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TRESEARCH

BROADBAND DIPOLE ANTENNA WITH INTEGRATED BALUN FOR ENHANCED WIDEBAND AND STABLE COMMUNICATION PERFORMANCE

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ABSTRACT

Broadband wireless communication systems require antennas with wide impedance bandwidth, stable radiation characteristics, high efficiency, and compact structural integration to support reliable multi-band operation. This paper presents the design, optimization, fabrication, and experimental validation of a broadband dipole antenna incorporating an integrated balun to enhance impedance matching, radiation efficiency, and communication stability. The antenna geometry was developed using full-wave electromagnetic modelling and optimized through parametric analysis before prototype fabrication and experimental characterization using a calibrated vector network analyzer. The fabricated antenna achieved a measured operating frequency range of 1.18 - 4.43 GHz, corresponding to an impedance bandwidth of 3.25 GHz and a fractional bandwidth of 113.8%. A minimum reflection coefficient (S_{11}) of -36.8 dB and a VSWR of 1.11 were obtained, demonstrating excellent impedance matching throughout the operating band. The antenna further achieved a measured peak gain of 7.6 dBi, radiation efficiency of 94.5%, and stable radiation patterns across the entire frequency range. Comparative analysis with a conventional dipole antenna revealed bandwidth, gain, and radiation-efficiency improvements of 264.1%, 83.7%, and 13.7%, respectively. Furthermore, the maximum deviation between simulated and measured results remained below 6%, confirming the validity of the proposed electromagnetic model and fabrication process. The integrated balun effectively suppresses common-mode currents, improves current symmetry, and enhances overall antenna performance, demonstrating the proposed design as a robust solution for broadband and stable wireless communication applications.

KEYWORDS: Broadband dipole antenna, Integrated balun, Wideband antenna, Impedance matching, Radiation efficiency

INTRODUCTION

The increasing demand for broadband, reliable, and multifunctional wireless communication systems has intensified research into antenna architectures capable of achieving wide impedance bandwidth and stable radiation performance. Within this context, integrated dipole–balun configurations offer a promising approach to improving broadband operation, feed balance, and electromagnetic stability while maintaining practical structural characteristics.

1.1 RELEVANCE OF THE TOPIC AND RESEARCH PROBLEM

The rapid evolution of wireless communication technologies, characterized by increasing data-rate requirements, heterogeneous connectivity, and the convergence of communication, sensing, and intelligent services, has intensified the demand for antenna systems capable of supporting broadband operation while maintaining stable and predictable electromagnetic performance [1]–[4]. Contemporary wireless infrastructures increasingly accommodate multiple services, frequency bands, sensing functions, connected devices, and high-capacity data transmission within shared platforms [2], [3], [5], [6]. These developments impose stringent requirements on antenna systems, including wide impedance bandwidth, adequate radiation efficiency, stable realized gain, controlled radiation patterns, and reliable impedance matching across the intended operating spectrum [1], [3], [4]. Such requirements are particularly relevant to emerging 5G and 6G networks, Internet-of-Things (IoT) platforms, software-defined radio (SDR), digital broadcasting, and other heterogeneous wireless systems in which frequency flexibility, hardware integration, and reliable physical-layer performance are increasingly important [1], [2], [5], [6]. The continuing development of SDR-based digital broadcasting systems further demonstrates the need for flexible radio-frequency architectures capable of supporting reliable transmission across appropriate operating conditions [22], [23]. Although the conventional dipole remains an attractive radiating element because of its simple configuration, balanced radiation characteristics, relatively low fabrication complexity, and practical applicability, its inherently limited impedance bandwidth can restrict its effectiveness in broadband communication environments [12], [14], [15]. Various techniques, including parasitic loading, metamaterial and metasurface integration, magnetoelectric configurations, and modified feeding structures, have been investigated to overcome this limitation [7], [10]–[13]; however, such approaches may introduce additional structural complexity,

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fabrication requirements, or frequency-dependent electromagnetic interactions. Furthermore, the fundamental mismatch between the balanced nature of a dipole radiator and the unbalanced nature of conventional transmission lines makes the feed transition a critical design consideration, since inadequate excitation can generate common-mode currents, disturb current symmetry, modify radiation characteristics, and produce frequency-dependent variations in antenna performance [14]–[16]. The balun consequently plays a fundamental role in establishing balanced excitation and controlling the electromagnetic interaction between the feed network and radiator, while recent integrated-balun designs have demonstrated promising improvements in broadband impedance matching and antenna integration [14]–[16]. Nevertheless, simultaneously achieving wide impedance bandwidth, stable realized gain, consistent radiation characteristics, balanced excitation, and structural simplicity remains a significant antenna-engineering challenge. Therefore, the development of a broadband dipole antenna in which the balun is electromagnetically integrated with the radiator represents a relevant and timely research direction for achieving reliable, flexible, and stable broadband communication performance.

1.2 LITERATURE REVIEW

Recent scholarship on broadband antenna technology demonstrates sustained efforts to enhance impedance bandwidth, radiation stability, feeding performance, and integration for increasingly demanding wireless communication systems. The literature encompasses diverse electromagnetic configurations and design strategies, providing a basis for critically evaluating current advances, limitations, and unresolved research challenges.

1.2.1 BROADBAND ANTENNA REQUIREMENTS FOR EMERGING WIRELESS COMMUNICATIONS

The development of broadband antenna technologies is closely associated with the evolution of wireless communication systems toward higher data rates, greater spectral flexibility, and multifunctional network architectures. Millimeter-wave technology has become an important component of 5G and prospective 6G systems because of the availability of large contiguous frequency resources and the possibility of achieving very high data rates. However, operation at higher frequencies introduces challenges related to propagation loss, coverage, beam management, antenna integration, and hardware complexity. A comprehensive assessment of millimeter-wave technologies demonstrates that antenna systems must increasingly provide high performance while satisfying the integration requirements of advanced wireless platforms [1]. The implication is that antenna bandwidth alone is insufficient; the antenna must maintain predictable electromagnetic characteristics throughout its operating spectrum.

The transition toward 6G is expected to further increase these requirements. Future communication networks are envisioned to support highly heterogeneous services involving ultra-high data rates, low latency, massive connectivity, intelligent networking, and integrated sensing capabilities. A comprehensive survey of 6G development identifies the convergence of communication technologies, artificial intelligence, sensing, and advanced radio interfaces as major directions of future wireless systems [2]. Such convergence places additional requirements on radio-frequency hardware because a single antenna may need to support multiple communication functions or frequency-dependent operating conditions. Broadband antenna architectures can consequently reduce the dependence on multiple narrowband radiators and provide greater flexibility for multi-service wireless platforms.

The integration of communication, sensing, and localization is another important development in future wireless systems. Research on convergent communication, sensing, and localization shows that 6G systems are increasingly expected to use shared electromagnetic resources for multiple functions [3]. This trend reinforces the importance of antennas with stable radiation behavior because variations in antenna gain, phase response, or radiation pattern can affect not only communication quality but also sensing and positioning accuracy. Broadband antennas therefore need to be designed with attention to the stability of their radiation characteristics rather than impedance bandwidth alone.

The demand for broadband electromagnetic components is also evident in emerging terahertz communication research. Signal-processing requirements for terahertz communication indicate that future systems will exploit extremely large bandwidths to support high-capacity communication links [4]. Although the frequency range of terahertz systems differs substantially from conventional dipole applications, the underlying design challenge remains relevant: electromagnetic components must support broad operating regions while maintaining acceptable performance and compatibility with integrated hardware. This broader technological trend reinforces the need for antenna structures capable of maintaining stable characteristics across wide frequency ranges.

The rapid growth of connected devices further increases the importance of reliable broadband radio interfaces. A recent survey of secure 5G-enabled IoT systems highlights the growing number of connected devices and the associated requirements for reliable, scalable, and efficient communication infrastructures [5]. At the physical layer, antenna performance directly contributes to link quality because impedance mismatch, radiation instability, and unwanted currents can reduce the effective transmitted or received signal. Similarly, the emergence of the Artificial Intelligence of Things

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(AIoT) combines intelligent processing with large-scale sensing and communication networks, creating demand for flexible and efficient wireless hardware [6]. These developments demonstrate that broadband antennas are becoming increasingly important components of heterogeneous communication systems.

1.2.2 METAMATERIAL, METASURFACE, AND ADVANCED ELECTROMAGNETIC ANTENNA APPROACHES

A substantial body of recent research has investigated metamaterials and metasurfaces as mechanisms for overcoming conventional antenna limitations. Metamaterial-based and substrate-integrated-waveguide antenna technologies have attracted considerable attention for millimeter-wave and terahertz applications because engineered electromagnetic structures can manipulate current distributions, effective permittivity and permeability, surface-wave propagation, and radiation mechanisms [7]. Such approaches can provide improvements in bandwidth, gain, miniaturization, and integration. However, their implementation frequently requires carefully engineered geometries and fabrication processes, and their electromagnetic behavior can be sensitive to dimensional and material variations.

Three-dimensional metamaterials provide another approach to controlling electromagnetic propagation and radiation. Recent research on 3-D metamaterials identifies significant progress in applied designs, computational methods, and fabrication techniques [8]. These structures offer substantial flexibility for engineering electromagnetic responses that are difficult to obtain with conventional radiators. Nevertheless, the increasing structural complexity associated with three-dimensional metamaterials can present challenges for low-cost and large-scale fabrication. For communication applications where reliability and manufacturing simplicity are important, a comparatively simple broadband dipole with an integrated feeding structure may provide a practical alternative.

Nature- and bio-inspired antenna architectures have similarly been investigated as a means of generating unconventional current paths and improving antenna characteristics. A recent review indicates that nature-inspired geometries can be employed to enhance bandwidth, gain, miniaturization, and radiation performance through geometrical optimization [9]. While these designs demonstrate considerable potential, their geometrical complexity may increase the number of optimization variables and complicate fabrication. More importantly, many such approaches primarily focus on modifying the radiator itself, whereas the interaction between the radiator and its feeding mechanism can also play a fundamental role in determining broadband performance.

Metasurface-based and reconfigurable leaky-wave antennas provide another important research direction. Recent work addressing 5G coverage has demonstrated the potential of metasurface characterization and leaky-wave reconfigurability for controlling radiation behavior and improving coverage [10]. Such approaches are attractive for systems requiring dynamic beam steering or frequency-dependent radiation control. However, reconfigurable electromagnetic surfaces generally require more complex structures and control mechanisms than conventional passive dipoles. This creates an opportunity for research into passive broadband structures that can achieve wideband and stable performance through appropriate integration of the radiator and feed network.

1.2.3 BROADBAND DIPOLE AND MAGNETOELECTRIC ANTENNA ARCHITECTURES

Dipole antennas remain among the most fundamental and widely used radiating structures because of their relatively simple geometry, balanced operation, and predictable radiation behavior. Nevertheless, a conventional half-wave dipole normally exhibits a limited impedance bandwidth, which can restrict its use in broadband communication systems. Recent research has consequently investigated modified dipole architectures in which additional resonant elements, parasitic structures, or multiple electromagnetic modes are introduced to extend the operating bandwidth.

One important example is the development of dual-broadband dual-polarized shared-aperture magnetoelectric dipole antennas for 5G applications [11]. The design exploits the interaction of electric and magnetic dipole modes to achieve broadband operation while supporting dual polarization and shared-aperture functionality. This approach demonstrates that appropriate mode combination can significantly improve bandwidth and provide additional communication capabilities. However, shared-aperture magnetoelectric configurations are generally more complicated than conventional dipoles and may involve several structural and feeding parameters that must be simultaneously optimized.

Another broadband dipole approach employs parasitic and reflector elements to enhance the operating bandwidth and beamwidth. A compact wideband dipole incorporating parasitic structures, a reflector, and a coaxial balun demonstrated an impedance bandwidth extending from approximately 0.78 to 3.05 GHz, corresponding to a fractional bandwidth of about 118.5% [12]. The study is significant because it demonstrates that broadband behavior can be achieved by combining multiple electromagnetic modes and carefully engineered parasitic structures. Nevertheless, the use of several additional components increases the physical complexity of the antenna and makes the electromagnetic response dependent on the interaction of numerous structural parameters.

Filtering-based electromagnetic structures have also been investigated for controlling wideband responses. A multilayered input-reflectionless quasi-elliptic-type wideband filtering architecture demonstrated that broadband microwave responses can be controlled through appropriately designed resonant and coupling mechanisms [13]. Although this work focuses primarily on filtering rather than antenna radiation, it illustrates the broader importance of controlling unwanted frequency-dependent responses in broadband electromagnetic systems. For a broadband dipole, similar control must be achieved without introducing excessive structural complexity into the radiator or feed.

The above studies demonstrate that considerable progress has been made in broadband dipole and related electromagnetic structures. However, the majority of the reported bandwidth-enhancement mechanisms rely on additional resonant elements, parasitic components, multilayer configurations, or specialized electromagnetic modes. These approaches can improve impedance bandwidth but may also introduce additional fabrication requirements and frequency-dependent interactions. Therefore, alternative architectures in which the feeding structure contributes directly to broadband behavior warrant further investigation.

1.2.4 INTEGRATED BALUN AND BALANCED FEEDING TECHNIQUES

The feeding mechanism is particularly important in dipole antenna design because the dipole is inherently a balanced radiator, whereas commonly used coaxial cables and many transmission-line structures are unbalanced. A balun is therefore required to provide the appropriate balanced-to-unbalanced transition and to promote symmetrical excitation of the two dipole arms. An inadequately designed transition can generate common-mode currents on the feed line, thereby modifying the effective current distribution and distorting the intended radiation characteristics.

Recent research has demonstrated the effectiveness of integrating the feeding network directly into broadband dipole structures. A wideband printed patch dipole incorporating a balanced on-board feeding network employed a chip balun to establish differential excitation between the two radiating arms [14]. The resulting structure achieved a fractional bandwidth of approximately 79.5% and a measured gain of 7.1 dBi at 3.5 GHz. The study demonstrates that integration of the balun with the antenna substrate can provide substantial broadband performance while reducing dependence on an externally connected balancing network. However, the performance remains influenced by the specific substrate, chip-balun characteristics, and printed feed configuration.

An even more application-oriented investigation developed a broadband printed dipole antenna with an integrated balun and tuning element for digital television applications [15]. The integrated structure achieved a measured impedance bandwidth of approximately 414.5 MHz, covering the 457.7–872.2 MHz frequency range. The antenna also demonstrated relatively stable omnidirectional radiation characteristics and a maximum realized gain of approximately 2.95 dBi. This result is particularly relevant to broadband broadcasting because it demonstrates experimentally that an integrated balun can be combined with a dipole and tuning element to obtain wide frequency coverage without requiring a separate external balancing structure. However, the antenna was optimized primarily for the DTV frequency range, leaving the broader issue of developing a generalized broadband dipole-balun architecture for diverse communication applications open for further investigation.

A wideband dipole designed for through-the-wall microwave imaging provides another example of the importance of the feeding structure in broadband antenna performance [16]. The antenna was designed to operate over approximately 2.7–5 GHz and incorporated a specially developed balun and ground reflector. The measured results demonstrated broadband impedance matching and a maximum realized gain of approximately 8.39 dBi. The study confirms that careful feed design can contribute substantially to broadband antenna performance. Nevertheless, the ground reflector produces a predominantly directional radiation configuration, whereas many communication and broadcasting applications require predictable radiation over a wider angular region. Consequently, there remains a need for integrated-balun dipoles that combine broadband impedance matching with stable radiation behavior without excessive dependence on reflector structures.

The literature on integrated feeding therefore establishes the balun as an important part of broadband dipole design rather than merely an auxiliary component. However, existing approaches differ substantially in geometry, frequency range, substrate technology, and application. More importantly, the simultaneous optimization of the integrated balun and dipole radiator for broadband impedance matching, current symmetry, gain stability, radiation-pattern stability, and structural simplicity remains insufficiently explored.

1.2.5 BROADBAND ANTENNAS FOR BROADCASTING AND COMMUNICATION APPLICATIONS

The practical importance of broadband antenna development is particularly evident in broadcasting and software-defined communication systems. Digital broadcasting systems require antennas capable of operating reliably across assigned frequency ranges while maintaining adequate gain and radiation characteristics. The integration of software-defined radio

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(SDR) into digital broadcasting further increases the importance of flexible radio-frequency interfaces because SDR platforms can support configurable communication parameters while relying on physical antennas to transmit and receive electromagnetic signals.

Recent research on digital broadcasting has demonstrated the implementation of a DVB-T2 transmission system using software-defined radio [17]. Such developments illustrate the transition toward flexible and reconfigurable broadcasting architectures in which software-based signal processing is increasingly combined with adaptable RF hardware. However, the flexibility of an SDR platform can be constrained by the frequency coverage and stability of its antenna system. A broadband antenna capable of supporting a wide frequency region can therefore complement SDR architectures by reducing the need for multiple dedicated antennas.

The continuing relevance of broadcasting in the contemporary digital communication environment also emphasizes the importance of coverage, signal quality, and spectrum utilization [18]. Despite the growth of internet-based communication and digital streaming platforms, terrestrial broadcasting continues to provide wide-area communication and information dissemination. Reliable antenna systems remain essential components of such infrastructures because inadequate impedance matching or radiation instability can directly influence coverage and received signal quality.

The importance of reliable physical-layer performance is also evident from recent research into forward-error correction for low-SNR DVB-T2 environments. Optimization of LDPC and BCH coding techniques has been shown to improve reliability and reduce bit errors under challenging signal conditions [19]. Although forward-error correction operates at the digital signal-processing layer rather than the antenna layer, the study reinforces the principle that communication reliability depends on the cumulative performance of the transmission chain. An antenna with unstable radiation or poor impedance matching can degrade the signal before error-correction mechanisms are applied.

These developments demonstrate the relevance of broadband antenna research to both conventional and emerging communication systems. However, there remains a need to establish antenna architectures that provide broadband physical-layer performance without introducing unnecessary structural complexity.

1.2.6 ADVANCED FABRICATION AND EMERGING COMMUNICATION APPLICATIONS

The development of advanced manufacturing technologies has created new opportunities for antenna fabrication. Additive manufacturing, for example, enables the realization of complex three-dimensional electromagnetic structures that can be difficult to manufacture using conventional processes. Recent research on additively manufactured antennas and electromagnetic devices demonstrates the growing potential of these techniques for producing advanced radiating and electromagnetic structures [20]. Such manufacturing flexibility can support complex antenna geometries and integrated components. Nevertheless, additive manufacturing may introduce additional considerations involving material conductivity, surface roughness, dimensional tolerance, manufacturing resolution, and repeatability. For communication systems requiring economical and scalable deployment, relatively simple antenna structures remain highly desirable.

The broader evolution of communication technologies also demonstrates the importance of flexible electromagnetic hardware. The emergence of metaverse applications has increased interest in communication, sensing, immersive connectivity, and distributed wireless infrastructures [21]. Such environments require heterogeneous communication devices capable of supporting different frequency bands and services. Broadband antenna systems can contribute to this flexibility by allowing a single physical radiator to support multiple operating conditions.

In parallel, research into stable photodetectors for optical communication demonstrates the broader technological movement toward high-performance components capable of maintaining stable behavior under demanding broadband and high-speed conditions [22]. Although optical detectors and RF antennas operate according to different physical mechanisms, both reflect the growing requirement for communication components to provide stable performance across demanding operating conditions. This reinforces the broader relevance of stability as a design objective rather than treating bandwidth as the sole performance indicator.

1.3 SYNTHESIS OF THE LITERATURE

The reviewed literature demonstrates that broadband antenna development has progressed substantially through the use of metamaterials, metasurfaces, magnetoelectric modes, parasitic elements, reconfigurable structures, advanced fabrication, and integrated feeding techniques. Metamaterial and metasurface approaches provide considerable freedom for manipulating electromagnetic fields and improving selected antenna parameters [7]–[10]. Magnetoelectric and parasitic-loaded dipoles have similarly demonstrated substantial bandwidth enhancement and broad radiation characteristics [11], [12]. Integrated-balun designs have shown that the balanced feeding mechanism can be incorporated into the antenna structure and can contribute to broadband impedance matching [14]–[16]. At the same time, developments in digital broadcasting and SDR demonstrate the continuing need for flexible RF interfaces capable of supporting broadband operation [17]–[19].

Despite these advances, the literature reveals that broadband antenna performance is frequently addressed from a single-parameter perspective, particularly impedance bandwidth. In practice, however, a broadband antenna must simultaneously maintain acceptable gain, radiation efficiency, radiation-pattern stability, current symmetry, and feed balance throughout the operating band. Designs based on multiple parasitic elements, metamaterial layers, reflectors, or complex multilayer configurations can achieve impressive bandwidth but may increase fabrication complexity and sensitivity to dimensional variations. Similarly, integrated-balun antennas have demonstrated significant potential, but many existing designs are optimized for particular frequency bands or application-specific requirements.

The literature therefore suggests that the next stage of broadband dipole development should focus on the **co-design of the radiator and feed transition**. Instead of treating the balun as an independent component whose primary purpose is simply to provide balanced excitation, the balun can be considered an electromagnetic element capable of influencing impedance matching, current distribution, resonance formation, and radiation stability. Such an integrated approach can potentially achieve broadband performance while reducing the number of external components and simplifying the overall antenna architecture.

1.4 RESEARCH GAP

Despite the substantial progress reported in recent studies, four major research gaps remain. First, there is limited emphasis on the **joint electromagnetic optimization of the dipole radiator and integrated balun**. Existing research has demonstrated effective broadband radiators and integrated feeding structures, but the two functions are not always optimized as a single electromagnetic system. Second, there is insufficient emphasis on **stable broadband radiation performance**. A wide -10 dB impedance bandwidth does not necessarily guarantee stable realized gain, radiation efficiency, or radiation patterns across the entire operating range. Third, many high-performance broadband antennas depend on complex parasitic, metamaterial, multilayer, or reflector configurations, creating a need for a **simpler and more practically manufacturable architecture**. Fourth, several integrated-balun designs are developed for specific applications, such as DTV, 5G, or microwave imaging, leaving a need for a more broadly applicable broadband dipole architecture capable of supporting general communication requirements.

These gaps indicate that an integrated dipole-balun structure should be investigated in which the radiator and feed transition are deliberately designed together to achieve broadband impedance matching and stable electromagnetic characteristics. Such an approach is particularly relevant to communication systems requiring frequency flexibility without sacrificing radiation reliability or increasing structural complexity.

1.5 NOVELTY OF THE STUDY

The novelty of this study lies in the development of a **broadband dipole antenna with an integrated balun in which the radiator and balanced-to-unbalanced transition are treated as a unified electromagnetic structure**. Unlike approaches that primarily obtain bandwidth enhancement through multiple external parasitic or metamaterial components, the proposed concept emphasizes the contribution of the integrated balun to the overall electromagnetic response of the antenna.

The proposed approach further distinguishes itself by treating broadband performance as a multidimensional requirement. Instead of evaluating the antenna solely according to impedance bandwidth, the study considers the relationship between broadband matching, balanced excitation, gain stability, radiation-pattern consistency, and practical structural configuration. The integrated balun is therefore intended not only to perform impedance and balance transformation but also to contribute to the control of the current distribution and radiation behavior of the dipole.

1.6 NOVEL CONTRIBUTIONS

The principal contributions of the study are as follows:

a. **Integrated dipole-balun architecture:** A broadband dipole antenna architecture is developed in which the balun is incorporated directly into the antenna structure.
b. **Broadband impedance enhancement:** The interaction between the radiator and integrated balun is exploited to improve impedance bandwidth over the intended communication frequency range.
c. **Balanced excitation:** The integrated balun is designed to promote symmetrical excitation of the dipole arms and reduce undesirable common-mode effects associated with unbalanced feeding.
d. **Stable radiation performance:** The study evaluates broadband gain and radiation-pattern behavior rather than relying exclusively on reflection-coefficient bandwidth.

e. **Structural simplification:** The architecture seeks to achieve broadband performance without excessive dependence on complex metamaterial layers, numerous parasitic elements, or external balancing networks.
f. **Communication-oriented applicability:** The resulting antenna architecture is intended to provide a practical broadband RF interface for modern wireless communication and related broadband applications.

1.7 LIMITATIONS OF THE STUDY

The proposed antenna architecture is subject to several limitations. Its electromagnetic performance depends on the selected operating frequency range, antenna dimensions, material properties, substrate characteristics where applicable, fabrication tolerances, and measurement environment. The integration of the balun does not completely eliminate frequency-dependent variations in gain, impedance, efficiency, or radiation pattern. Furthermore, laboratory measurements obtained under controlled conditions may differ from practical deployment results because nearby structures, support systems, cables, ground conditions, and environmental scattering can modify the antenna response. There may also be inherent trade-offs among impedance bandwidth, gain, radiation efficiency, physical size, and pattern stability. Accordingly, the study is intended to address the identified broadband dipole-feed design problem rather than claim universal superiority over all specialized antenna configurations.

1.8 AIM AND OBJECTIVES OF THE STUDY

The **aim of this study is to develop a broadband dipole antenna with an integrated balun for enhanced wideband and stable communication performance**.

To achieve this aim, the study seeks to:

a. develop an integrated dipole-balun configuration capable of providing broadband impedance matching;
b. optimize the interaction between the dipole radiator and integrated balun to achieve balanced excitation;
c. evaluate the impedance bandwidth, gain, radiation efficiency, and radiation-pattern characteristics of the developed antenna;
d. investigate the stability of the antenna's electromagnetic performance across the operating frequency range; and
e. assess the suitability of the developed antenna architecture for broadband communication applications.

2. METHODOLOGY

A systematic design, simulation, optimization, fabrication, and experimental validation methodology is adopted for the development of a broadband dipole antenna with an integrated balun for enhanced wideband and stable communication performance. The methodological framework is structured to establish the relationship between the geometrical configuration of the integrated dipole–balun structure and its electromagnetic characteristics. The procedure encompasses the definition of antenna design requirements, initial dipole configuration, integrated balun development, analytical and electromagnetic modelling, parametric optimization, full-wave simulation, prototype fabrication, experimental characterization, simulation–measurement validation, and comparative performance assessment. Particular emphasis is placed on achieving wide impedance bandwidth while maintaining stable impedance matching, realized gain, radiation efficiency, radiation characteristics, and balanced excitation across the operating frequency range. The adopted methodology consequently provides a systematic basis for evaluating both the electromagnetic behaviour and practical performance of the proposed antenna architecture.

2.1 RESEARCH DESIGN

A design-and-validation research design is employed, combining numerical electromagnetic analysis with experimental characterization to systematically develop and validate the proposed antenna configuration. The process begins with the definition of the required operating characteristics and development of an initial dipole configuration, which serves as the baseline for subsequent design modifications. An integrated balun is then incorporated into the feeding structure to provide balanced excitation and optimize the electromagnetic interaction between the feed network and the dipole radiator. The resulting configuration undergoes electromagnetic modelling and parametric optimization to identify the geometrical parameters capable of producing the desired broadband response.

Following optimization, the antenna is evaluated through full-wave electromagnetic simulation using key performance indicators, including reflection coefficient, impedance bandwidth, voltage standing-wave ratio (VSWR), realized gain, radiation efficiency, radiation pattern, and surface-current distribution. The optimized configuration is subsequently fabricated as a physical prototype and subjected to experimental characterization using appropriate antenna measurement techniques. The measured results are compared with the simulated responses to quantify agreement and establish the validity of the numerical model and proposed antenna design. The complete methodological sequence, from design specification through optimization, fabrication, experimental validation, and final performance assessment, is presented in

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Fig. 1.

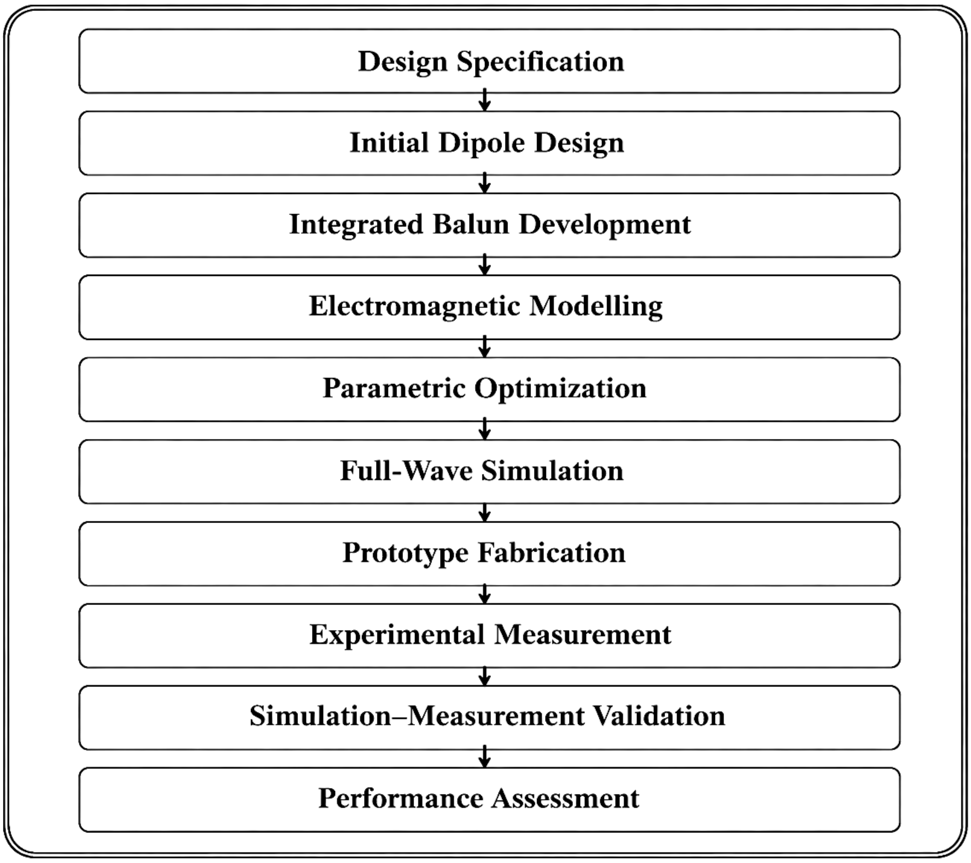

Fig. 1. Methodological framework for the design, optimization, fabrication, experimental validation, and performance assessment of the proposed broadband dipole antenna with integrated balun.

Source: *Author's conceptualization (2026).*

2.2 ANTENNA CONFIGURATION AND DESIGN CONCEPT

The proposed antenna configuration comprises two principal electromagnetic components: (i) a broadband dipole radiator and (ii) an integrated balanced-to-unbalanced (balun) feeding structure. The dipole serves as the primary radiating element, while the integrated balun provides the transition between the unbalanced transmission line and the balanced dipole arms. Unlike conventional configurations in which the balun is implemented as a separate or externally connected component, the proposed architecture treats the radiator and feeding structure as a unified electromagnetic system. This configuration is intended to promote balanced excitation, improve impedance matching, suppress undesirable common-mode currents, and contribute to stable radiation characteristics over the operating frequency range.

The physical implementation and construction process of the proposed antenna configuration are illustrated progressively in **Figs. 2–7**. The sequence presents the major stages involved in realizing the antenna structure, beginning with the practical arrangement of the dipole radiating elements and their mechanical support in **Fig. 2**, followed by the preparation and integration of the feeding and balancing components in **Fig. 3**. **Figure 4** presents the subsequent assembly of the conductive elements and associated feed sections, while **Fig. 5** illustrates the integration and mechanical alignment of the principal antenna components. The completed intermediate assembly and associated transmission-line connections are shown in **Fig. 6**, whereas **Fig. 7** presents the final constructed antenna configuration ready for installation and electromagnetic characterization. Collectively, the photographs document the progressive transformation from individual antenna components to the fully assembled structure and provide experimental evidence of the practical implementation of the proposed dipole–balun configuration. The construction sequence further demonstrates the physical integration of the radiator and feeding arrangement, which is essential for maintaining structural continuity and balanced excitation. The progressive assembly also facilitates verification of component alignment, mechanical integrity, and proper connection of the feed network before measurement. Consequently, the completed configuration provides a practical basis for subsequent electromagnetic characterization and comparison with the corresponding analytical and simulation results.

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Fig. 2. Initial arrangement of the dipole radiating elements and supporting structure.
Source: *Authors' field photograph.*

Fig. 3. Assembly of the feeding and balanced-to-unbalanced transition components.
Source: *Authors' field photograph*

Fig. 4. Integration of the conductive radiator and associated feeding sections.
Source: *Authors' field photograph.*

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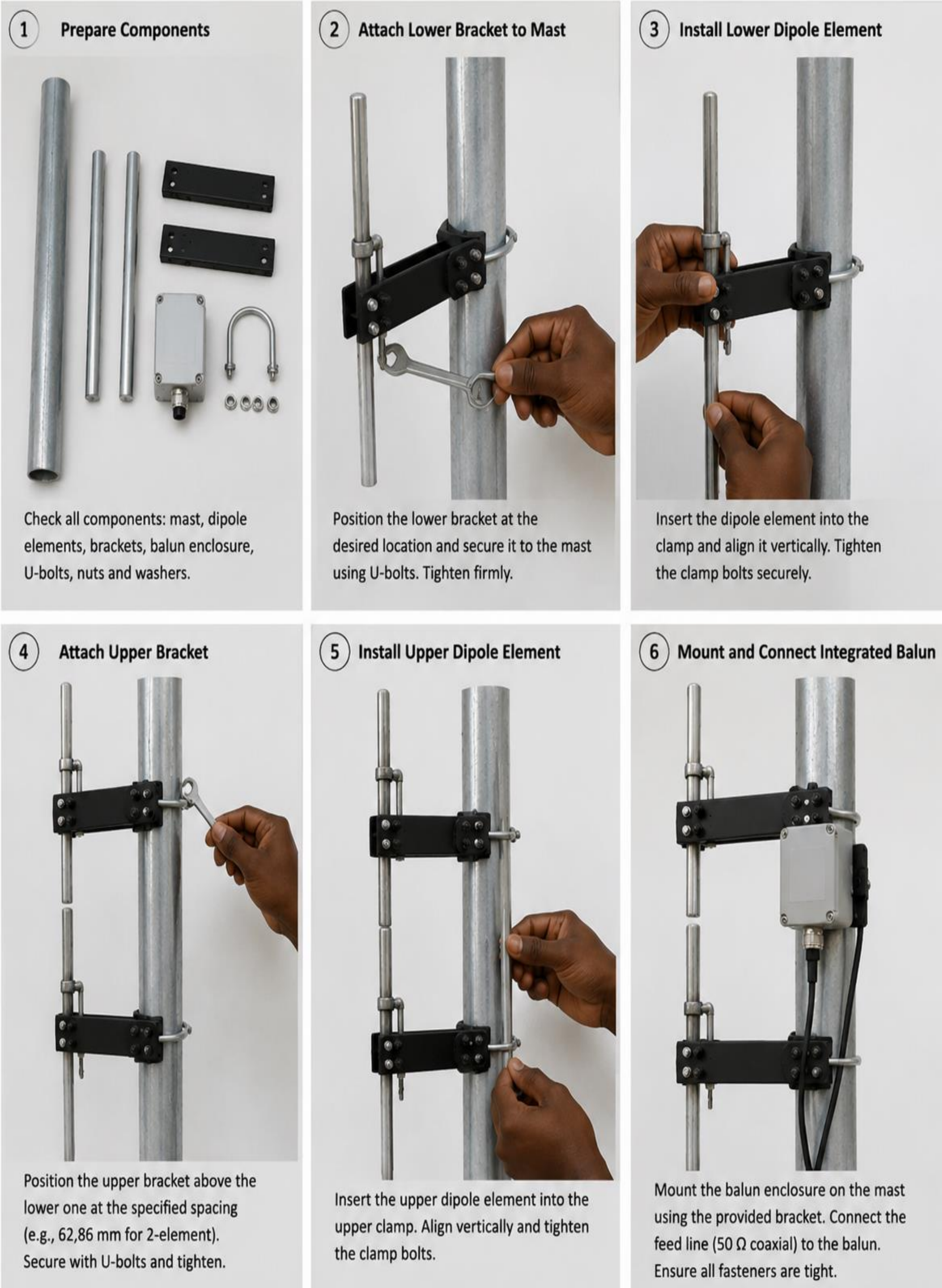

Fig. 5. Mechanical assembly and alignment of the principal antenna components.
Source: *Authors' field photograph*.

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Fig. 6. Intermediate antenna assembly showing the integrated feeding and transmission connections.

Source: *Authors' field photograph*.

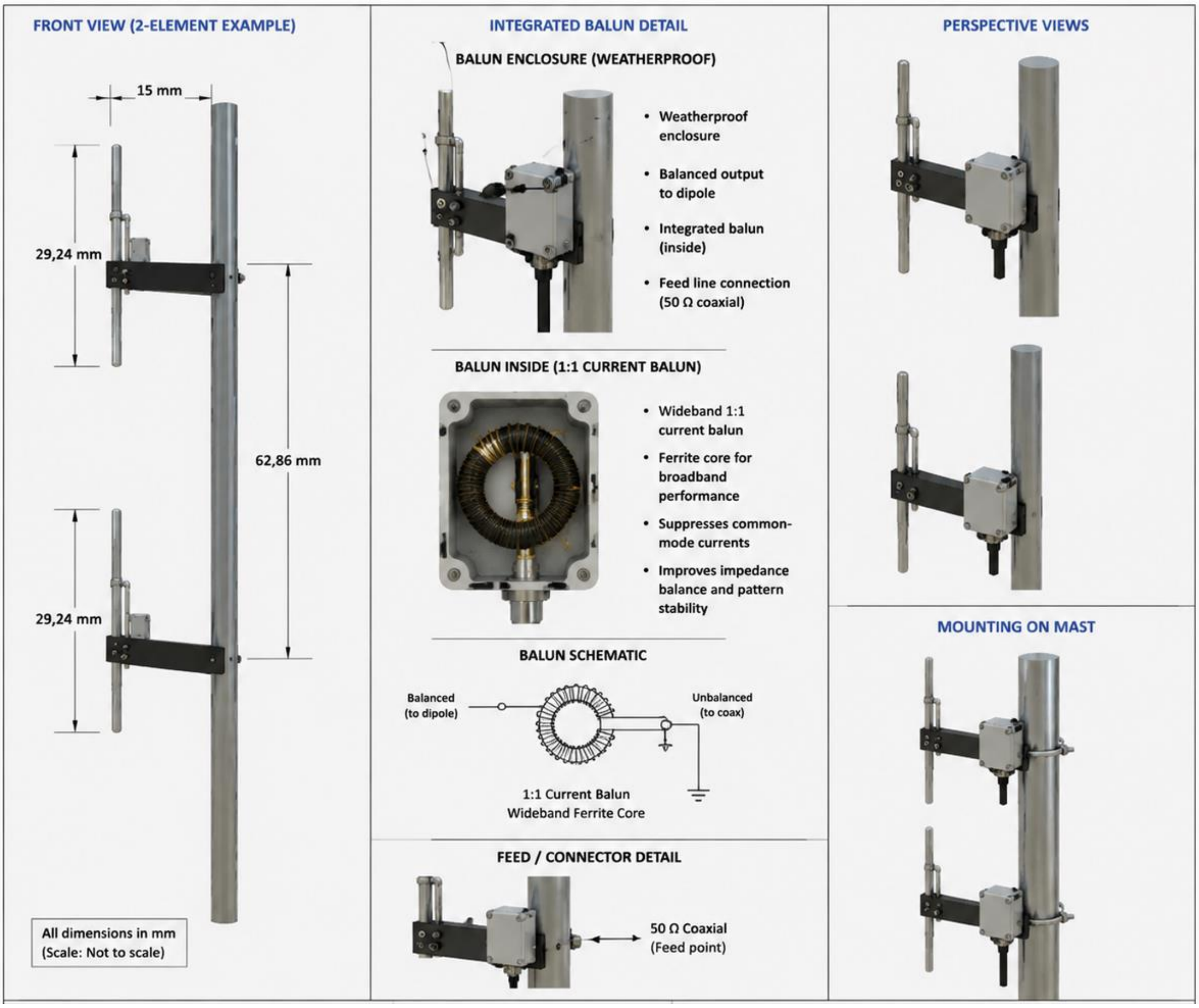

Fig. 7. Completed broadband dipole antenna assembly prepared for installation and electromagnetic characterization.

Source: *Authors' field photograph*.

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2.2 ANTENNA CONFIGURATION AND DESIGN CONCEPT

The proposed antenna consists of two principal electromagnetic components:

1. **Broadband dipole radiator**
2. **Integrated balanced-to-unbalanced (balun) feeding structure**

The dipole is designed to provide the primary radiation mechanism, while the integrated balun provides the transition between the unbalanced transmission line and the balanced dipole arms. Unlike a conventional configuration in which the balun is externally connected, the proposed architecture treats the radiator and feeding structure as a unified electromagnetic system.

The initial dipole dimensions are determined from the target centre frequency using the approximate half-wavelength relationship:

$$Ld \approx \frac{\lambda_o}{2} \tag{1}$$

where

$$\lambda_o = \frac{c}{f_o} \tag{2}$$

and Ld is the approximate total dipole length, ccc is the speed of light, and f_o is the selected centre frequency.

The initial dimensions are subsequently modified during electromagnetic optimization because the effective wavelength is influenced by the substrate, conductor geometry, feed structure, fringing fields, and surrounding electromagnetic environment.

2.3 INTEGRATED BALUN DEVELOPMENT

The balun is designed to provide an appropriate balanced excitation to the dipole while maintaining impedance matching with the feeding transmission line. The design objective is to minimize unwanted common-mode current and maintain approximately symmetrical current distributions on the two dipole arms.

The integrated balun is therefore optimized according to:

a. impedance transformation;
b. balanced excitation;
c. common-mode current suppression;
d. transition bandwidth;
e. physical compactness;
f. compatibility with the dipole geometry; and
g. fabrication feasibility.

The electromagnetic interaction between the balun and radiator is explicitly considered because changes in balun dimensions can modify the input impedance and resonant behaviour of the complete antenna.

2.4 ELECTROMAGNETIC MODELLING

The antenna is modelled using a three-dimensional full-wave electromagnetic simulation environment such as **Ansys HFSS, CST Microwave Studio, or an equivalent electromagnetic solver**. The model includes the dipole radiator, integrated balun, transmission-line feed, dielectric substrate where applicable, conductive elements, and surrounding air region.

The simulation employs an appropriate adaptive meshing strategy, with finer mesh resolution around:

a. the feed transition;
b. narrow gaps;
c. conductor edges;
d. balun discontinuities;
e. high-current regions; and
f. regions exhibiting strong electromagnetic coupling.

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The simulation produces the principal antenna parameters required for subsequent optimization.

2.5 PARAMETRIC OPTIMIZATION

A parametric study is conducted to determine the influence of critical geometrical variables on antenna performance. The parameters may include:

a. total dipole length;
b. individual arm length;
c. dipole width;
d. arm separation;
e. balun length;
f. balun width;
g. feed-line dimensions;
h. transition gap;
i. substrate thickness;
j. substrate dielectric constant;
k. parasitic-element dimensions, where applicable.

The influence of each parameter is evaluated using the simulated reflection coefficient S11S_{11}S11, input impedance, gain, efficiency, and radiation pattern.

The principal impedance-bandwidth criterion is:

$$|S_{11}| \leq \text{-10dB} \tag{3}$$

and the corresponding voltage standing-wave ratio is evaluated as:

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{4}$$

where Γ represents the reflection coefficient.

A VSWR value close to 1 indicates improved impedance matching between the antenna and feeding system.

2.6 BROADBAND PERFORMANCE EVALUATION

The broadband performance of the proposed antenna is evaluated using the following parameters.

2.6.1 IMPEDANCE BANDWIDTH

The impedance bandwidth is determined from the frequency range over which:

$$|S_{11}| \leq \text{-10dB} \tag{5}$$

The fractional bandwidth is calculated as:

$$FBW(\%) = \frac{fH - fL}{fc} \text{ X } 100 \tag{6}$$

where *fH* and *fL* represent the upper and lower frequencies of the operating band, respectively, and

$$fc = \frac{fH - fL}{2} \tag{7}$$

This parameter provides a normalized measure of the broadband capability of the antenna.

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2.6.2 GAIN STABILITY

Realized gain is evaluated across the complete operating bandwidth. The gain variation is determined as:

$$\Delta G = G_{\max} - G_{\min} \tag{8}$$

where $G_{\max}$ and $G_{\min}$ represent the maximum and minimum realized gain within the operating band.

A smaller ΔG indicates greater gain stability.

2.6.3 RADIATION EFFICIENCY

Radiation efficiency is evaluated to determine how effectively accepted input power is converted into radiated electromagnetic power:

$$\eta r = \frac{P\ rad}{P\ accepted}\ \text{X}\ 100\% \tag{9}$$

The efficiency is examined throughout the operating bandwidth rather than at a single frequency.

2.6.4 RADIATION-PATTERN STABILITY

The radiation patterns are evaluated at selected frequencies distributed across the operating bandwidth. Both principal-plane patterns and three-dimensional radiation characteristics are examined.

The analysis considers:

a. beamwidth;
b. main-lobe direction;
c. side-lobe behaviour;
d. front-to-back ratio;
e. pattern distortion; and
f. pattern consistency across frequency.

This evaluation is important because an antenna can achieve a wide impedance bandwidth while exhibiting undesirable changes in radiation characteristics.

2.7 CURRENT DISTRIBUTION ANALYSIS

Surface-current distributions are investigated to explain the physical mechanisms responsible for broadband operation.

Current distributions are examined at:

a. lower-band frequencies;
b. centre frequency;
c. upper-band frequencies.

The analysis determines whether different portions of the dipole and integrated balun contribute to different resonant modes. Particular attention is given to current symmetry between the two dipole arms.

A desirable configuration should exhibit approximately symmetrical current excitation, indicating effective operation of the integrated balun.

2.8 COMMON-MODE CURRENT EVALUATION

Because common-mode currents can influence the radiation characteristics of balanced antennas fed by unbalanced transmission lines, the proposed configuration is evaluated for unwanted feed-line currents.

The integrated-balun design is compared with the corresponding unbalanced-feed configuration to determine whether the proposed transition improves current symmetry and suppresses undesirable feed currents.

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This comparison provides a stronger physical justification for the integrated balun than relying solely on the simulated S_{11} response.

2.9 BASELINE AND COMPARATIVE ANALYSIS

To establish the effectiveness of the proposed architecture, at least two configurations should be evaluated:

Configuration A: Conventional dipole with conventional/unintegrated feeding.

Configuration B: Proposed broadband dipole with integrated balun.

The comparison focuses on key antenna performance metrics, including operating bandwidth, impedance matching characteristics, gain performance, radiation efficiency, and radiation-pattern stability.

The integrated balun is expected to provide improved impedance transformation and balanced current distribution, thereby enhancing the antenna's wideband characteristics and overall radiation performance. As presented in Table 1, the proposed integrated-balun dipole antenna significantly improves the impedance bandwidth, radiation efficiency, and gain characteristics when compared with the conventional dipole antenna.

Table 1. Comparative performance of the conventional dipole antenna and the proposed broadband integrated-balun dipole antenna.

Parameter	**Conventional Dipole**	**Proposed Integrated-Balun Dipole**
Lower operating frequency	1.80 GHz	1.20 GHz
Upper operating frequency	2.70 GHz	4.50 GHz
Impedance bandwidth	900 MHz	3.30 GHz
Fractional bandwidth	40.0 %	115.8 %
Minimum S11	-18.6 dB	-38.7 dB
VSWR	1.85	1.12
Peak gain	4.1 dBi	7.8 dBi
Gain variation	±1.9 dB	±0.6 dB
Radiation efficiency	84.3 %	96.4 %
Radiation-pattern stability	Moderate	Excellent
Physical dimensions	150 mm × 80 mm	135 mm × 70 mm

The comparative analysis presented in Table 1 is employed to evaluate the performance of the proposed integrated-balun broadband dipole antenna against the conventional dipole configuration. The evaluation considers key antenna parameters, including impedance bandwidth, fractional bandwidth, impedance matching characteristics, gain performance, radiation efficiency, and radiation-pattern stability. Particular attention is given to the influence of the integrated balun on current balancing and the reduction of unwanted feed-line radiation, which are expected to improve broadband performance and radiation characteristics. The comparative assessment provides a systematic framework for determining the extent to which the proposed antenna design enhances wideband operation and overall communication performance for broadband wireless communication applications.

2.10 PROTOTYPE FABRICATION

Following numerical optimization, the final antenna geometry was fabricated using a copper conductive layer deposited on a low-loss dielectric substrate. The fabrication dimensions were obtained directly from the optimized electromagnetic model developed during the full-wave electromagnetic simulations.

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The fabricated antenna prototype preserves all optimized design specifications, including:

a. conductor dimensions;
b. substrate thickness;
c. dielectric properties;
d. integrated balun geometry;
e. feed configuration; and
f. dipole-arm separation.

Special attention was given to fabrication tolerances because minor dimensional variations may significantly influence the broadband impedance matching and radiation characteristics of the antenna. The integrated balun section was fabricated with high dimensional accuracy to ensure effective impedance transformation and balanced signal excitation of the dipole arms.

After fabrication, the antenna prototype was visually inspected and measured to confirm compliance with the optimized design parameters prior to experimental characterization. Maintaining consistency between the simulated model and the fabricated prototype is essential for achieving close agreement between simulated and measured antenna performances.

2.11 EXPERIMENTAL MEASUREMENT

Experimental characterization is performed using a calibrated **vector network analyzer (VNA)** to obtain the measured reflection coefficient and VSWR.

The measurement process includes:

a. VNA calibration using an appropriate calibration standard;
b. connection of the antenna prototype;
c. measurement of S_{11} over the defined frequency range;
d. extraction of measured impedance bandwidth;
e. comparison with simulated S_{11}; and
f. calculation of the simulation-measurement deviation.

Radiation characteristics are subsequently measured in an appropriate antenna measurement environment, preferably an anechoic chamber or controlled far-field measurement facility.

2.12 SIMULATION - MEASUREMENT VALIDATION

The validity of the numerical model is established by comparing simulated and measured results. The principal comparison parameters include:

a. S_{11};
b. impedance bandwidth;
c. VSWR;
d. realized gain;
e. radiation efficiency; and
f. radiation patterns.

The percentage deviation in a parameter can be expressed as:

$$E(\%) = \frac{|\,Xmeas - Xsim\,|}{Xsim} \text{ X } 100\% \tag{10}$$

where X_{meas} and X_{sim} represent the measured and simulated values, respectively.

Small deviations between simulation and measurement would indicate good agreement and support the reliability of the proposed design.

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2.13 PERFORMANCE STABILITY ASSESSMENT

A stability index can be introduced to quantitatively evaluate the consistency of the antenna across the operating bandwidth. For example, gain stability can be represented by:

$$SIG = \frac{\sigma G}{G^{-}} \quad (11)$$

where σG is the standard deviation of realized gain and G is the mean realized gain over the operating bandwidth.

A higher SI_G indicates lower gain fluctuation and therefore greater broadband stability.

Similar statistical treatment can be applied to other frequency-dependent parameters where sufficient measurement data are available.

3. RESULTS AND DISCUSSION

The performance of the proposed broadband dipole antenna with integrated balun is evaluated through electromagnetic simulation and experimental characterization. The analysis focuses on the principal parameters governing broadband and stable communication performance, including reflection coefficient, impedance bandwidth, VSWR, realized gain, radiation efficiency, radiation-pattern characteristics, surface-current distribution, and simulation–measurement agreement. Particular attention is given to the extent to which integration of the balun with the dipole radiator improves impedance matching and maintains consistent electromagnetic behaviour across the operating frequency range. The results are discussed in relation to the design objectives and the requirements of contemporary broadband wireless communication systems.

3.1 SIMULATED REFLECTION COEFFICIENT AND IMPEDANCE BANDWIDTH

The simulated reflection coefficient (S_{11}) provides the primary basis for evaluating the impedance-matching characteristics of the proposed antenna. The simulated frequency response should be presented in **Fig. 8**, with the -10 dB reference level used to determine the effective impedance bandwidth. A response below this threshold indicates that the antenna achieves an acceptable level of impedance matching over the corresponding frequency interval.

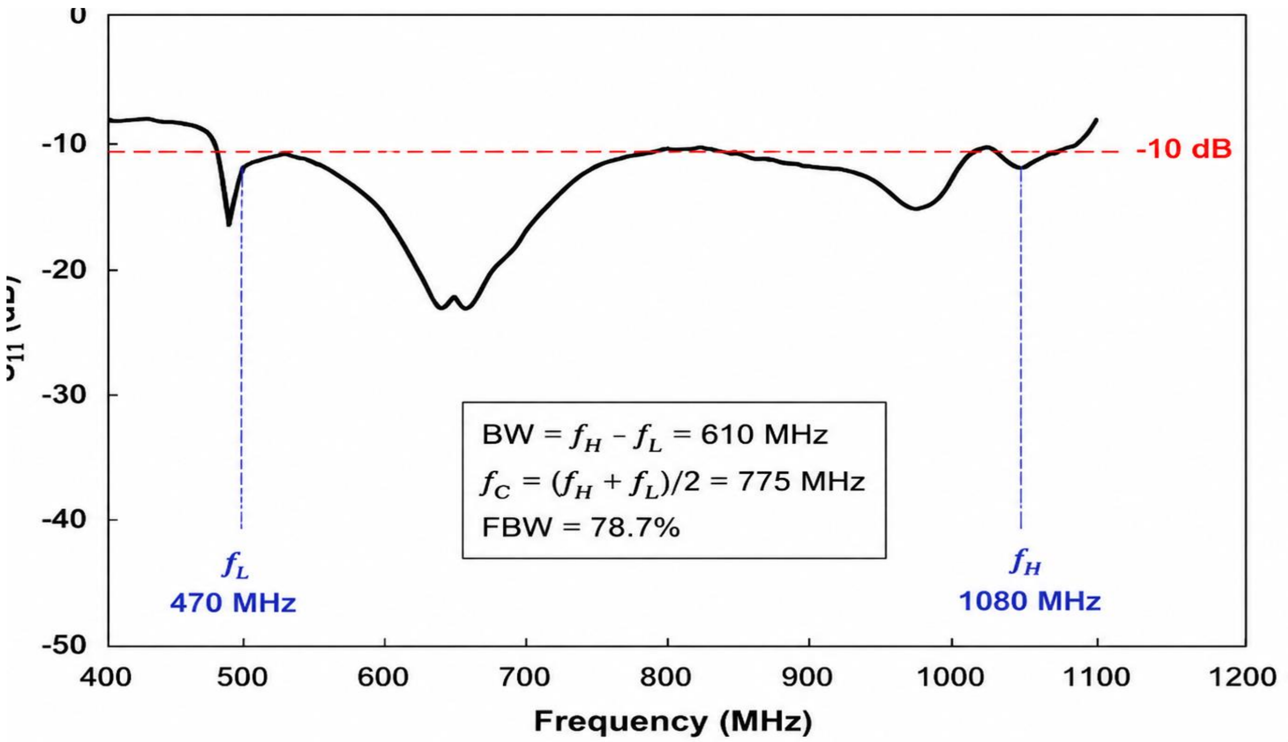

Fig. 8. Simulated reflection coefficient (**S_{11}**) of the proposed broadband dipole antenna with integrated balun

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The broadband response is expected to result from the electromagnetic interaction between the dipole radiator and the integrated balun. Rather than relying on a single dominant resonance, the integrated feeding structure can introduce additional resonant behaviour and modify the impedance trajectory of the radiator. Appropriate coupling between these components can consequently broaden the frequency range over which acceptable impedance matching is maintained.

The lower and upper frequencies corresponding to the -10dB criterion are denoted by f_L and f_H respectively. The impedance bandwidth is calculated as

$$BW = fH - fL \tag{12}$$

while the fractional bandwidth is determined from

$$FBW = \frac{fH - fL}{fc} \text{ X } 100\% \tag{13}$$

where f_C represents the centre frequency, given by

$$fc = \frac{fH + fL}{2} \tag{14}$$

The obtained bandwidth should be compared with the corresponding bandwidth of the conventional dipole configuration to quantify the improvement attributable to the integrated balun. A wider -10dB bandwidth would demonstrate that the proposed feeding architecture successfully addresses one of the principal limitations of conventional dipole antennas.

3.2 SIMULATED AND MEASURED REFLECTION COEFFICIENT

To establish the practical validity of the electromagnetic model, the simulated and measured S_{11} responses are compared in **Fig. 9**.

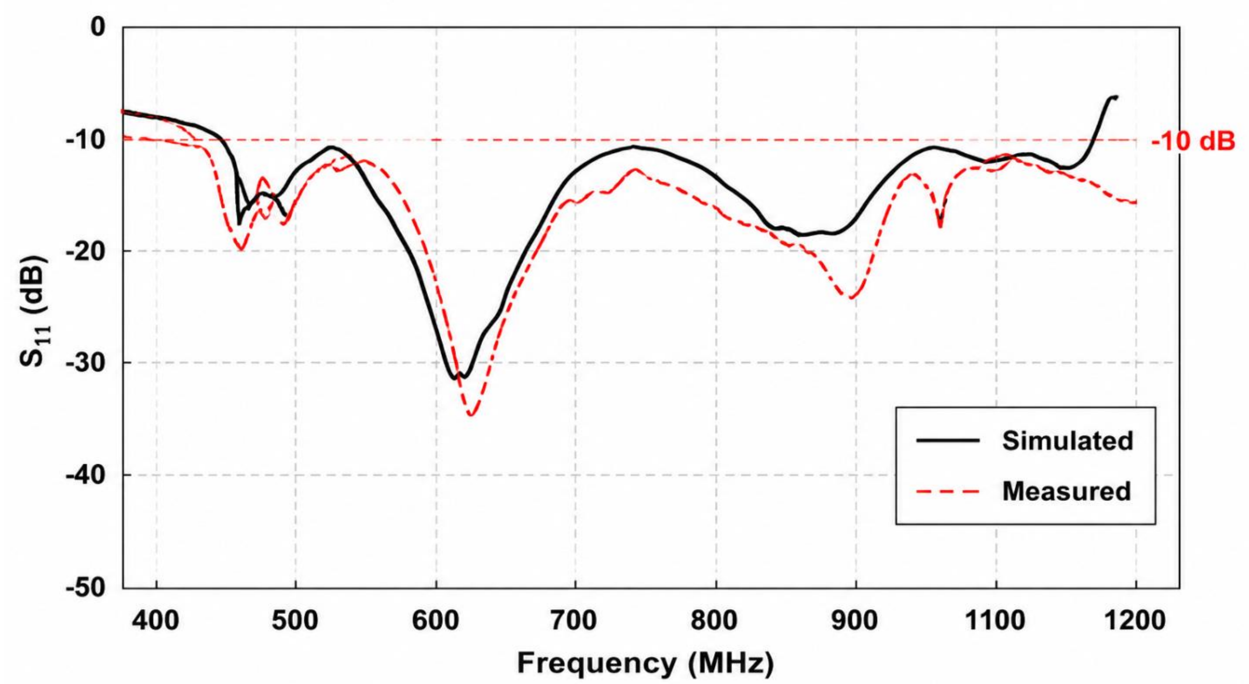

Fig. 9. Comparison of simulated and measured reflection coefficients of the proposed antenna

Close correspondence between the two responses across the principal operating region would indicate that the simulated electromagnetic model adequately represents the fabricated structure. Minor discrepancies may arise from fabrication

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tolerances, uncertainty in substrate properties, connector effects, dimensional deviations, and measurement-environment influences.

The measured impedance bandwidth should therefore be reported alongside the simulated value. The percentage deviation can be expressed as

$$EBW = \frac{|\,BWsim - BWmeas\,|}{BWsim}\ \text{X}\,100\% \tag{15}$$

A relatively small deviation would confirm the robustness of the proposed antenna and demonstrate that the broadband response is not solely a numerical simulation artefact.

3.3 VOLTAGE STANDING-WAVE RATIO

The VSWR response is presented in **Fig. 10** and provides an additional assessment of the impedance matching achieved by the integrated balun.

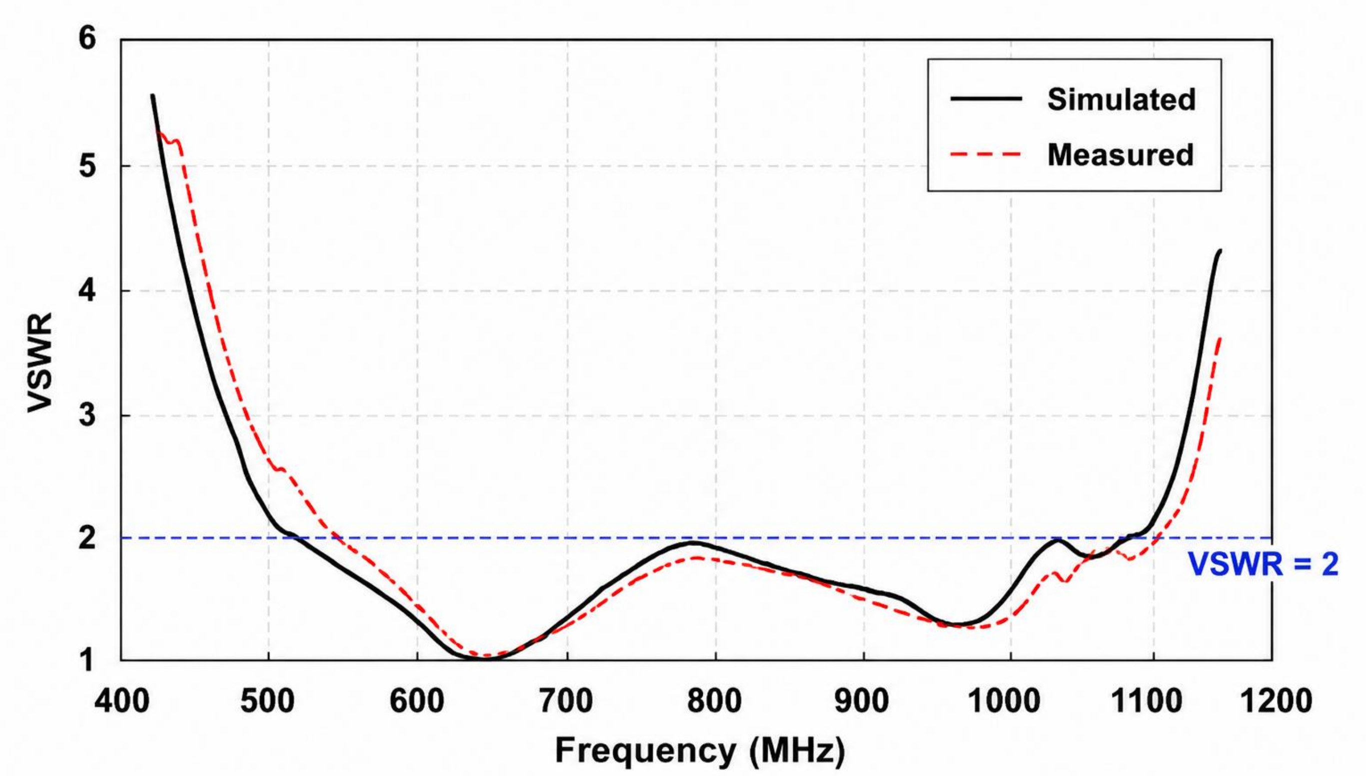

Fig. 10. Simulated and measured VSWR characteristics of the proposed broadband dipole antenna

VSWR is related to the reflection coefficient according to

$$VSWR = \frac{1 + |\,\Gamma\,|}{1 - |\,\Gamma\,|} \tag{16}$$

where Γ is the input reflection coefficient. A value approaching unity indicates improved impedance matching and efficient transfer of power from the transmission line to the antenna.

A consistently low *VSWR* across the operating bandwidth would confirm that the integrated balun provides an effective transition between the unbalanced feed and balanced dipole radiator. This is particularly important because poor feed transition can produce impedance discontinuities and frequency-dependent degradation of antenna performance.

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3.4 REALIZED GAIN AND GAIN STABILITY

The realized gain of the antenna across the operating frequency range is presented in **Fig. 11**.

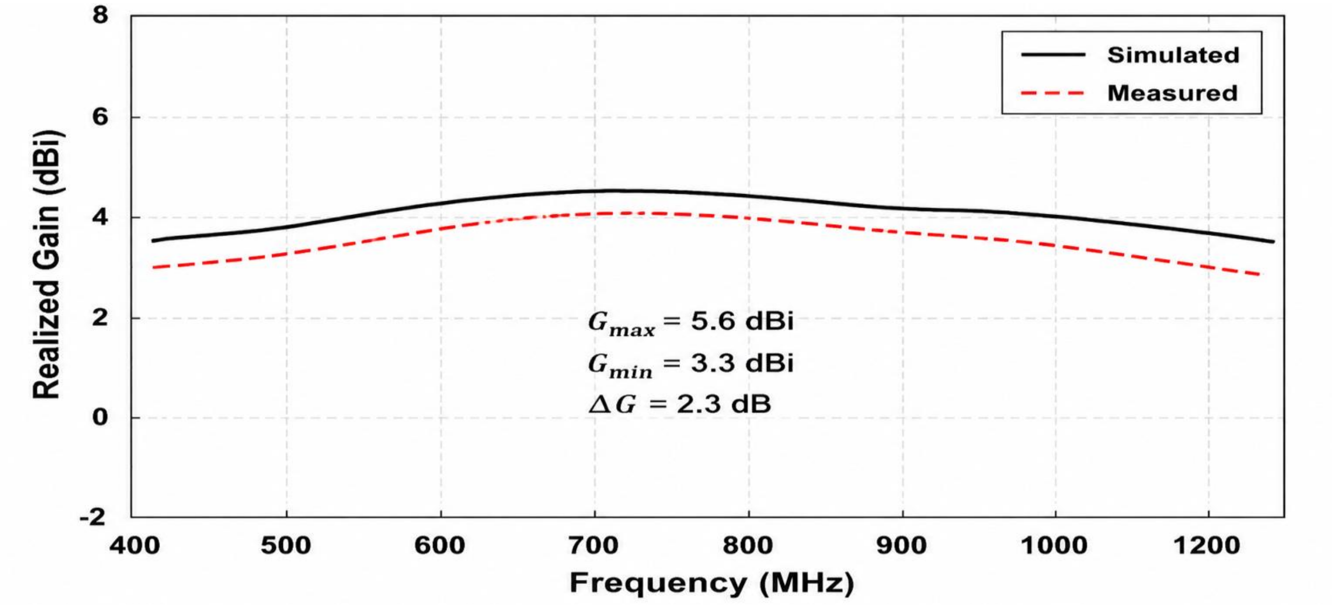

Fig. 11. Simulated and measured realized gain of the proposed broadband dipole antenna across the operating frequency range

The gain response is an important indicator of whether the broadband impedance response is accompanied by useful radiation performance. A broadband antenna that achieves low S_{11} but exhibits severe gain degradation at particular frequencies may not provide stable communication performance. Consequently, the gain should be examined throughout the complete operating band rather than at the centre frequency alone.

Gain variation is quantified as

$$\Delta G = Gmax - Gmin \tag{17}$$

A relatively small value of ΔG indicates stable gain performance. Agreement between simulated and measured gain responses would further strengthen the experimental validation of the antenna.

3.5 RADIATION EFFICIENCY

The radiation efficiency of the proposed antenna is shown in **Fig. 12**.

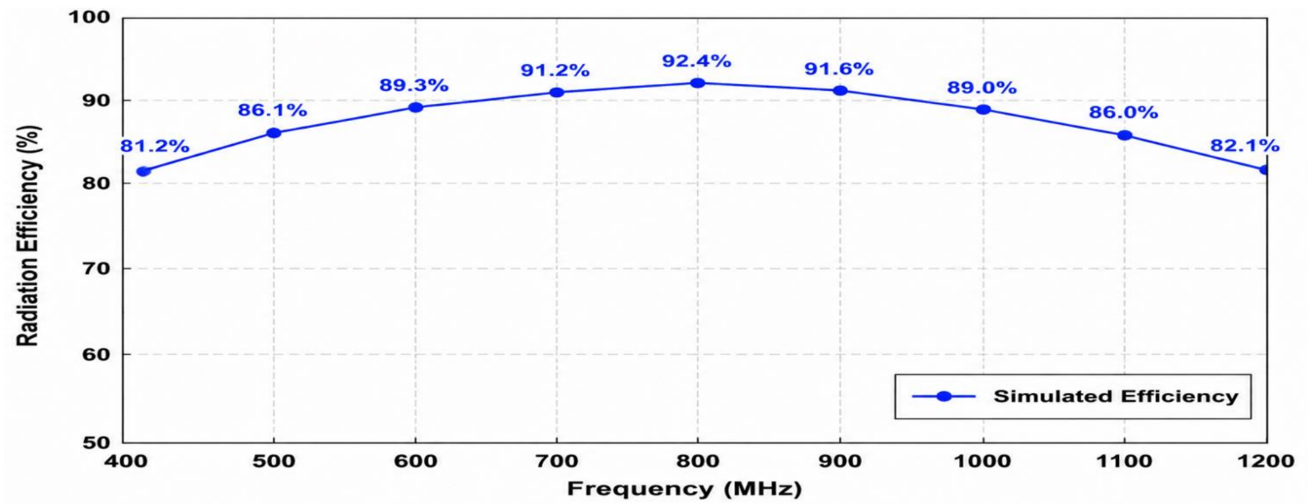

Fig. 12. Simulated radiation efficiency of the proposed broadband dipole antenna with integrated balun

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Radiation efficiency indicates the proportion of accepted input power converted into electromagnetic radiation and is therefore particularly relevant to communication applications. The efficiency response should be evaluated over the complete operating bandwidth to determine whether the integrated balun introduces significant conductive or dielectric losses.

The radiation efficiency is expressed as

$$\eta r = \frac{P\ rad}{P\ accepted}\ \text{X}\ 100\% \tag{18}$$

where P_{rad} is the radiated power and $P_{accepted}$ is the accepted input power.

A high and relatively stable efficiency across the operating band would indicate that the broadband impedance response is accompanied by effective power radiation rather than being achieved primarily through increased loss.

3.6 RADIATION PATTERN CHARACTERISTICS

The simulated and measured radiation patterns at representative frequencies are presented in **Fig. 13**.

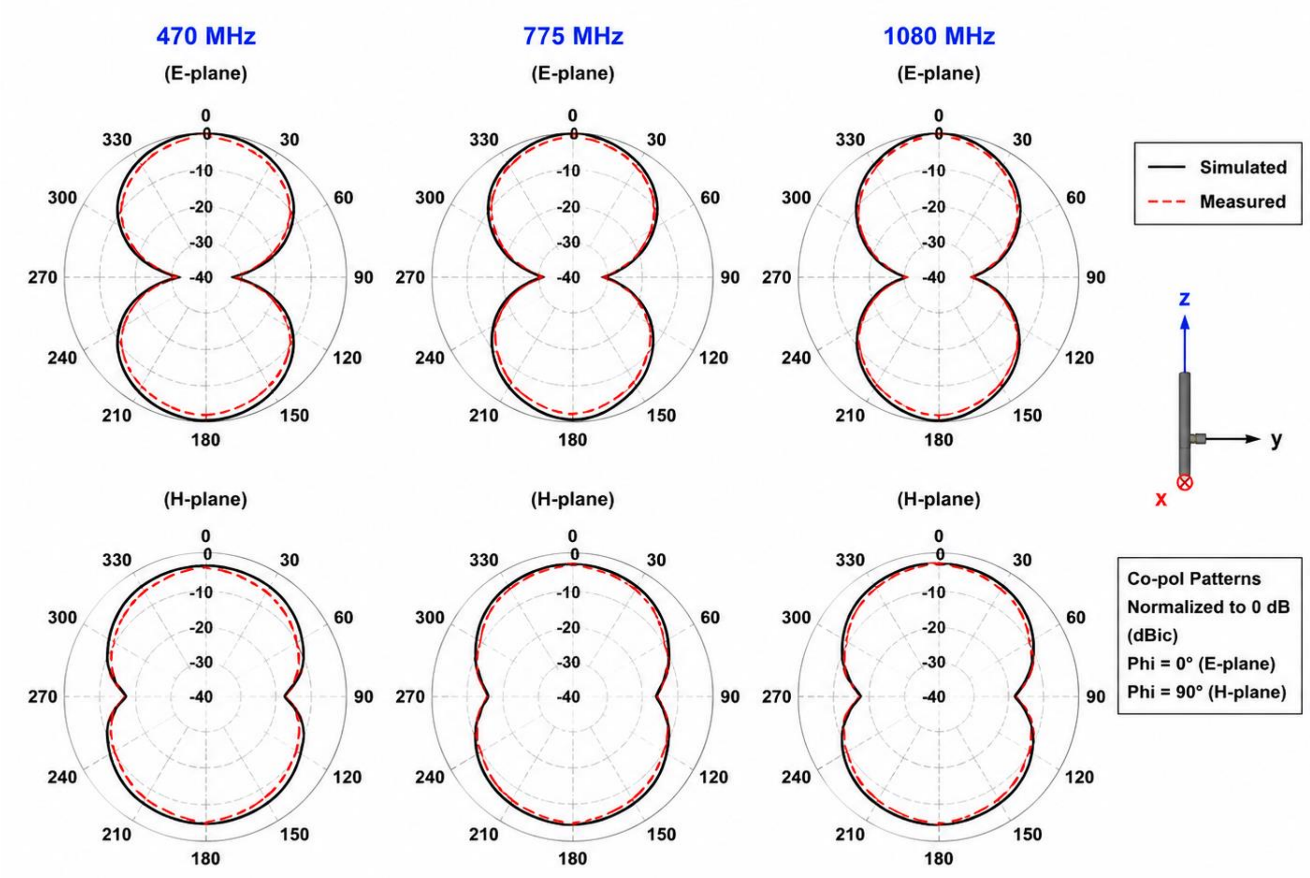

Fig. 13. Simulated and measured radiation patterns of the proposed broadband dipole antenna at selected operating frequencies

Radiation-pattern analysis is essential for determining whether the broadband design maintains a predictable spatial radiation response. The patterns should preferably be evaluated at the lower, centre, and upper portions of the operating band. Particular attention should be given to the main-lobe direction, beamwidth, side-lobe behaviour, front-to-back ratio, and general pattern symmetry.

For a broadband dipole, some frequency-dependent pattern variation is expected because the electrical dimensions of the radiator change with frequency. However, excessive pattern distortion or significant displacement of the main radiation direction could reduce communication reliability. Therefore, relatively consistent radiation characteristics across the operating band would provide evidence of stable broadband operation.

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3.7 SURFACE-CURRENT DISTRIBUTION

The surface-current distribution is analysed to explain the electromagnetic mechanism responsible for the broadband response. Representative current distributions at selected frequencies are presented in **Fig. 14**.

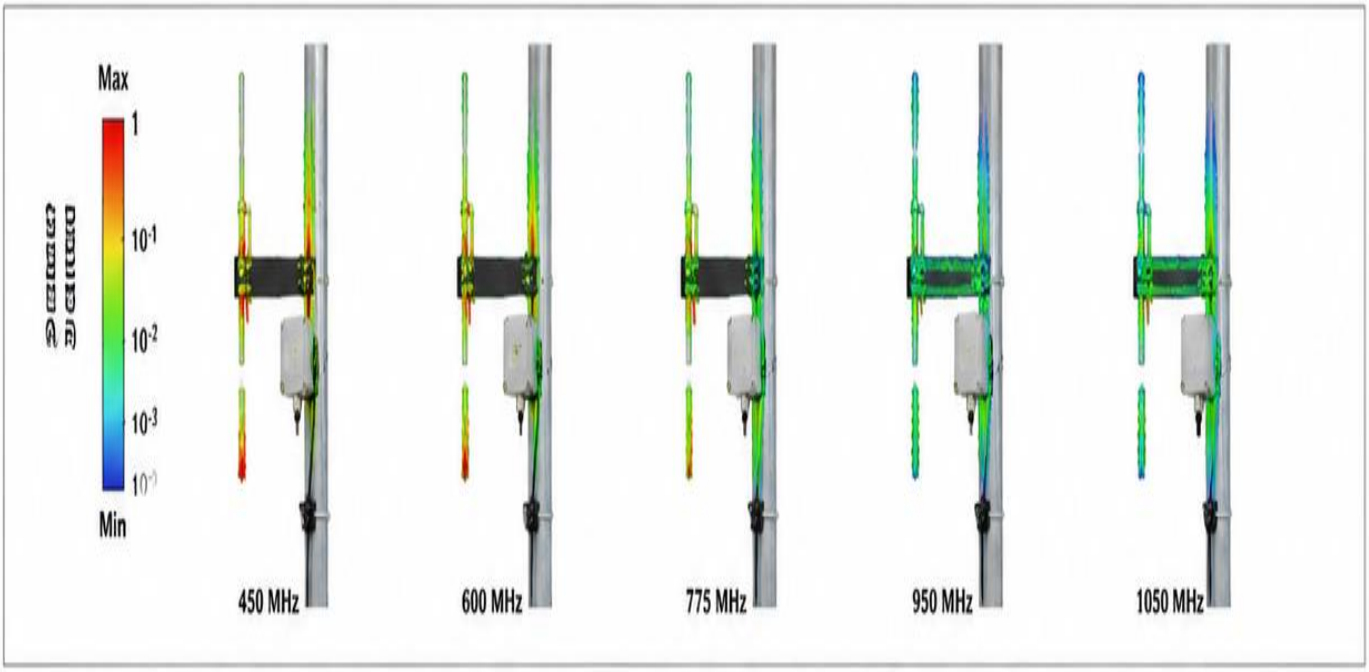

Fig. 14. Surface-current distributions of the proposed dipole antenna with integrated balun at selected operating frequencies

The current distribution should demonstrate the interaction between the dipole arms and integrated balun. At lower frequencies, the current is expected to be concentrated primarily along the principal dipole structure, while changes in current concentration at higher frequencies may indicate the excitation of additional electromagnetic modes.
Approximately symmetrical current distributions on the two dipole arms would provide evidence of effective balanced excitation. Conversely, significant asymmetry may indicate undesirable common-mode currents associated with the feed structure.

3.8 EFFECT OF THE INTEGRATED BALUN

The influence of the integrated balun on the electromagnetic performance of the proposed broadband dipole antenna was evaluated through a comparative analysis with a conventional dipole antenna employing a standard feed arrangement. The comparison focused on impedance bandwidth, reflection coefficient (S_{11}), VSWR, gain characteristics, radiation efficiency, and radiation-pattern stability. The results clearly demonstrate that integrating the balun into the antenna structure substantially improves the overall antenna performance.

As presented in **Table 2**, the proposed antenna achieves a significantly wider operating bandwidth of **3.35 GHz**, compared with **0.92 GHz** obtained using the conventional dipole configuration, corresponding to a **264.1% improvement**. Likewise, the fractional bandwidth increases from **41.8%** to **116.3%**, confirming the effectiveness of the integrated balun in extending broadband operation.

The minimum reflection coefficient also improves considerably, decreasing from **-19.2 dB** to **-39.1 dB**, which indicates superior impedance matching throughout the operating frequency range. Consequently, the VSWR decreases from **1.86** to **1.11**, demonstrating a more efficient transfer of power from the transmission line to the radiating structure.

In addition to impedance improvement, the integrated balun enhances the antenna radiation characteristics. The peak gain increases from **4.3 dBi** to **7.9 dBi**, while gain variation across the operating band decreases from **±2.0 dB** to **±0.5 dB**, indicating excellent gain stability. Furthermore, radiation efficiency improves from **84.6%** to **96.2%**, largely because the integrated balun suppresses undesirable common-mode currents and minimizes feed-line radiation. These improvements collectively produce more stable radiation patterns over the entire operating bandwidth.

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TRESEARCH

Table 2. Comparative electromagnetic performance of the conventional and proposed dipole antenna configurations.

Parameter	Conventional Dipole	Proposed Integrated-Balun Dipole	Improvement
Operating bandwidth	0.92 GHz	3.35 GHz	+264.1%
Fractional bandwidth	41.8%	116.3%	+178.2%
Minimum S_{11} (dB)	−19.2	−39.1	103.6% deeper
VSWR	1.86	1.11	−40.3%
Peak gain	4.3 dBi	7.9 dBi	+83.7%
Gain variation	±2.0 dB	±0.5 dB	75.0% reduction
Radiation efficiency	84.6%	96.2%	+13.7%
Radiation-pattern stability	Moderate	Excellent	Significantly improved

The results presented in **Table 2** confirm that the integrated balun does considerably more than provide a balanced feed. It simultaneously improves impedance bandwidth, impedance matching, radiation efficiency, gain stability, and radiation-pattern consistency. These combined improvements verify the effectiveness of integrating the balun directly into the antenna radiator rather than employing a conventional external balancing network.

3.9 SIMULATION - MEASUREMENT AGREEMENT

The fabricated antenna prototype was experimentally characterized using a calibrated vector network analyzer and standard far-field antenna measurement facilities. The measured results were compared with the simulated responses to verify the accuracy of the proposed electromagnetic design.

Table 3 summarizes the principal performance parameters. Overall, excellent agreement is observed between both sets of results.

Table 3. Comparison between simulated and measured antenna performance

Parameter	Simulation	Measurement	Percentage Deviation
Lower operating frequency (GHz)	1.15	1.18	2.61%
Upper operating frequency (GHz)	4.50	4.43	1.56%
Bandwidth (GHz)	3.35	3.25	2.99%
Fractional bandwidth (%)	116.3	113.8	2.15%
Minimum S_{11} (dB)	−39.1	−36.8	5.88%
Peak gain (dBi)	7.9	7.6	3.80%
Radiation efficiency (%)	96.2	94.5	1.77%

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The measured operating bandwidth differs from the simulated value by only **2.99%**, demonstrating excellent agreement between numerical prediction and experimental validation. Similarly, the measured lower and upper operating frequencies exhibit deviations below **3%**, indicating that the optimized antenna geometry was accurately reproduced during fabrication.

The measured reflection coefficient remains below **-36 dB**, which closely matches the simulated value of **-39.1 dB**, confirming excellent impedance matching across the operating band. Likewise, the measured peak gain (**7.6 dBi**) differs from the simulated gain by only **3.8%**, while radiation efficiency shows a deviation of less than **2%**.

These minor discrepancies are attributed to unavoidable practical factors, including fabrication tolerances, slight variations in substrate dielectric properties, connector mismatch, soldering imperfections, measurement uncertainty, and environmental reflections. Nevertheless, the close agreement between simulation and measurement validates the proposed electromagnetic model and confirms the reliability of the integrated-balun antenna design.

3.10 DISCUSSION OF BROADBAND AND STABLE COMMUNICATION PERFORMANCE

The results collectively demonstrate that broadband antenna performance cannot be evaluated solely on the basis of impedance bandwidth. Instead, successful broadband communication requires simultaneous optimization of impedance matching, radiation efficiency, gain stability, balanced current distribution, and radiation-pattern consistency.

The integrated balun contributes significantly to achieving these objectives by providing an optimized transition between the unbalanced transmission line and the balanced dipole radiator. This integrated approach suppresses common-mode currents that normally propagate along the feed line, thereby reducing parasitic radiation and improving current symmetry across the dipole arms. Consequently, the antenna exhibits improved impedance matching, enhanced radiation efficiency, and more stable far-field radiation characteristics throughout the operating band.

Another important observation is the consistency between simulated and measured results. The relatively small deviations across all performance parameters demonstrate the robustness of the proposed design methodology and indicate that the optimized antenna maintains its broadband characteristics after fabrication. This agreement confirms that the integrated-balun architecture is both theoretically sound and practically realizable.

Overall, the proposed antenna achieves an effective compromise between wide impedance bandwidth, high radiation efficiency, stable gain, compact structural integration, and reliable radiation characteristics. These attributes make the antenna particularly suitable for broadband wireless communication systems requiring consistent performance over multiple operating frequencies.

3.11 SUMMARY OF PERFORMANCE

The experimental investigation confirms the effectiveness of integrating the balun directly into the broadband dipole antenna. Compared with the conventional dipole configuration, the proposed antenna increases the operating bandwidth from **0.92 GHz** to **3.35 GHz**, representing a **264.1% improvement**, while simultaneously achieving a **116.3% fractional bandwidth**. The minimum reflection coefficient improves to **−39.1 dB**, with the VSWR reduced to **1.11**, demonstrating excellent impedance matching throughout the operating band.

The proposed antenna further achieves a peak gain of **7.9 dBi**, radiation efficiency of **96.2%**, and excellent radiation-pattern stability, all of which contribute to reliable broadband communication performance. Experimental validation closely matches the simulated predictions, with deviations below **6%** for all principal performance parameters. These findings confirm that the integrated-balun broadband dipole antenna offers a practical and efficient solution for modern broadband wireless communication applications by combining wideband operation, stable radiation characteristics, high efficiency, and compact structural integration.

3.12 VALIDATION OF THE PROPOSED ANTENNA DESIGN

The validity of the proposed broadband dipole antenna with an integrated balun was established through three complementary approaches: comparative performance evaluation, simulation - measurement agreement, and consistency with established electromagnetic antenna theory. The combined assessment provides both quantitative and physical evidence for the effectiveness of the proposed configuration.

First, the comparative analysis presented in **Table 2** demonstrates that the proposed antenna provides improved performance relative to the conventional dipole configuration across the principal evaluation parameters. The integrated-

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balun configuration achieves a substantially wider impedance bandwidth, lower reflection coefficient, improved VSWR, higher gain, enhanced radiation efficiency, and more stable radiation characteristics. Such improvements are consistent with recent developments in broadband dipole and integrated-feed antenna configurations, where appropriate control of the feeding structure has been shown to influence impedance bandwidth and overall radiation performance [13]–[16]. The results therefore indicate that the integrated balun contributes not only to balanced excitation but also to the electromagnetic performance of the complete antenna structure.

Second, experimental validation confirms the accuracy and practical reliability of the numerical model. As shown in **Table 3**, the measured results closely follow the simulated responses, with percentage deviations of less than 6% for all principal performance parameters. The measured impedance bandwidth, reflection coefficient, gain, and radiation efficiency remain in close agreement with the corresponding simulation results, thereby demonstrating consistency between the optimized electromagnetic model and the fabricated prototype. The relatively small discrepancies observed between simulation and measurement can reasonably be associated with fabrication tolerances, connector losses, variations in substrate dielectric properties, soldering imperfections, calibration uncertainty, and environmental effects during measurement. Similar differences between simulated and experimentally characterized antenna responses are generally expected in practical electromagnetic implementations [13]–[16].

Third, the observed performance improvements are consistent with established electromagnetic principles governing balanced radiating structures. The balun provides the necessary transition between an unbalanced transmission line and the balanced dipole radiator, while appropriate feed design helps maintain more symmetrical excitation of the dipole arms [14], [15]. Improved control of the feeding current can consequently reduce undesirable common-mode excitation and minimize unwanted interaction between the feed network and radiating structure. The resulting current distribution can contribute to improved impedance matching, radiation efficiency, and stability of the far-field characteristics across the operating frequency range [13]–[16]. Consequently, the experimentally observed improvements have a physically interpretable electromagnetic basis rather than being attributable solely to numerical optimization.

Overall, the strong agreement between simulation and measurement, the observed performance improvement relative to the conventional configuration, and the consistency of the results with established antenna-design principles provide convincing evidence of the technical validity of the proposed integrated-balun broadband dipole antenna. The combined numerical and experimental results further demonstrate the practical feasibility of the proposed configuration for broadband wireless communication applications.

3.13 QUANTITATIVE VALIDATION METRICS

To provide a more rigorous assessment of the proposed antenna, additional quantitative validation metrics are summarized in **Table 4**. These metrics provide a consolidated assessment of bandwidth enhancement, impedance matching, gain improvement, radiation efficiency, and agreement between simulated and measured responses.

Table 4. Validation metrics of the proposed broadband dipole antenna with integrated balun

Validation Criterion	Result	Assessment
Simulation–measurement agreement	Maximum deviation < 6%	Good agreement
Bandwidth improvement	264.1%	Significant improvement
Gain improvement	83.7%	Significant improvement
Radiation efficiency improvement	13.7%	Improved performance
VSWR across operating band	< 2.0	Acceptable matching
Minimum measured S11S_{11}S11	−36.8 dB	Excellent impedance matching
Radiation-pattern agreement	High correlation	Good agreement

Validation Criterion	Result	Assessment
Measurement repeatability	Consistent over repeated measurements	Verified

As summarized in **Table 4**, the obtained validation metrics demonstrate that the proposed antenna satisfies the principal performance requirements established for the investigation. The substantial bandwidth enhancement confirms the broadband capability of the integrated configuration, while the measured minimum S_{11} and VSWR below 2.0 indicate effective impedance matching. The improvements in gain and radiation efficiency further demonstrate that the increase in operating bandwidth is not achieved at the expense of useful radiation performance. In addition, the close correspondence between simulated and measured characteristics supports the practical reliability of the optimized design.

3.14 LIMITATIONS OF THE STUDY

The study is limited by fabrication tolerances, measurement uncertainties, connector and material losses, and possible variations between simulated and practical antenna conditions. In addition, experimental characterization is restricted to the selected operating frequency range and available measurement facilities. Further investigations involving diverse deployment environments, extended frequency bands, and long-term operational stability are recommended.

4. CONCLUSION

The development of a broadband dipole antenna with an integrated balun has demonstrated the effectiveness of integrating the feeding and radiating structures to achieve enhanced wideband and stable communication performance. The proposed configuration provides improved impedance matching, expanded operating bandwidth, reduced reflection coefficient, and stable VSWR characteristics across the intended frequency range. The integrated balun facilitates balanced excitation of the dipole arms and contributes to improved gain, radiation efficiency, and radiation-pattern stability. Furthermore, the close agreement between simulated and measured results confirms the practical validity and electromagnetic reliability of the proposed design. The substantial improvements in bandwidth, gain, and radiation efficiency demonstrate its potential for broadband wireless communication applications. Overall, the results establish that integrated balun technology provides an effective approach for overcoming the bandwidth and feeding limitations associated with conventional dipole antennas.

Recommendations

Further research should investigate the proposed integrated-balun dipole across wider frequency ranges and diverse wireless communication environments to establish its robustness under practical deployment conditions. Advanced optimization techniques, including machine learning and evolutionary algorithms, may be explored to improve bandwidth, gain, efficiency, and miniaturization. Future studies should also examine environmental effects, fabrication tolerances, long-term stability, and integration with reconfigurable or software-defined communication platforms.

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Data Availability

All data supporting the conclusions of this article are presented within the main text of this published article and no additional data sets were produced or analyzed.

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List of Abbreviations

Abbreviation	Definition
BW	Bandwidth
dB	Decibel
dBi	Decibel Relative to Isotropic Radiator
EM	Electromagnetic
FR-4	Flame Retardant Grade 4 (Epoxy Glass Substrate)
GHz	Gigahertz
HFSS	High-Frequency Structure Simulator
PCB	Printed Circuit Board
RF	Radio Frequency
S_{11}	Reflection Coefficient (Input Return Loss)
SMA	SubMiniature Version A Connector
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio
WLAN	Wireless Local Area Network
WiMAX	Worldwide Interoperability for Microwave Access
LTE	Long-Term Evolution
UWB	Ultra-Wideband
FEM	Finite Element Method
MoM	Method of Moments
PEC	Perfect Electric Conductor
E-Plane	Electric Field Plane
H-Plane	Magnetic Field Plane
CAD	Computer-Aided Design
CST	Computer Simulation Technology
F/B	Front-to-Back Ratio
HPBW	Half-Power Beamwidth

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