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For 5G applications, high-gain patch antenna in Ka-Band

Safa Nasssr Nafea[1], Nasser N. Khamiss[2]
[1]Department of Computer Networks Engineering, College of Information Engineering, Al-Nahrain University, Baghdad, Iraq
[2]Department of Systems Engineering, College of Information Engineering, Al-Nahrain University, Baghdad, Iraq

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ABSTRACT

The fifth generation (5G) of telecommunications is an attractive application for many researchers during the last years. The 5G requires high date rate with low latency communication medium and patch antenna was used recently for this application. In this article a patch antenna for 5G at 38 GHz was proposed. This article worked on enhancing the gain of patch antenna at Ka-Band and reducing side lobes level (SLL) in radiation pattern. The gain of the patch antenna was improved using a reflector layer located under antenna's ground with free space air gap separating between two layers. Moreover, the SLL were reduced to satisfy low latency condition for 5G communications. The proposed antenna shows high gain around 8.10 dB with high front-to-back (F/B) ratio of 16.24 dB and wide operating bandwidth around 1.4 GHz for high data rate requirements as well as having reduced overall size antenna. The article based on analytical calculations for patch dimensions and optimization procedure to achieve the desired performance of antenna. Computer simulation technology (CST) had been used as an environment for simulation.

Corresponding Author:

Safa Nasssr Nafea
Department of Computer Networks Engineering, College of Information Engineering
Al-Nahrain University
Baghdad, Iraq
Email: safanafea@gmail.com

1. INTRODUCTION

There are many well-known features which are considered as advantages for patch antenna such as being low weight antenna with low cost and fabricated easily, as well as the ability to operate with dual, triple or even four operating frequencies [1]. It is usually suffers from being a low gain antenna with narrow operating bandwidth which has a radiation pattern with high side lobes level [2]. Many researches have been conducted to present effective techniques for improving antenna's gain such as using an array of patches; which is a traditional technique. An array of 325 patch elements have been deployed to achieve high gain of 29 dB [3]. The use of grooved ground instead of planed ground is an effective technique which led to achieve gain increment around 10.2 dB for the grooved ground antenna [4]. The use of near zero indexed metamaterial caused a gain enhancement of 2.05 dB for the patch antenna at frequency of 5.2 GHz [5], while the gain of 2x1 patch array was increased from 4.3 dB to 8 dB using split-ring resonator [6]. Moreover, the gain of 2x1 patch array increased by adding a layer consists of 2x4 array of artificially magnetically conduction material (AMC) [7]. Etching four slots from surface of patch antenna enhanced the gain [8]. Using multilayer antenna structure is an effective technique for gain increment. Adding 5x5 partially reflected surfaces (PRS) printed on bottom of a superstrate, which located above the antenna, caused an increment in gain of antenna [9]. Moreover, adding layers of dielectric material without PRS above feeding patch caused into obvious increment in gain [1]. More than a single technique can be used instantaneously to improve the gain, adding three layers of superstrates enhanced the gain of antenna proposed by [2] to 12.20 dB, while adding a reflecting layer under the overall structure was enhanced the gain to 12.60 dB. Mekki *et al*. [10] used both defected ground structure (DGS) and reflecting layer caused in gain increment to be 5.20 dB compared to 3.3 dB without using of reflecting and DGS. Researches also have been conducted to discover new techniques for improving the bandwidth of patch antenna. Using multilayer antenna structure is an effective method for enhancing general performance of antenna, where the operating bandwidth was improved due to adding superstrate layers above a patch antenna with specific height for each layer [1], [2]. Another effective technique has significant improvements for the bandwidth, which is etching slots from the surface of radiating patch [8].

The multilayer antenna structure also worked obviously on eliminating side lobes level (SLL) of radiation pattern. The multilayer antenna in used Roggers RO3006 layers above the patch to eliminate the SLL [1]. While proposed antenna by Nafea [2] had used three slabs of dielectric material above the patch and reflecting layer under it to eliminate SLL. The reflector layer can be used as a standalone technique to reduce the impact of SLL on antenna's radiation pattern [10]. As we mentioned earlier; the patch antenna has the ability to operate within multiple operating frequencies, where a tri-band antenna has three operating frequencies of 3.3 GHz, 4.5 GHz, and 5.8 GHz [11]. A multiple band patch antenna for S and C–Bands was proposed with four operating frequencies in rage of (2.53–7.707) GHz [12].

The patch antenna has been used recently for 5G communications over different frequency bands such as S, C, K, and Ka-Bands. Many designs had been presented for patch antenna operating for 5G applications at S-Band, where a patch antenna was printed on an FR4 material with two pin diodes used to initiate a single mode of operating for each diode and has an operating frequency of 3.6 GHz [13]. A patch antenna with doubled square ring was proposed to operate at 3.7 GHz for 5G use [14]. Multiple input multiple output (MIMO) antennas had been proposed for 5G applications with frequency of 3.41 GHz and gain of 4.2 dB [15].

An F-shaped patch antenna was proposed by [16], to operate at 25 GHz at the K-Band. Colaco and Lohani [17] proposed a patch antenna to operate over the K-Band at 26 GHz. Many designs have been conducted to presents patch antennas operating over Ka-Band at different resonating frequencies. A summarization of design issues have been discussed as well as a patch antenna was proposed to operate at 28 GHz with low reflection coefficient (S_{11}) of -35 dB [18]. Marzouk *et al*. [19], 2x1 MIMO antenna with two inverted I-shaped slots have been presented to operate at 28 GHz and 38 GHz. Moreover, a patch antenna with three resonating points: 10 GHz, 28 GHz, and 38 GHz, have been proposed for 5G applications at both 28 GHz and 38 GHz. A patch antenna with LI-Slotted shapes had proposed for 5G applications at 26.28 GHz (K-Band), and 28.54 GHz (Ka-Band) [20]. The 5G applications requires high date rate and low latency; in other words requires an antenna with high gain and wide operating bandwidth. Many studies have been presented to improve the gain of patch antenna at K and Ka-Bands. An array of 1x4 elements had been used to improve the gain of antenna to 12.20 dB compared to 6.90 dB for single patch element at 38 GHz [21]. A mathematical have been proposed by Mohammed *et al*. [22] to study the impact radiating conductor thickness on the gain of antenna. A layer of AMC array (8x8) had located between the radiating patch and ground, which led to gain increment from 3 dB to 5.80 dB [23]. To satisfy high data rate conditions of 5G applications, a DGS was deployed to the ground of 2x2 MIMO caused to achieve bandwidth of 5.13 GHz and 11.63 GHz for operating frequencies of 28 GHz and 38 GHz, respectively [24]. Moreover, the ground of patch antenna; proposed by Sabek *et al*. [25], was partially removed and caused to achieve a wide operating bandwidth in the Ka-Band. Etching slots from patch surface also led to achieve wide operating bandwidth [26].

This article is proposing a patch antenna for 5G applications at 38 GHz Ka-Band. The proposed design composed of a rectangular-shaped patch with two squared-shapes located on both right and left upper corners of the radiating patch. A free space is isolating between the patch and two inverted staircases-shapes located on both sides of the patch. To improve the gain of antenna in terms on gain increment and SLL decrement, a reflector had been added under patch antenna with a free space air gap between reflector and antenna's ground. The proposed antenna achieved high gain with wide bandwidth and low SLL radiation pattern without any need to use a technique which would cause a huge increment in its overall dimensions. Compare to antennas presented in previous works to operate over Ka-Band at 38 GHz, the proposed antenna achieved higher gain compared to patch antenna in [24] and comparable gain with respect to antenna proposed by [19], [27] due to high size reduction factor achieved by the proposed antenna.

2. METHOD OF DESIGN

This section describes the steps of designing the proposed 5G antenna at Ka-Band. The geometry of proposed antenna will be discussed also. The design process was accomplished through two main stages:

- Stage 1: In this stage the analytical calculations for the width and length for the rectangular-shaped radiating patch was accomplished based using very well-known information about resonating frequency, dielectric constant, and thickness of substrate using (1)-(5) [28].

$$W = \frac{c}{2 f_O \sqrt{\frac{(\epsilon_r + 1)}{2}}} \quad (1)$$

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

$$L_{eff} = \frac{c}{2 f_O \sqrt{\epsilon_{r\,eff}}} \quad (2)$$

and

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

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

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

and finally, the length of the patch (L) is given by (5).

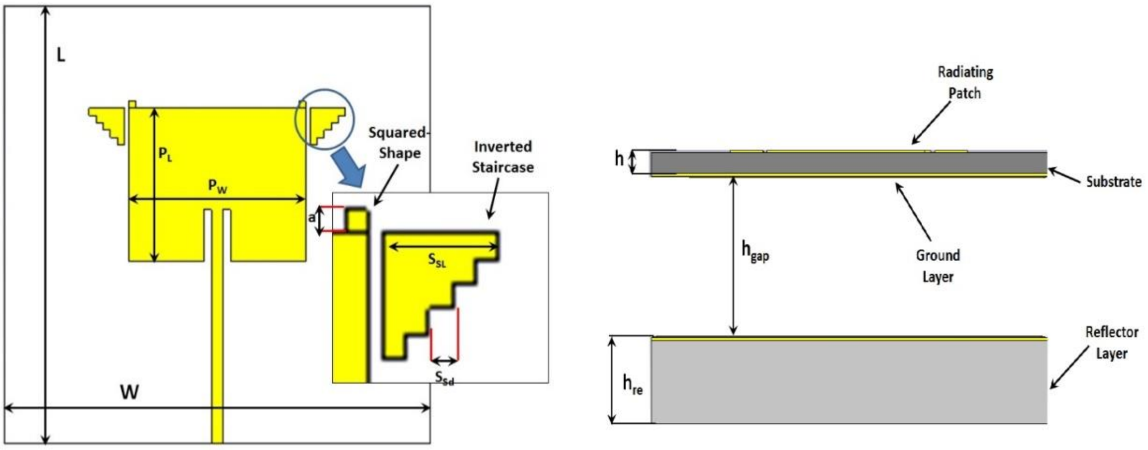
$$L = L_{eff} - 2\Delta L \quad (5)$$

- Stage 2: This section describes the geometry of antenna, the antenna composed of a rectangular-shaped patch with two squared-shapes on both left and right upper corners of the patch. Two inverted staircases-shaped objects were added adjacently to both upper sides of the rectangular-shaped patch. The proposed antenna printed on Roggers RO3003 substrate with dielectric constant of (εr = 3) and loss tangent of (tanδ = 0.0013). The overall dimensions of the substrate are (LxWxh); where (L) is referring to the length, while (w) to the width, and h to the thickness of substrate.

The radiating patch has dimensions of ($P_L x P_w$); where (P_L) is the length and (P_w) is the width of the patch. The squared-shapes on both upper corners of the patch have side length of (a). Both of the staircases-shaped have the same dimensions with squared-shape with side length of (S_{SL}). Each staircase has five horizontal as well as five vertical steps with a step length of (S_{Sd}). (G_{ps}) is the distance that separates rectangular-patch from each staircase. The thickness of copper of the radiating patch is (t). The antenna was fed using microstrip line feeding and its dimensions are (F_L) and (F_w) for the length and width, respectively. The rectangular-shaped patch has two notches on both sides of the feeder with dimensions of (n_L) and (n_W) for the length and width, respectively. A reflecting layer is added under the ground of antenna with an air gap of (h_{gap}). This layer composed of an FR4 material; with dielectric constant of (ϵ_r = 4.3) and loss tangent of (tanδ=0.025), which has the same length and width of antenna's substrate with thickness of (h_{re}). The geometry of proposed antenna shown in Figure 1, where Figure 1(a) shows top and side view for the proposed 5G applications antenna Ka-Band while side view of proposed antenna is presented in Figure 1(b). Design dimensions are provided in Table 1.

Table 1. List of parameters and dimensions for the proposed design

No.	Parameter	Dimension
1	Length of substrate - L	6 mm
2	Width of substrate - W	6 mm
3	Thickness of substrate - h	0.25 mm
4	Substrate's dielectric constant - ϵ_r	3
5	Substrate's loss tangent - tan δ	0.0013
6	Length of rectangular patch - P_L	2.10 mm
7	Width of rectangular patch - P_W	2.50 mm
8	Separations distance rectangular-patch from each staircase - k	0.10 mm
9	Staircase-shaped side length - S_{SL}	0.50 mm
10	Staircase-shaped step size - S_{Sd}	0.10 mm
11	Squared-shapes side length - a	0.10 mm
12	Notches length - n_L	0.70 mm
13	Notches width - n_W	0.10 mm
14	Length of microstrip line feeder - F_L	2.50 mm
15	Width of microstrip line feeder - F_W	0.20 mm
16	Free space air gap between reflector and ground - h_{gap}	2.00 mm



(a) (b)

Figure 1. 5G Ka-Band proposed antenna (a) side view and (b) top view

3. PARAMETRIC STUDY AND RESULTS

This section presents a parametric study for the proposed 5G applications antenna at Ka-Band design and its results. The main steps for this study is to evaluate the performance of antenna with the dimensions obtained from (1)-(5) in the previous section. The second step and later steps is optimizing the dimensions of the patch as well as adding squared-shapes and the staircase-shaped and finally adding the reflector layer. In each step of this study steps the performance of the antenna was evaluated to achieve a performance which will satisfies the condition of having low latency with high data rate communications for the fifth generation.

- Step 1: According to (1)-(5) had been used to estimate the dimensions of patch. The analytical calculations for the dimensions of the rectangular patch give results of 2.1 mm and 2.8 mm for the length and width, respectively. Based on these parameters the antenna resonates at 38.1 GHz with a reflection coefficient of -21.43 dB.
- Step 2: This step was conducting for improving the performance of antenna. To improve the S11 parameter, the width of the rectangular-shaped patch was changed to 2.5 mm. Steps of change were 0.1 mm and the performance of the proposed 5G antenna was observed as shown in Table 2.

Table 2. Proposed antenna parameters in step 2

No.	P_w (mm)	Resonance frequency (GHz)	S_{11} (dB)
1	2.8	38.10	-21.43
2	2.7	38.25	-25.35
3	2.6	38.35	-34.97
4	2.5	38.45	-37.21

- Step 3: This step was conduscted for resonance tunning. This step discusses shifting resonance toward 38 GHz by adding two squared shapes on both upper corners of the radiating patch. This step was accomplished by adding the right-hand square and the left-hand square as shown in Table 3.

Table 3. Proposed antenna parameters in step 3

Step	Resonance frequency (GHz)	S_{11} (dB)	Gain (dB)
Adding right-hand square	38.35	-33.12	6.90
Adding left-hand square	35.20	-31.61	6.95

- Step 4: This step was also conduscted for resonance tunning. To shift the resonating frequency toward the 38 GHz frequency, two inverted staircase-shaped have been added adjacently to both top sides of the patch. The performance of the antenna was observed as shown in Table 4.

Table 4. Proposed antenna parameters in step 3

Step	Resonance frequency (GHz)	S_{11} (dB)	Gain (dB)
Adding right-hand inverted staircase	38.00	-27.26	7.10
Adding left-hand inverted staircase	35.05	-27.47	7.22

The previous four steps of design have been employed to achieve the most possible optimum performance of antenna at a resonance frequency close to 38 GHz as much as possible. As we mentioned earlier, 5G applications requires high data rate and low latency communications. The performance of antenna in Step-Four shows an operating bandwidth of 1.40 GHz, but the antenna still suffers from high SLL in its radiation pattern. To solve this problem a reflector layer will be added in next step of the parametric study.

- Step 5: This step was also conduscted for SLL reduction. To improve the performance of the antenna in terms of reducing SLL as well as increasing the gain of antenna, a reflector had been added under patch antenna with an air gap of free space between two layers. An optimization for the thickness of the reflector was accomplished as shown in Table 5 and based on the optimization results, hre was selected to be 1 mm only.

Table 5. Proposed antenna parameters in step 5

No.	h_{re} (mm)	Resonance frequency (GHz)	S_{11} (dB)	Gain (dB)
1	0.90	38.10	-25.22	8.07
2	1.00	38.10	-26.14	8.10
3	1.10	38.10	-26.19	8.07
4	1.20	38.10	-26.23	8.03
5	1.30	38.10	-26.26	8.00
6	1.40	38.10	-26.31	7.98

Adding the reflector layer caused to have resonance at 38.10 GHz. The gain was increased to 8.10 dB compared to 7.22 dB in case of a single layer patch antenna (step-Four) with a reduced SLL far field and S_{11} of -26.14 dB with an operating bandwidth of 1.40 GHz. S_{11} for the proposed antenna is shown in Figure 2.

The overall dimensions of the proposed 5G applications patch antenna at Ka-Band are 6x6x3.25 mm^3. The antenna has much reduced size compared to 38 GHz antennas presented in previous works with higher gain or even a comparable gain. Using the reflecting layer had reduced the SLL in radiation patter without any need to use another technique which will lead to increase the overall dimensions of the antenna in obvious scale.

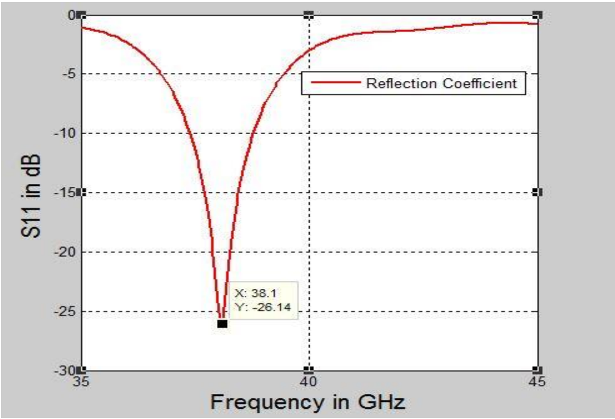
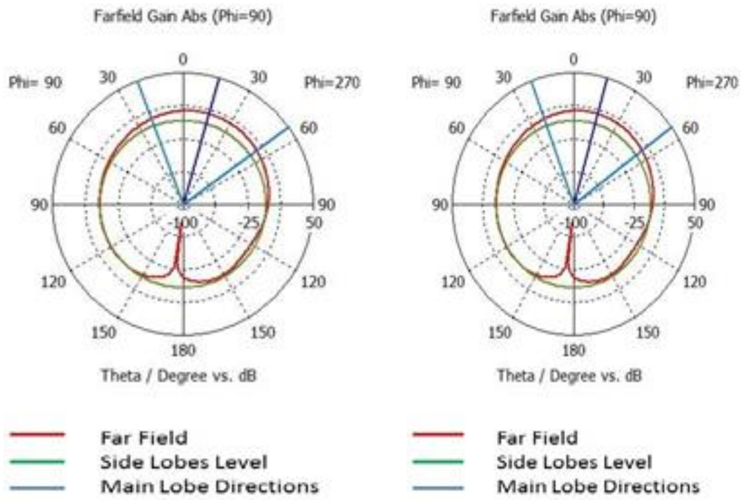


Figure 2. S_{11} for the proposed antenna

4. DISCUSSION

The proposed antenna for 5G applications at Ka-Band achieved high gain of 8.10 dB with F/B ratio of 16.27 dB due to the use of low loss dielectric material with a reflector layer which caused to an obvious decrement in SLL of radiation pattern. The radiation pattern of antenna shown in Figure 3, where Figure 3(a) shows radiation pattern of step-four while Figure 3(b) shows radiation pattern of Step-5. The red line in radiation pattern refers to main lobe magnitude and blue refers to main lobe direction while the green indicates the SLL. Figure 4 shows gain over the operating bandwidth of the proposed antenna which shows gain variation of only 0.30 dB.



(a) (b)

Figure 3. Radiation Pattern for (a) Step-4 and (b) Step 5

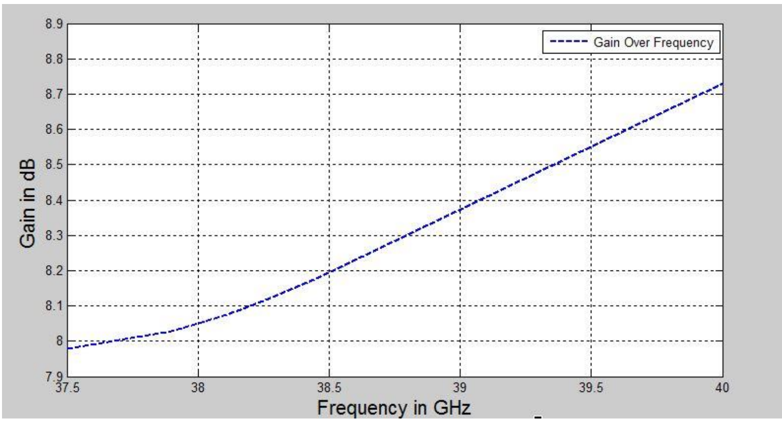


Figure 4. Gain over operating bandwidth for the proposed antenna

The proposed antenna is suitable for high data rate communications with low latency since it has an operating bandwidth of 1.40 GHz with a directive radiation pattern and high gain. The antenna has a reduced size compared to 38 GHz antennas in previous works as shown in Table 6. Moreover, the proposed design shows a higher gain compared to 2x2 MIMO antenna in [24] with very high percentage of size reduction and a comparable gain compared to 2x1 MIMO antenna in [19] and patch antenna proposed by [27] high size reduction percentage. It is very clear that there a slight difference between the analytical calculations for the dimensions of the rectangular-shaped patch and dimensions used in optimization steps.

Table 6. Size reduction percentage compared to relative designs

Ref.	Overall dimensions (mm^3)	Size reduction achieved by proposed antenna	Gain (dB)
[19]	110x55x0.508	96.19%	8.07
[27]	20x16.5x0.508	30.20%	8.10
[24]	16.71x21.98x0.50	36.28%	8.07

5. CONCLUSION

A patch antenna for 5G applications at Ka-Band was proposed in this work. The antenna has high gain of 8.10 dB at 38.10 GHz and wide operating bandwidth of 1.40 GHz. The proposed antenna has high F/B ratio of 16.27 dB and gain variation of 0.30 dB. The SLL in far field were eliminated due to adding FR4 reflector layer which caused to have high gain with a high size reduction percentage compared to antennas in related works.

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BIOGRAPHIES OF AUTHORS

Safa Nasssr Nafea received the Engineer degree in Electronic and Communications Engineering from College of Engineering, Al-Nahrain University in 2008. He received the Master degree in Networking and Communication Engineering from Department of Computers and Telecommunications Systems Department, Faculty of Engineering, University Putera Malaysia (UPM) in 2016. Currently, he is an assist lecturer at Computer Networks Engineering Department, College of Information Engineering, Al-Nahrain University, Iraq. He can be contacted at email: safanafea@gmail.com.

Nasser N. Khamiss is Professor at the Department of Systems Engineering, College of Information Engineering, Al-Nahrain University, Iraq, where she has been a faculty member since 1990. From 2007-2013, she was also the Dean of College of Information Engineering, Al-Nahrain University. B.Sc. degree in Electric and Electronic Engineering from Mosul University, Iraq, in 1980, and an M.Sc. in Communicatios Engineering from Technology University, Iraq in 1989. He completed her Ph.D. in Communicatios from the University of Lodz, Poland, in 2000. Her research interests are primarily in the area of wireless communications and networks as well as multimedia systems and 5G networks. He can be contacted at email: nassrnafea@gmail.com.