Bitlis Eren Üniversitesi Fen Bilimleri Dergisi
BİTLİS EREN UNIVERSITY JOURNAL OF SCIENCE
ISSN: 2147-3129/e-ISSN: 2147-3188
VOLUME: 11 NO: 3 PAGE: 812-819 YEAR: 2022
DOI: 10.17798/bitlisfen.1106917

The Development of Broadband Microstrip Patch Antenna for Wireless Applications

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Keywords: Microstrip patch antenna, Wireless Applications, Bandwidth, CST Microwave Studio, ISM 2.4 GHz band, Return Loss.

Abstract
In recent years, the use of unlicensed wireless communication bands has been widely used in different applications such as biomedical, military, and textile/wearable systems. This paper presents the design of the broadband microstrip patch antenna operating in the ISM 2.4 GHz band (2400-2485 MHz). The study includes a three-dimensional antenna model, a simulation phase, and a fabrication/measurement phase. The small volume of microstrip antennas has low fabrication costs and easy fabrication, which has accelerated the work in this area. For the low cost of the antenna, FR-4 with a relative dielectric constant of 4.3 and a loss tangent tan 0.02 is preferred as the substrate material. The dielectric material thickness is determined as 1.6mm. The length of the feed line and the dimensions of the rectangular patch were found by mathematical calculations with the transmission line model. In the ISM band, antennas with low return loss and high bandwidth are required. The most important disadvantage of the patch antennas is their narrow bandwidth, which should be increased optimally. There are slots on the antenna, which is an especially simple method in order to improve the bandwidth parameters of the antenna. In the paper, four different designs are presented, the results are compared, and the proposed antenna has a rational bandwidth of 42.2% (979 MHz bandwidth), 24.529 dB return loss, and 2.68 dBi directivity gain at -10 dB at the resonance frequency of 2.316 GHz. The changes made in the antenna design have improved the resultant bandwidth compared to the conventional microstrip patch antenna. The proposed antenna is suitable for use in ISM band applications.

1. Introduction

The ISM Band (Industrial, Scientific, and Medicine) is the frequency spectrum without the use of many countries ‘licenses. The 2.45 GHz ISM band is a band accepted worldwide by the ITU (International Telecommunication Union) [1]. The ISM frequency band is frequently used for wireless communication in biomedical applications [2], military applications [3], and textile applications [4]. Communication can be defined as the transfer of information from one point to another. The information transfer can be done by modulating the information into the electromagnetic wave. When this wave reaches its destination, it is demodulated to obtain the actual information signal. Nowadays, antennas are the most important components of communication connections. In many areas, such as high-performance vehicles, aircraft, spacecraft, radar systems, satellites, and missile applications; microstrip antennas have become a popular antenna type among microwave antennas due to their advantages, such as low cost, performance, easy installation, and production with modern printed circuit technology [5]. The concept of a microstrip antenna was first introduced by GA Deschamps in

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Received: 21.04.2022, Accepted: 05.08.2022

1953 [6] but has not been implemented for many years. In 1955, Gutton and Baissinot patented the first microstrip structure [7]. The first microstrip antenna communication experiments were conducted by Munson on the missile data system in the 1970s. Howell in 1972 and Munson in 1974 introduced the first easily applicable microstrip antenna structure [8]. The development of the microstrip antenna has accelerated with printed circuit technology. In 2003, S. Weigand performed frequency analysis according to patch and cleft dimensions [9]. Besides, it is an up-to-date issue since it allows different designs. In addition, the most important disadvantage is the narrow bandwidth. Narrow bandwidth is wanted in security applications but refused for broadband applications. Several methods have been used to increase bandwidth. In 2005, Deshmukh and Kumar examined the flow paths formed by the U-shaped slot cut on the patch and observed that the pattern increased the bandwidth by spreading to two frequencies [10]. A.Khidre et al. presented a broadband U-slot patch probe-fed antenna on a 67 mm x 74 mm Rogers RT/duroid substrate [11]. Another widely used method to increase the bandwidth in the literature is to open slots on the patch in various ways [12-14]. Lee et al. achieved a 20%-30% impedance bandwidth by loading a U-shaped slot onto a rectangular patch fed by a coaxial probe. The antenna has a width of 35.5 mm and a length of 26 mm. The gain at 4.1 GHz is 7.30 dB. The bandwidth at 3 dB is 28.50% at 3.79-5.05 GHz [15]. In another study, an antenna design with a circular patch fed by a microstrip line operates at a frequency of 2.49 GHz. It has achieved a bandwidth of 80 MHz and a directivity gain of 2.611 dBi [16]. Several methods have been introduced, such as using slits [17], slots [18], DGS (Defected Ground Structure) [19], partial ground plane [20-21], split-ring resonator [22], substrate integrated waveguide (SIW) [23], dielectric rezonator (DRA) [24], using air gap [25], shorting pin [26] and using EBG (Electromagnetic Band Gap) structures [27]. Although there are many studies in the literature to increase the bandwidth, the easiest way to increase the bandwidth is to use slots in the patch plane and make changes in the ground plane [10-27].

This paper presents the design of a slotted microstrip patch antenna operating in the ISM 2.4 GHz band (2400-2485 MHz). Four types of antennas are presented to observe the effect of slots on resonance frequency, bandwidth, return loss, and gain. The design and simulation of the antennas are carried out in the CST Microwave Studio program. The dimensions of the first antenna were taken as reference and the length of the feed line and patch dimensions of the antennas were kept constant, the slots were opened, various parameters were optimized, and the proposed antenna was reached. In the first stage, the antenna, the dimensions of which are calculated by the transmission line model, is drawn, and the slot is not used in this antenna, the results should be improved. Slots are opened in the patch on the second antenna. On the third antenna, the ground is cut off. Finally, the proposed antenna is achieved by opening slots on both the patch and the ground, which optimizes the parameters. The other proposed antennas compared to the other three antennas have the widest bandwidth and resonance frequency of 2.316 GHz, -10 dB with a bandwidth of 979 MHz and a directional gain of 2.68 dBi.

2. Material and Method

FR-4 has a relative dielectric constant and is preferred as the substrate material for the designed antennas. Dielectric material thickness is determined as 1.6 mm. The transmission line model is used for the design of a microstrip patch antenna. The dimensions of the rectangular patch on the antenna, the length of the feed line, and other parameters are calculated by the transmission line model and mathematical calculations. The results are optimized, and the antenna is simulated. The slots are then used to improve the results. Figure 1 shows the front and rear views of the antennas.

Moreover, to better understand the design of the antenna proposed in Figure 2, parameters are assigned to the lengths and the values of these parameters are given in Table 1.

Table 1. Proposed antenna dimensions

Parameter	Dimension	Parameter	Dimension
W	50	c	4.5
L	55	d	5
W_P	24.5	f	18
L_P	22.5	p	2
W_F	3	r	5
a	11	z	1
b	23	h	1.6

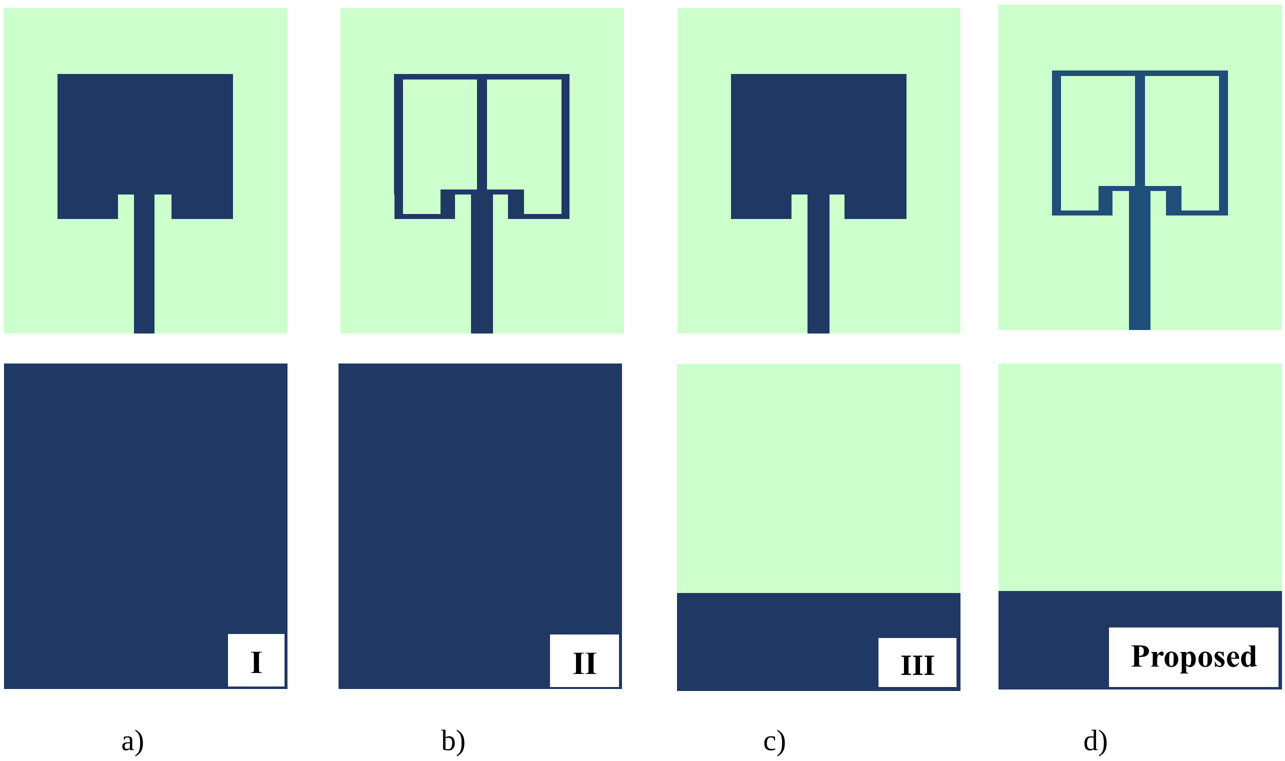

Figure 1. (a) Conventional patch antenna – Antenna I, (b) Slotted patch antenna – Antenna II, (c) Partial ground structure antenna – Antenna III, (d) Partial ground structure with slotted patch antenna – Proposed antenna

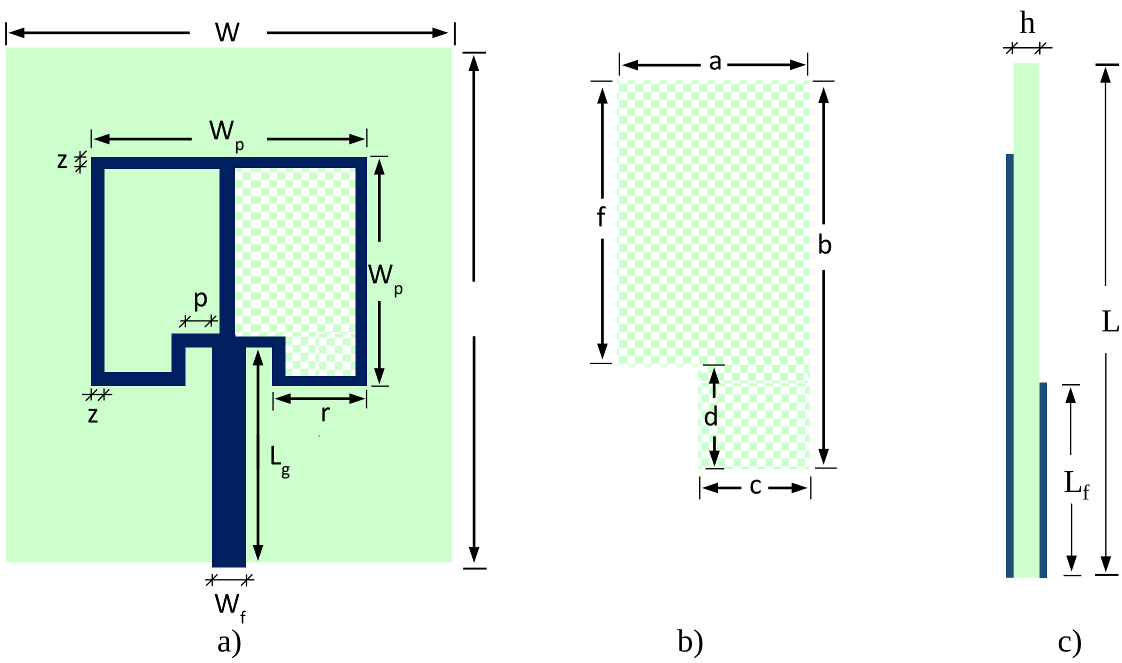

Figure 2. (a) Front view of the proposed antenna, (b) Detailed view of the slot, (c) (c) Detailed view of the feed patch and partial ground plane

Antenna dimensions are obtained using mathematical equations [5]. Width of the rectangular patch,

$$W = \frac{1}{2 f_r \sqrt{\mu_0 \varepsilon_0}} \sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{c}{2 f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

The equation is given by (1). Here, c the speed of light, f_r the resonance frequency, ε_0 the dielectric constant of the cavity, μ_0 the magnetic permeability of the cavity. The actual length of the rectangular patch;

$$L = \frac{c}{2 f_r \sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{2}$$

Here is the ε_{eff} effective dielectric constant. Equation (3) from ε_{eff} and equation (4) from ΔL are provided.

$$W/h > 1$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-1/2} \tag{3}$$

$$\Delta L = 0.412 h \frac{\left(\varepsilon_{eff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{eff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)} \tag{4}$$

The dimensions of dielectric material are given in Equation (5) and equation (6)

$$W_m = 6h + W \tag{5}$$

$$L_m = 6h + L \tag{6}$$

The antenna is excited using the microstrip line supply. To match the input impedance between the feeder line and the antenna, the feed inset is used as shown in Figure 2 (a). The physical slots next to the input feed form the input capacitance, which can affect the resonance frequency by about 1%. The length of the recess can be calculated from the equation (7).

$$R_{in}(y = y_0) = \frac{1}{2(G_1 \pm G_{12})} \cos^2\left(\frac{\pi}{L} y_0\right) \tag{7}$$

3. Results and Discussion

The antenna is designed in the CST Microwave Studio program, and the LKPF S63 is used as a printed circuit board scraping machine. FR-4 dielectric substrate is selected as the dielectric material. The thickness of the dielectric layer is used in h=1.6mm and the thickness of the copper is used 0.035mm. The completed antenna is shown in Figure 3.

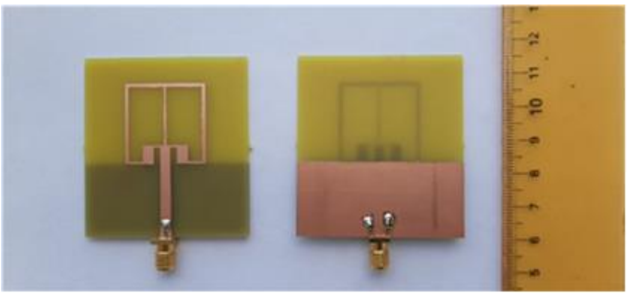

Figure 3. Front and back side view of the proposed antenna

The simulated and measured reflection coefficient S_{11} is given in figure 4. Antenna I does not shine below -10 dB, thus, it cannot be said that it works efficiently. Antenna II has a bandwidth value of 60 MHz and has a -16.37 dB return loss at a resonant frequency of 2.405 GHz. Antenna III has a bandwidth value of 300 MHz and a -27.39 dB return loss at a center frequency of 2.64 GHz. The proposed antenna reflection coefficient is shown in figure 5 and has a 979 MHz bandwidth and -24.529 dB return loss at -10 dB between 2.0767 - 3.0558 GHz.

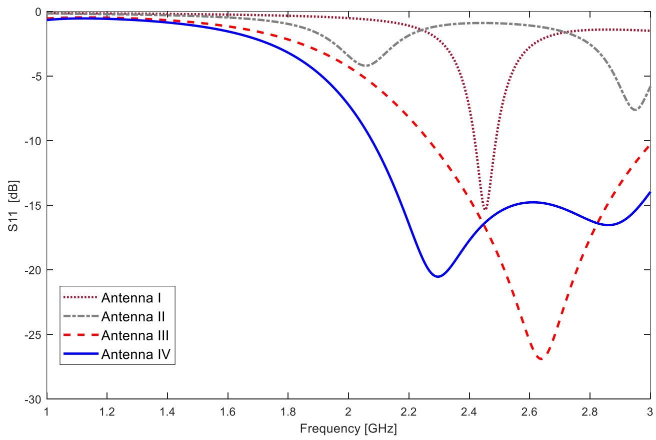

Figure 4. S_{11} simulation comparison results of antennas

A comparison between measurement results and the simulation results provided by the CST Microwave Studio software is presented in Figure 5. The slight difference between the simulation and the measurement results may have occurred due to the fabrication tolerances, SMA connector and coaxial cable losses.

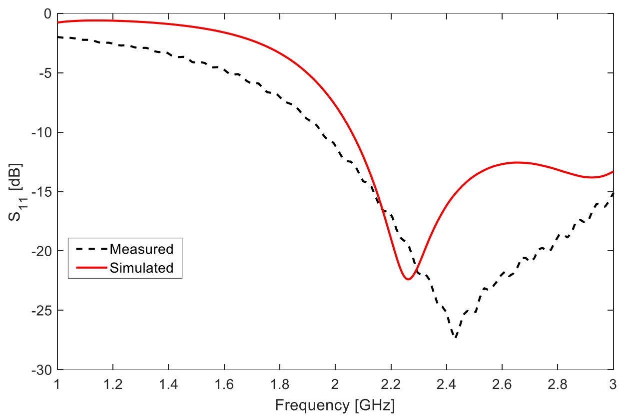

Figure 5. S_{11} simulation and measurement results of the proposed antenna

The 2-D radiation pattern of the proposed antenna is plotted together in plane E and plane H in figure 6 at a frequency of 2.316 GHz.

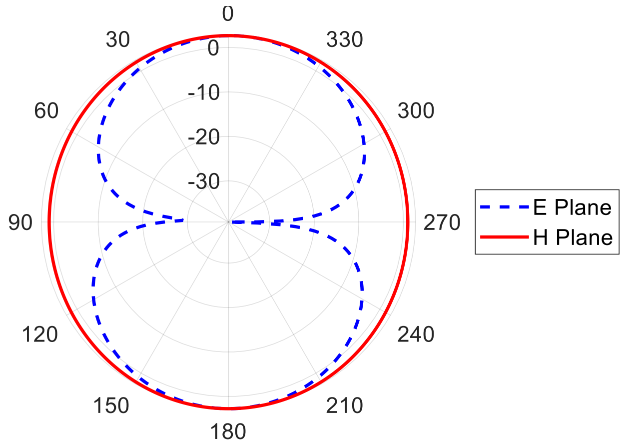

Figure 6. 2-D Radiation pattern of patch antenna at 2.316 GHz frequency

Figure 7 shows a comparison of the frequency-gain graph for the antenna I, antenna II, antenna III, and proposed antenna. The directivity gain variation of antenna I varies between 2.56 dBi and 6.8 dBi. Antenna II directivity gain varies between 2.49dBi and 5.75 dBi. The antenna III directivity gain with the change in the ground plane is obtained as 1.83 dBi to 3.309 dBi. The directivity gain value of the slot and partial ground plane proposed antenna opened in the latest patch plane ranges from 1.85 dBi to 3.3 dBi, and at the center resonant frequency it is obtained as 2.68 dBi. The application of a partial ground plane reduces the antenna gain, but the bandwidth obtained with antenna I is 2.91%, while the bandwidth value of the proposed antenna is 42.2%.

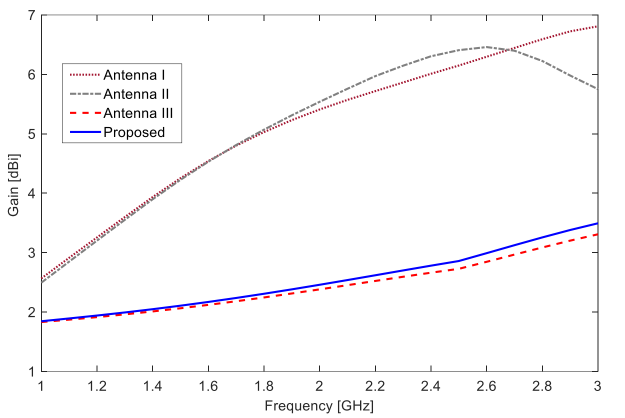

Figure 7. Frequency - Directivity Gain graph of the proposed antenna

Figure 8 shows the rectangular microstrip patch antenna gain diagram at 2.316 GHz frequency. The antenna has a gain of 2.68 dBi at a resonance frequency of 2.316 GHz.

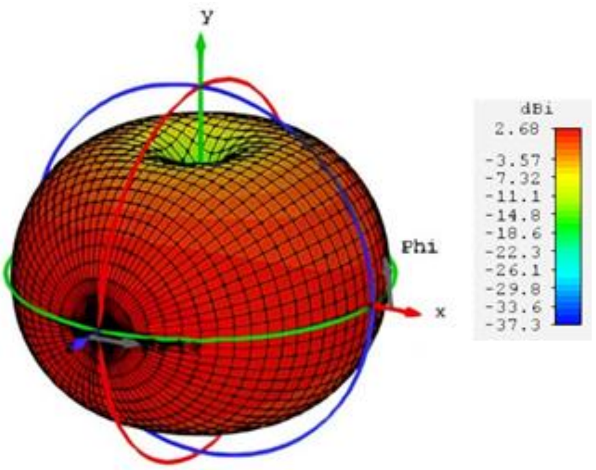

Figure 8. 3-D gain diagram of patch antenna at 2.316 GHz frequency

Figure 9 shows the proposed antenna of the surface current graph. The maximum surface current amplitude is found to be 150 dBµA/m at 2.316 GHz resonance frequency.

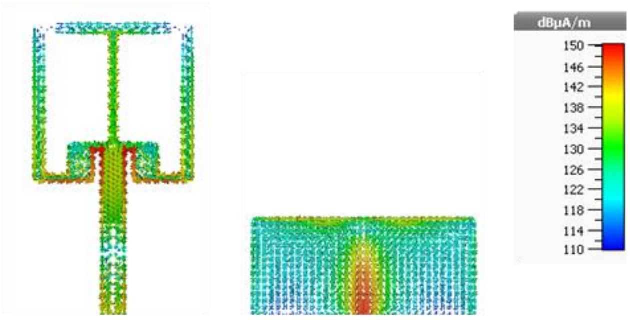

Figure 9. Graph of surface currents of the proposed antenna

Figure 10 shows the frequency-standing wave ratio (VSWR) of the proposed antenna, which is caused by reflections resulting from the impedance difference between the transmission line and the load. Regarding the amplitudes of the transmission signal and the reflected signal; a standing wave occurs when the maximum and minimum points overlap. VSWR is found by proportioning the maximum and minimum voltage levels of this standing wave.

It is desirable that the VSWR is less than 2. Antenna II does not radiate. The VSWR value is 1.37 at a frequency of 2.405 GHz for antenna II, and the VSWR value is greater than 2. The VSWR value is 1.16 at a frequency of 2.64GHz for antenna III. The VSWR value of the proposed antenna at 2.31 GHz resonance frequency is found to be 1.17.

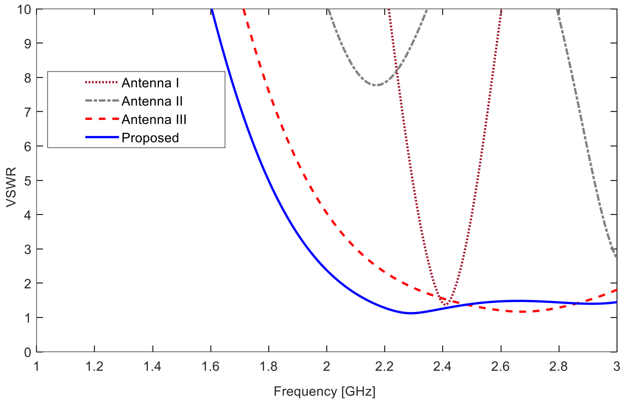

Figure 10. Graph of standing wave ratio (VSWR) of the proposed antenna

The bandwidth, return loss, directivity gain, and VSWR of the antennas compared in this paper are given in Table 2. It is seen from the table that the proposed antenna reaches the maximum bandwidth.

Table 2. Comparison of antennas

Parameter	Antenna I	Antenna II	Antenna III	Antenna IV
Center Frequency	2.405 GHz	-	2.64 GHz	2.31 GHz
Bandwidth	60 MHz	-	300 MHz	979 MHz
Return Loss	-16.37 dB	-	-27.39 dB	-24.529 dB
Directivity Gain	6.3 dBi	-	2.87 dBi	2.68 dBi
VSWR	1.37	-	1.16	1.17

4. Conclusion and Suggestions

Microstrip antennas are preferred in communication systems because of their easy manufacturability, low-cost effect, and small volume antennas. This paper introduces the slotted antenna operating in the ISM 2.4 GHz band (2400-2485 MHz) for usage in wireless and mobile communications. When the measurement results are compared with the results obtained from the CST Microwave Studio program, the results are found as consistent with each other. The proposed antenna has a bandwidth of 979 MHz at -10 dB at a resonance frequency of 2.316 GHz, and a directivity gain of 2.68 dBi, which gives the best results compared with the Antenna I-II and III designs. As can be seen from the results, opening slots on the antenna increased the bandwidth and had a positive effect on the gain value. The antenna is suitable for usage in the ISM band, which is widely used in wireless communication systems.

Contributions of the authors

All authors contributed equally to the study.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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