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An Analysis of Methods for Enhancing Gain and Bandwidth in Ultra-Wideband Microstrip Patch Antennas

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Abstract

In the realm of contemporary wireless communication systems, microstrip patch antennas are increasingly preferred due to their lightweight construction, straightforward design, and ease of manufacturing. To achieve optimal performance, especially in ultra-wideband (UWB) applications, researchers are diligently exploring various strategies to enhance both gain and bandwidth. However, finding a balance between these two critical performance metrics poses a considerable challenge. This paper delves into a variety of techniques designed to improve gain and bandwidth, with a particular emphasis on design modifications that influence radiation characteristics. Among the key techniques discussed are slot insertion, innovative feeding methods, slot loading, the use of parasitic patches, air gaps, defected ground structures, electromagnetic band gap structures, horizontal patch gaps, split-ring resonators, metamaterials (including single-negative metamaterials and near-zero refractive index materials), dielectric resonators, superstrates, partially grounded surfaces, shorting pins, optimized dielectric substrates, antenna arrays, frequency-selective surfaces, substrate removal, photonic band gap structures, and multiple or dual feeding techniques. Each of these approaches can be tailored to address the specific needs of various UWB applications, offering a flexible pathway toward performance enhancement. A comprehensive comparison highlights key trade-offs associated with antenna size, fabrication complexity, and performance outcomes. The study concludes that hybrid design approaches-carefully integrating structural innovations, material optimization, and feeding techniques-present the most effective strategy for achieving high-performance UWB antenna systems. Future work emphasizes the need for empirical validation and advanced optimization frameworks to translate theoretical advancements into practical implementations.

Categories: Microwave and RF Engineering, Wireless Communication Systems
Keywords: slots, microstrip patch antennas, uwb, gain and bandwidth enhancing, metamaterials

Introduction And Background

The increasing demand for efficient wireless communication systems has significantly accelerated interest in Ultra-Wideband (UWB) technology. UWB's capacity to operate across a wide frequency spectrum makes it particularly advantageous for various applications, including radar imaging, medical telemetry, and high-speed data transfer [1]. At the core of UWB systems lies the microstrip patch antenna (MPA), which is highly regarded for its low-profile, lightweight design, and seamless integration with other circuit components [2]. However, despite these inherent advantages, achieving optimal gain and bandwidth in MPAs continues to present challenges, leading researchers to explore a variety of enhancement techniques. To ensure effective signal transmission and reception, improving the gain of MPAs is crucial. Strategies such as utilizing antenna arrays, employing specially designed dielectric substrates, and incorporating metamaterials have demonstrated promising outcomes in enhancing gain [3]. In parallel, bandwidth enhancement is equally vital, as traditional MPAs often exhibit narrow bandwidth limitations. Techniques including slot cutting, the integration of parasitic elements, and wideband feeding methods have proven effective in overcoming these bandwidth constraints [4].

This study systematically investigates how to optimize MPAs for UWB applications by simultaneously enhancing gain and bandwidth while addressing critical design trade-offs. While various techniques-including slot loading, defected ground structures (DGSs), metamaterials, and advanced feeding methods-have demonstrated performance improvements, their effectiveness depends on balancing fabrication complexity, cost, and physical constraints. The review evaluates these methods to determine their suitability for different UWB applications, such as radar, medical telemetry, and high-speed communications. Ultimately, the findings highlight that no single approach universally outperforms others, emphasizing the need for tailored, hybrid designs that integrate multiple techniques. Future research should focus on experimental validation, material innovations, and optimization algorithms to further advance UWB antenna performance.

Review

Literature review

The enhancement of gain and bandwidth in UWB MPAs involves various structural modifications, material innovations, and advanced feeding techniques. Among the structural modifications, slot-loading techniques-such as U-shaped, H-shaped, or circular slots-introduce additional resonant frequencies, thus improving bandwidth while maintaining compactness [5-6]. Horizontal patch gaps (HPGs) alter current distribution, optimizing bandwidth without significantly increasing antenna size [7-8]. Air gaps lower the effective dielectric constant, improving field propagation and impedance matching. Additionally, DGSs and partially grounded surfaces suppress surface waves, enhancing radiation efficiency [9-10].

Material-based enhancements include metamaterials-such as split-ring resonators (SRRs) and near-zero refractive index (NZRI) materials-which manipulate electromagnetic wave interactions to improve both gain and bandwidth [11]. Dielectric resonators (DRs) and superstrate layers introduce controlled resonances and focus electromagnetic waves, thus increasing antenna efficiency [12-13]. Moreover, antenna arrays leverage constructive interference to achieve higher gain, while frequency-selective surfaces (FSS) and photonic band gap (PBG) structures act as frequency filters, tailoring the bandwidth for specific applications [14-15].

Substrate removal reduces dielectric losses, enhancing radiation efficiency, whereas shorting pins enable antenna miniaturization by lowering resonant frequencies [16-17]. Feeding techniques, including microstrip line, coaxial probe, inset, waveguide (coplanar waveguide (CPW)), aperture-coupled, and proximity-coupled feeds, significantly influence impedance matching and bandwidth expansion [18-19]. However, these strategies often involve trade-offs in terms of fabrication complexity, cost, and physical dimensions. Stacked parasitic patches and electromagnetic band gap (EBG) structures offer high performance but may introduce design intricacies [20]. By integrating these methods-whether through geometric adjustments, material innovations, or advanced configurations-engineers can tailor solutions for UWB applications while balancing performance metrics with practical constraints [21].

Several studies have been conducted to enhance the gain and bandwidth of UWB antennas using various techniques. One such approach involved the development of a small UWB frequency-selective surface-microstrip-fed circular monopole antenna to achieve higher gain. This antenna, as described in [22], demonstrated a maximum gain of 8.1 dB at 9 GHz. In the pursuit of UWB scenarios, a defective ground configuration compressed patch antenna was proposed [23]. This antenna achieved a gain of 3.30 dBi at 3.50 GHz. Additionally, a compact wide-gain UWB unidirectional monopole antenna with a defective ground structure was reported in [24]. The antenna was fabricated using FR4 substrate material and had overall dimensions of 26.6 mm by 29.3 mm by 1.6 mm. It exhibited a peak gain of 7.20 dB, an efficiency of 95%, and a bandwidth of 7.4 GHz (3.2-10.6 GHz). To further enhance the gain of UWB antennas, two designs of FSS reflectors (FSS1 and FSS2) were suggested in [25]. FSS1 had overall dimensions of 82.5 × 82.5 mm^2, while FSS2 measured 62.5 × 62.5 mm^2. These reflectors were proposed to be used in conjunction with UWB antennas and resulted in gain enhancements of 2.5 dB and 2 dB, respectively. Another study [26] employed a single-layered FSS to enhance the gain of a UWB antenna with geometrical dimensions of 41 × 34 mm^2. With this configuration, the antenna's gain was increased by 2-3.5 dB, reaching a peak gain of 7.6 dB across the full resonant range.

In [27], a UWB monopole antenna was described that utilized a single-layered FSS, resulting in an enhancement of 4.5 dBi in gain. An innovative compact UWB antenna was designed in [28], incorporating a rectangular notch that served as a modified patch (MP) and EBG structure. This design effectively controlled the center frequency and notched bandwidth, resulting in an improved bandwidth spanning from 3.1 GHz to 12.5 GHz, along with a maximum gain of 4.5 dBi. For UWB applications, a reduced UWB microstrip antenna was developed in [29], utilizing a metamaterial array and computer simulation technology (CST) software. The outcomes demonstrated a significant gain of 5.6 dB and an expanded bandwidth ranging from 2.6 GHz to 20 GHz. An upgraded UWB antenna was developed in [30] by employing a FR4 substrate, which led to a boosted gain. The research findings showcased an impedance bandwidth ranging from 2.2 GHz to over 12 GHz, equivalent to a 138% fractional bandwidth. Additionally, an elevated gain exceeding 6.5 dB was achieved. In [31], a microstrip antenna design was proposed that employed a DGS and HPG to enhance both the bandwidth and gain. The gain achieved was measured at 2.8 dBi, accompanied by a bandwidth of 764.4 MHz.

Research conducted by [32] investigated the use of a combination of U-shaped and Quad L-shaped slots, along with L-shaped DGSs and U-shaped dual parasitic components, for the design of an antenna. The desired antenna aimed for a gain of 7.2 dB and a bandwidth of 1.40 GHz. Another study [33] focused on the development of an innovative UWB antenna with a semi-circular shape, measuring 35 × 30 × 1.6 mm^3. This antenna utilized opposite split-ring resonators to expand the bandwidth and frequency selective surface reflectors to enhance gain. It achieved an impressive bandwidth of 130.3% from 3.16 to 15 GHz, with a maximum gain of 10.9 dB. To further enhance the gain, researchers proposed an antenna with a rectangular microstrip patch design [34]. Through simulation results, they were successful in increasing the gain from 6.907 to 9.179 dB.

A CPW-fed UWB "strawberry artistic-shaped" printed monopole antenna integrated with a single-layer FSS was developed to enhance gain [35]. This design features a 10 × 10 FSS array, achieving an impedance bandwidth of 8.85 GHz (3.05-11.9 GHz) and improved gain ranging from 1.65 to 7.87 dBi in the lower band and 6.3 to 9.68 dBi in the upper band. Fabricated on an FR4 substrate with an FSS reflector, the antenna exhibits a directional, balanced far-field radiation pattern, making it suitable for UWB and ground-penetrating radar (GPR) applications. The overall dimensions are 61 mm × 61 mm × 1.6 mm. Three hexagonal patch antennas designed for circular polarization were experimentally validated in [36]: a simple patch, a slotted-ground patch, and a parasitic-element-loaded patch. Their measured fractional impedance bandwidths were 2%, 5.2%, and 6.35%, respectively. The slotted-ground and parasitic-element designs achieved axial ratio bandwidths of 4.73% and 3.33%, respectively. Radiation patterns matched simulations, and the average gain of each variant was evaluated. A compact FSS was integrated, yielding a 3 dB gain improvement within the operating band.

A broadband MPA with FSS-based gain enhancement for wireless communications was presented in [37]. Three configurations were analyzed: an E-shaped patch, a combined E-T-shaped patch, and the latter integrated with an FSS. The final design, incorporating a modified ground plane with U-shaped slits and slots, achieved a 6.4 GHz bandwidth (2.9-9.3 GHz) and a peak gain of 8.12-5.12 dBi improvement over the non-FSS design. It supports WiMAX (3.5/5.8 GHz) and WLAN (3.6/4.9/5/5.9 GHz) standards. For sub-6 GHz 5G applications, a 30 mm × 30 mm × 1.6 mm modified circular-loop FSS paired with a slot antenna was developed [38]. The FSS reduces the resonant frequency without increasing size, enabling operation from 3.6 to 6.1 GHz with an average gain of 7-7.5 dBi and a peak gain of 7.87 dBi. The FSS superstrate enhances gain by 4 dB while maintaining favorable reflection characteristics for 5G. A compact UWB monopole antenna with a U-shaped radiating patch and truncated ground plane was proposed in [39], measuring 16 mm × 22 mm × 1.6 mm and operating over 3.1-18.6 GHz with a peak gain of 9.4 dBi. Adding a patch-type FSS improved directivity and achieved a ~10 dB front-to-back lobe ratio. The FSS-integrated design (52 mm × 62.5 mm × 23.2 mm) was experimentally validated for high-gain compact wireless systems. A compact UWB multiple-input multiple-output (MIMO) antenna with triple-band notches and strong isolation (below −20 dB) was introduced [40]. This was achieved using DGS and L-stubs. It demonstrates excellent ECC (<0.025) and DG (>9.98 dB), making it suitable for UWB applications

A uniplanar UWB stopband FSS with a unit cell size of 0.095λ × 0.095λ was designed for microwave imaging [41]. Integrated with a hexagonal monopole and a 3 × 3 FSS array, the system achieved a 3.5 dBi gain improvement, unidirectional radiation, and a bandwidth of 3.8-10.6 GHz, demonstrating high resolution in UWB baggage scanners. A genetic algorithm-optimized wideband FSS integrated with an M-shaped monopole antenna achieved 98.07% bandwidth and a stable gain of 9-10.1 dBi across 2.6-8.1 GHz [42]. A leaf-shaped UWB antenna (40 × 30 × 0.8 mm) with dual FSS layers (44 × 44 × 1.6 mm) achieved 8.7 dBi peak gain and 2-4.5 dBi enhancement over 3-14.64 GHz, suitable for GPR with >114% bandwidth and 85% efficiency [43]. A compact UWB antenna (35 × 30 × 0.8 mm) with a bent ground plane and umbrella-shaped radiator (3.05-13.4 GHz) was proposed in [44]. A dual-layer FSS boosted gain to 5.5-8.5 dBi, achieving >90% efficiency and omnidirectional patterns for GPR. A UWB circularly polarized (CP) antenna with an inverted L-shaped patch and FSS achieved 58.15% axial ratio bandwidth (5-9.1 GHz) and 3 dBi gain improvement, operating from 3.7 to 11.1 GHz with a peak gain of 9.4 dBi [45]. Another UWB design with a U-shaped patch and 4 × 4 uniplanar FSS achieved 2.5-5.2 dBi gain enhancement over 2.94-15.26 GHz and 76-84% efficiency for sandy-environment GPR [46]. A topology-optimized FSS (0.1λ × 0.1λ unit cell) enhanced a monopole antenna to 2.9-14.5 GHz bandwidth and 9.7 dBi peak gain, ideal for radar and Magnetic Resonance Imaging [47]. A hexagonal-patch UWB antenna with a 5 × 5 FSS achieved 3-18 GHz bandwidth and 10.5 dBi peak gain [48]. Finally, a semicircular UWB monopole with a 6 × 6 metallic FSS reflector improved gain by 4 dB (peak 8.3 dB) over 3-11 GHz for UWB/GPR applications [49].

An enhanced rectangular patch antenna with distinct S and rectangular slots was introduced to achieve a higher level of gain [50]. At a frequency of 2.4 GHz, this antenna exhibited a maximum gain of 4.26 dB. To achieve superior gain capabilities, a compact quad-notched CPW-fed UWB antenna measuring 35.4 × 26.6 × 1.6 mm^3 was recommended [51]. This antenna achieved an impressive elevated gain of 4.2 dBi. To enhance gain and efficiency in an UWB antenna, a simple circular slot integrated into a semi-circular patch antenna with a DGS was employed. Despite its small dimensions of 26 mm × 27 mm × 1.6 mm, this antenna achieved a maximum gain of 8.5 dB with an efficiency of 92% [52]. Telecommunication demands were met with the development of a high-gain UWB circular fractal antenna, featuring compact dimensions of 40 × 24.5 × 1.6 mm^3 [53]. Simulation results demonstrated an exceptional efficiency of 98% and a peak gain of 7.73 dB, with a wide bandwidth ranging from 2.7 to 11 GHz (8.3 GHz bandwidth). A high-isolation structure-shared planar UWB MIMO antenna specifically designed for mobile devices was described [54]. This antenna boasted a significant gain increase of 6 dB, along with a bandwidth ranging from 3 to 10 GHz (7 GHz bandwidth). A planar patch utilizing a CPW and supporting UWB circular polarization was presented [55]. This antenna exhibited an impedance bandwidth of 7.5 GHz (3.10-10.6 GHz) and a gain of 3.5 dB.

A high-frequency range CPW microstrip antenna, specifically designed to operate at 3.1-10.6 GHz, was successfully developed by utilizing metallic plates [56]. This antenna design achieved a bandwidth of 3.1-6 GHz and a gain of 2-2.5 dB. For WLAN and WiMAX applications, a compact UWB antenna was created with the use of two different feeding strategies: co-axial feed and line feed [57]. The performance of this antenna exhibited peak gains of 6.8 dBi, 5.5 dBi, 3.75 dBi, and 6.17 dBi at frequencies of 4 GHz, 5.1 GHz, 7.6 GHz, and 9 GHz, respectively. Another UWB antenna was developed, featuring a rectangular slot on the patch and a DGS [58]. This antenna had a size of 20 × 15 × 1.6 mm^3 and operated at a frequency range of 3.1-10.6 GHz, delivering a peak gain of 3.61 dB. A probe-fed UWB patch antenna with dimensions of 46 × 46 × 1.5 mm^3 was also presented, incorporating an artificial magnetic conductor (AMC reflector) which resulted in a maximum gain of 5.5 dB [59]. Additionally, a UWB planar antenna measuring 15 × 20 × 1.5 mm^3 and equipped with a curved staircase grounding surface was demonstrated. It showcased a bandwidth of 130.4% (2.4-11.4 GHz), a peak gain of 3.5 dB, and an efficiency of 76% [60]. Furthermore, a modern UWB planar antenna measuring 20 × 25 × 1.5 mm^3 was proposed, utilizing a MP and defective ground plane (DGP). This antenna achieved an impedance bandwidth of 110% (3.1-10.8 GHz), a maximum gain of 5.1 dB, and a peak radiation efficiency of 89% [61].

A wide range of frequencies, spanning from 3.08 to 14.1 GHz, were discussed [62] for a particular type of metamaterial known as a single negative (SNG) metamaterial. This metamaterial, combined with a NZRI, was used to create a consolidated UWB monopole antenna measuring 14.5 × 22 × 1.6 mm^3. This antenna exhibited a greater gain of 6.12 dBi. Another antenna, designed in a size of 40 × 20 × 1.6 mm^3, was specifically developed for narrow UWB MIMO applications [63]. It achieved an impressive impedance bandwidth of 8 GHz, ranging from 3.00 to 11.00 GHz, and a maximum gain of 5 dBi. A unique combination of a DR, a thin flat monopole antenna, and a CPW feeding mechanism was utilized to create another UWB antenna [64]. This antenna had dimensions of 17.6 mm × 33.6 mm × 1.524 mm and demonstrated a bandwidth of 110% covering frequencies from 3.20 to 10.96 GHz. Its total gain was measured at 3.30 dBi. A fragile UWB monopole antenna, featuring a V-shaped slot dedicated to Wi-Fi systems, was invented [65]. This antenna was relatively larger, measuring 27 mm × 33 mm × 1.5 mm, and provided an impressive bandwidth of 126% across frequencies ranging from 3.20 to 14 GHz. It achieved the highest gain among the antennas mentioned, reaching 3.90 dBi.

A compact slot antenna measuring 24 mm × 16 mm × 0.787 mm was developed with excellent capability to discriminate band edges and adjustable options for excluding specific frequency bands. This antenna was designed for UWB applications and achieved a bandwidth of 114% (3.1-11.1 GHz) and a maximum gain of 4 dBi [66]. Another versatile circular patch antenna with dimensions of 14 × 18 × 1.6 mm^3 and a grounded surface resembling a pestle shape demonstrated a fractional bandwidth of 118% (3.1-12.13 GHz) and a peak gain of 3.2 dB [67]. Furthermore, a tiny UWB slit antenna measuring 20.25 × 8 × 1.27 mm^3 featuring three inclined spectral bands and three L-shaped slots inscribed on the ground surface was introduced [68]. This antenna achieved the highest gain of 3.35 dBi and a bandwidth of 122.6% (2.65-11.05 GHz). An inconspicuous UWB antenna with dimensions of 60 mm × 60 mm × 1.58 mm, based on probe-supply imperfect ground configurations, was demonstrated [69]. It attained an optimal gain of 2.6 dBi and an impedance spectrum with a 10 dB point covering 109% bandwidth (4.2-14.3 GHz). Additionally, a UWB monopole circular patch antenna utilizing faulty ground arrangements achieved a bandwidth of 123.66% (2.5-10.6 GHz) with a maximum gain of 8.4 dBi [70]. A line-fed rectangular patch antenna designed for UWB applications employed a partially grounded surface and incorporated right-angle triangle slots [71]. This antenna showcased an impressive bandwidth of 138.16% (3.2-17.5 GHz) with a peak gain of 6.4 dBi at 12.5 GHz. For Ku-band wireless communications, a microstrip line-fed UWB antenna utilizing a DGS was developed [72]. It achieved a 10.48 GHz (9.34-9.82 GHz) bandwidth and a maximum gain of 6.27 dB. Moreover, a slotted UWB patch antenna was designed and it showcased a cumulative gain of 5.93 dB with a bandwidth of 41.61% (16.58-25.29 GHz) for Ku-band wireless communications services [73].

A unique and innovative rectangular patch antenna, measuring 30 × 35 × 1.6 mm^3, was created [74]. By incorporating a partially grounded structure, this antenna achieved an impressive bandwidth of 152.9% (2-15 GHz) and a peak gain of 4.69 dB. Another UWB rectangular patch antenna, measuring 60 × 55 × 1.59 mm^3, was developed [75] using a DGS. This antenna exhibited exceptional performance with a gain of 5.6 dBi and a bandwidth of 8.28 GHz (3.42-11.7 GHz). In the pursuit of wireless capabilities, a SGS was utilized to construct a compact UWB antenna measuring 45 × 45 × 1.565 mm^3 [76]. This antenna surpassed expectations by achieving a remarkable 104% bandwidth ranging from 2.08 to 6.64 GHz, coupled with a high gain of 5.4 dB. To meet the demands of UWB applications, a pentagonal patch antenna measuring 30 × 17.59 × 1.6 mm^3 was designed [77]. Despite its smaller dimensions, this antenna provided a broad bandwidth of 121% (2.66-10.82 GHz) and a gain of 3.38 dB. A square UWB antenna, measuring 24 × 24 × 1.6 mm^3, was fabricated using a partial ground surface [78]. This antenna boasted an impressive gain of 7.2 dB and a high bandwidth of 106.92% (3.53-11.64 GHz).

A microstrip line was utilized in the creation of a rectangular patch antenna with a small size of 40401.6 mm^3. The antenna showcased a bandwidth of 97.88% and reached a maximum gain of 6.725 dB [79]. A study was conducted on a novel compact antenna featuring a MF, complemented by rectangular parasitic elements and a defective ground plane, specifically designed for UWB applications [80]. The antenna's overall dimensions are remarkably compact, measuring just 20 × 20 × 1.6 mm^3. It successfully attained a bandwidth of 8.3 GHz, spanning from 2.7 to 11 GHz, along with a gain of 3.34 dB and an impressive antenna efficiency of 79.8%. A CPW ground-slotted corner trimmed UWB patch antenna with dimensions of 50 × 50 × 1.6 mm^3 exhibited a bandwidth of 152.69% (1.56-1.63 GHz) and a gain of 4.46 dB [81]. The investigation also focused on a CPW-fed UWB planar antenna with an elongated U-shaped ground plane and a reversed L-shaped structure [82]. This antenna was designed for portable communication devices and achieved a maximum efficiency of 94.4%, a peak gain of 4.98 dBi, and a bandwidth of 8.2 GHz (3.05-11.25 GHz). An UWB planar monopole MPA was also developed, featuring ideal dimensions of 20 × 20 × 1.6 mm^3 [83]. This antenna utilized an extended patch and a discreet ground layer. It boasted an impressive 127% impedance bandwidth (3.13-14.07 GHz), a peak gain of 3.4 dB, and an efficiency of 78%, truly showcasing its wideband capabilities. The study presented in [84] explored a rectangular MPA that utilizes multi-slotted patch and partial grounding plane techniques to enhance both gain and bandwidth. The antenna was designed with optimal dimensions of 30 × 20 × 0.8 mm^3. It achieved an impressive impedance bandwidth of 151.54% (ranging from 3.15 to 22.85 GHz), a peak gain of 8.06 dB, and an efficiency rate of 96.83%, effectively demonstrating its exceptional wideband performance.

A monopole circular patch antenna with DGS was proposed, achieving an impedance bandwidth of 8.1 GHz (2.5-10.6 GHz) and significant return loss values of −34.84 dB at 2.9 GHz and −33.74 dB at 9.1 GHz [85]. A modified elliptical microstrip antenna with dimensions of 40 mm × 40 mm × 1.6 mm was developed, achieving a measured bandwidth of 4.28% and a return loss of −42 dB at 7.05 GHz [86]. A FSS-loaded UWB antenna (40 × 40 × 30 mm^3) for high-gain applications was introduced, achieving a peak gain of 8.6 dBi and a bandwidth of 10.45 GHz within the 2.55-13 GHz range [87]. A staircase-defected ground structure MPA was designed for UWB frequencies from 3.1 to 10.6 GHz, achieving a maximum gain of 5 dB [88]. The antenna exhibited bidirectional radiation patterns and a return loss below −10 dB across the UWB spectrum. A printed planar patch antenna was introduced, featuring a compact size of 10 × 16 × 1.575 mm^3 and a bandwidth from 3.6 to 14.6 GHz [89]. It demonstrated a peak gain of 3.28 dBi and an average radiation efficiency of 68%, making it suitable for various UWB applications. A multi-slot patch antenna designed for UWB applications was developed [90], measuring 26 × 28 × 0.8 mm^3 and operating from 3.15 to 10.79 GHz. It achieved a maximum gain of 3.22 dBi and over 80% efficiency, making it suitable for UWB wireless applications. A UWB band patch antenna was designed [91] to operate at 6.56 GHz with a bandwidth of 507.7 MHz. It details substrate selection, antenna dimensions, and feedline configuration, ensuring efficient radiation characteristics for radar sensing applications.

A patch antenna designed for UWB applications was presented [92], featuring a low dielectric constant FR-4 substrate. It achieved a return loss of −20.03 dB and a bandwidth of 641.8 MHz, making it suitable for integration into portable devices. A compact MPA with dimensions of 37 × 30 × 1.6 mm^3 demonstrated a high gain of 5.45 dBi and a radiation efficiency of 94%, suitable for applications like medical diagnostics and security screening [93]. An analytical design of a new compact CPW-fed UWB antenna with dimensions of 17 × 15 × 0.787 mm^3, operable in the spectrum between 23 and 150 GHz, was demonstrated [94]. The antenna achieved a fractional bandwidth of 147.2%, a gain over 4.5 dBi, and an efficiency of over 90%, highlighting its potential for next-generation wireless communication. A novel approach to enhance the performance and radiation efficiency of a UWB miniaturized antenna was reported [95]. It consists of a rectangular patch supplied by a 50-ohm microstrip line and a rectangular slot inserted on the radiating element on stair treads between the feed and the antenna. The antenna achieved a bandwidth of 13.6 GHz (3.1-16.7 GHz). A new optimization algorithm, combining genetic algorithm and particle swarm optimization, was mentioned [96]. It introduced two new methods of automatic design: automatic search on the patch for cutting (ASC) and creating DGS. The antenna achieved a bandwidth of 17.5 GHz (2.5-20 GHz).

A stacked MPA designed for UWB applications was noted [97], utilizing two different substrates: FR4 and Rogers RT/duroid 5880, with dielectric constants of 4.4 and 2.2, respectively. The antenna dimensions are 27 mm × 30 mm × 4.7 mm, achieving bandwidths of 3.34-4.42 GHz and 6.00-12.56 GHz, with gains ranging from 4.5 to 8 dB. The design ensures proper matching with $S11 < -10$ dB across the operational frequency range. A hexagonal MPA with dimensions of 36.96 mm × 38.52 mm × 1.59 mm for UWB applications was revealed [98]. The simulated results showed a peak gain of 5.32 dB with a radiation efficiency of 90.88%. A low return loss UWB CPW-fed patch antenna with dimensions of 35 mm × 30 mm × 1.6 mm for mobile wireless communications was explained [99]. The antenna achieved a bandwidth of approximately 4.9 GHz (2.32-7.23 GHz) with a resonant frequency at 3.66 GHz for 5G wireless mobile applications. It exhibited a return loss coefficient of around −70 dB, a Voltage Standing Wave Ratio of 1.002, a directivity of 3.28 dBi, and a positive gain of 1.73 dBi at 3.66 GHz and 4.02 dBi at 6.86 GHz. A single-element UWB MPA with an overall size of 62.5 mm × 52 mm × 24.9 mm, using a partial ground, modified U-shaped radiating patch, and FSS, was provided [100]. The antenna achieved a peak gain of 9.7 dBi.

An UWB planar patch antenna with a volume of 32 × 32 × 1.6 mm^3 using the DGS technique was advised [101]. Covering a wide frequency range across UWB, X, and Ku bands, the antenna achieved a bandwidth of 16.8 GHz (3.02-19.82 GHz), with a peak gain ranging from 2 to 6.8 dB and a radiation efficiency exceeding

85%. A novel microstrip antenna of compact dimensions, constructed utilizing advanced metamaterials tailored for UWB applications, was stated [102]. The antenna structure measures 30.8 × 27.6 × 0.8 mm^3 and achieved a bandwidth of 11 GHz (3.5 GHz to beyond 14.5 GHz). A UWB fractal MPA with dimensions 25 × 30 × 0.55 mm^3, utilizing a DGS and artificial neural networks (ANNs) for vehicular communication applications at futuristic frequencies, was recommended [103]. The antenna achieved a bandwidth of 4600 MHz (25-36.5 GHz) with a gain of 9 dB. A hybrid fractal antenna with dimensions 30 × 30 × 1.6 mm^3, inspired by Giuseppe Peano and Sierpinski Carpet, was proposed for UWB applications [104]. The antenna achieved a bandwidth of 8.64 GHz (3.32-11.96 GHz) and a maximum gain of 5.6 dB. A CP inverted-F antenna with dimensions 60 × 60 × 1 mm^3 for UWB applications, incorporating two rectangular slots of different sizes at opposite corners of the ground plane, was indicated [105]. The antenna achieved an impedance bandwidth covering 5.1-7 GHz (31.4%) and 7.5-11.1 GHz (38.7%), while the axial ratio bandwidth ranges from 5.3 to 6.8 GHz (24.8%) and 7.8-10.8 GHz (32.3%) in the lower and upper frequency bands, respectively.

An UWB antenna with dimensions 30 × 37 × 1.6 mm^3, featuring a rectangular stepped patch, an FR-4 substrate, and a uniquely truncated partial ground plane, was showed [106]. The antenna achieved an impedance bandwidth of 7.73 GHz (3.04-10.77 GHz) for S11 < -10 dB. An UWB MPA based on a Koch fractal resonance unit and CSRRs defective ground unit was implied [107]. The overall antenna size is 35 × 30 × 1.6 mm^3, achieving an impedance bandwidth of 12.55 GHz (2.95-15.5 GHz) with a gain of 5.14 dBi. A novel corner-etched rectangular-shaped UWB antenna, loaded with a truncated ground plane for microwave imaging, was promoted [108]. The antenna size is 35 × 30 × 1.6 mm^3, achieving an impedance bandwidth of 11.38 GHz (3.25-14.63 GHz) with a gain of 9.68 dB. A compact, offset edge-fed monopole hybrid fractal antenna designed for UWB and space applications, operating at 3.2 GHz, was suggested [109]. The antenna (38.12 mm × 38.42 mm) integrates Koch and Minkowski fractal geometries and resonates at four frequencies (3.2 GHz, 4.94 GHz, 7.21 GHz, 10.10 GHz). It achieves a wideband fractional bandwidth of 119.55% (2.85-11.32 GHz), exceeding the FCC standard. The antenna provides high gain (up to 8.26 dBi) with a maximum efficiency of 89.81%. It is CP at 3.14-3.30 GHz and 9.07-9.45 GHz, and linearly polarized elsewhere. With a 16.37% size reduction, it is suitable for WiMAX, ISM, WLAN, military, satellite, and radar applications.

A U-shaped MPA with dimensions 24 × 28 × 0.787 mm^3, utilizing novel parasitic tuning stubs for UWB applications, was devised [110]. The antenna achieved an UWB impedance bandwidth (S11 < -10 dB) as high as 129%, with gain ranging from 1.6 to 5.3 dBi across different frequencies. A UWB antenna with dimensions 47 × 35 mm^2, incorporating a DGS structure optimized using the Grey Wolf Optimization algorithm, was put forward [111]. The antenna achieved a bandwidth of 20.12 GHz (2.38-22.5 GHz) with a gain of 6.5 dBi. A UWB MPA with dimensions 45 × 34 × 1.6 mm^3, featuring variable band-notched characteristics, was offered [112]. The antenna achieved a large −10 dB bandwidth of 7.8 GHz (2.9-11 GHz) and a peak radiation efficiency of more than 87%.

A miniature broadband microstrip antenna with dimensions 20 × 14 × 1.6 mm^3, featuring high gain, was claimed [113]. The antenna exhibited a -10 dB impedance bandwidth of 19.5 GHz (5 GHz-24.5 GHz) with a fractional bandwidth of 132%, covering a major portion of the UWB band (3.1-10.6 GHz), X-band (8-12 GHz), Ku-band (12-18 GHz), and a large part of the K-band (18-27 GHz). A single-layer frequency selective surface (FSS) was integrated into the antenna to enhance the gain to 5.9 dBi across the entire frequency band. A microstrip-fed patch antenna (22 × 29 × 1.6 mm^3) for UWB applications, utilizing a partial ground plane with a rectangular slot in both the ground plane and the patch, was pointed out [114]. The antenna achieved a wide bandwidth of 9.1 GHz (2.5 GHz-11.6 GHz).

A compact UWB monopole MPA for wireless body area network applications, with dimensions 20 × 15 × 0.5 mm^3, was introduced [115]. The antenna achieved a bandwidth of 11.52 GHz (3.48-15 GHz), a realized gain of 2.3-7.2 dBi, and high efficiency of 77-95%. An UWB circular patch MIMO antenna, featuring a DGS, was developed [116]. The antenna has an area of 60 × 30 mm^2, achieving a bandwidth of 18 GHz (2.0-20.0 GHz). A folding-strip-shaped compact UWB high-gain MPA, utilizing planar metamaterial concepts, was provided [117]. The compact antenna size is 27.6 × 28.8 mm^2, achieving a bandwidth of 11.6 GHz (3.7 GHz to more than 15.3 GHz) and an average gain of more than 4.5 dB for Rogers 5880 substrate and 5.1 dB for FR4 substrate.

A miniaturized microstrip antenna (60 × 43.85 mm^2) with tunable double band-notched characteristics for UWB applications was outlined [118]. It consists of a semi-circle ring-like radiating patch with an elliptical-shaped slot and double SRRs on the top surface, and a DGS on the bottom surface. The antenna achieved a bandwidth of 10.3 GHz (1.3-11.6 GHz) with gains of −5.3 dBi and −5 dBi.

Discussion

The design of UWB MPAs presents a complex interplay between achieving wide bandwidth, high gain, and maintaining a compact structure. Numerous techniques have been explored to address these challenges, each offering distinct advantages while introducing inevitable trade-offs. Slot-loading techniques, such as U-shaped and L-shaped slots (illustrated in Figure *1*), have proven effective in creating multiple resonant frequencies, thereby widening the operational bandwidth without significantly increasing the physical size of the antenna. These slots strategically alter the current path, enhancing the antenna's impedance matching and supporting broadband characteristics. However, introducing slots can sometimes compromise the structural stability of the antenna and increase surface current losses, necessitating careful mechanical design.

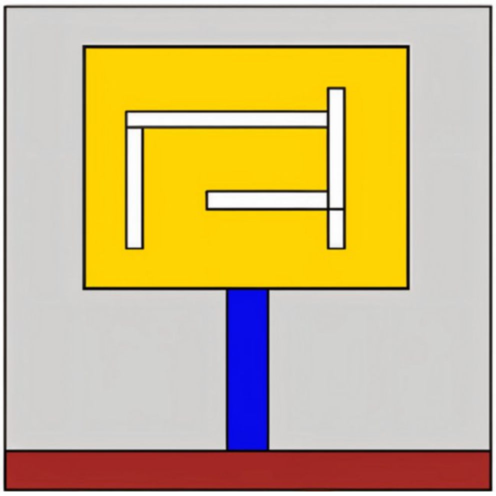

FIGURE 1: U-shaped and L-shaped Slot Antenna Designs

DGS offer another compelling solution. As shown in Figure 2, DGS involves etching patterns or slots into the ground plane beneath the patch, disrupting surface wave propagation and improving impedance matching. This technique effectively broadens the bandwidth and enhances radiation efficiency, although it may slightly weaken the mechanical robustness of the ground plane and complicate fabrication processes.

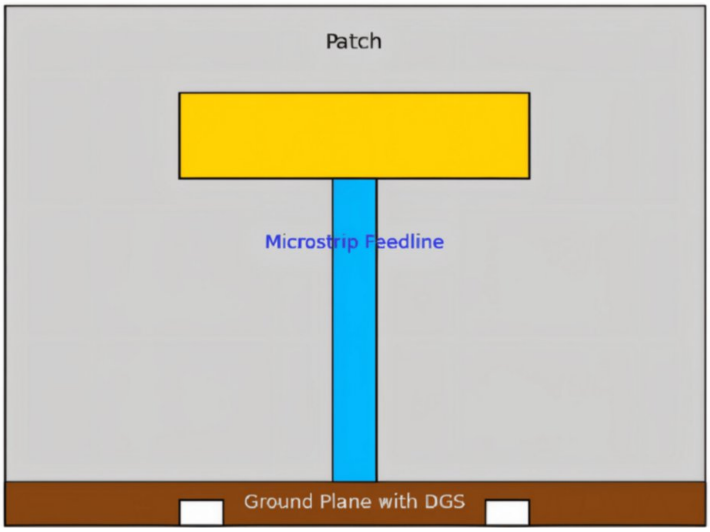

FIGURE 2: Defected Ground Structure (DGS) Configuration

Advanced material integrations, such as FSS and metamaterials (depicted in Figure 3), have been incorporated into antenna designs to achieve superior gain and bandwidth enhancements. FSS layers introduce band-pass or band-stop filtering properties, allowing selective frequency operation, while metamaterials like SRRs introduce negative permittivity and permeability effects that improve antenna radiation performance. Nonetheless, these methods often introduce higher complexity in fabrication, greater cost, and increased antenna thickness.

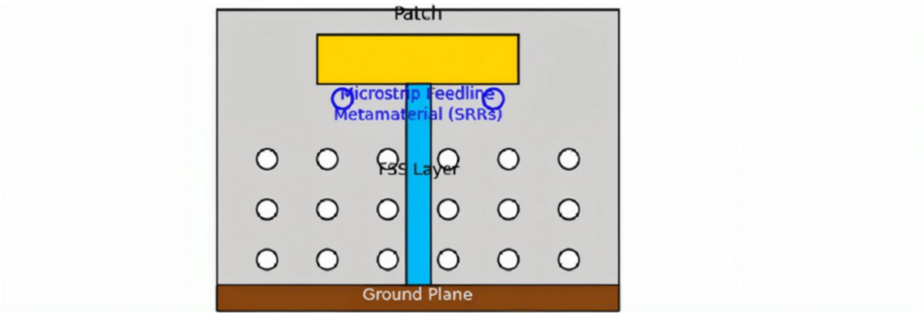

FIGURE 3: Frequency Selective Surface (FSS) and Metamaterial-Enhanced Antenna

Feeding techniques also play a vital role. CPW-fed patch antennas, illustrated in Figure *4*, offer low dispersion, planar integration, and wideband impedance matching capabilities. CPW feeding is particularly advantageous because it simplifies fabrication and maintains a compact form factor. However, precise design optimization is essential to avoid radiation losses and ensure proper impedance matching.

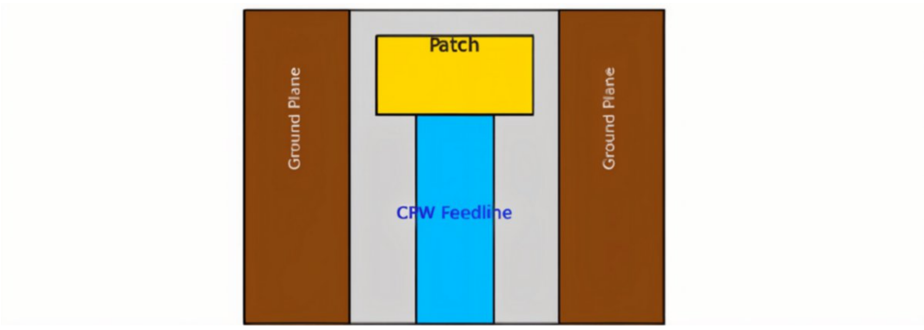

FIGURE 4: CPW-Fed Patch Antenna Structure

CPW, coplanar waveguide

While each enhancement method independently offers performance improvements, they also come with inherent limitations. Techniques such as slot loading and DGS are simpler and cost-effective but typically provide only moderate gain and bandwidth improvements. In contrast, methods like FSS and metamaterial loading achieve superior performance but increase design complexity and require larger physical structures. Future work should prioritize experimental validation by integrating full-wave simulations (e.g., CST, HFSS) with real-world prototyping and measurements in anechoic chambers. This is essential because simulations alone may not fully account for fabrication imperfections, substrate tolerances, and environmental influences. Table *1* provides a comparative summary of the reviewed designs, highlighting key aspects such as antenna size, bandwidth, gain, enhancement techniques, applications, and limitations. From this comparison, it becomes evident that hybrid approaches-combining methods like DGS, slot loading, and FSS-can offer an optimal balance between performance and design complexity. In conclusion, while no single technique presents a universal solution, the strategic combination of multiple enhancement strategies tailored to specific application needs can significantly optimize the performance of UWB MPAs. This is particularly relevant for advanced wireless communication, radar imaging, and Internet of Things systems.

Refs.	Antenna size (mm^3)	Bandwidth (GHz)	Gain (dBi)	Methods	Applications	Limitations
[22]	30 × 30 × 1.6	3.3–10.8 (7.5 GHz)	8.1 dB	Frequency-selective surface (FSS) integration	Gain enhancement	Limited bandwidth details
[23]	50 × 40 × 1.6	2.1–12.70 (10.6 GHz)	3.30	Defective ground configuration	UWB scenarios	Moderate gain
[28]	16 × 25 ×	3.1–12.5 (9.4 GHz)	4.5	Rectangular notch, EBG	UWB with controlled notched	Moderate gain

	1.52			structure	bandwidth	
[29]	36 × 38 × 1.58	2.6–20 (17.4 GHz)	5.6 dB	Metamaterial array, CST simulation	UWB applications	Complex design
[30]	55 × 56 × 1.6	2.2–12 (9.8 GHz)	>6.5 dB	Substrate material optimization	UWB with high fractional bandwidth	Material cost
[32]	46.6 × 51.3 × 3	4.75–6.15 (1.4 GHz)	7.2 dB	U-shaped/Quad L-shaped slots, DGS, parasitic elements	Wi-MAX/Wi-Fi	Design complexity
[33]	35 × 30 × 1.6	3.16–15 (11.84 GHz)	10.9 dB	Split-ring resonators (SRRs), FSS reflectors	Broadband applications	Large size
[35]	61 × 61 × 1.6	3.05–11.9 (8.85 GHz)	1.65–9.68	CPW-fed "strawberry" monopole with FSS	UWB, ground-penetrating radar (GPR)	Directional radiation pattern
[37]	20 × 19.5 × 1.6	2.9–9.3 (6.4 GHz)	8.12	E/T-shaped patch with FSS, modified ground plane	WiMAX, WLAN	Complex feeding structure
[40]	38 × 29 × 1.58	3.1–11 (7.9 GHz)	9.98 dB	DGS and L-stubs for MIMO	UWB MIMO	Notch band limitations
[42]	77.4 × 77.4 × 20	2.6–8.1 (5.5 GHz)	10.1	Genetic algorithm-optimized FSS	Wideband applications	Optimization complexity
[43]	40 × 50 × 0.8	5–14.64 (9.64 GHz)	8.7	Leaf-shaped patch with dual FSS layers	Ground-penetrating radar (GPR)	Dual-layer complexity
[51]	35.4 × 26.6 × 1.6	2.85–11.45 (8.6 GHz)	4.2 dB	Quad-notched CPW-fed design	UWB with notched bands	Moderate gain
[53]	40 × 24.5 × 1.6	2.7–11 (8.3 GHz)	7.73 dB	Circular fractal design	Telecommunications	Fabrication complexity
[57]	46 × 36 × 1.544	3.7−4.1 (0.4 GHz), 4.9−5.2 (0.3GHz), 7.4−7.8 (0.4 GHz), 9.2−9.9 (0.7 GHz)	5.5–6.8 dB	Coaxial/line feed for WLAN/WiMAX	Multi-band wireless	Feeding complexity
[60]	15 × 20 × 1.5	2.4–11.4 (9 GHz)	5.5 dB	Curved staircase grounding	Wideband applications	Efficiency trade-offs
[61]	20 × 25 × 1.5	3.1–10.8 (7.7 GHz)	5.1 dB	Modified patch (MP) and defective ground plane (DGP)	Compact UWB	Moderate gain
[62]	14.5 × 22 × 1.6	3.08–14.1 (11.02 GHz)	6.12 dB	Single-negative (SNG) metamaterial, NZRI materials	UWB monopole	Complex material integration
[64]	17.6 × 33.6 × 1.524	3.20–10.96 (7.76 GHz)	3.30 dB	Dielectric resonator (DR), CPW feeding	UWB applications	Low gain
[66]	24 × 16 × 0.787	3.1–11.1 (8 GHz)	4 dB	Compact slot antenna with adjustable band exclusion	UWB applications	Moderate gain
[67]	14 × 18 × 1.6	3.1–12.15 (9.05 GHz)	3.2 dB	Pestle-shaped grounded surface	UWB applications	Low gain
[68]	20.25 × 8 × 1.27	2.65–11.05 (8.4 GHz)	5.35 dB	Three L-shaped slots on ground surface	UWB applications	Small size may limit power handling
[69]	60 × 60 × 1.58	4.2–14.3 (10.1 GHz)	2.6 dB	Probe supply-imperfect ground configurations	UWB applications	Low gain
[77]	30 × 17.59 × 1.6	2.66–10.82 (8.16 GHz)	3.38 dB	Pentagonal patch design	UWB applications	Small size may limit power handling
[80]	20 × 20 × 1.6	2.7–11 (8.3 GHz)	3.34 dB	Modified patch, parasitic elements, defective ground plane	UWB applications	Low gain
[89]	10 × 16 × 1.575	5.6–14.6 (9 GHz)	3.28 dB	Printed planar patch	UWB applications	Low gain

[97]	27 × 30 × 4.7	3.34–4.42 (1.08 GHz), 6.00–12.56 (6.56 GHz)	4.5–8 dB	Stacked microstrip patch	UWB applications	Multi-substrate complexity
[99]	35 × 30 × 1.6	2.32–7.23 (4.9 GHz)	1.73–4.02	Low return loss CPW-fed patch	5G wireless mobile applications	Moderate gain
[103]	25 × 30 × 0.55	25–36.5 (4.6 GHz)	9 dB	Defected Ground Structure (DGS), ANNs	Vehicular communication	High-frequency design
[104]	30 × 30 × 1.6	3.32–11.96 (8.64 GHz)	5.6 dB	Hybrid fractal (Peano and Sierpinski Carpet)	UWB applications	Moderate gain
[109]	38.12 × 38.42	2.85–11.32 (8.47 GHz)	8.26	Koch and Minkowski fractal geometries	UWB, space, WiMAX, ISM, WLAN, military, satellite, radar	Complex design
[111]	47 × 35	2.38–22.5 (20.12 GHz)	6.5	DGS optimized with Grey Wolf Optimization algorithm	UWB applications	Wide bandwidth
[118]	60 × 43.85	1.3–11.6 (10.3 GHz)	-5.3, -5	Semi-circle ring-like patch, DGS	UWB applications	Negative gain

TABLE 1: Comparative Summary of Reviewed UWB Antenna Designs

UWB, ultra-wideband; EBG, electromagnetic band gap; CST, computer simulation technology; CPW, coplanar waveguide; MIMO, multiple-input multiple-output; NZRI, near-zero refractive index; ANN, artificial neural network

Conclusions

The development of high-performance UWB MPAs necessitates a multidimensional design strategy. This study explored a comprehensive range of enhancement techniques aimed at optimizing key performance metrics, particularly gain and bandwidth-critical for modern applications such as radar, high-speed communication, and precision sensing. Through structural innovations like slot insertion, parasitic patches, and advanced feeding mechanisms, designers can fine-tune resonance and impedance matching. Material-based approaches-including metamaterials, dielectric resonators, and photonic bandgap (PBG) structures-offer further opportunities to improve bandwidth and radiation efficiency. Additionally, the incorporation of DGS, EBG features, and FSS has shown substantial benefits in controlling radiation behavior and broadening operational bandwidths. Despite their effectiveness, each technique presents trade-offs in complexity, cost, and manufacturability. The findings suggest that hybrid designs-carefully combining structural, material, and feeding techniques-provide the most promising path toward achieving optimized UWB antenna performance. Looking ahead, experimental validation remains essential. Future work will include prototyping, anechoic chamber testing, and real-world deployment to evaluate performance under practical conditions. Furthermore, the integration of advanced optimization algorithms and emerging materials is expected to drive continued improvements, enabling next-generation wireless systems with enhanced communication, sensing, and imaging capabilities across the UWB spectrum.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Md. Firoz Ahmed, M. Hasnat Kabir

Acquisition, analysis, or interpretation of data: Md. Firoz Ahmed, M. Hasnat Kabir

Drafting of the manuscript: Md. Firoz Ahmed, M. Hasnat Kabir

Critical review of the manuscript for important intellectual content: Md. Firoz Ahmed, M. Hasnat Kabir

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