

A Comprehensive Survey of Microstrip Patch Array Antennas: Feeding Techniques, Design Approaches, Performance Enhancement, and Emerging Trends

Nilesh Singh

Department of Electronics Engineering
Harcourt Butler Technical University
Kanpur, India

Dr.Nand Kishore

Department of Electronics Engineering
Harcourt Butler Technical University
Kanpur, India

Abstract - Microstrip patch array antennas are widely studied for applications requiring improved gain, directivity, bandwidth, and beam control while maintaining a low-profile structure. This paper presents a comprehensive survey of microstrip patch array antennas, focusing on array configurations, feeding techniques, design parameters, and performance-enhancement methods. Corporate, series, corporate-series, aperture-coupled, proximity-coupled, and probe-fed configurations are reviewed along with techniques for bandwidth and gain enhancement. Mutual-coupling reduction methods based on defected ground structures, electromagnetic band-gap structures, and metamaterial concepts are also discussed. Recent developments in wideband, multiband, circularly polarized, reconfigurable, and phased arrays are comparatively examined. Finally, key research challenges and emerging directions for the development of compact, high-performance microstrip patch arrays are identified.

Keywords - Microstrip patch antenna, antenna array, feeding techniques, mutual coupling, bandwidth enhancement, gain enhancement, EBG, DBS, reconfigurable antenna, phased array.

I. INTRODUCTION

Microstrip patch antennas are widely used in modern wireless and microwave systems because of their low profile, light weight, simple fabrication, and ease of integration with planar circuits [1], [5]–[8]. A conventional patch antenna consists of a conducting radiating element printed on a dielectric substrate above a ground plane. Although single patch antennas offer a compact structure, their relatively limited gain, directivity, and impedance bandwidth can restrict their use in applications requiring higher radiation performance [1], [7].

To overcome these limitations, multiple patch elements can be combined to form an antenna array. The overall radiation characteristics of an array depend on the number and arrangement of elements, their spacing, and the amplitude and phase of excitation [1], [16], [18]. Configurations such as 1×2 , 2×2 , 4×4 , and larger planar arrays can provide increased gain and directivity compared with individual elements. However,

increasing the number of elements also increases feed-network complexity, physical size, losses, and mutual coupling between adjacent elements [16], [24].

The feeding network plays an important role in determining the performance of a microstrip array. Corporate-feed, series-feed, corporate-series-feed, probe, aperture-coupled, and proximity-coupled techniques have been investigated for different array requirements [11], [18], [22]–[24], [29]. Each technique provides different trade-offs in terms of impedance matching, bandwidth, phase control, fabrication complexity, and efficiency. Therefore, appropriate selection and design of the feeding arrangement are essential for achieving the desired array characteristics.

Bandwidth, gain, and mutual coupling are among the major performance considerations in microstrip patch arrays. Several techniques, including slots, stacked patches, parasitic elements, and modified feeding structures, have been proposed to improve bandwidth [25]–[29]. Electromagnetic band-gap (EBG), defected ground structure (DGS), and metamaterial-based approaches have also been investigated to reduce mutual coupling and improve array performance [31]–[35]. In addition, circularly polarized, wideband, multiband, reconfigurable, and phased-array designs have expanded the capabilities of microstrip arrays for advanced wireless and microwave applications [10], [37]–[46].

This paper presents a survey of microstrip patch array antennas with emphasis on their evolution, configurations, feeding techniques, design parameters, and performance-enhancement methods. The study also reviews mutual-coupling reduction, bandwidth and gain enhancement, polarization control, reconfigurable arrays, and phased-array technologies. A comparison of representative published works is provided to identify existing limitations and research gaps. Finally, emerging trends and potential directions for future development of high-performance microstrip patch arrays are discussed.

II. FUNDAMENTALS AND EVOLUTION OF MICROSTRIP PATCH ANTENNA

A. Fundamentals of Microstrip Patch Antennas

A microstrip patch antenna is a planar radiating structure formed by placing a metallic patch on one side of a dielectric

substrate and a conducting ground plane on the other side. The patch is generally designed to operate near a selected resonant frequency, with its dimensions and substrate properties determining the dominant electromagnetic behavior [1], [3], [7]. Radiation is mainly produced by the fringing fields at the edges of the patch, allowing the antenna to provide a broadside radiation pattern with a relatively low-profile structure [1], [6].

The rectangular patch is one of the most commonly investigated geometries because its dimensions can be determined systematically and it can be readily integrated with printed feeding networks. Important parameters such as substrate permittivity, substrate thickness, patch dimensions, and feeding location influence impedance matching, bandwidth, radiation efficiency, and resonant frequency [1], [7], [8]. Different feeding arrangements, including microstrip line, probe, aperture-coupled, and proximity-coupled techniques, have been developed to obtain the required impedance and radiation characteristics [11], [12].

Although a single patch provides several advantages, its relatively limited gain and bandwidth can become restrictive when higher directivity or wider frequency coverage is required. These limitations provided the motivation for combining several radiating elements into an array [1], [6].

B. Evolution of Microstrip Patch Arrays

The development of microstrip antenna technology progressed from individual radiating patches toward linear and planar array configurations. Early research established the basic operating principles and practical characteristics of microstrip antennas, while subsequent studies investigated their use in phased and array configurations [3], [4], [14], [16]. The use of multiple elements allows the individual radiation contributions to combine constructively in desired directions, resulting in improved directivity and greater control over the radiation pattern [1], [18].

In a microstrip array, the elements are interconnected through a suitable feeding network that determines the excitation amplitude and phase of each element. Corporate-fed, series-fed, and hybrid feeding arrangements became important approaches for realizing practical arrays [16], [18], [23], [24]. As array technology developed, researchers also investigated planar, multilayer, wideband, circularly polarized, and phased configurations to obtain additional control over antenna performance.

The transition from a single element to an array provides higher effective aperture and improved directional radiation, but it also introduces additional design issues. Element spacing, feed-network losses, phase errors, and mutual coupling must be considered because they can influence the impedance characteristics and radiation pattern of the complete array [18], [24], [53]. Therefore, the evolution of microstrip arrays has been driven not only by increasing the number of elements but also by developing better feeding, coupling-control, and performance-enhancement techniques.

C. Array Configuration

Microstrip patch arrays can be classified according to the number and arrangement of their radiating elements. A 1×2 configuration consists of two elements arranged along one direction and provides a simple approach for increasing directivity while maintaining relatively low design complexity. A 2×2 array extends the arrangement into two dimensions and provides improved aperture utilization and more symmetrical radiation characteristics. Larger configurations such as 4×4 and higher-order planar arrays can provide still greater gain and narrower beamwidth, although the associated feed network and mutual-coupling problems become increasingly complex [16], [18], [45].

The selection of an array size depends on the required gain, beamwidth, physical dimensions, operating frequency, and available feeding architecture. Increasing the number of elements does not automatically guarantee proportional improvement in practical performance because conductor loss, dielectric loss, feed-network radiation, phase imbalance, and mutual coupling can become significant in larger structures [24], [31], [53]. Consequently, practical array design requires a balance between aperture size, electromagnetic performance, fabrication complexity, and overall system requirements.

Overall, the evolution of microstrip patch arrays represents a transition from a single radiating element to increasingly larger and more controllable planar configurations. As illustrated in figure.1, the progression from a single patch to 1×2 , 2×2 , 4×4 , and larger planar arrays provides progressively greater aperture, directivity, gain, and beam-control capability. However, this improvement is accompanied by increased feed-network complexity, mutual coupling, physical size, and design challenges. Therefore, practical array design requires an appropriate balance between electromagnetic performance, structural complexity, and fabrication requirements [16], [18], [24], [53].

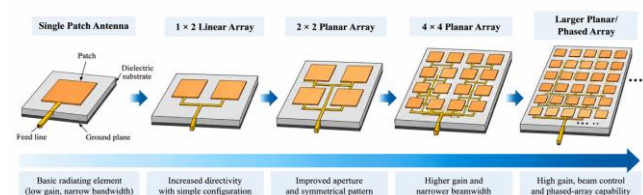


Figure. 1: Evolution of microstrip patch antennas from a single element to larger planar array configuration

III. FEEDING TECHNIQUES AND DESIGN PARAMETERS

The feeding network is a critical part of a microstrip patch array because it transfers electromagnetic power from the input port to the individual radiating elements while establishing the required amplitude and phase distribution. The choice of feeding arrangement directly affects impedance matching, bandwidth, radiation efficiency, sidelobe level,

polarization purity, and overall array performance [1], [6], [16], [24]. Studies of microstrip arrays have also shown that losses and radiation from the feed network itself can become significant, particularly as the number of array elements increases.

D. Feeding Techniques

1) Corporate Feed:

A corporate-fed array uses a branching transmission-line network to distribute the input power among individual patches. Power is normally divided through successive junctions or power dividers, allowing the amplitude and phase supplied to each element to be controlled independently [16], [24]. This configuration is particularly suitable for planar arrays because equal or unequal power distribution can be achieved according to the desired radiation pattern. Impedance-transforming sections, including quarter-wave transformers, can also be incorporated to provide proper matching between different transmission-line impedances. Corporate feeding provides good control over the excitation of individual elements, although the network can become relatively large and lossy for arrays containing many elements [18], [24]. The effect of the printed feed network on radiation, directivity, and gain has been investigated extensively for microstrip arrays.

2) Series Feed:

In a series-fed array, the radiating elements are connected sequentially along a transmission line. Power reaches each element through the same feeding path, which can result in a simpler and more compact network than a fully corporate-fed arrangement [18], [23]. The reduced number of transmission-line branches can lower the physical complexity of the array. However, the phase distribution is strongly related to the electrical length between successive elements, making the radiation characteristics more sensitive to frequency. Consequently, series-fed arrays can experience beam squint and variations in excitation when operated over a wide frequency range [18], [23].

3) Corporate-Series Feed:

A corporate-series configuration combines the characteristics of both feeding methods. A corporate section first divides the input power into branches, while series-fed sections are subsequently used to excite groups of elements. This arrangement can provide a useful compromise between feed-network size, power distribution, phase control, and efficiency [23], [41]–[43]. Such hybrid networks have been investigated for high-efficiency microstrip arrays and are particularly useful when a completely corporate network would become unnecessarily large.

4) Aperture-Coupled Feed:

In aperture coupling, the radiating patch and feeding transmission line are generally placed on different substrate layers and are electromagnetically coupled through an opening

in the ground plane [11], [12]. This arrangement provides greater freedom in selecting the substrate for the radiating element and the feed network. The separation of the feed and radiating structures can also reduce unwanted feed radiation and facilitate bandwidth enhancement. However, multilayer fabrication and accurate alignment of the coupling aperture increase manufacturing complexity [11], [29].

5) Proximity-Coupled Feed:

Proximity coupling transfers electromagnetic energy from a microstrip feed line to the patch without requiring a direct electrical connection. The coupling strength depends on parameters such as the overlap between the feed and patch, substrate properties, and separation between the layers [22]. This technique can provide wide impedance bandwidth and reduced spurious radiation, but it generally requires multilayer fabrication and precise control of the overlapping structures.

6) Coaxial/Probe Feed:

A coaxial or probe-fed patch is excited by connecting the inner conductor of a coaxial connector to the radiating patch while the outer conductor is connected to the ground plane. The feed position can be adjusted to obtain an appropriate input impedance and improve impedance matching [1], [7]. Probe feeding is relatively straightforward for individual patches and small arrays, although the presence of the probe can introduce inductive effects, and fabrication becomes more complicated when many elements require individual probes.

E. Important Design Parameters

The performance of a microstrip patch array is determined not only by the feeding technique but also by several geometric and electromagnetic parameters. Element spacing is particularly important because it determines the interaction between neighboring patches and affects the array factor, mutual coupling, sidelobe level, and possibility of grating lobes [18], [21], [53]. Closely spaced elements generally increase mutual coupling, whereas excessive spacing can produce undesirable radiation characteristics and grating lobes.

The amplitude and phase distribution of the excitation determine how the individual element fields combine in space. Equal amplitude and phase excitation is commonly used for broadside arrays, while amplitude tapering can be introduced to reduce sidelobe levels. Phase differences between elements can also be deliberately introduced to steer the main beam, forming the basis of phased-array operation [18]–[20], [45], [46]. The behavior of finite microstrip arrays is influenced by both element characteristics and mutual interactions, making accurate array analysis necessary for practical designs.

The substrate is another important design parameter. Its relative permittivity and thickness influence the physical dimensions, effective wavelength, impedance, bandwidth, surface-wave excitation, and radiation efficiency of the antenna [1], [7], [8]. A suitable substrate must therefore be

selected by considering both electromagnetic performance and fabrication requirements.

Finally, the feed-network geometry must be designed to minimize insertion loss and maintain the required amplitude and phase balance. Transmission-line widths, junctions, bends, impedance transformers, and power dividers all contribute to the overall behavior of the array. In larger arrays, these effects become increasingly important because losses and unintended radiation from the feed network can reduce the theoretical gain advantage obtained by increasing the number of radiating elements [16], [24].

Overall, feeding and array parameters must be considered together rather than independently. An appropriately selected feed architecture combined with optimized element spacing, phase distribution, substrate properties, and impedance matching can provide a practical balance between gain, bandwidth, efficiency, beam control, and structural complexity, as illustrated by the different feeding configurations shown in Figure. 2.

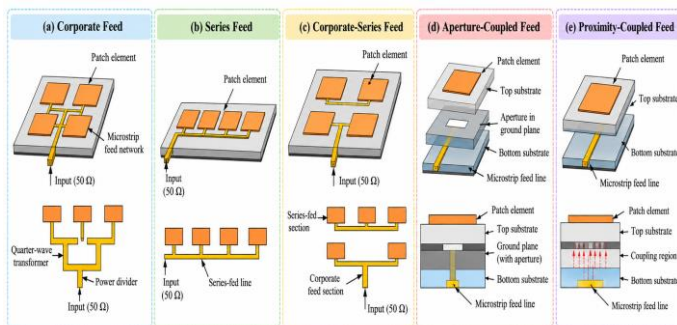


Figure 2. Common feeding configurations for microstrip patch arrays: (a) corporate feed, (b) series feed, (c) corporate-series feed, (d) aperture-coupled feed, and (e) proximity-coupled feed.

IV. PERFORMANCE ENHANCEMENT TECHNIQUES

The performance of a microstrip patch array is generally evaluated in terms of impedance bandwidth, gain, directivity, radiation efficiency, and radiation-pattern characteristics. Conventional patch arrays can provide good directional radiation, but their performance may be limited by narrow bandwidth, dielectric and conductor losses, surface-wave excitation, and mutual coupling between adjacent elements [1], [6], [7]. Consequently, different structural and electromagnetic techniques have been developed to improve the overall performance of microstrip arrays.

F. Bandwidth Enhancement

Bandwidth enhancement is one of the major challenges in microstrip patch antenna design because the conventional patch operates as a resonant structure with a relatively narrow impedance bandwidth [1], [7], [8]. Several techniques have therefore been proposed to introduce additional resonances or improve impedance matching. Common approaches include increasing substrate thickness, using lower-permittivity substrates, incorporating slots into the patch, employing

parasitic elements, stacking multiple patches, and using coupled feeding configurations [25]-[29].

Slot loading is an effective approach in which additional slots are introduced into the radiating patch to modify the current distribution and generate additional resonant modes. U-shaped and other modified slot geometries have been widely investigated for obtaining wider impedance bandwidth while maintaining a relatively compact structure [27], [28]. Such techniques work by producing resonances close to the fundamental patch resonance, allowing the individual modes to combine and form a wider operating band.

Stacked-patch configurations provide another important method for bandwidth improvement. In this approach, an additional parasitic patch is positioned above the driven patch, producing electromagnetic coupling between the layers. The resulting multiple resonances can be appropriately positioned to obtain a wider impedance bandwidth than that of a conventional single-layer patch [25]. Aperture-coupled and proximity-coupled configurations can also provide enhanced bandwidth because the feed and radiating structures can be independently optimized [11], [22], [29]. The effectiveness of stacked and coupled configurations has also been demonstrated in more recent wideband designs.

G. Gain And Directivity Enhancement

Gain and directivity are important performance parameters when a concentrated radiation beam is required. In a patch array, increasing the effective aperture through the addition of radiating elements can generally increase directivity and reduce the main-beam width [1], [16], [18]. The element spacing and excitation distribution must, however, be optimized because inappropriate spacing can introduce grating lobes, while nonuniform excitation can affect sidelobe levels.

The feeding network also has a significant influence on achievable gain. Transmission-line losses, discontinuities, impedance mismatch, and unwanted radiation from the feed structure can reduce the realized gain of an array [16], [24]. Therefore, low-loss transmission lines and properly designed power-dividing networks are essential, particularly for arrays with a large number of elements. Corporate-series feeding can provide a practical compromise between feed-network complexity and excitation control [23], [41]-[43].

Additional electromagnetic structures can also be used to improve radiation performance. Reflectors, parasitic elements, superstrates, and engineered periodic structures can modify the electromagnetic environment surrounding the patches and influence the effective aperture and radiation efficiency [31]-[35]. These techniques are particularly useful when gain enhancement is required without substantially increasing the number of driven elements.

H. DBS, EBG And Metamaterials-Assisted Arrays

Defected ground structures (DGS) modify the current distribution on the ground plane by introducing deliberately shaped slots or defects. Depending on their geometry and

location, DGS structures can alter the effective inductance and capacitance of the transmission structure, suppress unwanted surface currents, improve impedance characteristics, and reduce coupling between antenna elements. Their effectiveness depends strongly on the defect geometry, position, and operating frequency.

Electromagnetic band-gap (EBG) structures provide another widely investigated approach for controlling surface-wave propagation. EBG structures exhibit frequency-selective electromagnetic behavior and can suppress surface-wave modes within a particular frequency range [31]–[35]. In patch arrays, this property can be exploited to reduce electromagnetic interaction between neighboring elements. Yang and Rahmat-Samii investigated EBG-integrated microstrip arrays specifically for reducing mutual coupling, demonstrating the potential of periodic structures for improving array isolation [31]. The broader application of EBG structures in antenna engineering has also established their usefulness for controlling surface-wave and electromagnetic propagation characteristics [33], [34].

Metamaterial-assisted designs extend this concept by using engineered structures whose effective electromagnetic response is determined by their geometry rather than solely by the properties of naturally occurring materials. Split-ring resonators, complementary resonant structures, and other metamaterial-inspired configurations have been investigated for reducing coupling, controlling current distribution, miniaturizing antenna structures, and improving radiation characteristics [31]–[35]. These approaches can be particularly attractive for compact arrays where conventional element spacing cannot be increased sufficiently to control mutual coupling. Recent array research continues to investigate EBG and metamaterial structures as methods for maintaining isolation while reducing the physical size of dense antenna configurations.

I. Combined Performance Enhancement

In practical array design, bandwidth, gain, efficiency, and mutual coupling cannot generally be optimized independently. A technique that improves one parameter may adversely affect another. For example, increasing substrate thickness can improve bandwidth but may increase surface-wave excitation, while adding periodic structures can reduce coupling but introduce additional fabrication complexity and losses. Similarly, increasing the number of elements can improve directivity but results in a more complicated feed network and greater overall dimensions [16], [24], [31].

Consequently, recent research increasingly focuses on combining multiple enhancement mechanisms within a single array. Examples include stacked patches with aperture coupling, EBG-loaded arrays, slot-loaded patches, and reconfigurable structures. Such combinations can produce multiple resonances, suppress unwanted coupling, and improve gain while maintaining an acceptable physical profile. Recent literature also demonstrates continued interest in combining advanced materials, modified geometries, and

reconfigurable techniques to achieve simultaneous improvements in gain, bandwidth, and functional flexibility.

Overall, performance enhancement of microstrip patch arrays is based on controlling the electromagnetic behavior of both the radiating elements and the surrounding feed and substrate structures. Bandwidth-enhancement techniques primarily focus on generating additional resonances and improving impedance matching, whereas gain-enhancement and EBG/metamaterial approaches emphasize aperture utilization, surface-wave control, and radiation efficiency. The most effective designs therefore require simultaneous optimization of the patch geometry, feeding network, element spacing, substrate, and electromagnetic enhancement structures.

V. MUTUAL COUPLING AND POLARIZATION CHARACTERISTICS

J. Mutual Coupling

Mutual coupling is an important consideration in microstrip patch arrays because electromagnetic energy from one element can interact with neighboring elements. This interaction modifies the input impedance, reflection coefficient, radiation pattern, gain, and overall array performance [1], [18], [21], [53]. The coupling strength depends mainly on element spacing, relative orientation, substrate properties, and array geometry. Closely spaced elements generally experience stronger coupling, while excessive spacing can increase the overall array size and may produce unwanted grating lobes [18], [19].

Several techniques have been investigated to reduce mutual coupling, including defected ground structures (DGS), electromagnetic band-gap (EBG) structures, parasitic elements, and metamaterial-based configurations [31]–[35]. EBG structures are particularly useful because they suppress surface-wave propagation between neighboring elements, thereby improving isolation and preserving the desired radiation characteristics [31], [34]. Proper element spacing and optimized feed-network design also contribute to coupling reduction [16], [24], [53].

K. Polarization Characteristics

Polarization describes the orientation and time variation of the electric-field vector radiated by an antenna. Microstrip patch arrays can be designed for linear, circular, or dual polarization depending on the patch geometry, feeding arrangement, and excitation mechanism [1], [5], [10]. Linear polarization is commonly obtained from conventional rectangular patches, whereas circular polarization can be achieved by exciting two orthogonal modes with an appropriate phase relationship [1], [37].

Polarization purity is important because unwanted cross-polarized radiation can reduce system efficiency and degrade signal quality. Techniques such as sequential rotation, optimized element geometry, dual feeds, and specialized array configurations can improve polarization performance [10], [37], [45]. Therefore, mutual coupling and polarization should

be considered together during array design to achieve good isolation, stable radiation patterns, and low cross-polarization.

Overall, effective control of mutual coupling and polarization is essential for maintaining the desired performance of microstrip patch arrays, particularly as the number of elements and array density increase. As illustrated in figure. 3, mutual coupling between adjacent patches can be controlled using techniques such as defected ground structures (DGS), electromagnetic band-gap (EBG) structures, and parasitic elements, while appropriate polarization configurations help achieve the required radiation characteristics. Optimized element spacing and polarization-control techniques therefore provide practical approaches for improving isolation, radiation performance, and overall array characteristics [31]–[35].

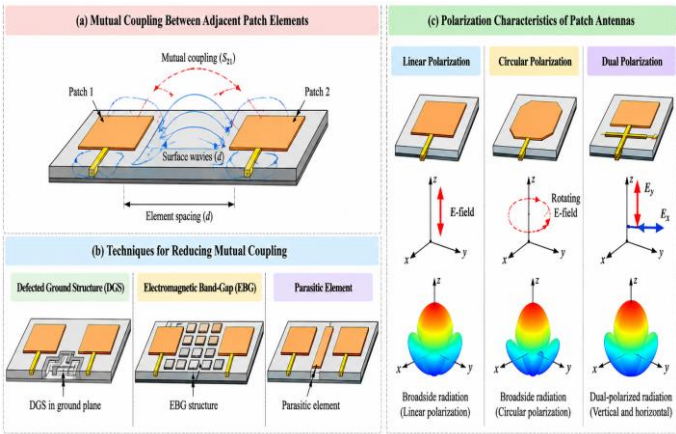


Fig. 3. Mutual coupling and polarization characteristics of microstrip patch arrays: (a) mutual coupling between adjacent elements, (b) mutual-coupling reduction techniques, and (c) polarization characteristics

VI. WIDEBAND, MULTIBAND, RECONFIGURABLE AND PHASED ARRAYS

L. Wideband And Multiand Arrays

Conventional microstrip patches generally have limited impedance bandwidth, which restricts their operation over multiple frequency channels. Wideband performance can be obtained using stacked patches, aperture coupling, slots, parasitic elements, and modified patch geometries [8], [25]–[29]. Multiband arrays employ multiple resonant modes or appropriately modified radiating elements to support more than one operating frequency, providing greater frequency flexibility without significantly increasing the antenna footprint [8], [27], [28].

M. Reconfigurable Arrays

Reconfigurable arrays can dynamically modify their operating frequency, bandwidth, polarization, or radiation pattern according to system requirements. Switching or tuning elements such as PIN diodes, varactors, RF MEMS, and other controllable structures can be incorporated into the radiating elements or feed network [10], [37], [40]. Such designs provide additional flexibility but introduce practical challenges related to biasing networks, switching losses, fabrication complexity, and control circuitry.

N. Phased Arrays

Phased arrays control the direction and shape of the radiation beam by adjusting the relative phase and, when required, amplitude of individual elements. The phase distribution across the array determines beam steering, sidelobe levels, and scanning characteristics [18]–[20], [45], [46]. Microstrip patch elements are widely suitable for phased arrays because of their planar structure and compatibility with integrated feed networks. However, increasing the scanning range can introduce mutual coupling, impedance variation, and scan-related performance degradation [18], [19].

O. Emerging Array Architectures

Recent developments combine wideband operation, reconfigurability, and beam steering to provide multifunctional antenna systems. Such architectures aim to achieve frequency agility and directional control while maintaining compact size and acceptable efficiency. Reconfigurable parasitic arrays and polarization-reconfigurable phased arrays demonstrate the potential of combining these capabilities in a single antenna platform [10], [37].

Overall, wideband, multiband, reconfigurable, and phased-array techniques extend the functionality of conventional microstrip arrays beyond fixed-frequency operation. The major design challenge is to achieve greater flexibility and beam-control capability without significantly increasing losses, size, coupling, and implementation complexity.

VII. COMPARATIVE ANALYSIS OF MICROSTROP PATCH ARRAY ANTENNA

Array Configuration	Feeding / Technique	Main Advantage	Major Limitation	References
Corporate-Fed Array	Corporate feed	Independent amplitude and phase control	Larger feed network and high loss	[16], [18], [24]
Series-Fed Array	Series feed	Simple and compact structure	Frequency-dependent phase variation	[18], [23]
Corporate-Series Array	Hybrid feed	Balanced control and compactness	Increased feed complexity	[23], [41]–[43]
Aperture-Coupled Array	Aperture coupling	Good bandwidth and feed isolation	Multilayer fabrication	[11], [12], [29]
Proximity-Coupled Array	Electric coupling	Wideband operation	Sensitive to fabrication	[22]

Array Configuration	Feeding / Technique	Main Advantage	Major Limitation	References
Stacked/Parasitic Array	Stacked or parasitic patches	Enhanced bandwidth	tolerance Increased thickness and complexity	[25]–[28]
DGS/EBG-Assisted Array	DGS/EBG structures	Reduced mutual coupling	Additional design complexity	[31]–[35]
Reconfigurable Array	Switching elements	Frequency/pattern flexibility	Requires biasing and control circuits	[10], [37], [40]
Phased Array	Phase-controlled excitation	Electronic beam steering	High control complexity	[18]–[20], [45], [46]

VIII. RESEARCH GAPS AND EMERGING TRENDS

Despite significant progress in microstrip patch array technology, several research challenges remain. Achieving high gain and wide bandwidth while maintaining a compact structure, low mutual coupling, high efficiency, and simple fabrication continues to be difficult. Increasing the number of array elements can improve directivity and beam control but also increases feed-network complexity, losses, and mutual coupling [16], [18], [24], [31].

Another important gap is the simultaneous achievement of frequency, radiation-pattern, and polarization reconfigurability without excessive switching, biasing, and control complexity. Existing reconfigurable designs often require additional active components and bias networks, which can affect efficiency and fabrication simplicity [10], [37], [40]. Recent research is therefore moving toward multifunctional arrays, tunable metasurfaces, advanced EBG structures, and electronically controlled beam-steering architectures.

Emerging trends also include higher-frequency and millimeter-wave arrays, MIMO integration, intelligent surfaces, flexible and conformal arrays, and multifunctional beamforming systems. These developments emphasize the need for improved coupling control, efficient feeding networks, low-loss materials, and reliable fabrication techniques [31]–[35], [45], [46]. Recent literature particularly highlights the integration of metamaterials, reconfigurability, beamforming, and intelligent surfaces as promising directions for future array antennas.

Overall, future research should focus on developing compact, low-loss, highly efficient, multifunctional, and electronically controllable microstrip patch arrays while reducing design and manufacturing complexity.

IX. FUTURE RESEARCH DIRECTIONS

Future development of microstrip patch arrays is expected to focus on achieving higher performance with reduced size, losses, and implementation complexity. One important direction is the development of compact wideband and multiband arrays using advanced substrates, metamaterials, metasurfaces, and EBG structures [31]–[35]. These techniques can provide improved gain, bandwidth, isolation, and surface-wave suppression.

Another promising direction is the integration of reconfigurable and electronically controlled arrays. Future designs can combine frequency, polarization, and beam reconfiguration within a single antenna platform, providing greater adaptability for multifunctional wireless systems [10], [37], [40]. Recent research also indicates increasing interest in MIMO integration, millimeter-wave arrays, beamforming, and intelligent surfaces for next-generation communication systems.

Reducing mutual coupling while maintaining a compact element spacing remains an important challenge, particularly for dense arrays. Advanced EBG, DGS, and metamaterial-based structures can be further investigated for efficient coupling suppression [31]–[35]. In addition, future work should emphasize low-cost fabrication, efficient feed networks, thermal reliability, and experimental validation of simulated designs.

Overall, future microstrip patch arrays are likely to evolve toward compact, wideband, low-loss, reconfigurable, and intelligent antenna platforms capable of supporting adaptive beamforming and multifunctional wireless applications.

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