Design of a pyramidal slotted wide-band patch antenna for directive wireless communications over Ka-Band

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ABSTRACT

A wide Band for directive wireless communications over Ka-Band was presented. The proposed antenna printed on Rogers RT/Duroid 5880 substrate and achieved a moderate gain of 6.80 dB at resonating freqenc of 28 GHz. The pyramidal antenna achieved a wide operating bandwidth of 11.55 GHz. The proposed antenna achieved high siz reduction percentage with a compact overall dimension of (4.8×6.9×1.5) mm^3. The antenna achieved the wide operating bandwidth based on two factors; the first is selection of low loss dielectric material to ensure etter antennas performance. The other is etching pyramidal with 2×2 squared – shapes slots array etched from patch’s surface to reduce stored reactive energy which decreases overall ualit factor of and improves the -10 dB bandwidth obviously.

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1. INTRODUCTION

Many works have been conducted during last few years about using patch antenna for many applications over different frequency bands. The patch antenna had been used for a wide variety of applications in field of wireless communications due to many advantages [1]. In spite of many advantages offered by patch antenna; it still suffering from having moderate gain with narrow operating bandwidth as well as a high side lobe level (SLL) far field [2].

To overcome the low gain of patch antenna and assure low latency communications many techniques had been evolved and developed. A traditional technique for increasing gain is patches array where adding these arrays in phase causes increment in the main loe level in the far field radiation pattern; due to incremented power concetration in this direction to achieve higher gain and directivity. An array of 325 patches formed a circular shape to achieve high gain [3]. Recently, arrays had been used with another technique simultaneously for better performance, where 2×4 artificially conduction objects have been added under array of two patches and caused 16.3% gain improvement [4]. An array of 2×1 achieved gain of 4.3 dB which improved to 8 dB due to adding a superstrate with metamaterial it [5]. Using of superstrate with 7×7 of non-zero-indexed-metamaterial above feeding patch; led to gain increment of 2 dB [6]. Defected ground structure (DGS) causes suppression of the surface waves which will lead to higher radiated waves to forward direction of antenna since the DGS is considered a high impedance surface and eliminates antenn’s suface waves. DGS was used to increase gain of patch antenna by 1 dB at 2.4 GHz [7]. The multilayer patch antenna is an effective technique for performance improvement in general, this technique can be used in many forms such as slabs of dielectric materials above patch plane [1]. These laers are acting as a dielectric lens which focuses and refracts the radiated power from feeding patch into forward direction of main lobe which increases the gain and directivity of antenna. Also, partial reflectors can be added under superstrate layer for performance improvement [2]. Moreover, the use of multilayer structures decreased SLL in antenna radiation pattern for very low level [1], [2]. The gain of patch antenna was incremented from 8.40 dB to 18.6 dB using grooved ground with 10 grooves/wavelength at 10.45 GHz [8]. Using an array of slots etched in surface of patch also is an effective technique which improved gain from 6.92 dB to 20 dB due to surface waves distribution disturbance [9].

Nowadays, most of wireless communications applications requires high data rate communications, and this is why the operating bandwidth improvement was a target for may researches. The use of multilayer antenna structures led to significant bandwidth improvement [1], [2]. Also etching rectangular slots from patch's surface shown bandwidth increment [9]. Moreover using a U-shaped ground led for significant -10 dB bandwidth enhancement due to adding an inductance and capacitance to the euivalent circuit of antenna. This will cause much more flat reflection cooefficient respose which means wider operating andwidth [10].

Many researches and designs have been conducted to design a patch antenna for fifth generation (5G) communications over S, C, Ku, K, and Ka-Bands. A semi-circular shaped patch with three quartered slots in surface operated at 3.6 GHz with gain of 4.8 dB at S-Band [11]. A triangular patch with double squred rings operated at 3.7 GHz for 5G [12]. MIMO is an attractive technique for 5G applications; a 2×2 MIMO patch antenna used for 5G at S-Band at 3.41 GHz [13]. For 5G transmissions at K-Band. An F-shaped patch was proposed to resonate at 25 GHz with gain of 7 dB [14], while a rectangular patch in [15] resonated at 26 GHz with high radiation efficiency and gain around 10 dB. Patch antenna can operate for multiband; where an antenna was proposed to operate in S and C-Bands [16].

Most of researched regarding designing a patch antenna for 5G applications were conducted for antennas operating in Ka-Band; a squared-shaped patch was proposed to operate in Ka-Band with a good reflection coefficient at 28 GHz [17]. Kiran *et al.* [18] a 5G patch was proposed with two removed slots from its surface with a slotted feeder strip line resonated at 28 GHz and 50 GHz. Moreover 2×1 patch MIMO elements resonated at 28 and 38 GHz with peak gain of 8.27 dB [19]. Removing parts from antenna's ground with two T-shapes for removing unwanted frequencies achieved gain of 9.57 dB to be operating in Ka-Band for 5G applications [20].

The modern communication applications in general and 5G especially require high data rate with low latency wireless communications. Based on that, many researches and techniques devolved and conducted to improve the gain of patch antenna over the Ka-Band. An array of 4×1 patches had been presented to achieve gain of 12 dB at 38 GHz [21], while [22] presented a mathematical approach to understand the impact of radiator on antenna's gain. The use of artificial magnet conduction (AMC) array as ground instead of regular ground caused a significant increment in antenna's gain [23]. A specific shapes could be removed from radiating patch's surface to increase the gain as in case of removing LI-shapes to achieve high gain of 11.23 dB in peak with two resonating frequencies at 26.28 and 28.5 GHz [24].

Also the operating bandwidth of the antenna is an important manner for many researchers conducting works in field of improving antenna's performance in Ka-Band. A stub-slotted shape for dual frequency operation at 28 GHz and 38.5 GHz with defect ground for achieving wide bandwidth [25], moreover in [26]; using partial ground achieved wider operating bandwidth. The use of 8×8 AMC also caused to achieve a wide bandwidth [23]. Using method of surface response is an effective technique used for improving bandwidth by etching PI-shaped slots from antenna's surface [27], and LI-shaped slots to achieve wide -10 dB bandwidth [24]. There are mainly two techniques to improve radiation pattern of antenna which are using reflector layer as in case of patch antenna with a reflecting layer [7], and the most effective technique is the multilayer antenna structure in case of using a single or multiple dielectric slabs [2].

The proposed antenna is composed of a rectangular patch with 2×2 squared-shapes slots array were etched from its surface with a pyramid shape etched from the patch and located between squared-shaped slots array. The proposed achieved a wide operating bandwidth based on the selection of substrate's thickness and use of etched squared-shapes. The proposed antenna achieved gain higher than proposed antenna for 5G in Ka-Band [25], with a percentage of gain enhancement of 17.24% and size reduction of 94.56% as well as a wider -10 dB bandwidth. The proposed antenna is suitable for 5G communications over Ka-Band.

2. MATERIALS AND METHODS

This section presents the specific details materials used in the proposed Ka-Band antenna design and the simulation environment used to achieve an accurate result. Moreover, the methods and equations which used for the calculation of the proposed Ka-Band antenna's dimensions. For the proposed antenna; Rogers RT/Duroid 5880 low loss dielectric material was used as a substrate layer. The used substrate has a dielectric constant of 2.2, while its loss tangent is 0.0009. The proposed design used substrate thickness of 1.575 mm and the radiating material was low loss copper and its thickness is 0.035 mm.

After selecting the substrate material and the conducting material and its properties, the next step will be estimating the dimensions of the used substrate such as length and width, as well as the dimensions of the radiating patch and the feeder of antenna. As a first step in this estimation process the dimensions of the radiating patch in terms of length and width as well as the effective length of patch based on the conventional patch antenna dimensions calculation (1-5) as given [28].

$$W = \frac{C}{2 f_O \sqrt{\frac{(\epsilon r + 1)}{2}}} \tag{1}$$

And the effective electrical length (L_{eff}) is given by:

$$L_{eff} = \frac{C}{2 f_O \sqrt{\epsilon_{r\,eff}}} \tag{2}$$

$$\epsilon_{reff} = \frac{(\epsilon_r + 1)}{2} \frac{(\epsilon_r - 1)}{2} \sqrt{1 + \frac{12h}{W}} \tag{3}$$

while the fringing current factor (ΔL) is given by:

$$\frac{\Delta L}{h} = 0.412 \frac{(\epsilon_{r\,eff} + 0.3)\,({}^{W}/_{h} + 0.264)}{(\epsilon_{r\,eff} - 0.258)\,({}^{W}/_{h} + 0.8)} \tag{4}$$

and finally, the length of the patch (L) is given by:

$$L = L_{eff} - 2\Delta L \tag{5}$$

To implement the proposed design, Microwave Studio Computer Simulation Technology (CST) has been used as a simulation environment. To achieve a well design parameters and dimensions optimization process a hexahedral simulation had been used with 30 cells per wavelength, 30 cells per max mode box edge, and 50 fractions of maximum cell near to model.

3. ANTENNA DESIGN

The proposed antenna has a patch printed on Rogers RT/Duroid 5880 substrate (єr= 2.2, tanδ = 0.0009). The dimensions of substrate are (sub_L) and (sub_W) for length and width, respectively, and its thickness is h. The general layout for the copper radiating element is a rectangular-shaped patch. The dimensions for the radiating patch are ($L_{RP} \times W_{RP} \times t$), where L_{RP} is the length of radiating copper and W_{RP} represents its width, while t refers to its thickness. This radiating element has five notched shapes which are used to achieve a wide operating bandwidth. These shapes are four squared-shapes and the fifth is a pyramid shape. The four squared-shapes are distributed around the pyramid and located in the four corners of an imaginary square shape. The dimensions for these shapes are the same and each has side length of (SS_{SL}).

The pyramid shape is composed of two symmetrical stair case shapes with five steps for each and a step dimension of (P_{SD}). With a triangular shape on the top of the pyramid. The pyramid has a base dimension of (P_{BW}) with total height of (P_H). The height of the upper triangular shape is (T_h) and its base dimension is (T_{BW}). The proposed wide-bandwidth antenna over Ka-Band had fed using a strip feeder. This feeder has a length of (F_L) and width of (F_W). the proposed design used a regular ground with dimensions of (G_L) and (G_W) for length and width, respectively. The top view of the proposed wide-bandwidth Ka-Band antenna is presented in Figure 1, while design parameters and dimensions are listed in Table 1.

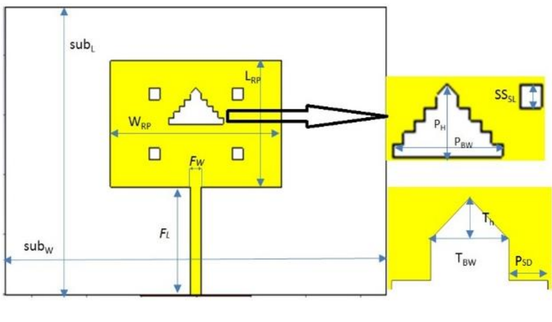

Figure 1. Top view of wide-bandwidth patch antenna

Table 1. Proposed antenna dimension

No.	Parameter	Value (mm)
1	Length of substrate - sub_L	4.800
2	Width of substrate - sub_W	6.900
3	Height of substrate - h	1.575
4	Length of patch - L_{RP}	2.100
5	Length of patch - W_{RP}	3.100
6	Copper thickness - t	0.035
7	Side length of etched square-shape - SS_{SL}	0.200
8	Staircase step size - PS	0.100
9	Pyramid's base width - P_{BW}	1.000
10	Pyramid's height - P_H	0.600
11	Triangle's height - T_h	0.100
12	Triangle's base width - T_{BW}	0.200
13	Feeder length - F_L	1.200
14	Feeder width - F_W	0.200
15	Ground length - G_L	4.800
16	Ground width - G_W	6.900
17	Pyramid's step dimension	0.100

4. RESULTS

This section presents the parametric study as well as results for Ka-Band wide band antenna design steps in terms of resonating frequency, bandwidth, gain, and reflection coefficient. The main steps of this study are generally focus on patch dimensions optimization as a first step. The second step represents results of etching four squared-slots from surface of patch and studying their effects on antenna's performance. After this step adding the pyramid shape above the patch which fed with rectangular patch. Studying and optimizing the dimensions of pyramids step dimension as well as the location of pyramidal shape from the radiating patch radiating edges to achieve better performance at the desired operating band with much possible wider bandwidth and good other antenna's operation parameters such as gain and S11.

- Step_1. This step provides the results for rectangular patch dimensions optimization in terms of width decrementing which caused a significant return loss reduction to guarantee a better antenna's performance. The tabulated data for this step are presented in Table 2. The reflection coefficient for the Ka-Band antenna at step-1 is shown in Figure 2.

Table 2. Tabulated results for width of patch optimization

No.	Width (mm)	Frequency (GHz)	Reflection Co. (dB)
1	3.8	28.63	-28.41
2	3.7	28.57	-30.84
3	3.6	28.51	-33.05
4	3.5	28.57	-36.65
5	3.4	28.57	-36.73
6	3.3	28.54	-38.10
7	3.2	28.66	-39.16
8	3.1	28.66	-39.27

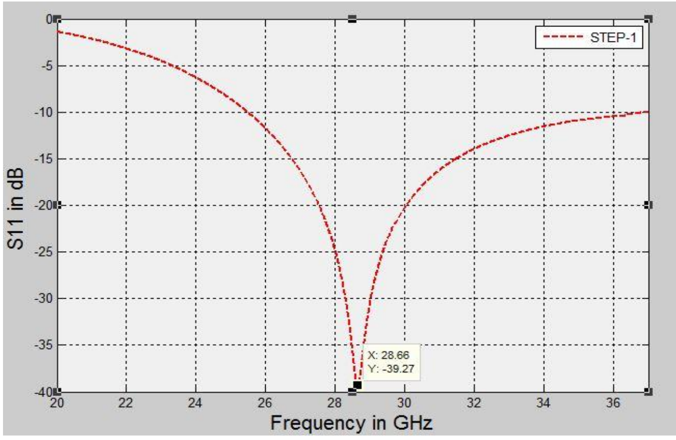

Figure 2. Ka-Band antenna's reflection coefficient in step 1 for patch width of 3.1 mm

The value for width of conventional patch found to be 3.80 mm according to conventional patch antenna design equations [28]. This width was optimized to be 3.10 mm based on antenna's performance investigation which caused to be resonating at 28.66 GHz with return loss of -39.27 dB. Moreover, the operating bandwidth found to be 10.11 GHz at this step.

– Step_2. This step provides the parametric results of etching four squared-slots from patch surface. The location of these slots is symmetrical around both X and Y-axial with respect to center point of radiating patch. These slots were etched for bandwidth improvement, which was improved to 10.88 GHz compared to 10.11 GHz in case of patch without squared-slots etching. The operating frequency shifted up to 28.75 GHz (9 MHz increment), and reflection coefficient of antenna found to be -37.90 dB. The reflection coefficient for the Ka-Band antenna at this step is shown in Figure 3.
– Step_3. This step provides the parametric results of etching a pyramidal shape from the radiating patch surface. The proposed wide-band antenna was resonated at 28 GHz, and its return loss was found to be -33.59 dB. The operating bandwidth found to be 11.55 GHz after etching pyramidal shape compared to 10.88 GHz and the operating frequency was shifted down compared to Step-2. The reflection coefficient for the proposed Ka-Band antenna at this step is shown in Figure 4. The results of proposed antenna during steps of this parametric study are presented in Table 3.

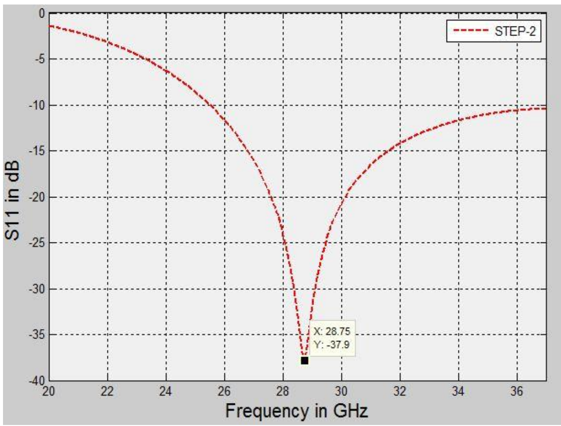

Figure 3. Ka-Band antenna's reflection coefficient in step 2 with four etched slots

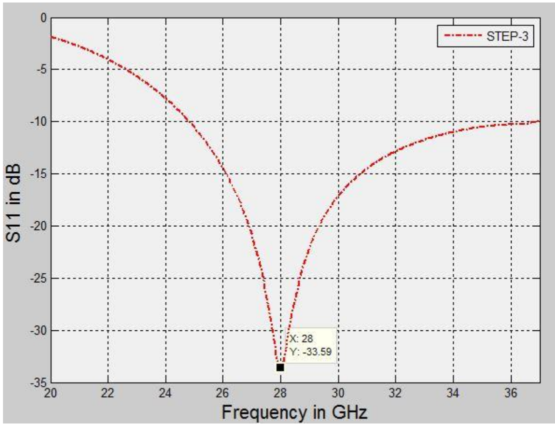

Figure 4. Ka-Band antenna's reflection coefficient in step 3 for proposed Ka-Band antenna

Table 3. Tabulated results for Ka-Band proposed antenna design steps

	Frequency (GHz)	Bandwidth (GHz)	S_{11} (dB)	Gain (dB)
Step_1	28.66	10.11	-39.27	6.73
Step_2	28.75	10.88	-37.90	6.71
Step_3	28.00	11.55	-33.59	6.80

5. DISCUSSION

The proposed Ka-Band patch antenna for directive wireless communications, was designed to operate over the Ka-Frequency band. The antenna achieved a wide operating bandwidth more than 11.50 GHz with moderate gain of 6.80 dB at 28 GHz. The wide operating and was aceived de to removing four sared-slots with pyramidal shape from the radiating patch. The remove of these five shapes causes disturbance in distribution of surface-waves which introduce a wider S_{11} response based on adding L-C circuit to the overall impedance of the antenna with reduction of quality factor which reversed proportional to antenna operating bandwidth. Moreover, it has a directive radiation pattern with low SLL which is suitable for directive wireless communication in Ka-Band such as 5G applications as shown in Figure 5. The proposed antenna has a directive radiation pattern without need for using mltilaer strcture for focusing radiated waves and redce the SLL which caused a significant reduced size compared and higher or relative operating bandwidth to other patch antenna designs as shown in Table 4.

The proposed antenna achieved higher bandwidth compared to antennas in [19], [20], [29], while compared to dual band antenna presented by [25]; the proposed antenna achieved a comparable bandwidth with high percentage of size reduction of 71.59%. The proposed antenna has a gain variation of less than 0.40 dB over its operating band with halfpower beam width of 65 degrees and SLL of -10 dB.

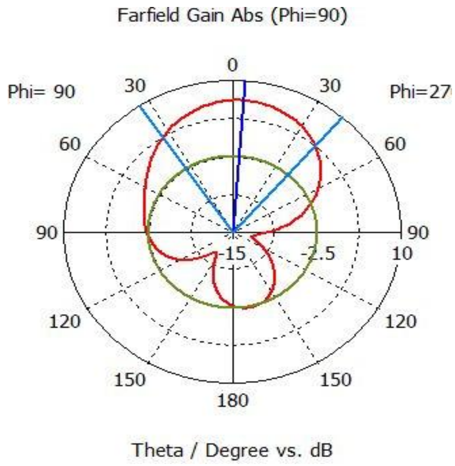

Figure 5. Ka-Band antenna's radiation patted

Table 4. Tabulated comparison for proposed antenna bandwidth and size with relative designs

Ref.	Overall antenna dimensions' (mm^3)	Operating bandwidth (GHz)	Gain (dB)	Percentage of size reduction (%)
Marzouk *et al.* [19]	55×110×0.508	1 GHz	7.18	98.10%
Hakim *et al.* [25]	16.710×21.980×0.500	11.60 GHz	6.38	71.59%
Abdelaziz and Hamad *et al.* [20]	20×16.500×0.508	1.50 GHz	5.67	68.88%
Dejen *et al.* [29]	15×15×0.500	3.80 GHz	7.10	53.63%
Proposed design	4.800×6.900×1.575	11.55 GHz	6.80	-----

6. CONCLUSION

A reduced size wide-band patch antenna for directive wireless communications was designed to operate over Ka-Band. A wide -10 dB bandwidth was achieved by the proposed design based on two factors: first is selecting low loss dielectric material for substrate with the optimum substrate thickness which caused to achieve an operating bandwidth more than 10 GHz. The second is etching pyramidal shape with four square slots from radiating surface of pach which caused bandwidth enhancement to be more than 11.5 GHz. The novelty of this design is achieving high size reduction percentage compared to previous designs in same frequency band and much wider -10 dB operating bandwidth.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P
Safa Nasssr Nafea	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Author states no conflict of interest.

DATA AVAILABILITY

The data availability statement is a valuable link between a paper's results and the supporting evidence. It is a brief statement about whether the authors of an article have made the evidence supporting their findings available, and if so, where readers may access it. Data availability statements help to promote transparency and reproducibility in research and to increase the visibility of valuable evidence produced or gathered during the course of research. As part of our commitment to supporting open research, our journal now requires all manuscripts to include a data availability statement in order to be accepted for publication. Examples:

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- Derived data supporting the findings of this study are available from the corresponding author on request.
- The data that support the findings of this study are available from the corresponding author, [author initials], upon reasonable request.

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