Novel five-patch compact microstrip Yagi-alike antenna for Ka-band applications

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ABSTRACT

This paper discusses the process of designing and fabricating a novel compact microstrip patch Yagi-like antenna having five-patch radiating element at operating frequency 31 GHz with a bandwidth of 1 GHz. The developed design aims to optimize the antenna performance. The overall dimension of the antenna being 17× 14 × 0.8 mm^3, based on RT Duroid 5880 substrate having dielectric loss tangent of 0.0009 and relative permittivity 2.2. The effectiveness of the performance of proposed design was evaluated using the electromagnetic solver Ansoft high-frequency structure simulator (HFSS) and validated by the laboratory measurements on the antenna prototype. The measured results are consistent with the simulation prediction. The designed antenna achieved directional radiation and the performances with voltage standing wave ratio (VSWR) < 1.32, return loss -17 dB and gain of 6 dBi. The measured results are compared with those existing in literature. The proposed antenna design has proven very effective in terms of the intended design and parameters which make it suitable for satellite application and wireless communication.

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1. INTRODUCTION

The researchers' goal is to create a multi-band frequency operational microstrip antenna for fifth and sixth generation wireless communication technologies such as the internet of things (IoT), artificial intelligence (AI), blockchain technology, cellular communication, and so on. Such problems are compounded when we correct one parameter measurement and the other one deteriorates. Consequently, efforts must be taken to guarantee that the antenna features the greatest reach and value. Researchers foresee difficulties in reducing free space travel loss, insulation loss, metal loss, and radiation loss while preserving the prominent features of antenna. The International Telecommunication Union (ITU) assigns different range of frequency for high thoroughput satellite communication [1]-[3]. High thoroughput satellites require antenna and sensors that are compact in size, easily integratable, low cost, high gain and bandwidth, optimum directivity and radiation characteristics.

In the past few years, thanks to the researchers, a stabilized and efficient technnique of microstrip patch antenna has developed. In this work, we present design and fabrication of a novel compact microstrip patch Yagi-like antenna having five-patch radiating element at operating frequency 31 GHz, with desired features. The first design along with the theoretical model of microstrip antenna, appeared in 1950 but it received appreciable attentions by researchers in the year 1970. High dimensional accuracy is still difficult due to the requirements of the power and signal polarization while using Ka-band at 26.5 GHz-40 GHz [4]-[9]. The microstrip patch antenna consists of a dielectric material in between a metallic surfaces in the role of ground and patch. The fringing fields between the two conductors causes the radiation. Wide band Ka-band astrolink, spaceway, and teledesic technologies aim to deliver multimedia services at terminals, the size of desktop computers [10]. The carrier frequencies will move to higher bands as the demand for bandwidth rises. For the deployment of well-designed ground systems, network connection dependability and resources to counteract the various weather impacts [11]-[15], suitable planning is required.

The first microstrip patch quasi-Yagi-Uda antenna was put out by Qian and colleagues in 1998 [16], and it is still a crucial topic in current research. This Yagi-Uda-like antenna combines the adaptability of the microstrip method with the superior radiation characteristics of the Yagi-Uda antenna. A microstrip line can be used to directly realize the Yagi-Uda antenna's feeding arrangement [17]. Designing phased-array and multiple-beam antennas may benefit from using a Yagi-Uda antenna array [18], [19]. It is possible to create a Yagi-Uda antenna array in microstrip patch form and use it in the mobile satellite (MSAT) area [20], [21].

This work proposes a reduced size rectangular patch antenna for use in Ka-band at 31GHz. Ramli *et al.* [22] have reported antenna design and its performance using different substrate material for 5G applications and have concluded that patch antennas are the ideal method to handle many challenges in Ka-band applications owing to their design advantages and inexpensive cost. Gain and bandwidth are largely decided by the nature of dielectric material and the thickness of the substrate. Giri *et al.* [23] has proposed combination of modified circles with concentric in-plane slots on a substrate size of 38×31 mm and have reported 3.1 GHz and 1.7 GHz bandwidth at resonating frequency of 28 GHz and 35 GHz. Yon *et al.* [24] discussed the advantages and disadvantages of microstrip antennas, as well as strategies to improve their performance in fifth generation communication using parasitic patches, arrays, and loaded antennas. Frequency reconfigurable mm wave microstrip patch antenna using MEMS switch mounted in between two L-shaped strips forming U-shaped structure has achieved 9 dB of gain and upto 75% of efficiency in the Ka band frequency from 26.5 GHz to 40 GHz [25]. Ul and Ullah [26] discussed the layout and function of cellular communication, and other patch antennas as well, including radiation patterns and polarization. An antenna constructed, simulated, and optimized using high-frequency structure simulator (HFSS) with substrate RT5880 with relative permittivity 2.2 and thickness 0.508 mm achieves 8 dB gain and a maximum reflection coefficient of -45 dB throughout the frequencies 27.28 GHz to 28.71 GHz [27]. Al-Kharusi *et al.* [28] provided an explanation of microstrip patch antenna composition and its determining parameters. The advantages of inserting air gaps inside the dielectric material to boost efficiency and how they affect gain and bandwidth were examined. A mm wave microstrip antenna has been developed at resonance frequency 28 GHz with RT5880 Rogers substrate material using HFSS. The designed antenna has achieved gain higher than 13 dB and return loss less than -10 dB [29]. Kumar *et al.* [30] has studied the effect of slots in the ground plane and patch on the resonance frequency, impedance bandwidth, gain, side lobe and radiation efficiency and have concluded that slot width and the resonance frequency have inverse dependence. Antenna with L-shaped strip fed with microstrip line designed for resonating frequency 2.48-5.9 GHz has reported an exact return loss of -10 dB [31]. A design based on two layers electromagnetically coupled rectangular patch inset fed with microstrip line has realized low return loss. Investigations have been done by increasing the thickness of substrate and patch and selecting substrate having lesser dielectric constant [32]. For an antenna measuring 5×4×1.575 mm, with an electrical size of $0.458\lambda 0 \times 0.366\lambda 0 \times 0.144\lambda 0$, where $\lambda 0$ denotes the wavelength in free space at 27.50 GHz, impedance bandwidths of 1.34 GHz and 2.26 GHz are reached in the 28 GHz and 38 GHz bands, respectively. Resonating frequency of antenna being 28.19 GHz and 38.56 GHz, with observed gain of 7.2 dB and 7.65 dB respectively. Because of its small size, the suggested antenna is an excellent contender for 5G communications [33].

Wang *et al.* [34] specified an antenna with high bandwidth and gain, with shorting of two sides, using cavity mode analysis and have realized gain upto 9.7 dBi, bandwidth of about 13% and a low cross polarization of -25 dB. The use of Rogers RT/Duroid 5880 and Taconic thin layer chromatography (TLC) makes antenna about 90% efficient. FR4 has a high bandwidth of 2 GHz, but Rogers RT/Duroid material has a reflection coefficient of -36 dB, gain of 5.9 dB, voltage standing wave ratio (VSWR) of 1 and bandwidth of 1.8 GHz [35]. Colaco *et al.* [36] designed a circular microstrip patch antenna with a microstrip feed line at 28.5 GHz resonance, suitable for fifth generation applications, employing Rogers RT/Duroid 5880 substrate of thickness of 0.6 mm. Analysis indicated a return loss of -32.86 dB, expanded bandwidth of 1.64 GHz, high gain of 10 dB, and nearly 100% antenna radiation efficiency. A meander line slot antenna operating at frequency 5.45 GHz to 5.7 GHz comprising a circular patch on total volumetric dimension of 15 × 14 × 1.57 mm3 has reported -10 dB impedance bandwidth, 1.3 dBi gain and about 84% efficiency in radiation [37]. Another work on microstrip patch antenna using two electromagnetically coupled patches has reported omnidirectional radiation pattern, maximum radiation loss of -47 dB and a good impedance match of 3.2 units [38].

Kiran *et al.* [39] designed an antenna resonating at double frequencies 28 GHz and 50 GHz, with return losses of -21dB and -31dB, respectively, a gain of 2.6 dB, volumetric dimension of antenna being 6.285 × 7.235 × 0.5 mm3. Darboe *et al.* [40] defined the design structure and dimension and determined the operating frequency based on simulation findings at 27.954 GHz and a reflection coefficient of -13.48 dB. Ponnapalli *et al.* [41] described in depth their architecture and slot orientation. Microstrip antenna having parasitic patch and mettalic elliptical shaped stripline achieves about 6% fractional bandwidth in the K-band frequency range using a six-way power division element. Measurement findings indicate a gain of 21.4 dBi. Work of Sehrai *et al.* [42] based on 64-element array antenna has realized a gain of 21.2 dB at resonating frequency of 37.2 GHz. Lodro *et al.* [43] proposed mm wave multi band patch antenna with dual resonance frequency 37 GHz and 54 GHz and gain of 6 dBi with a small form factor of 7.2 × 5.0 × 0.787 mm3 using simulation software CST MWS. An antenna developed for K band applications with gain of 21 gain and a bandwidth of 1 GHz is reportedly equipped with a 6 × 5 close coupled planar arrays [44]. Kim and Kim [45] worked on the substrate and cavity and have reported the dimensions of their design as well as the acquired findings. Hussain *et al.* [46] presented a small broadband antenna based on MIMO configuration for use at 28 GHz fifth generation applications employing Rogers RT/5880. A design of antenna at 30 GHz fed with microstrip line for 5G connectivity offered a gain of 8.45 dB and a reflection coefficient of -8 dB. It has a high directivity of 50 and a VSWR of 2.3 across a bandwidth of 3.5 GHz [47].

For better presentation, the paper is arranged in four parts. Section 2 showcases methodology of the steps used for the design of antenna. Section 3 describes the simulation results due to electromagnetic solver HFSS and the performance measurement on the antenna prototype. Finally, we present conclusion with findings and future direction in section 4.

2. METHOD

2.1. Theoretical design

Antenna's design and fabrication process were completed in four steps-theoretical design, software design, fabrication of antenna and performance measurement. First, the dimensions of the proposed antenna have been calculated using basic equations [48]. The width and length of the antenna patch follows as:

$$width\ of\ patch(w) = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \quad (1)$$

$$Length\ of\ patch(L) = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{w}{h}+0.8\right)}\right) \quad (2)$$

resonant frequency is determined through the relation:

$$f_0 = \frac{c}{2L_e\sqrt{\varepsilon_r}} \quad (3)$$

effective length of the antenna including the length extension coming from the fringing effect of the electric field:

$$effective\ length\ (L_e) = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} \quad (4)$$

subsequent to the effective length, the effective dielectric constant is determined as:

$$\varepsilon_{eff(\text{effective dielectric constant})} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{w}\right)}}\right] \quad (5)$$

were, $c = velocity\ of\ light,\ f_0 = resonant\ frequency,\ \varepsilon_r = substrate\ dielectric\ constant,\ h =$ substrate height, $L_e = effective\ length.$
The ground plane's dimensions follow as:

$$Lg = 6h + L \quad (6)$$

$$Wg = 6h + W \quad (7)$$

2.2. Software design

Stepwise design of antenna can be found in Figure 1. After assembling the copper metal ground and RT Duroid 5880 substrate material, copper patch was placed on the top of substrate, to realize the Yagi-alike structure. Then slots were cut the designated positions to finalize the design. Figure 1(a) depicts the proposed antenna configuration in sequential steps. It is made up of long and short patches and designed easy-to-implement branch structures. The proposed antenna is designed over a single-layered dielectric of size 17 × 14 × 0.8 mm^3. The first patch is 1.5 mm apart from the feed point and is of length 3 mm (step 1). The other four patches measure in length respectively 4 mm, 5 mm, 6 mm and 8 mm (step 2-6). All patches are of identical width of 1.2 mm. The non-uniform separation between the adjacent patches labelled as p_1, p_2, p_3, and p_4 are 1.2 mm, 1.6 mm, 1.0 mm and 1.8 mm. The fifth patch is 0.4 mm far from the end opposite to the feed point. Four identical square slots, labelled as S1, S2, S3 and S4, measuring 0.5 mm × 0.5 mm are cut out of the fifth and sixth patch (step 7-8). All five patches are branched out in a parallel configuration from a central patch. The middle patch of the proposed antenna functions as a dipole and receives the signal. The primary driving component of it is the patch. Two patches are referred to as the reflector and the director, respectively, depending on where they are relative to the central patch. The signal is focused on the middle patch by both the reflector and the director. A feed is used to excite in order to enable antenna radiate. The load antenna is matched to a microstrip line of 50 ohm impedance in order to power all-radiating patches.

The radiating element and the feed structure make up the HFSS design of antenna as shown in Figure 1(b). Five rectangular patches of varying sizes are used to create the radiating element in order to increase bandwidth. By adjusting the size of patches in the feeding section, antenna's impedance was matched. This comes after a prototype antenna that was made based on the outcomes of the HFSS simulations. The simulated bandwidth percentage of the proposed antenna is about 3.2% (30.5 GHz-31.5 GHz) with VSWR<2. The port isolation has improved over 13 dB across the operational frequencies with stable gain of 6 dBi.

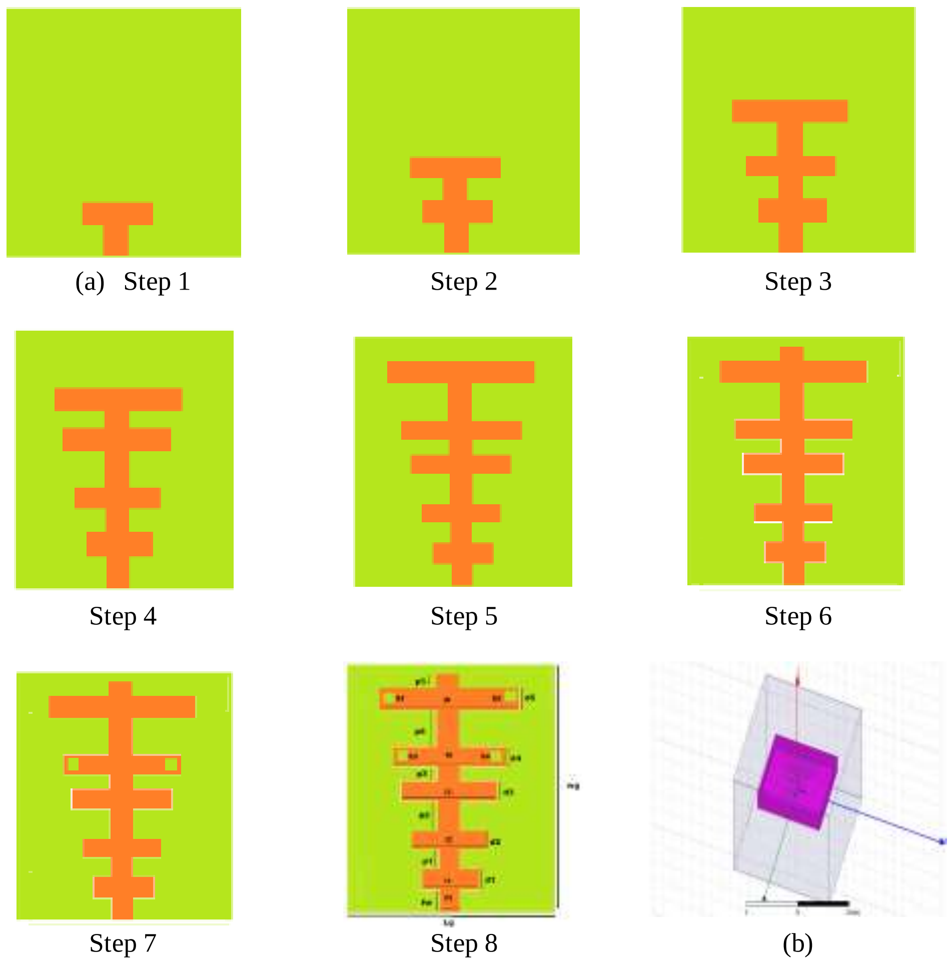
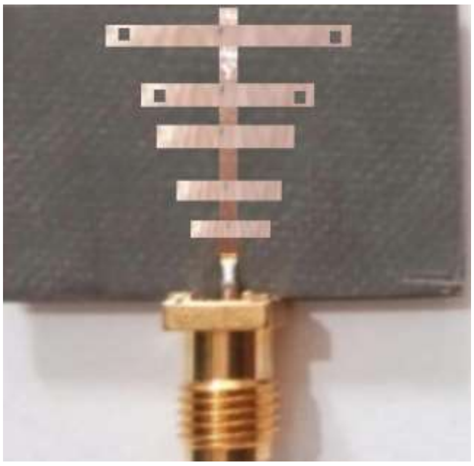


Figure 1. Stepwise design of the five-patch compact microstrip Yagi antenna (a) step 1-8 and (b) HFSS software design

2.3. Fabrication

The final software design is exported from the antenna design software. A milling machine is used to fabricate the antenna, with rotary cutters removing copper from two layered boards precisely according to the dimensions of the input file. Prototype of the antenna featuring above-mentioned optimized dimensions has been developed as shown in Figure 2. Figure 2(a) shows photograph of the fabricated antenna having frontal view and Figure 2(b) shows the back view. It is shown that the simulation design on HFSS and fabricated antenna both are identical.



(a)

(b)

Figure 2. Fabricated antenna (a) frontal view and (b) back view

3. RESULTS AND DISCUSSION

This work investigated the impact of slots on the non-uniform patches of a Yagi-alike structure antenna. While earlier works have reported the impact of slots on the patch of microstrip antenna, they have not explicitly looked into the influence of it on the patch of Yagi-alike design. We found that multi band operation correlates with the proposed design with good performances. The proposed method intended to have higher proportion of gain, VSWR and number of bands.

3.1. Simulation result and discussion

Figure 3 displays the simulation results. After design and simulation through HFSS the parameters of antenna were recorded. By altering the dimensions of particular parameters, the parametric analysis examined how their modifications affect the optimum performance of antenna. The parameter sweep function of the HFSS solver was used to examine the influence of slot position. Return loss, S11 versus frequency is shown for the five-patches in Figure 3(a), where S11 at 31.0606 GHz is -17.0753 dB. This implies that reflected signals won't have an impact on the sent signal. Furthermore, the insertion loss will be almost zero because the return loss is below -10 dB. Mostly, antennas are used with an optimal VSWR value of less than 2. The five-patch antenna's VSWR changes to 1.3257 at frequency 31.0606 GHz in Figure 3(b).

Frequency intervals in which an antenna meets specified parameters specification is referred to as its bandwidth. Two-dimensional radiation pattern for five-patch compact Yagi antenna is shown in Figure 3(c). The radiation pattern is at frequency 31 GHz on the plane $\varphi=0^o$ (red) and $\varphi=90^0$ (purple). Three-dimensional polar plot at 31 GHz shows a gain of 6.0507 dB in Figure 3(d). At frequency 31 GHz, the suggested antenna has realized a gain of 6.16 dB, and will provide better balance of range and will have the capacity to connect to nearby antennas placed at various heights with a coverage amounting to around 350^o. The quality factor being 31 in this case. The current distributions at various frequency values are shown in Figure 3(e), with the greatest tone (red colour) representing the strongest dispersion of surface current. It was observed that the distribution of current is obvious at the borderline of the patches at 31 GHz. Distribution of surface current was mostly focused at margins of inner rectangular slots. Surface currents on the margins of the slots make them more efficient than the feed line. Usually, surface current distribution along the patch lies between 0.5 A/m and 150 A/m.

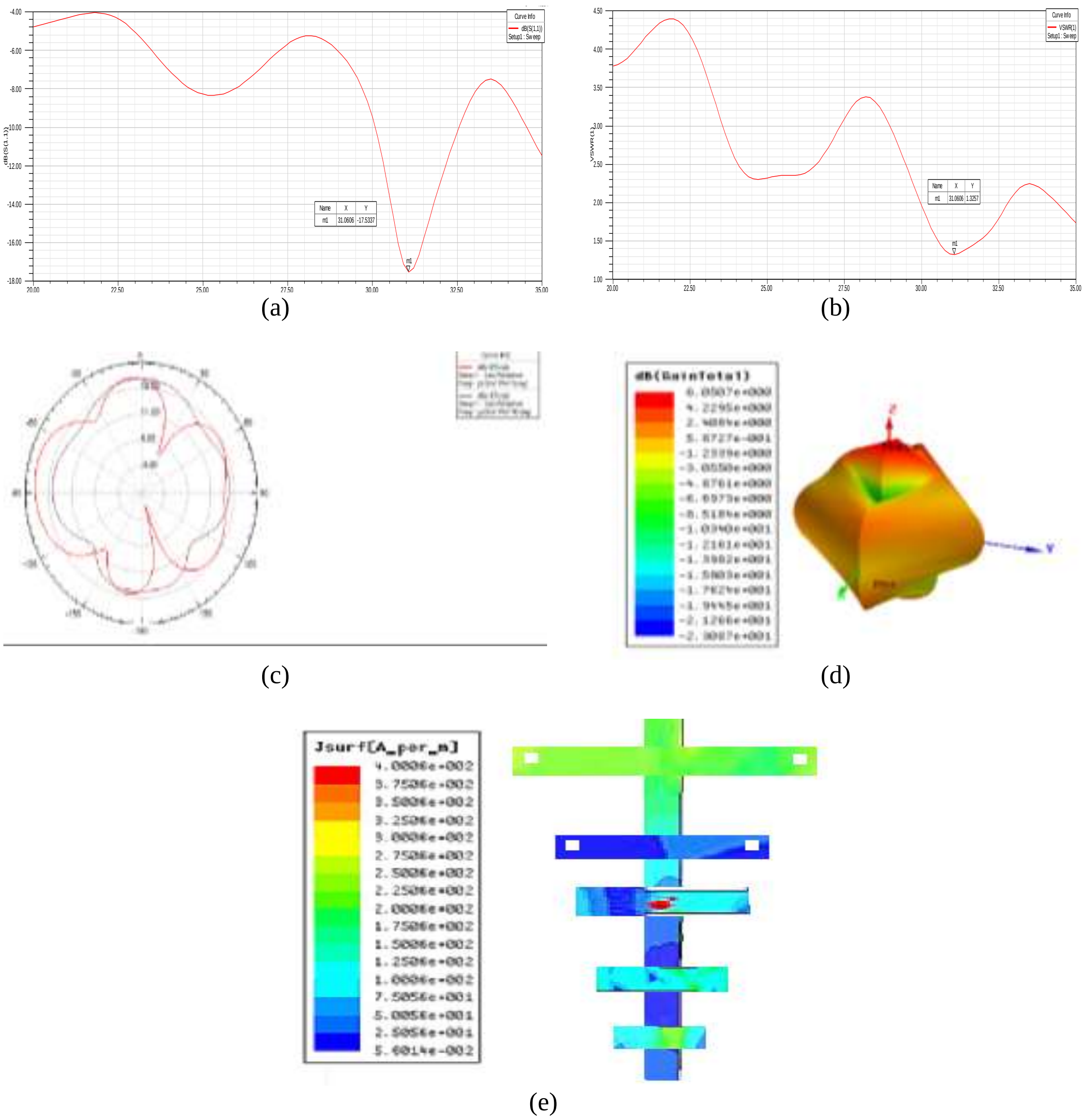
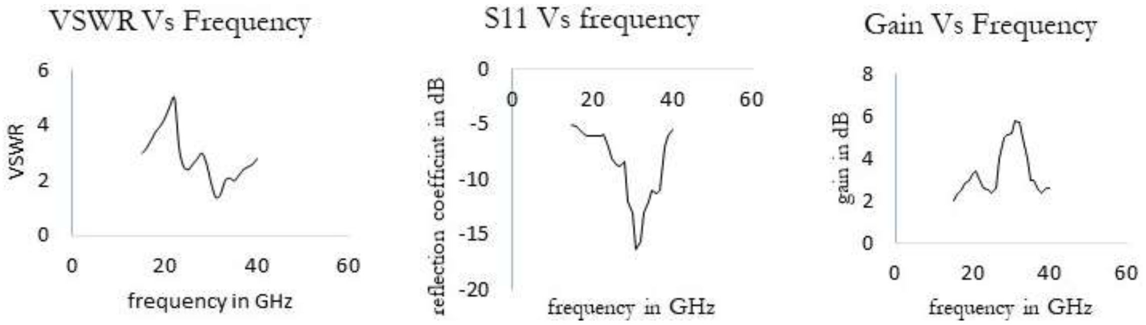


Figure 3. Simulation results for the proposed five-patch compact microstrip Yagi antenna at 31 GHz: (a) return loss, S11, (b) voltage standing wave ratio, VSWR, (c) two-dimensional radiation pattern, (d) three-dimensional polar plot, and (e) surface current distribution

3.2. Performance measurement

Performance measurement of antenna was tested in an anechoic chamber and the results on return loss, VSWR and gain were recorded using vector network analyzer. Figure 4 depicts the performance measurement results. The antenna VSWR is illustrated in Figure 4(a). As seen, at operating frequency, VSWR < 2. The simulation and performance measurement are almost in good agreement. Simulated reflection coefficient at 31 GHz frequency is -17 dB whereas the compared measured value is -15.38 dB. The simulation gain for the operating frequency was 6 dBi and that obtained from the measurement was 5.8 dBi. Plots of reflection coefficient and gain are shown in Figure 4(b) and Figure 4(c) respectively. The measured value of S11 and gain are closely matched to the simulated values. Thus, proposed antenna has successfully realized the performance values as in the objective of the work. Minor dissimilarity between simulation and measured results are due to fabrication tolerance, measurement conditions, feed contact with antenna and sensitivity towards environment temperature or possible physical stress occurring during the fabrication.

Table 1 lists comparison of simulation and laboratory measurement results. Measured value for the return loss is -15.38 dB which best fit with the simulated value of -17 dB. Simulated and measured VSWR values of the designed antenna are in good terms at 1.32 and 1.5. Measured gain of the antenna, 5.8 dBi, is in close agreement with the simulated value of 6 dBi.



(a) (b) (c)

Figure 4. Measured results of the antenna prototype: (a) voltage standing wave ratio, VSWR, (b) return loss, S11, and (c) gain

Table 1. Comparison table of simulation and performance measurement results

Antenna parameters→	S11(dB)	VSWR	Gain (dBi)
Simulated	-17	1.32	6
Measured	-15.38	1.5	5.8

3.3. Performance comparison

Table 2 shows performance comparison of the mentioned microstrip Yagi Uda antenna with results of some of the previously published works. Our study suggests that the higher gain and return loss values are not associated with any poor performance in the bandwidth. The compared results indicated that the suggested antenna has a more compact structure than those described in the literature and has achieved better impedance matching, lesser reflection coefficient, reasonable high gain and wide bandwidth. The suggested design is very simple to develop with high degree of tolerance. Analysis showed that the suggested design has relatively better performance in comparison to the published works. The proposed method may benefit from the VSWR value, high gain, good return loss and the availability of multi band operation without adversely impacting the bandwidth.

Table 2. Performance comparison with published works

Ref.	Freq. (GHz)	VSWR	S11 (dB)	Gain (dBi)	BW (GHz)
Mamarou *et al.* [33]	28 & 38	1.01, 1.05	-36, -32	7.2, 7.65	1.3, 2.2
Sharaf *et al.* [38]	28	1.13	-12.5	5.06	2.68
Kiran *et al.* [39]	28.3	1.58	-11	2.6	2.2
Hussain *et al.* [46]	28	< 2	-33	7.1	3.52
Kishore Rajak [47]	30	2.3	-8	8.45	0.5
This work	31	1.32	-17	6	1

This study explored a comprehensive operational feature of the design with but some minor deviations were also observed. These deviations between the two results may be assigned to fabrication tolerance, measurement conditions, feed contact with antenna and sensitivity towards environment temperature or possible physical stress occurring during the fabrication. The suggested antenna works in Ka band with a core resonance frequency at 31 GHz. Possible high frequency multiband could not be considered for the provided antenna size since it required antenna dimension scaling down to the nanoscale, which was beyond the authors' technological capabilities. However, further an in-depth study may be needed in future to confirm its performance in various environmental conditions, such as temperature variations, physical stress, and especially regarding impact of humidity. Future studies may explore performance of design in these conditions with feasible ways of producing more bands and bandwidth.

4. CONCLUSION

This paper introduces small innovative Yagi-like antenna with five rectangular patches of varying sizes to create the radiating element with enhanced bandwidth. Electromagnetic solver HFSS is used to design and simulate, while the prototype development helped to realise the laboratory measurements. The proposed antenna successfully achieved bandwidth of 3.2% (30.5 GHz-31.5 GHz) with voltage standing wave ratio less than 1.6, port isolation improved beyond 13 dB, a stable gain of 6 dBi across the frequency range of 30.5 GHz to 31.5 GHz, bandwidth of 1 GHz, which meet the requirement of wireless communication. It operates more effectively with shorter wavelengths in locations where a cable deployment is ineffective. Our observations suggest that contribution is noticeable and is associated with a quantum leap towards low cost, miniaturized, and efficient wireless communication systems. The designed antenna is suitable for military applications employing satellite communication. Future directions of this research include exploring how antennas work under various environmental conditions like, temperature changes, humidity and physical stress. These initiatives aim to improve antenna efficiency and usefulness, highlighting our design's potential to advance wireless communication technologies and their applications across several industries.

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