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Design and Simulation of 4 × 1 Microstrip Patch Antenna Array for X-Band Applications

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ABSTRACT

This paper presents the design and simulation of a 4 × 1 Microstrip Patch Antenna (MPA) array. A Microstrip Patch Antenna arrays, is the type of antenna used for gain enhancement of MPA. The design of the array may be 2 × 1, 4 × 1, 6 × 1, or 12 × 1, etc. depending on the application requirements. This work, started with the design of single-element MPA using copper and FR-4 material. The result obtained showed that, the single-element MPA antenna resonates at 10.164 GHz and reflection coefficient of -23.113, 544.75 MHz bandwidth and a low gain of 1.84 dB. To enhance the inherent problem of low gain in the MPA antenna design, the four-port power divider was designed and simulated. However, the four different single-element MPA with the same dimensions were designed and incorporated with the designed four ports power divider and formed a 4 × 1 antenna array. After the simulation, the result showed that the 4 × 1 antenna array resonates at 10.06GHz, at a reflection coefficient of -17.18, a bandwidth of 420MHz and the Gain of 7.33 dB. This result showed that the 4x1 antenna array had gained improvement over single-element MPA from 1.84 dB to 7.33 dB.

INTRODUCTION

Microstrip patch antenna (MPA) are categorized by attractive features which include: low cost and small in size, however, it has some drawbacks of low directivity, small gain, low efficiency, narrow bandwidth and low power handling capacity (Balanis, 2015) Improving the bandwidth, gain and directivity in antenna design has become an important issue. (Balanis, 2015). The problem of narrow Bandwidth (BW) and low gain of MPA can be solved using a thick layer of dielectric substrate with a low dielectric constant, defective ground structure, array and rectangular slot techniques on the patch to improve the gain and BW (Hui LI. et al., 2017)(Gupta, 2014). To support certain applications, various shapes of conducting patches such as circular, square, rectangular, dipole, elliptical and triangle are being used to design MPAs. In the design of an MPA array, a Power divider is used to split or divide the input signal equally depending on the number of ports (Dong, 2023.). The Power dividers can be defined as passive microwave components used to divide the input power equally at all ports (A. Sardi, 2015). The divider may have three ports, four ports, or more, and maybe (ideally) lossless. (A. Sardi, 2015). A power divider is normally used in radar technologies and multichannel radio frequency systems (Pozar, 2012). As stated earlier, an array antenna is used for enhancing the bandwidth (BW) and the gain of MPA. The design of the array may be 2 × 1, 4 × 1, 6 × 1 or 12 × 1, etc. depending on the application requirement. Many researchers have designed various antenna arrays which include: The design of an element patch array antenna at 2.4 GHz as reported in (Jagadish Khanal, 2019.). Another work in (Pra (G.V.P Pranathi, 2015.) designed 2 × 1 and 4 × 1, antenna arrays to work in the frequency range of 12 GHz. In the MPA array design, the insert feeding method was used for the patch because of its convenience in impedance matching (G.V.P Pranathi, 2015.). Also, in the MPA array, the Power divider excited with a 50 Ω source was used to feed the 2-element and 4-element patch array antenna (G.V.P Pranathi, 2015.). A different researcher stated that the design of the feed network plays a vital role in the array design because any mismatch in the power divider network can result in very poor performance (J. &. A. Floch, ,2013). Another work (Nella, 2016.), (Rene Kullock, 2020.) presents the design of a rectangular MPA array of 2 × 1 and 4 × 1, with a center frequency of 2.45 GHz for RFID applications. It has been observed that the 2 × 1 linear antenna array has improved directivity, and gain, and has better radiation patterns.

However, this work will focus on the design and simulation of a 4 × 1 antenna array to solve the inherent drawback of low gain and narrow bandwidth in the MPA design.

Model design

This work consists of the design of single element MPA, four-port power divider design and 4 × 1 MPA array design.

Single element MPA

In the design of MPA, Copper and FR-4 substrate material was used as conductive patch, ground plane and dielectric material respectively, due to its low cost and easy fabrication of Copper material when compared with that of gold and silver. Figure 1. shows the pictorial view of the proposed single-element MPA.

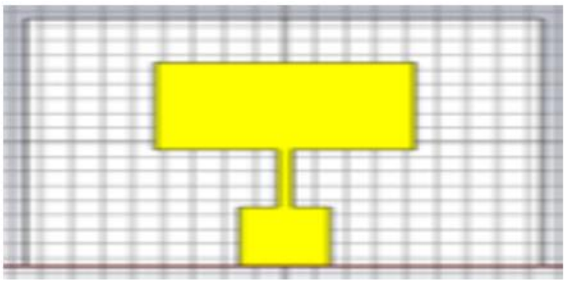

Figure 1: Proposed single Element MPA design

4 × 1 Power divider

Figure 2. shows the pictorial view of a proposed 4 × 1 Power divider model which shows four different ports. A microstrip feed line was used to feed the conductive patch elements.

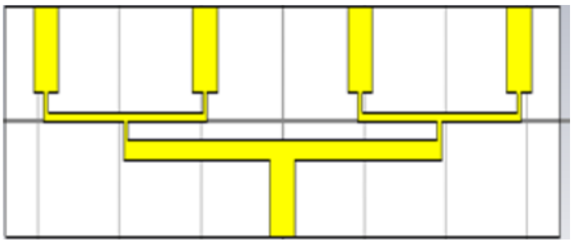

Figure 2: Proposed 4 × 1 Power divider

Antenna array

The proposed design of a 4 × 1 antenna array is shown in the pictorial view of Figure 3. The 4 - single element patch antenna was added to the 4-ports power divider in order to form 4 × 1 antenna array.

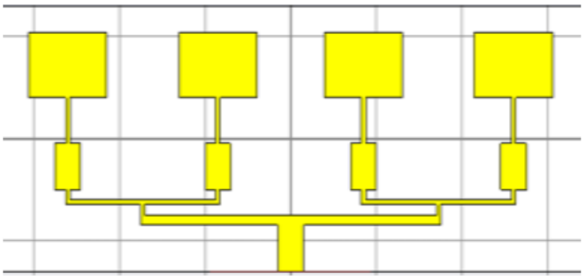

Figure 3: Proposed 4 × 1 Antenna array

Antenna design consideration and dimensions

Patch Element and Substrate dimensions

The dimensions of the rectangular patch element can be obtained using the mathematical equations adopted from (Abubakar A. A., 07-09 April, 2021) and (Abubakar A. A., November, 01-03, 2021) as follows:

The design was conducted on a 1.6 mm height FR-4 substrate, which had a tangent loss of 8.854 ×10-12 and a relative permittivity ε_r = 4.4. The patch's width and length as 'L_p' and 'W_p,' respectively, and the effective permittivity ε_{eff}. The dimensions of the patch were calculated using the following formulae (Abubakar A. A., 07-09 April, 2021) and (Abubakar A. A., November, 01-03, 2021) .

Width of the Patch element (Wp)

The width of the patch element was calculated using equation (1) as follows:

$$W = \frac{v_o}{2f_c}\sqrt{\frac{2}{1+\varepsilon_r}} \qquad (1)$$

Where:

W, is the width of the patch element.

V_o, is the velocity of light, a constant whose value is $3\ X\ 10^8\ m/s$.

f_c, is the centre frequency of the X-band and is given as fc = 8+12/2 = 10 GHz.

$\mathcal{E}r$ is the dielectric constant of the material which is FR-4 lossy substrate whose value is 4.4.

Therefore, by substituting the value of $\mathcal{E}r$, Fc and Vo into (1) the width of the patch element (wp) is given as,

$$W = 9.128709285\ mm$$

Effective dielectric constant (Eeff*).*

Moreover, the effective dielectric constant $\mathcal{E}_{eff}$, was also calculated from (2) as follows:

$$\mathcal{E}_{eff} = \frac{1+\varepsilon_r}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{-1/2} \qquad (2)$$

By substituting the value of Er and w into (2) the value yield to be

ε_{eff} = 2.497

Change in Length (ΔL)

Therefore, change in length was obtained using (3) as,

$$\Delta L = 0.412\text{h}\frac{(\varepsilon_{\text{eff}}+0.3)(\frac{\text{W}}{\text{h}}+0.264)}{(\varepsilon_{\text{eff}}-0.258)(\frac{\text{W}}{\text{h}}+0.8)} \quad (3)$$

After substituting the value Eeff, W and the height (h) the change in length result is,

$$\Delta L = 0.7055$$

Effective Length ($\mathbf{L_{eff}}$)

Also, the effective length of the patch element L_{eff}, was calculated using (4).

$$L_{eff} = \frac{v_o}{2f_c\sqrt{\varepsilon_{eff}}} \quad (4).$$

By substituting the value of the constant given into (4) the effective length of was obtained to be

$$L_{eff} = 9.49$$

Change of Length Effective ($\Delta\mathbf{L_{eff}}$)

The change of Length effective of the Microstrip patch antenna was calculated using (5).

$$\Delta L_{eff} = L + 2\Delta L \quad (5)$$

When substituting the value of L and ΔL, the change in length effective result is given as,

$$= 7.98 + 2(9.49)$$

$$\Delta L_{eff} = 26.96mm$$

Actual Length (L)

The actual length of the patch element L,was calculated using (6).

$$L = \frac{v_o}{2f_c\sqrt{\varepsilon_{eff}}} - 2\Delta L \quad (6)$$

$$= \frac{3 X 10^8}{2(10X 10^9)\sqrt{2.5}} - 2(0.7055)$$

Substituting the value of Fc, Vo, Eeff and ΔL into (6) the actual length of the patch element was calculated to be:

$$L = 7.98mm$$

However, the calculated value of the actual length of the patch element was 7.98mm, using this length value in the design the resonant frequency happened to be less than the desired resonant frequency. Various adjustments were made for the antenna to resonate at the desired resonant frequency (10GHz), in which the antenna resonates at 10.164 GHz when Lp equals 6.422mm.

Dimensions of Substrate Material

The calculated dimensions of the substrate material used in the proposed design will be presented as follows:

Length of the substrate material (Ls)

The length of the substrate material used in the proposed design was calculated using (7).

$$ls = 6Sh + lp \quad (7)$$

By substituting the value of h and lp the Ls value was obtained to be,

$$ls = 16.022mm$$

Width of the substrate material (ws)

The width of the substrate material was calculated using (8) as,

$$Sw = 6Sh + wp \qquad (8)$$

After substituting the value of Sh, and wp the width of the substrate material happened to be

$$Sw = 6\ x\ 1.6 + 9.122$$

$$Sw = 18.722mm$$

Ground Plane Dimensions of Microstrip Patch Antenna

The length Gl, and width Gw, of the ground plane should be the same as the dimension of the substrate as presented in (9) and (10). As adopted from [7].

Ground plane length (Gl)

$$Gl = Sl \qquad (9)$$

By equating the value of substrate length and ground plane, the length value of ground plane obtained to be,

$$Gl = 16.022mm$$

Ground plane width (Gw)

$$Gw = Sw \qquad (10)$$

Also, by equating the width value of the substrate and the ground plane, the Gw obtained to be,

$$Gw = 18.722mm$$

Port Dimension of the proposed design

The width and length of the proposed design were calculated using (11) and (12) as presented as follows:

Width of the port (wpt)

$$Wpt = 6Fw \qquad (11)$$

By substituting the value of feed line width (Fw) which is 3 in to (11), the wpt yields to be,

Wpt = 18mm.

Length of the port (Lpt)

The length of the port of the proposed design was calculated using (12) as,

$$Lpt = 5St + Gt \qquad (12)$$

Substituting the value of substrate thickness (St) which is 1.6mm and the value of ground plane thickness (Gt) which is 0.035mm, the value of port length gives as,

Lpt = 8.035mm

By using equations provided in [23] and [24], the physical parameters of the antenna were obtained and the optimized values are; W_p = 9.128709285mm, L_p = 6.422mm, W_s = 18.722mm, L_s = 16.022mm, W_f = 3.0 mm, L_f = 4.0 mm, and the height of the substrate h = 1.6 mm. Table 1. shows the various calculated dimensions used in the design of single element MPA.

Table 1. Calculated Dimension of MPA

Parameters	Values
Patch length (Lp)	6.422 mm
Patch width (Wp)	9.122 mm
Patch thickness (St)	0.035 mm
Substrate Length (Ls)	16.022 mm
Substrate width (ws)	18.722 mm
Substrate height (hs)	1.6 mm
Ground plane length (Gl)	16.022 mm
Ground plane width (Gw)	18.722 mm
Ground plane height	0.035 mm
Feed line length (Lf)	4.0 mm
Feed line width (Fw)	3.0 mm
Feed line thickness	0.035 mm
Input impedance	49 mm
Port length (Lpt)	8.035 mm

Dimensions of the proposed 4-port power divider

The calculated dimensions of the proposed 4 × 1 power divider are presented in Table 2.

RESULTS AND DISCUSSION

This section presents the simulated result obtained from the proposed design of single element MPA, 4 ports Power divider and 4 × 1 antenna array. The results include: Reflection coefficient (S_{11}), Bandwidth (BW) voltage wave standing ratio (VSWR) and gain.

Reflection coefficients (S_{11})

The reflection coefficient (S_{11}) plot of the single element MPA, 4-port power divider and the **4** × **1** antenna array are presented as follows:

Reflection coefficient (S_{11}) of Single element MPA

The reflection coefficient's (S_{11}) plot of the single element MPA is presented in Figure 4.

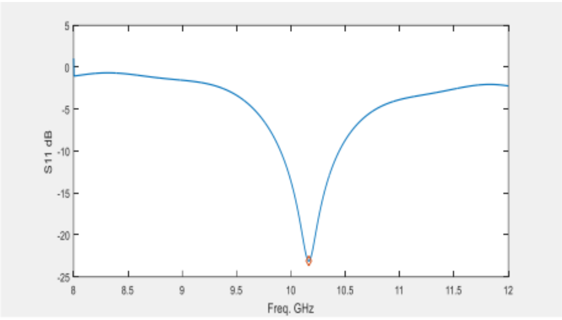

Figure 4: S_{11} Result of single-element antenna

Table 2. (4 × 1) **Power Divider Dimensions**

Four port power divider dimensions	
Parameters	Values
Substrate height (h)	1.6 mm
Substrate length (Ls)	12 mm
Substrate width (Ws)	68 mm
Feed line length 1. (lf1)	4.5 mm
Feed line length 2 (lf2)	4.0 mm
Lf3 = Lf4 = Lf5	1.0 mm
Lf6 = Lf7	0.5 mm
Lf8 = Lf9	1.0 mm
Lf10	4.5 mm
Lf11 = Lf12	1.0 mm
Lf13 = Lf14	4.5 mm
Thickness of the feed line (t)	0.035 mm
Feed line width (wf1)	3.0 mm
Feed line width (wf2)	40 mm
Wf3 = wf4	0.5 mm
Wf5 = wf6	20 mm
Wf7 = wf8	0.5 mm
Wf9 = wf10	3.0 mm
Wf11 = wf12	0.5 mm
Wf13 = wf14	3.0 mm

From Figure 4, the antenna with a single element patch resonates at 10.164 GHz with a reflection coefficient (S_{11}) of (-23.113 dB). This result indicated that the antenna can be applied for x-band applications since the range of x-band is from 8GHz to 12GHz.

Reflection coefficient (S_{11}) of Antenna Array

The reflection coefficient (S_{11}) plot of the Antenna array is presented in Figure 5.

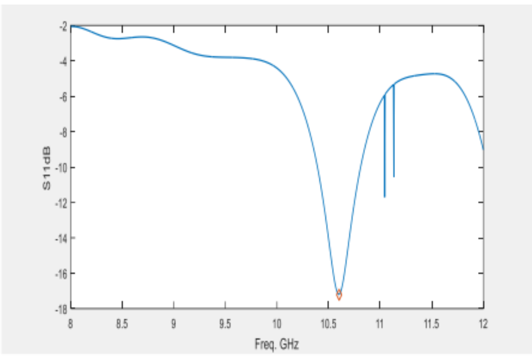

Figure 5: S_{11} Result of 4x1Antenna Array

From the result in Figure 5, the array antenna resonates at the frequency of 10.6 GHz and the reflection coefficient of (-17.18 dB). This implies that the antenna can be applied for x-band applications.

Bandwidth of the Proposed Antenna

The Bandwidth of the proposed design of MPA using a single element, 4 ports power divider and the 4 × 1 antenna array is presented as follows:

Bandwidth of MPA using Single Element

The Bandwidth of the proposed design of MPA using a single element is presented in Figure 6.

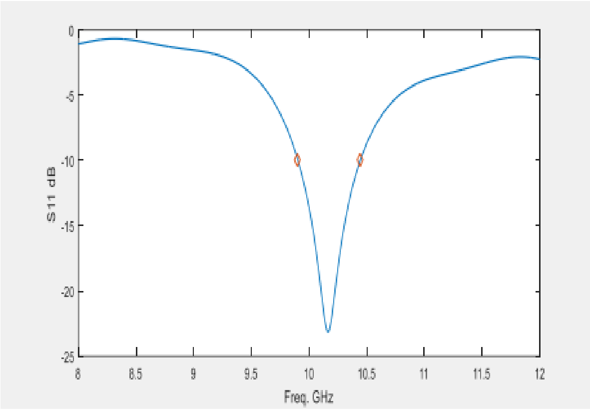

Figure 6: Bandwidth of single patch antenna

From Figure 6, the result showed that the MPA using a single element has lower and upper frequencies of 9.8993 GHz and 10.444 GHz respectively. From which the bandwidth was obtained as 544.75 MHz This is by subtracting lower from upper as: (10.444 GHz - 9.8993 GHz) = 0.5447 GHz.

Bandwidth of 4 × 1 Antenna array

The Bandwidth of the proposed design of antenna array is presented in figure 7.

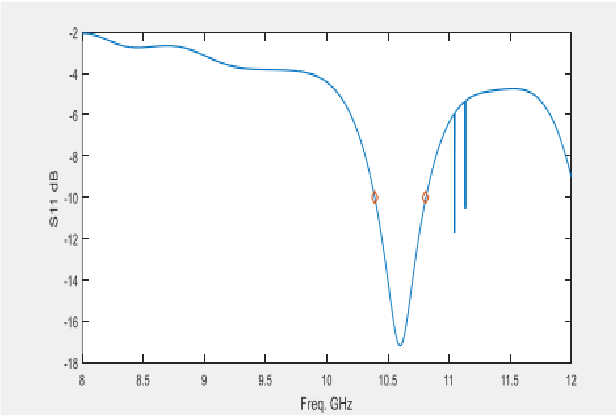

Figure 7: Bandwidth of 4 × 1 Antenna array

From Figure 7, the bandwidth of the 4x1 Antenna array was obtained to be 414 MHz, this is by subtracting the minimum frequency from the maximum frequency as:(10.806 GHz - 10.392 GHz) = 0.414 GHz.

Gain of the Proposed Antenna Design

The Gain of the proposed single-element MPA and 4 × 1 antenna array is presented in Figure 8 and 9.

Gain of the Proposed MPA using a single element

The Gain of the proposed element MPA is presented in Figure 8.

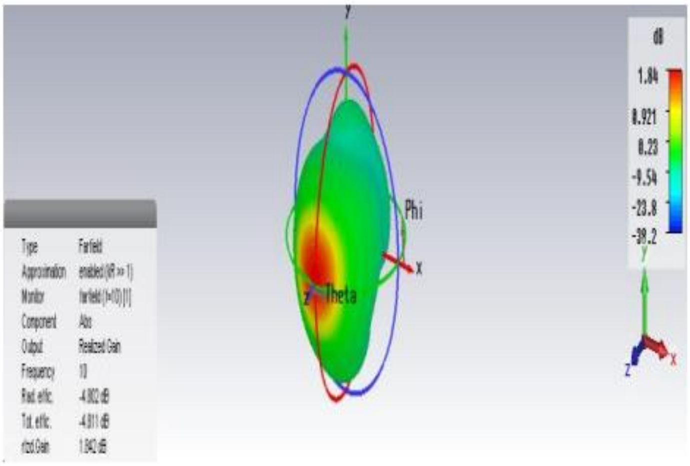

Figure 8: Gain of single-element MPA

Figure 8 shows the gain result of single-element MPA. The gain obtained was 1.8dB. From this result, it was indicated that with the use of a single element, the MPA has a low gain.

Gain of the Proposed 4 × 1 Antenna array

The Gain of the proposed 4 × 1 Antenna array is presented in Figure 9.

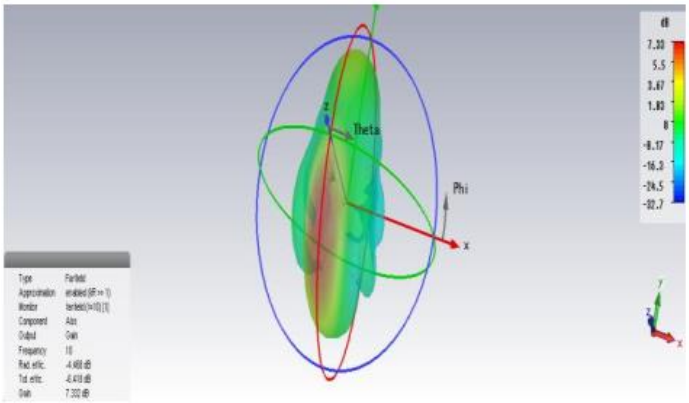

Figure 9: Gain of the 4 × 1 antenna array

From Figure 9, the result shows that the gain of the 4 ×1 antenna array was 7.33dB, which is greater than that of MPA using a single element.

Voltage Standing Wave Ratio (VSWR) of the Proposed Antenna

The Voltage Standing Wave Ratio (VSWR) of the proposed design of single-element MPA and 4 × 1 antenna array is presented in Figure 10 and 11.

VSWR of the proposed MPA using single element

The VSWR of the proposed design of MPA using a single element is presented in Figure 10.

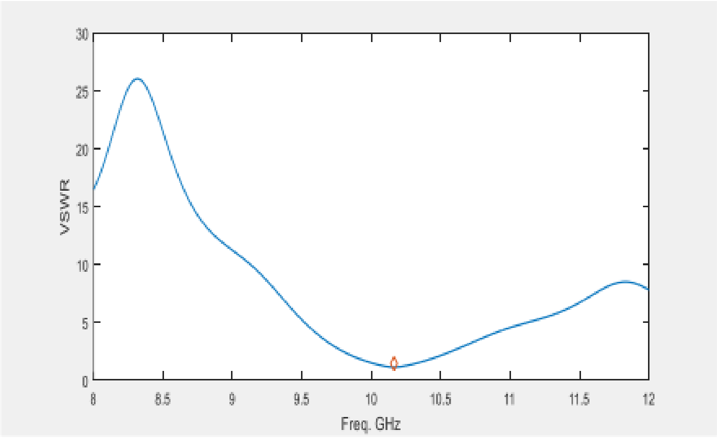

Figure 10: VSWR of MPA using a single element

Figure 10 shows the voltage standing wave ratio VSWR result of the single element MPA which was obtained to be 1.1502.

VSWR of the Proposed 4 × 1 Antenna array

The VSWR of the proposed design of a 4 × 1 antenna array is presented in figure 11.

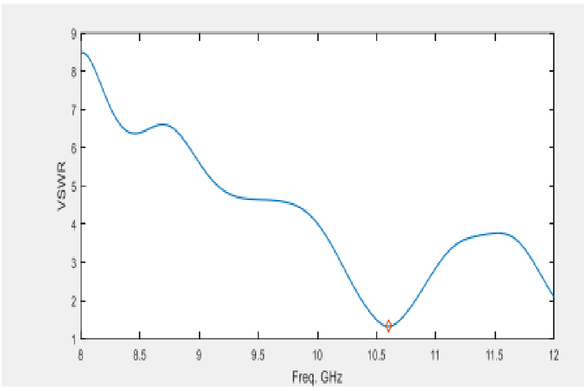

Figure 11: VSWR of the 4 × 1 Antenna array

Figure 11 shows the result of VSWR of the 4 × 1 antenna array. The result obtained was 1.32.

However, all the VSWR results of single element MPA and 4 × 1 antenna array were obtained to be 1.1502 and 1.32 respectively. This shows that all the values are less than 2. Since the recommended range value of VSWR should be between 1.0 to 2.0. Therefore, all the two antennas have a better VSWR.

CONCLUSION

The simulated results obtained from the proposed design of a single element Microstrip Patch Antenna (MPA) using copper and a 4 × 1 antenna array reveal specific characteristics, including a resonant frequency at 10.164

GHz, reflection coefficient (S_{11}) value of - 23.113 dB, a bandwidth of 544.75 MHz, VSWR of 1.1502 and gain of 1.84 dB.

Table 3. Comparison of single-element MPA and 4 × 1 array antenna design

Parameters	MPA single element	4x1 antenna array
Fr. GHz	10.164	10.06
S11 dB	-23.113	-17.18
BW MHz	544.75	414
VSWR	1.1502	1.32
Gain dB	1.84	7.3

This integration leads to a significant improvement in the gain of the MPA, elevating it from 1.84 dB to 7.33 dB. FR-4 Substrate material having a dielectric constant of 4.4 and Copper material as a conductive patch were used for all the model designs. The Computer Simulation Technology (CST) software and MATLAB were used for both simulations and the generation of the results for the proposed design. The present work can be applicable where the high gain antenna is needed. This work only focuses on gain enhancement, but there is a need to apply bandwidth enhancement techniques to improve the bandwidth such as; defective ground structure (DGS), slot, and Slit where necessary.

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