

Microstrip Patch Antenna Loaded with Triangle and Circle Shapes Using Metamaterial Structure: A Comprehensive Review

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Abstract-The ongoing demand for compact, high-performance antennas in modern wireless communications has accelerated research into innovative antenna designs. Microstrip patch antennas (MPAs) are widely used due to their low cost, ease of fabrication, and planar form factor. However, conventional MPAs are often limited by narrow bandwidth, low gain, and size constraints. Integrating metamaterial structures and geometric loading such as triangular and circular shapes has emerged as an effective approach to enhance antenna performance metrics, including bandwidth, gain, radiation efficiency, and multiband behavior. This review systematically examines the state-of-the-art of microstrip patch antennas with triangle and circle shape loadings backed with metamaterial structures. It discusses design principles, theoretical underpinnings, metamaterial configurations, performance improvements, tradeoffs, and future research directions.

Keywords: Microstrip Patch Antenna, Metamaterial Structure, Triangular Patch, Circular Patch, Split Ring Resonator (SRR), Complementary Split Ring Resonator (CSRR),

1. Introduction

Microstrip patch antennas (MPAs) are ubiquitous in wireless communication systems due to their planar configuration and compatibility with printed circuits. Despite these advantages, conventional MPAs suffer from inherent drawbacks, particularly narrow bandwidth, limited gain, and surface wave losses. To meet the requirements of emerging applications such as 5G, Internet of Things (IoT), and satellite communication, researchers have explored novel strategies to engineer antenna characteristics beyond the classical patch designs.

Loading the patch with geometric shapes such as triangles, circles, slots, and fractals modifies current distribution, enabling multi-resonant behavior, size reduction, and improved impedance characteristics. Specifically, triangle and circle patches have shown promise in effectively controlling surface currents, achieving miniaturization, and enhancing bandwidth.

Metamaterials are artificially engineered structures exhibiting extraordinary electromagnetic properties not commonly found in natural materials, such as negative permittivity/permeability, near-zero refractive index, and electromagnetic bandgaps. Embedding metamaterial elements such as split-ring resonators (SRRs),

complementary SRRs (CSRRs), or other resonant inclusions with MPAs introduces additional degrees of freedom to manipulate antenna performance.

Microstrip patch antennas (MPAs) have become one of the most widely used antenna types in modern wireless communication systems due to their low profile, lightweight structure, ease of fabrication, and compatibility with planar and integrated circuits. Since their introduction in the 1970s, microstrip antennas have attracted significant attention from researchers and engineers for applications ranging from mobile communications and satellite systems to radar, biomedical devices, and emerging 5G and Internet of Things (IoT) technologies. Their ability to be fabricated using standard printed circuit board (PCB) techniques makes them highly suitable for mass production and compact system integration.

A typical microstrip patch antenna consists of a metallic radiating patch printed on one side of a dielectric substrate, with a continuous ground plane on the opposite side. The radiating patch can take various shapes such as rectangular, circular, triangular, elliptical, or more complex geometries depending on the desired performance characteristics. Radiation primarily occurs due to the fringing electromagnetic fields at the edges of the patch when it is excited by a suitable feeding mechanism such as coaxial probe feed, microstrip line feed, aperture coupling, or proximity coupling. Among these, rectangular and circular patches are the most commonly used owing to their simple design and predictable radiation behavior.

Despite their numerous advantages, conventional microstrip patch antennas suffer from inherent limitations, including narrow impedance bandwidth, relatively low gain, and reduced radiation efficiency, particularly when fabricated on high-permittivity or lossy substrates. These limitations arise mainly from surface wave excitation and the resonant nature of the patch structure. As modern wireless systems demand compact antennas with wide bandwidth, high gain, multiband operation, and enhanced efficiency, significant research efforts have been directed toward overcoming these drawbacks through innovative design techniques.

Various approaches have been proposed to enhance the performance of microstrip patch antennas, such as the use of different patch shapes, slot loading, defected ground structures (DGS), stacked patches, parasitic elements, and advanced materials. Among these techniques, geometric modification of the patch and the incorporation of metamaterial structures have emerged as highly effective methods for achieving bandwidth enhancement, size

reduction, and multiband characteristics. By carefully engineering the shape and electromagnetic properties of the antenna, it is possible to control current distribution and resonant modes more efficiently.

In recent years, microstrip patch antennas have continued to evolve to meet the requirements of next-generation communication systems. Their adaptability, combined with ongoing advancements in materials, simulation tools, and optimization techniques, ensures that MPAs remain a key research area in antenna engineering. Consequently, a thorough understanding of microstrip patch antenna fundamentals is essential for the development of high-performance antennas for contemporary and future wireless applications.

2. Fundamentals of Microstrip Patch Antennas

2.1 Basic Operation

A microstrip patch antenna consists of a metallic radiating patch on a dielectric substrate backed by a ground plane. Radiation primarily occurs due to fringing fields at the edges of the patch.

2.2 Limitations of Conventional Designs

- Standard rectangular or circular MPAs typically exhibit:
- Narrow impedance bandwidth (often a few percent)
- Moderate gain
- Surface wave excitation leading to efficiency loss
- Size constraints at lower frequencies
- These limitations motivate advanced design strategies including shape loading and metamaterial integration.

3. Geometric Shape Loading: Triangle and Circle Patches

3.1 Triangular Patch Antennas

Triangular patches inherently provide different current paths compared to rectangular patches.

Advantages

- Size reduction due to longer effective current paths
- Improved bandwidth
- Potential for dual-band operation
- Compact for phased array implementation

Design Considerations

- Edge feed vs. probe feed
- Optimization of vertex angles for impedance matching
- Impact of substrate permittivity on resonant frequencies

3.2 Circular Patch Antennas

Circular patches support TM modes and can be easily tuned by varying radius.

Advantages

- Circular symmetry leads to omnidirectional patterns
- Relatively broad impedance bandwidth
- Efficient radiation with less surface wave loss

Design Considerations

- Mode control (TM₁₁, TM₂₁, etc.)
- Feed position and type for matching

4. Metamaterial Structures in Antenna Design

4.1 Overview of Metamaterials

Metamaterials consist of periodic elements like SRRs, CSRRs, and complementary structures capable of producing negative permittivity or permeability near resonance.

4.2 Common Metamaterial Inclusions

4.2.1 Split-Ring Resonators (SRRs)

SRRs produce negative permeability near resonance, aiding miniaturization and bandwidth control.

4.2.2 Complementary SRRs (CSRRs)

CSRRs etched into ground planes or patches can create complementary resonances, affecting current distribution and enabling multi-band behavior.

4.2.3 Electromagnetic Bandgap (EBG) Structures

EBGs suppress surface waves and improve radiation efficiency and gain.

5. Literature Review:

The first practical Microstrip Patch Antenna was developed by Munson (1974). Howell (1975) designed and analyzed the practical Microstrip Patch Antennas initially. Lo et al. (1979) presented a Microstrip Patch Antenna analysis technique using cavity model theory. The initial theoretical predictions matched with the measured results. Garg et al. (2001) investigated the various patch geometries that are used to design a simple microstrip antenna. Triangular, circular, elliptical and rectangular patches are most commonly used for simplified design and analysis. Pozar (1992) explained the use of thick substrates with low dielectric constant in the Microstrip Patch Antenna for high performance.

The calculation of far fields and radiation conductance of microstrip antenna design was presented by Derneryd (1979). Guha & Siddiqui (2003) presented the method of resonant frequency calculation of circular patch antenna with dielectric superstrates. The calculations are proved experimentally also.

Dual stacked monopoles were introduced by Kuo & Wong (2003). Dual T shaped monopoles were used to realize the multiband operation. Ashim Kumar Biswas and Ujjal Chakraborty (2019) investigated the wideband wearable jeans antenna with stub structure. This structure supports Wireless Local Area Network (WLAN) in 2.4 GHz, 5.3 GHz and 5.75 GHz range. The satellite communication downlink and uplink application in C band is also supported by this antenna. Ashim Kumar Biswas and Ujjal Chakraborty (2019) investigated a wideband antenna with microstrip neutralization lines. The design supports C band satellite communication in 3 to 6 GHz range and defense applications in 7 to 8 GHz range. Saraswat R K and Kumar M (2016) presented a wideband metamaterial antenna for low frequency satellite communications. Prasad Jones Christy S and Pranit Jeba Samuel C (2019)

presented a triple band antenna for low frequency WLAN, industrial, scientific and medical purposes.

Sameena et al. (2009) recorded the conventional patch antenna with different slot structures. The effect of single slotted structure, L shaped slots and G shaped slots on reflection coefficient of antenna was presented. The multiband performance with compact antenna size was realized by the slot geometries. H shaped slotted antenna presented by Shaalan (2009) operated in 3.4 to 4 GHz frequency range and recorded better gain characteristics.

Abd-Alhameed et al. (2003) explored different methods for achieving small scale miniaturized broadband antenna. A dual band antenna proposed by Heng-Tung Hsu et al. (2010) resonates at 2.4 and 3.5 GHz. E-shaped patch structure and cavity models used in antenna design are examined. Unequal slot structures in Microstrip Patch Antenna was investigated by Bhunia (2009). The unequal slotted antenna achieved 67 percent miniaturization and resonated at two different band.

Ghalibafan et al. (2010) presented a Microstrip Patch Antenna with U-shaped slots. The effect of slot dimensions on resonant frequency control is investigated. The U shaped slotted Microstrip Patch Antenna investigated by Shackelford et al. (2001) describes the effect of slot in compact antenna design. The addition of slots reduced the antenna's size to 94 percent. A series of slots are inserted in the conventional Microstrip Patch Antenna by Mudar A. Al-Joumayly et al. (2010) and achieved miniaturized dual band antenna. Mahmoud N. Mahmoud & Reyhan Baktur (2011) suggested the usage of dual slot structures to achieve dual band resonance.

The F-shaped patch antenna investigated by Lal et al. (2006) operating in 1.85 and 2.42 GHz dual band, Slotted antenna with L shaped strips proposed by Hu et al. (2010) operating in dual band WLAN frequencies and slotted rectangular patch antenna operating in 4.84 to 6.56 GHz band proposed by Mohamed Nabil Srifi et al. (2010) explains the effect of slot on resonance and miniaturization.

The application of Photonic Band gap (PBG) and Electronic Band Gap (EBG) structures to realize high gain antennas were presented by Yongxi Qian et al. (1998) and Halim Boutayeb & Tayeb A Denidni. (2007). The EBG and PBG structures used in basic patch antenna geometry proved bandwidth performance. Amit A. Deshmukh (2009) designed a rectangular patch antenna with half U slot and rectangular slots in patch element to achieve small sized antenna with broadband resonance.

Islam et al. (2010) structured a ring shaped microstrip patch antenna. The antenna has air between the field and the patch as a dielectric and RT Duroid as dielectric superstrate to enhance the performance of antenna. The stacked laminated radiating patches was engineered by Latif et al. (2011) to realize high gain antenna. Lee & Sun. (2008) presented a multiband printed slotted antenna with high gain and multiband operation. Inverted L shaped slots were employed to achieve multiband operation.

Lin Peng & Cheng-Li Ruan (2009) engineered an antenna with dual inverted L stub for 2.4, 5.2 and 5.8 GHz frequency. The investigation focused on influence of L stub dimension on the gain performance of antenna. The gain enhancement of antenna using unequal slots and circular slot structures were presented by Sarkar et al. (2010). The antenna resonates in four various frequencies with high gain. Jhamb et al. (2011) designed a dual integrated patch antenna for multiband applications. A triangular patch and a slotted semiconductor patch are integrated to achieve resonance at multiple operating bands with high gain.

The various microstrip antennas designed for miniaturization, high gain and multiband performance have been extensively reviewed. The literature review focused on the use of slots, EBG structures, metamaterials and arrays to achieve multiband characteristics. This extensive study is carried out to develop wide and narrow band antennas with compact size for multiband applications.

Veselago (1968) presented the idea of negative index materials. The characteristics of left handed materials or negative index materials with negative electric permittivity ' ϵ ' and magnetic permeability ' μ ' were discussed. The practical realization of artificially engineered metamaterials were investigated and presented by Pendry et al. (1999). Capolino (2009) investigated the application of perfect magnetic metamaterial conductors for the design of compact miniaturized antenna systems.

Sievenpiper et al. (1999), Feresidis et al. (2005) and Erentok et al. (2005) discussed the characteristics and application of high impedance surface and metamaterials. It is cleared that the metamaterials are the better choice for the design of compact low profile high performance antennas.

The broadside coupled split ring metamaterial geometry proposed by Zhao & Cui (2006) and the Omega shaped metamaterial ring geometry proposed by Simovski & He (2003) explains the various metamaterial geometries for the antenna design. These structures are experimentally analyzed and the behaviour of artificial metamaterial structures are presented based on the analysis.

Saber Dakhli et al. (2014) presented a super directive metamaterial monopole antenna. The directivity of a compact monopole antenna with split ring resonator metamaterial was investigated.

Aysegul Pekmezci & Levent Sevgi (2014) discussed the modelling and simulation of metamaterial structures. The frequency dependency of permeability and permittivity of metamaterial structures are simulated and proved. Soumen Pandit et al. (2017) presented a patch antenna with metamaterial slab structures for line of sight communication. This structure helped to suppress cross polarization.

Square shaped split ring resonator is realized on a FR4 substrate by Rahim et al. (2009). The enhancement of gain and polarization purity is achieved using the metamaterial

loading. Sulaiman et al. (2010) presented the performance enhancement of microstrip patch antenna using omega shaped metamaterial array structures. The design helps to achieve miniaturization also. Pattnaik et al. (2010) introduced a multiple split ring resonator structure for bandwidth enhancement.

Palandoken et al. (2009) discussed the use of split ring resonator metamaterial geometry in antenna for performance enhancement and size reduction. A circular microstrip patch antenna on metamaterial structure was presented by Boubakri & Bel Hadj Tahar (2011). The study proved the improved radiation characteristics by suppressing the side lobe and back lobes.

6. Conclusion

Microstrip patch antennas integrated with geometric loadings such as triangles and circles, enhanced with metamaterial structures, represent a powerful and versatile paradigm in antenna engineering. These configurations overcome classical limitations by improving bandwidth, gain, efficiency, and enabling miniaturization. Although challenges remain, especially in fabrication and design complexity, continued advances in metamaterials, optimization algorithms, and materials technologies are likely to unlock new possibilities for next-generation wireless systems.

References

1. Abd-Alhameed, RA, Khalil, K, Excell, PS & See, CH 2003, 'Simulation and Measurement of Broadband Microstrip Patch Antenna for 3G Wireless Communications', IEEE, pp. 477-480.
2. Abd-Alhameed, RA, McEwan, NJ, Excell, PS, Ibrahim, MM & Ibrahim, BAW 1998, 'Procedure for analysis of microstrip patch antennas using the method of moments', IEE Proceedings Microwaves, Antennas and Propagation, vol. 145, no. 6, pp. 455-459.
3. Alemaryeen, A & Noghianian, S 2019, 'On-Body Low-Profile Textile Antenna with Artificial Magnetic Conductor', IEEE Transactions on Antennas and Propagation, vol. 67, no. 6, pp. 3649-3656.
4. Alu, A, Engheta, N, Erentok, A & Ziolkowski, RW 2007, 'Single-Negative, Double-Negative, and Low-Index Metamaterials and their Electromagnetic Applications', IEEE Antennas and Propagation Magazine, vol. 49, no. 1, pp. 23-36.
5. Amer Basim Shaalan & Ammar Nadal Shareef 2014, 'Characteristics of Microstrip Fractal Antenna Shape Covered by Modified Split Ring Resonator', IOSR Journal of Electrical and Electronics Engineering, vol. 9, no. 4, pp. 13-17.
6. Amit A Deshmukh & Ray, KP 2009, 'Compact Broadband Slotted Rectangular Microstrip Antenna', IEEE antennas and wireless propagation letters, vol. 8, pp. 1410-1413.
7. Arghand Lafmajani, I & Rezaei, P 2012, 'A novel frequency-selective metamaterial to improve helix antenna', J. Zhejiang Univ. - Sci. C, vol. 13, pp. 365-375.
8. Ashim Kumar Biswas & Ujjal Chakraborty 2019, 'A compact wide band textile MIMO antenna with very low mutual coupling for wearable applications', Int J RF Microw Comput Aided Eng, p. e21769.
9. Ashim Kumar Biswas & Ujjal Chakraborty 2019, 'Investigation on decoupling of wide band wearable multiple-input multiple-output antenna elements using microstrip neutralization line', Int J RF Microw Comput Aided Eng, p. e21723.
10. Ashish Gupta, Abhipsha Patro, Akanksha Negi & Arpit Kapoor 2019, 'A Compact Dual-Band Metamaterial Inspired Antenna with Virtual Ground Plane for WiMAX and Satellite Applications', Progress in Electromagnetics Research Letters, vol. 81, pp. 29-37.
11. Aysegul Pekmezci & Levent Sevgi 2014, 'FDTD-Based Metamaterial (MTM) Modeling and Simulation', IEEE Antennas and Propagation Magazine, vol. 56, no. 5, pp. 289-303.
12. Azim, R, Islam, MT & Misran, K N 2013, 'Microstrip Line-fed Printed Planar Monopole Antenna for UWB Applications', Arabian Journal for Science and Engineering, vol. 38, pp. 2415-2422.
13. Bae-Ian Wu, Weijen Wang, Joe Pacheco, Xudong Chen, Tomasz M. Grzegorzczuk & Jin Kong 2005, 'A Study of Using Metamaterials as Antenna Substrate to Enhance Gain', Progress in Electromagnetics Research, vol. 51, pp. 295-328.
14. Bao, L & Cui, TJ 2020, 'Tunable, reconfigurable, and programmable metamaterials', Microw Opt Technol Lett, vol. 62, pp. 9-32.
15. Bhunia, S & Sarkar, PP 2009, 'Reduced Sized Dual Frequency Microstrip Antenna', Indian J. Phys, pp. 1457-1461.
16. Boubakri, A & Bel Hadj Tahar, J 2011, 'Steerable and compact antenna using a cavity-based metamaterial', 2011 11th Mediterranean Microwave Symposium (MMS), pp. 233-235.
17. Caloz, C & Itoh, T 2005, 'Electromagnetic Metamaterials Transmission Line Theory and Microwave Applications', 1st edition, John Wiley & Sons Inc, USA.
18. Caloz, C, Okabe, H, Iwai, T & Itoh, T 2004, 'A simple and accurate model for microstrip structures with slotted ground plane', IEEE Microwave and Wireless Components Letters, vol. 14, no. 3, pp. 127-129.
19. Capolino, F 2009, 'Metamaterials Handbook. Applications of Metamaterials', CRC Press, vol. 2.
20. Carver, KR & Coffey, EL 1979, 'Theoretical Investigation of the Microstrip Antenna: A Semi-annual Progress Report', Physics Science Laboratory, New Mexico State University, Las Cruces, NM.
21. Carver, KR & Mink, JW 1981, 'Microstrip antenna technology', IEEE Transactions on Antennas and Propagation, vol. 29, no.1, pp. 2-24.
22. Chaabane, A, Djahli, F & Redadaa, S 2014, 'A Dual-Band-Notched Antenna for UWB Communication Systems Using Two Different Shaped Slots', Arabian Journal for Science and Engineering, vol. 39, pp. 6215-6223.
23. Chair, R, Mak, CL, Lee, KF, Luk, KM & Kishk, AA 1983, 'Miniature Wide- and Half U-Slot and Half E-Shaped Patch Antennas', IEEE Trans. Antennas Propag, vol. 53, no. 8, pp. 2645-2652.