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Smart Antennas

Latest Trends in Design and Application

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This book is dedicated to my late father, who taught me to be an independent and determined person, without whom I would never be able to achieve my objectives and succeed in life.

Late (Sr.) Dharamveer Singh

Preface

This edited book aims to bring together leading academic scientists, researchers, and research scholars to exchange and share their experiences and research results on all aspects of planer and printed antenna design. The book primarily focuses on the latest trends in the field of patch and printed antenna design and their application in various fields of wireless communication, mobile communication, vehicular communication, and wearable applications. Students from different branches of electronics, communication, and electrical engineering, researchers, and industry persons will benefit from this book. This book provides the literature students and researchers can use to design antennas for the above-mentioned applications. It also provides a premier interdisciplinary platform for researchers, practitioners, and educators to present and discuss the most recent innovations, trends, and concerns as well as practical challenges encountered and solutions adopted in the field of planer antenna design.

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Contents

Part I Overview and Introduction of Microstrip Antenna

Part II Performance Analysis of Micro-strip Antenna

Part III Multiple Input Multiple Output (MIMO) Antenna Design and Uses

Part IV Fractal and Defected Ground Structure Microstrip Antenna

Part V Importance and Uses of Microstrip Antenna in IoT

Part VI Ultra-Wide-Band Antenna Design for Wearable Applications

Part VII Microstrip Antenna Design for Various and Miscellaneous Applications

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Joan Lu is in the Department of Computer Science and is the research group leader of Information and System Engineering (ISE) at the Centre for High Intelligent Computing (CHIC), having previously been team leader in the IT department of Charlesworth Group publishing company. She successfully led and completed two research projects in the area of XML database systems and document processing in collaboration with Beijing University. Both systems were deployed as part of company commercial productions. Professor Lu has published seven academic books and more than 200 peer-reviewed academic papers. Her research publications have 1388 reads and 185 citations by international colleagues, according to incomplete statistics from the research gate. Professor Lu has acted as the founder and a program chair for the International XML Technology Workshop for 11 years and serves as chair of various international conferences. She is the founder and editor-in-chief of the *International Journal of Information Retrieval Research* and serves as a BCS examiner of Database and Advanced Database Management Systems, and is an FHEA. She has been the UOH principle investigator for four recent EU interdisciplinary (computer science and psychology) projects: Edumecca (student responses system) (143545-LLP-NO-KA3-KA3MP), DO-IT (multilingual student response system) used by more than 15 EU countries (2009-1-NO1-LEO05-01046), and DONE-IT (mobile exam system) (511485-LLP-1-2010-NO--KA3-KA3MP), HRLAW2016 - 3090 / 001 - 001.

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Part I

Overview and Introduction of Microstrip Antenna

Microstrip Antenna: An Overview and Its Performance Parameter

Hirendra Das, Mridusmita Sharma, and Qiang Xu

1 Introduction

Antennas are the most critical components in modern age for wireless communications. The first wireless electromagnetic system was demonstrated in 1886 [1], and in 1901, Marconi succeeded in sending signals over long distances from England to Newfoundland, Canada. In 1950, the idea of microstrip antenna was first introduced [2]; however, it took almost 20 years for researchers to practically realize the concept, thanks to the development of printed circuit board (PCB) in the 1970s [3]. The necessity for having antennas with low profile, low weight, low cost, easy integration into arrays and microwave-integrated circuits, or polarization diversity, encouraged the researchers to develop microstrip antennas [4, 5]. The compatibility of microstrip antennas with integrated electronics is very evident and is a great impetus to antenna designers particularly so, now that a large variety of new substrate materials are commercially available in the market. Unlike other antennas, microstrip patch antennas can be configured with either the transmitting or receiving modes of operations. The limitations of the original microstrip antennas such as narrow bandwidth, poor polarization purity, spurious feed radiation, limited

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power-handling capacity, and tolerance problems have been overcome by continuous research, design developments, and performance optimizations. This leads to the design of novel microstrip antenna configurations with accurate and versatile analytical models for the understanding of inherent limitation of microstrip antennas to satisfy increasingly stringent system requirements [6, 7]. The three main fundamental disadvantages of microstrip antenna are narrow bandwidth, low gain, and relatively large size. Among these three, narrow bandwidth is the most significant one and can be directly improved by increasing the substrate thickness. However, with increasing thickness of the substrate, the radiation power decreases [8]. Different ways are proposed by the researchers to improve the bandwidth of the antenna without compromising the radiation power, including impedance matching networks using stub [9, 10]; novel designs [11, 12]; using different shapes and sizes of shots on the patch or in the ground plane such as U, step U, half step U, and L-shaped rectangular microstrip antenna [13]; W-shaped patch antenna [14]; M-slot folded patch antenna [15]; microstrip antennas using magneto-dielectric substrate [16]; complementary rhombus resonator [17]; nanomaterial-based microstrip antenna [18]; etc. The low-gain problem can be solved by using cavity backing, which eliminates the bidirectional radiation to provide higher gain compared to conventional microstrip antenna [19]. The large size of the microstrip antenna particularly at lower microwave frequencies is another limitation which could be addressed by inductive or capacitive loading techniques [20] to fabricate electrically small microstrip antenna. In some other studies, works are also reported on different composite metamaterial resonators and magneto-dielectric substrate-based microstrip antennas for size reduction.

It is evident from the above discussion that continuous improvements and performance enhancement of microstrip antenna are ongoing to meet the demands of compact, highly efficient, lightweight, and low-cost devices. Lately, the demand of compact wireless designs has necessitated the importance of continuously size-decreasing configurations. Emerging novel nanomaterials could also play an important part in the development of next-generation microstrip patch antennas. However, it is important to have a balance among bandwidth, gain, and size of microstrip antenna. In this chapter, we will discuss the basic theory and different design and performance parameters of microstrip antennas followed by a state-of-the-art review of the recent trends in this area.

2 Design and Performance Parameters of Microstrip Antenna: An Overview

Due to features like compact design, efficiency, high performance, lightweight, low cost, etc., microstrip patch antennas (MPA) have become common elements in modern transmit-receive systems. The microstrip antennas are often termed as microstrip patch antenna (MPA). The radiating elements and feed lines are usually photo etched on the dielectric substrate. The basic structure of a rectangular microstrip patch antenna is shown in Fig. 1a. Depending on the shape of the patch, the antenna

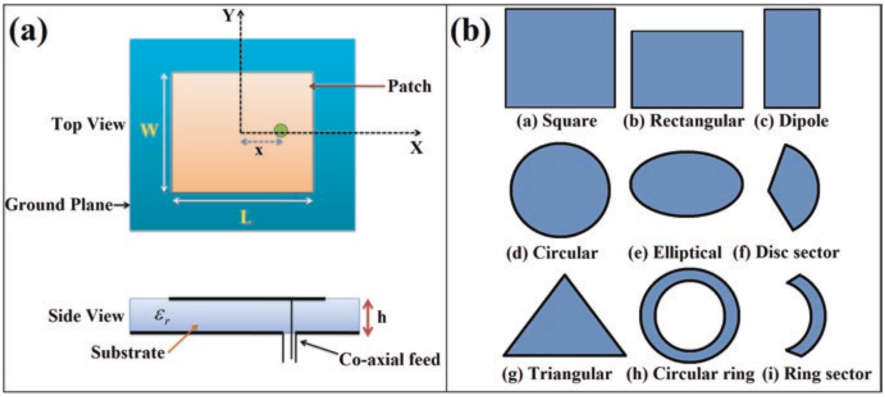


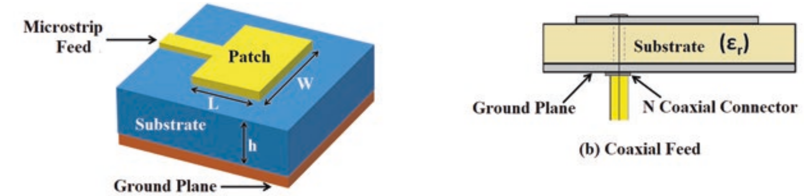
Fig. 1 (**a**) Schematic of a rectangular microstrip patch antenna (**b**) Shapes of microstrip patch element

may be square, rectangular, thin strip (dipole), circular, elliptical, triangular, or any other configuration as shown in Fig. 1b. The length "L" defines the resonant frequency of the antenna, and width "W" determines the radiation which in turn determines the bandwidth and gain of the antenna. There are many feeding methods which can be used in microstrip antennas. The traditional microstrip antennas have the impedance bandwidth of only a few percent and radiation pattern with omnidirection, which obviously does not meet the requirements of various wireless applications. To solve this problem, a variety of different design topologies have been used with different microstrip antenna element structures and different microstrip array arrangements to meet the requirements of ultra-wideband (UWB), high-gain, multi-polarized, and compact design.

2.1 Feeding Techniques

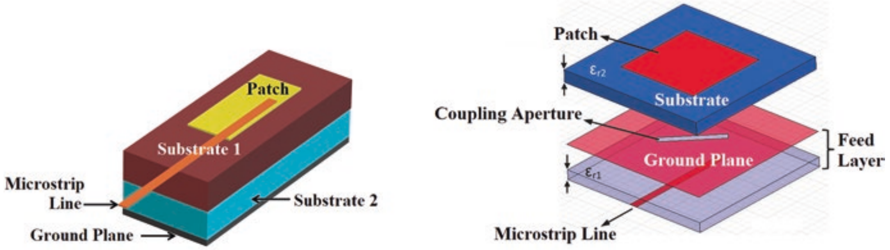
Feeding techniques are one of the most important things to be considered while designing a microstrip antenna because many potential good designs have been rejected because of their bad feeding quality. The four most commonly used feeding techniques are microstrip line feed, coaxial feed, aperture coupling, and proximity coupling. The schematic diagram of the four types of feeding techniques is given in Fig. 2.

Microstrip line feeding is the most widely used technique because of its simplicity in design and easy manufacturing process [21–23]. Figure 2a shows a patch with microstrip line feed from the side of the patch. This type of feeding is used in both single- and multi-patch (array) antennas. Coaxial feed which is also known as coplanner feed is one of the cheapest and simplest ways to couple power to the patch antenna through a probe. The N-coaxial connector is coupled to the ground plane, and the center connector of the cable is soldered to the patch as shown in Fig. 2b.



(a) Microstrip Line Feed

(b) Coaxial Feed



(c) Proximity Coupling

(d) Aperture Coupling

Fig. 2 A schematic representation of different feeding techniques used in microstrip antenna

The coaxial feed connected at exactly 50 ohm does not require any external matching network for impedance matching.

Proximity coupled, which is also known as electromagnetically coupled, microstrip feed is shown in Fig. 2c. Two different substrates with different dielectric constants are used at the top and bottom of this structure as ground plane. The patch is at the top, and the microstrip line is connected to the power source lying between the two substrates. The working principle is based on the capacitive behavior of the patch and the feed strip line which can be used for impedance matching of the antenna. This design is relatively complicated compared to the earlier two techniques. Figure 2d shows the aperture coupling mechanism used for microstrip antenna. A circular or rectangular aperture at the ground plane separates the upper substrate ε_{r1} with the patch on it and the lower substrate ε_{r2} which contains the microstrip feed line under it. A wider bandwidth can be achieved using this feeding technique with improved polarization purity.

All the feeding techniques have their advantages and disadvantages and are used based on the requirements. A comparison between different parameters of the four feeding techniques can be seen in Fig. 3. From the pie chart, a comparison among return loss, bandwidth, and impedance of the four feeding techniques could be obtained. Microstrip feed provides balanced characteristics among the four, except the bandwidth. Aperture feed provides the best bandwidth, whereas return loss is maximum for coaxial feeding technique. The discussion and comparison of feeding techniques are very important as they affect important parameters of the microstrip antenna such as the bandwidth, patch size, VSWR, and return loss up to a great extent. Table 1 shows an overall comparison among the parameters of different feeding techniques.

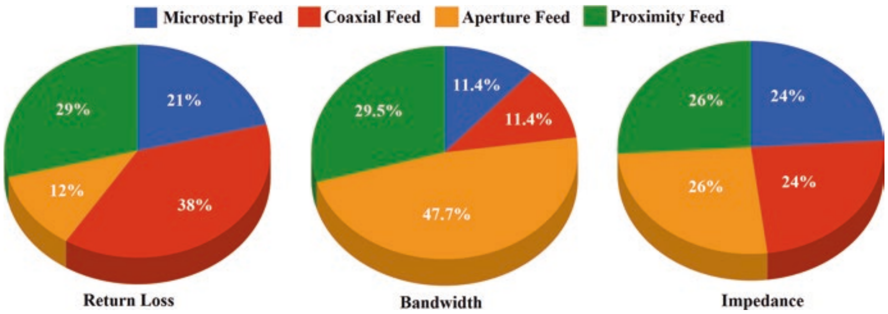


Fig. 3 Comparison of return loss, bandwidth, and impedance parameters of different feeding techniques

Table 1 Parameters of different feeding techniques: a comparison

Characteristic	Microstrip feed	Aperture feed	Coaxial feed	Proximity feed
Bandwidth	2–5%	21%	2–5%	13%
Return loss	Less	Less	More	More
Impedance matching	Easy	Easy	Easy	Easy
Reliability	Better	Good	Poor	Good
Resonant frequency	More	Least	Less	Highest
VSWR	< 1.5	~ 2	1.4–1.8	< 1.23
Polarization	Poor	Excellent	Poor	Poor

2.2 *Performance Parameters*

2.2.1 Directivity and Gain

The directivity of an antenna is defined as the ratio of the radiation intensity U in a given direction from the antenna to the radiation intensity averaged over all directions.

Mathematically it can be represented as:

$$\mathrm{Directivity}\left(\mathrm{D}\right) = \frac{4\pi U}{\mathrm{P}_{\mathrm{rd}}} \tag{1}$$

Here, P_{rd} is antenna input power.

Gain can be defined as the directivity reduced by losses on the antenna structure. Losses are represented by radiation efficiency e_r $(0 \leq e_r \leq 1)$. Mathematically:

$$\mathrm{Gain}\left(\mathrm{G}\right) = \mathrm{e}_{\mathrm{r}}\mathrm{D} \tag{2}$$

Continuous works are being reported by the researchers to enhance the directivity and gain of the MPA. A narrow bandwidth (BW) and unidirectional dual-layer microstrip patch antenna with small-sized design for specific use in security and military systems were designed in 2014 [24], where they have achieved a gain of 5.2 dB with directivity 7.6 dB by using a dual substrate layer of FR-4 of thickness of 1.6 mm. Another report proposed two MPA arrays with enhanced gains of 12.41 and 10.11 dB as compared to 5.06 dB of conventional microstrip antenna array [25]. In a recent study, enhancement of gain up to 5.54 dB was reported using proximity coupled MPA operating in 7.067GHz–7.40 GHz frequency range [26].

2.2.2 Return Loss

The return loss of MPA can be given by the measure of how properly the devices or lines are matched. For a mismatched load, the whole input power is not delivered to the load, and a fraction of the power is returned, which is termed as return loss. Mathematically it can be given by:

$$\mathrm{R_L}\left(\mathrm{dB}\right) = 10\log_{10}\frac{\mathrm{P_{in}}}{\mathrm{P_{rd}}} \tag{3}$$

where $\mathrm{R_L}$ → return loss in dB
$\mathrm{P_{in}}$ → incident radiation
$\mathrm{P_{rd}}$ → reflected power.

From Eq. 3, return loss can also be defined as the logarithmic ratio of the antenna input power from the transmission line to the antenna's reflected power.

$$\mathrm{R_L} = 20\log_{10}\frac{\mathrm{SWR}}{\mathrm{SWR}-1} \tag{4}$$

Here, SWR is the standing wave ratio. Return loss is an important parameter to describe the quality of the MPA, and several studies can be found in this area [27–29].

2.2.3 Radiating Pattern and Efficiency

It is defined as the ratio of radiating power to the incident power of the antenna. The value of radiating efficiency lies between 0 and 1, and "d" is measured in terms of percentage (%). Mathematically it is given by:

$$\mathrm{e_r} = \frac{\mathrm{P_{rd}}}{\mathrm{P_{in}}} \tag{5}$$

Here, $\mathrm{e_r}$ → radiating power. It is less than 100% due to the losses in the antenna.

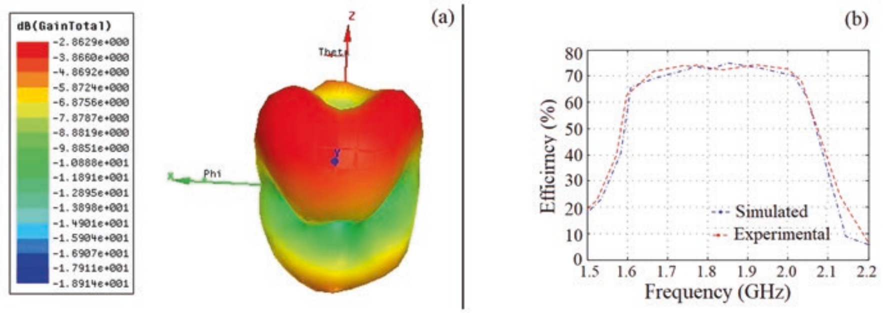


Fig. 4 (**a**) 3D Radiation pattern and (**b**) efficiency vs. frequency graph of a microstrip antenna

Antenna efficiency is given by the radiation efficiency multiplied by the impedance mismatch, which is always less than the radiating efficiency. Researchers are continuously working to enhance the efficiency of MPA using different designs and other techniques, which can be found in various reports [30–33]. The 3D simulated radiation pattern and efficiency of a novel microstrip patch antenna designed at 1.84 GHz is shown in Fig. 4a and b, respectively. From the radiation pattern, it can be observed that the maximum gain for the microstrip antenna is 2.86 dB.

2.3 *Microstrip Antenna Topologies: A Review of Literature*

A wide variety of MPA design topologies, along with different microstrip antenna element structures and array arrangements, have been investigated throughout the years by the researchers to achieve high gain and ultra-wideband operations. The lowest frequency for which microstrip antenna is designed and fabricated is 450 MHz, published in 2017 [34]. The highest-frequency microstrip antenna published till date is 60 GHz antenna reported in 2019 [35]. They measured a bandwidth of 4.92 GHz for this antenna that covers channels 2 and 3 of 60 GHz WLAN/WPAN applications. A novel wideband quasi-Yagi microstrip antenna design with operating frequency in the range of 4.4–9.6 GHz and gain higher than 5 dB at most frequency band was reported [36]. Works are being reported on the design of a wideband planar microstrip-fed quasi-Yagi antenna using two rows of directors to achieve a higher gain [37]. This proposed structure results a frequency range of 1.84–4.59 GHz and a gain of about 4.5–9.3 dB.

The current emerging wireless systems and radar applications require wide frequency bands, which encourages the researchers to design wideband antennas. In a recent study, researchers have proposed a compact high-gain quasi-Yagi antenna array using split-ring resonator (SRR) at an operating frequency of 2.45 GHz [38]. The SSR antenna could be used to suppress mutual coupling with possible high gain. Ground-plane slot microstrip antennas have the advantages of large bandwidth and good impedance matching [39]. Works are also being proposed by researchers on combining different types of MPA and frequency selective surfaces (FSSs) to enhance certain antenna characteristics [40, 41]. Researchers have also used FSS superstrate layer to increase the impedance bandwidth as well as the gain of an aperture coupled microstrip patch antenna [42]. Other significant works and recent developments are also being reported on the use of microstrip antennas for broadband applications [43, 44], mobile and satellite 5G communication [45, 46], radio-frequency identification [47], WLAN/WiMAX applications [48], automobile application [49], and so on.

In recent times, researchers are also exploring the idea of nanomaterial and low-dimensional structure-based efficient microstrip antenna for a wide range of applications. Tools like physical vapor deposition (PVD) and chemical vapor deposition (CVD) can be used to deposit the required amount of conductive patch material on the dielectric substrate instead of the conventional lithographic process or removing the unwanted metal from a dielectric substrate. Nano-thin films as radiating patch used to fabricate aperture coupled microstrip patch antenna (ACMPA) by researchers were reported in 2012 [50]. A nanotechnology-based proximity coupled patch antenna in the X band frequencies was reported in 2013 [51]. They have discussed the effect of nano-thin films as radiating patch on the antenna resonant frequency and bandwidth. Nano-fillers such as fumed silica and aluminum oxide were used with RT/duroid 5880 to fabricate antenna substrates with compact dimensions [52]. Silver nanoparticles are used to fabricate flexible microstrip antenna using a polymer substrate [53]. An inkjet printer was used to print the antenna using the silver nanoparticles. The said antenna is flexible and weighs only 0.208 g, which makes it suitable for applications in wearable electronic devices. Works are also reported on the use of carbon nanotube-based patch for microstrip antenna design to enhance the gain of the system [54]. The reported multi-walled carbon nanotube (MWCNT)-based microstrip patch antenna was fabricated using spin coating technique operating in the frequency range of 8.5–11 GHz, which exhibits an increased impedance bandwidth of 20%. In a recent study, researchers have reported investigation of graphene-based microstrip radiating structure for possible use in L- and S-band applications [55]. They obtained a multiband and tunable frequency response by changing the reflection coefficient by varying the chemical potential of graphene. The designed antenna showed the highest gain of 9.42 dB at a resonance frequency of 3.25 GHz.

3 Design Parameters of Microstrip Antenna

The performance of MPA depends on different design parameters. One major design parameter is the choice of the substrate. Substrate dielectric constant and thickness are two major parameters for the selection of substrate. A few popular substrates for MPA with the most pertinent parameters, such as substrate name, thickness, dielectric constant, frequency range, and loss tangent, are given in Table 2.

Table 2 Different substrates with most pertinent parameters

Substrate	Thickness (mm)	Dielectric constant (ε_r)	Frequency (GHz)	Loss tangent (tanδ)
Duroid 5880	0.127	2.20	0–40	0.0009
RO 3003	1.575	3.00	0–40	0.0010
RO 3010	3.175	10.2	0–10	0.0022
RO 4350	0.168	3.48	0–10	0.0037
HK 04 J	0.025	3.50	0.001	0.0050
IS 410	0.05–3.2	0.10	5.40	0.0350
FR4	0.05–100	4.70	0.001	–
DiClad 870	0.091	2.33	0–10	0.0013
RF-60A	0.102	6.15	0–10	0.0038
NH 9320	3.175	3.20	0–10	0.0024
Polyguide	0.102	2.32	0–10	0.0005

Apart from the abovementioned substrates, many others are also present in the market. From the above, RO series along with FR4 is very popular for microstrip antenna design. The bandwidth of the antenna related to the material substrate is given by the following equation:

$$\mathrm{BW} \cong \frac{96\sqrt{\mu_\mathrm{r}/\varepsilon_\mathrm{r}}\,\dfrac{t}{\lambda_0}}{\sqrt{2}\left[4+17\sqrt{\mu_r\varepsilon_\mathrm{r}}\right]} \tag{6}$$

where “t” is the thickness of the substrate and “λ_0” is resonance frequency wavelength. The term $\sqrt{\mu_\mathrm{r}\varepsilon_\mathrm{r}}$ is known as miniaturization factor or refractive index, which determines the size of the antenna.

The dimensions of the patch (length and width) are also vital for antenna performance. “W” is always related to the radiation edge, whereas “L” is always related to the non-radiating edge. The width for an efficient radiator is given by:

$$\mathrm{W} = \frac{c}{2f_\mathrm{r}}\left(\frac{\varepsilon_\mathrm{r}+1}{2}\right)^{-1/2} \tag{7}$$

where $c \rightarrow$ velocity of light
$f_\mathrm{r} \rightarrow$ antenna operating frequency
$\varepsilon_\mathrm{r} \rightarrow$ dielectric constant.

The length of the patch is given by:

$$\mathrm{L} = \frac{c}{2f_\mathrm{r}\sqrt{\varepsilon_\mathrm{e}}} - 2\Delta\mathrm{l} \tag{8}$$

Here, ε_e is the effective dielectric constant, and Δl represents the line extension at the ends given by Hammerstad as:

$$\Delta l = 0.412h \frac{(\varepsilon_e + 0.3)(w/t + 0.264)}{(\varepsilon_e - 0.258)(w/t + 0.8)} \tag{9}$$

where “t” is the substrate thickness.

4 Conclusions

A brief overview of microstrip antenna with different performance and design parameters is provided in this chapter. From the above discussion, it can be observed that using different substrates and feeding techniques and controlling the performance parameters, MPAs can be designed with different topologies and structures to meet the modern-day requirements such as high flexibility, high gain and bandwidth, compact, lightweight, and low cost. A state-of-the-art literature review is also included in the chapter to outline the continuous research development works in this field and future prospects for these structures. It is also observed from the study that extensive works are ongoing nanomaterial-based microstrip antennas, which are showing promising improvements in recent years. These new classes of materials could be a game changer for developments of next-generation microstrip antennas.

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A Compact Dual-Fed Self-Diplexing Antenna for Wireless Communication Application

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1 Introduction

Modern wireless communication system requires a multi-band antenna system with better performance in terms of gain, size, and isolation among the frequency band [1, 2]. The wireless device operated at different frequencies requires the dual-band antenna with high isolation between ports. To reduce the requirement of the diplexer, the idea of self-diplexing antenna is used nowadays. By reducing the required component, it results in a less-dense RF front-end as well as a lower cost.

Various efforts are put by the researcher for the development of diplexer and triplexer antennas. A substrate integrated waveguide (SIW)-based self-triplexer antenna is proposed in [1]. Cavity-backed slot antenna concept is used for the realization of the antenna. A self-diplexer antenna concept using half-mode SIW (HMSIW) is proposed in [2]. A tunable self-diplexing patch antenna is proposed by [3], in which two U-shapes are etched on the radiating patch and fed by two ports.

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A multilayer patch antenna with additional filtering techniques to improve the port's isolation is given in [4, 5]. A nonplanar self-diplexing antenna is proposed in [6, 7].

A self-diplexing patch antenna design based on slot antenna concept is proposed in this paper. A circular patch is divided into two parts, with the slot on the top plane. Rectangular and tilted shape slots are created on top of the patch, excited by two separate feed lines to resonate at two different frequencies in S-band 2.4 GHz (2–4 GHz) and C-band 4.3 GHz (4–8 GHz). A high return loss and better isolation between two input ports are achieved by properly optimizing the antenna dimensions.

2 Realization of Self-Diplexing Antenna

To realize the self-diplexing antenna, initially, a circular patch antenna is designed for the cutoff frequency of 2.4 GHz. Equation 1 is used to calculate the diameter of the patch. Inset type of feeding is used in a proposed antenna. Figure 1a shows the patch antenna design with its associate dimension. Simulation is carried out with the high-frequency structure simulator (HFSS) software which used the finite element method. Simulation result of the structure for return loss is shown in Fig. 1b. It provides resonance at 2.4 GHz of frequency.

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi \varepsilon_{\Upsilon} F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}}} \qquad (1)$$

$$F = \frac{8.791 \times 10^{9}}{f_{\mathrm{r}}\sqrt{\varepsilon_{\mathrm{r}}}}$$

Here in Eq. 1, a is the patch's radius, ε_{r} is the dielectric constant, f_{r} is the resonance frequency, and h is the height of the substrate. Fr4 is used as a substrate material having a dielectric constant of 4.4.

For the realization of the self-diplexing antenna, the above structure is divided into two parts, as shown in Fig. 2. Dimensions of Fig. 2 are tabulated in Table 1. Separate excitation is provided to both positions, as shown in Fig. 2. For the realization of the antennas, two rectangle type slots are provided in the first part. In the second part of the antenna, the tilted type of slots is introduced. A detailed dimension of the proposed antenna is tabulated in Table 1.

A simulated S-parameter result of the proposed antenna is shown in Fig. 3. It shows that it provides the resonance at 2.4 GHz of frequency when the excitation is provided at port 1 and resonates at 4.3 GHz of frequency while the excitation is at the port 2. Isolation among the port is near 20 dB, as shown in Fig. 3.

Figure 4 indicates the simulation result of the radiation pattern and gain at the required frequency of operation. It provides 3.26 dBi gain at 2.4 GHz of frequency and 3.72 dBi at 4.3 GHz of frequency. A 3D polar plot for the same is shown in Fig. 3.

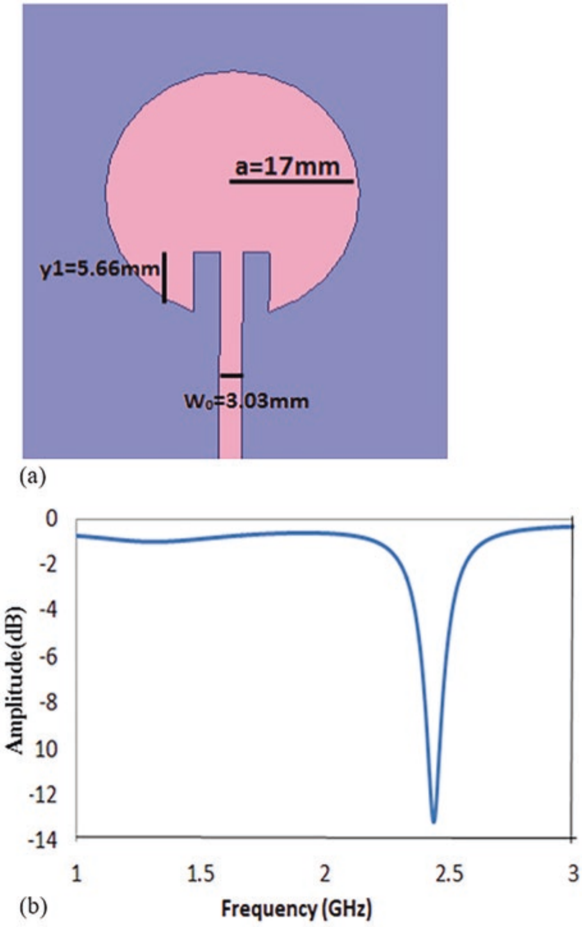

Fig. 1 (**a**) Circular patch antenna (**b**) Simulated return loss

3 Hardware Realization

For the proof of concept, the proposed structure is fabricated and tested. Figure 5a shows the realized hardware of the proposed design. Agilent RF analyzer N9912A is used for the measurement. It is a two-port network analyzer with a frequency range of 2 MHz–6 GHz. A test setup for the same is shown in Fig. 5b. A measured result of the realized structure is shown in Fig. 6. It indicates a similar performance as a simulated one.

A comparison has been carried out of the proposed antenna with previously published diplexer antennas in size, resonance frequency, and gain. A comparison table for the same is tabulated in Table 2. The proposed structure provides small size and better gain.