, a 2-dimensional parallel plate is constructed. It uses a multiple-beam feed to achieve lens collimation. The fan beam is produced after the feed, which illuminates a cylindrical parabolic reflector. An elevation steering is implemented by positioning the reflector correctly, and through multiple-beam feed, the azimuth steering is achieved. The inhomogeneous lens design method provides constant potential, which helps in wide-angle beam steering, and it also offers a uniform beam quality throughout the scan region. The diameter of the lens designed for this antenna is 12mm, and the frequency of operation is 70 GHz band.Fig.10 shows the lens antenna design [63–65].

5. Planar Inverted-F Broadband Antenna Structure

Planar inverted-F antenna structure (PIFA) is another type of antenna that uses mm-wave frequency for communication. A single-layer superstrate dielectric load is introduced in the structure [54]. The antenna size is 15mm × 15mm, covering a 28 GHz mm-wave frequency band (27.47 - 28.45 GHz). The antenna with the Rogers5870 as a substrate is integrated at the front end of the mobile phone using a K-connector or GSG probe. The maximum radiation efficiency in the presence of a battery is recorded as 97% for 27.47 GHz and 99% for 28.45 GHz. The total gains are 8.8dBi and 8.5dBi, with total efficiencies of 88% and 96% for 27.47 GHz and 28.45 GHz, respectively [66–67].

F. Broadband Antenna Array Design

The antenna array is an arrangement of two or more antennas in a specific way to attain an enhanced bandwidth and improved performance. The geometrical configuration of the antennas in an array plays an essential role in determining the characteristic of the antenna. The antenna array is designed by arranging the radiators in linear, triangular, and rectangular or in the circular lattice, and the gap between them, called periodic spacing, is adjusted to achieve the desired radiation pattern. The choice of the alignment of the antenna in an array and the way of excitation of each element define the beam-forming performance of the antenna array [68–69].

Designing a large antenna array provides many separate paths to a single user, leading to higher data rates than the present data scenario. An enhanced signal-to-noise ratio is achieved through the antenna array as it provides highly directional beams. The signals at near and far away devices do not break due to the enhanced beam-forming; thus, the array antenna provides an uninterrupted signal. Due to the antenna size, this antenna array can easily fit inside a standard mobile handset. Designing the antenna array is done so that they are orthogonal to each other, which results in polarization diversity. Table 6 shows the comparison of different broadband millimeter-wave array antennas [70–71].

Broadside beam-forming arrays are essential candidates for millimeter-wave applications. Antenna arrays with switch beam technology are introduced, and Butler matrices are used as feeding methods. 2×2 planar antenna arrays are designed using the patches' four layers. The antennas' main beams are switched in four different directions by applying different phases to the patches' four layers, thus resulting in wider beam widths. Usually, Butler matrix feeding is used for 1-D systems; hence, proper element spacing and feed order arrangements are needed for the antenna arrays. They are designed for four-layer PCB technology, providing gains of 8dBi. The antennas' bandwidth ranges from 55 to 67 GHz.[72–73].

Different broadband antenna array designs are used for 5G communication systems. Planar loop antenna arrays show broadband characteristics with easy integration into mobile systems. The loop antennas are usually designed on FR-4 as cheap and readily available substrates. Phased loop antenna arrays are modified for recent millimeter-wave antenna applications.

Dipole antennas are fed by integrated baluns with folded microstrip lines, which enhance the broadband characteristics of these antennas. The dipole antennas are designed with angles of 45° to make them compact. The advantage of such wideband designs is the broader scanning capacity with low side lobe levels (SLL). Broadband antenna arrays are widely used for imaging applications. One such design is HIS (high-impedance surface) patch antenna arrays, which are meta-surfaced to avoid collisions in imaging applications, thus helping visually impaired patients. The comparison table of the state-of-the-art work with the proposed review is presented in Table 7.

The table reveals that earlier studies primarily involved circularly polarized antennas, 5G multi-element antennas, or rectennas. In contrast, this review emphasizes the operational principles of broadband antennas across the entire millimeter-wave range.

The mathematical analysis of the dispersion characteristics of broadband antennas in the millimeter range is comprehensively elucidated. Additionally, this review places significant emphasis on the selection of materials and dielectrics for antennas, highlighting the critical role of material choices in broadband antenna design.

TABLE 6
COMPARISON OF BROADBAND MILLIMETER – WAVE ARRAY ANTENNA

Ref.	Antenna	Freq (GHz)	Substrate	Dimension (λ_0 in mm)	B.W (%)	Feeding Technique	Gain (dB)	Fab Tech	Design Specification
[69]	Antenna Array	60	Rogers RT5880	20×20×5	30.7%	SIW feed	25.1	Multi-layer PCB	Enhanced radiation pattern
[70]	Endfire Array	26	RT Duroid	9×1×0.02	32%	Coaxial feedline	7	PCB	Beam-steering and scanning
[71]	Comb line Array	79	ε_r=5.9	0.15×0.15×.146	29%	Microstrip	15.8	PCB	Narrower tilted beam directions
[72]	Lens Antenna Array	28	RO5880, RO4350B, RO4450B	4×4× 0.25	25%	ACMA feed array	8.2	PCB	High directivity
[73]	Dipole Antenna Array	28 and 39	Taconic TLY-5 ε_r= 2.2	0.6×0.2×0.025	50.7%	SICL Feeding Network	16.3	PCB	High Gain

* B.W= Bandwidth (GHz), F.T= Feeding Technique, Fab Tech= Fabrication Technique

IV. Future Scope and Application of Broadband Millimeter Wave Antenna

Most electronic devices at homes are usually explicitly limited to frequencies up to 30 GHz in radiofrequencies. The mentioned frequency ranges are over-jammed; thus, a focus is to shift the current wireless communication standards to ranges above 30 GHz. Only precise amounts of data can be squeezed by carriers in specified radio frequency spectral [74].

In multifold connections of wireless devices, there are considerable drops in the efficiency of data-carrying and thus face network congestion. Companies and governments make different investigations and formulate strategies for alternative ways to overcome the increasing data demand.

Some of the solutions being considered are surveying the uses of the unutilized frequencies which are assigned for combined agencies, T.V. stations, and other wireless communication spectrum usages of alternative technologies which can be used to cover short-range communications, which include significant area broadband usages, radios, Wi-Fi, LTE-U, and also scrutinizing the other unutilized spectra.

The millimeter-wave spectra are one of the solutions which are considered to meet the congestion problem [75–76].

A. Small Cell Deployments

The available millimeter-wave spectra, ranging from 24 GHz to 86 GHz, positions them as crucial candidates to meet the high data rate demands of 5G. Technical teams are actively investigating and testing millimeter-wave antennas for potential future deployments in small cell infrastructures. In upcoming communication systems, millimeter waves may even replace traditional fibre optic transmission lines [32].

B. Enhanced Communication Technologies

To support future millimeter-wave media display interfaces and wireless devices operating at gigabit rates, new technologies such as the Wireless Gigabit Alliance (WiGig) have been developed.

These WiGig wireless protocols enable high-performance communication between devices and computers. High-frequency radar technologies using millimeter waves are also emerging for various applications.

These technologies primarily leverage the beamwidth properties of millimeter waves and, due to their high frequencies, they are compact and used in different applications such as car speed detection, collision avoidance systems, and more.

Millimeter waves are essential candidates for satellite communications. They operate flawlessly at higher altitudes in orbit, offering superior data rates and low latency [77]

C. High-Definition Videos

Millimeter waves are essential for broadcasting ultra-high-definition (UHD) videos to HDTV through wireless modes. Integration of small transmission modules on millimeter-wave devices, gaming setups, and other HD video sources is employed to facilitate HD transmissions.

TABLE 7
COMPARISON OF STATE-OF-ART WORK AND PROPOSED REVIEW

Type of Antenna	Main Characteristics	Application	Reference
Circular Polarized Antenna	1.Highlight the methodologies for circular polarization 2. Future Scope	Multiband for WLAN, WiMAX, Wi-Fi, C-band communication	[74]
5G Multi-element	1. 5G design 2. Tera-Hertz technology.	THz application	[32]
Rectenna	1. Rectenna design and power transmission for energy harvesting system.	Energy Harvest	[77]
Millimeter-wave antenna	1. Working principle of Millimeter wave broadband antenna 2. Mathematical analysis of Millimeter broadband antenna and its dispersion characteristic 3. Different fabrication and feeding technique and Material selection 4. Future scope and review on recent development in millimeter-wave	IoT, High Definition communication, Medical Therapy, Security Purpose, 5G application.	This review

D. Worlds Of Technology

Millimeter waves are being considered as options in autonomous driving and are at the forefront of discussions in these new technological realms. Autonomous driving, in particular, requires obstacle detection in millisecond time frames.

Due to their ability to scan with high accuracy and cause minimal harm to human bodies, millimeter waves are anticipated to be used as future body scanners in airport security. As reported, these systems operate within millimeter-wave frequency ranges between 70 GHz and 80 GHz, with transmitter powers of 1 mW. Millimeter waves are an excellent fit for the most anticipated aspects of virtual reality systems. Thanks to their high bandwidth, millimeter-wave communications can readily support the high-definition video and audio transmission demands of virtual reality experiences [78].

E. Millimeter Wave Medical Therapies

For treating acute pains and other severe medical therapies, millimeter wave technologies with frequency ranges between 40 GHz and 70 GHz are very helpful. [79].

F. Intelligence, Surveillance and Recon (ISRs)

Broadband antennas are utilized in ISR (Intelligence, Surveillance, and Reconnaissance) systems to facilitate the coordination of information processing with precision and intelligence support for the clusters of activities led by chief commanders. These antennas play a crucial role in ISR operations, enabling the establishment of accurate and in-depth information in military operations and communication channels.

G. Signals Intelligence (SIGINT)

Broadband antennas find application in signals intelligence (SIGINT) operations, which contribute to national security by collecting data and information that reveal the actions and intentions of the surrounding environment. These antennas aid military personnel in maintaining vigilance against potential threats.

H. Broadband Mode Converter Antennas

In recent times, the introduction of new Pattern Director Antennas (PDAs) has addressed certain issues associated with symmetric azimuthal output modes when used in high-power microwave sources. PDAs are capable of directly receiving symmetric azimuthal modes from electromagnetic sources without requiring mode conversion, resulting in directive output radiation patterns. To enhance their conductive properties, aluminum is chosen as a coating material for these antennas.

The materials selected for PDA designs are both cost-effective and environmentally friendly. The gains achieved by such antennas typically range from 16.8 to 21.8 dB within an operating frequency range of 7 GHz to 15 GHz. In the realm of high-frequency systems for 5G communications, coaxial mediums are transitioning to waveguide mediums. Consequently, cone-shaped impedance-matching transition setups have been introduced to facilitate these transitions in high-frequency systems.

These systems offer superior performance and can be easily applied to various waveguides due to their simple design structures [80-81].

V. Conclusion

The millimeter-wave wireless system is poised to catalyze the growth of mobile internet and the Internet of Things (IoT) in future communication infrastructure. Several pivotal factors contribute to the broadband characteristics of antennas. The primary focus of this manuscript is to underscore the significance of these factors in achieving broadband characteristics in millimeter-wave antenna designs.

The initial section of the manuscript places emphasis on elucidating the working principles of the chosen millimeter-wave antenna design. A comprehensive review of various broadband antennas is presented in this paper. The techniques for achieving broadband characteristics, along with the working principles of different millimeter-wave antennas, are thoroughly discussed in this segment. Other critical aspects, such as mathematical analyses of broadband techniques, dispersion characteristics of broadband antennas, feeding mechanisms of broadband antennas, and the importance of dielectric and material selection in designs, are also addressed here. The effects of different materials, such as nanocomposite polyesters like polyethylene terephthalate (PET), silicone polymers like polydimethylsiloxane (PDMS), and substrates like FR-4, Rogers5800, Taconic TLY-5, etc., have been explored and elaborated upon.

In the subsequent part, the design configuration of broadband antennas is elaborated. Different structural patterns for broadband antenna designs are discussed. Broadband structural patterns are thoroughly examined based on metamaterial, fractal, antipodal, multimode broadband, unique slot, and antenna array designs. A comparison table highlighting various broadband antenna structures is included. The final section compares this manuscript with recent reviews on millimeter-wave broadband antennas. The future scope and recent developments in millimeter-wave technology are also discussed in this part. This review aims to assist new researchers in selecting design structures and appropriate principles for achieving broadband antennas, offering mathematical proofs and precise analyses of broadband techniques. Finally, the author expresses regret for unintentionally overlooking any significant novel contributions during this research.

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