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Research Article

Design of 24-28 GHz band 5G Antenna Based on Symmetrically Located Circular Gaps

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Abstract

5G (fifth generation) cellular system is expected to work in a wide frequency range to meet the demand for mobile services and applications. Antennas will be addressed to the future 5G applications should pose superior characteristics, such as high gain and ultra-large bandwidth response by considering atmospheric absorption/free-space path loss on planned millimeter-wave frequency range of 5G communications. Therefore, antenna design for the future 5G applications is a challenging process. In this article we present a high-gain, broadband mm-Wave antenna based on a circular patch structure with a ground plane and resonator gaps. The designed antenna is analyzed using a widely used full-wave electromagnetic solver. The major antenna figure-of-merits including reflection coefficient, VSWR (voltage-standing wave ratio), antenna patterns in E- and H-planes, surface current distribution, antenna directivity and maximum gain, are obtained. The simulation results show that the gapped circular patch based design has the S11 response less than −10 dB in the frequency range of 21.6-28.8 GHz, which includes 24-28 GHz band of 5G cellular systems. Moreover, it is observed that the symmetrically located circular gaps on both top and bottom layers decrease the side lobe level under −10 dB value, and enhance the gain. We attribute the improvement in the antenna performance to the created current regions due to gaps hosting large vortex current distributions. With 10 mm × 13mm surface area, the proposed antenna demonstrates the peak gain of 9.44 dBi and the radiation efficiency of over 85%. High gain and compact size make this antenna suitable for coming 5G devices.
Keywords: 5G, cellular systems, millimeter-wave antenna.

Simetrik Olarak Yerleştirilmiş Dairesel Boşluklara Dayalı 24-28 GHz bant 5G Anten Tasarımı

Öz

5G (beşinci nesil) hücresel sistemlerin, mobil hizmet ve uygulamalara olan talebi karşılayacak geniş bir frekans bölgesinde çalışması bekleniyor. 5G uygulamalara yönelik antenlerin, 5G haberleşmenin planlanan milimetre dalga frekans aralığında atmosferik soğurma / boş alan yayılım kaybı dikkate alınarak kompak yapı, üstün kazanç ve ultra bant genişliği sağlamaları beklenmekte. Bu sebeple gelecek 5G uygulamaları için anten tasarımı süreci oldukça çetrefilli bir süreç tanımlıyor. Bu makalede, toprak düzlemi ve rezonatör kısmı boşluk içeren dairesel bir yama yapısına dayanan yüksek kazançlı, geniş bantlı bir mm dalga anten geliştirilmiştir. Tasarlanan anten, yaygın olarak kullanılan bir tam dalgalı elektromanyetik çözücü ile analiz edilmiştir. Sırasıyla, S11 yansıma katsayısı, E düzlemi ve H düzlemindeki anten ışıma demetleri, yüzey akım dağılımı (J), anten yönlülüğü (D) ve antenin maksimum kazanç değerlerini kapsayan anten tasarımına ilişkin esas başarım ölçütleri elde edilmiştir. Simülasyon sonuçları, aralıklı dairesel yama tabanlı tasarımın, 5G hücresel sistemlerin 24 − 28 GHz bandını kapsayan 21.6 − 28.8 GHz frekans aralığında −10 dB altında S11 yanıtına sahip olduğunu ortaya koymaktadır. Ayrıca, alt toprak tabakaya ve üst yayıcı tabakaya simetrik olarak yerleştirilen daire şeklindeki eş merkezli boşlukların yan lob seviyesini −10 dB değerinin altına düşürdüğü, ve anten kazancını arttırdığı gözlemlenmiştir. Anten performansındaki bu iyileşme, boşluklar sayesinde oluşturulan yeni akım bölgelerinin büyük girdap akım dağılımlarına ev sahipliği yapmasına bağlanmaktadır. 10 mm × 13 mm yüzey alanı ile önerilen anten 9.44 dBi tepe kazancı ve %85'in üzerinde bir ışıma verimliliği göstermiştir. Yüksek kazanç ve kompak yapısı sbebiyle önerilen anten gelecek nesil 5G aygıtlarla uyumluluk göstermektedir.

Anahtar Kelimeler: 5G, hücresel sistemler, milimetre dalga anten.

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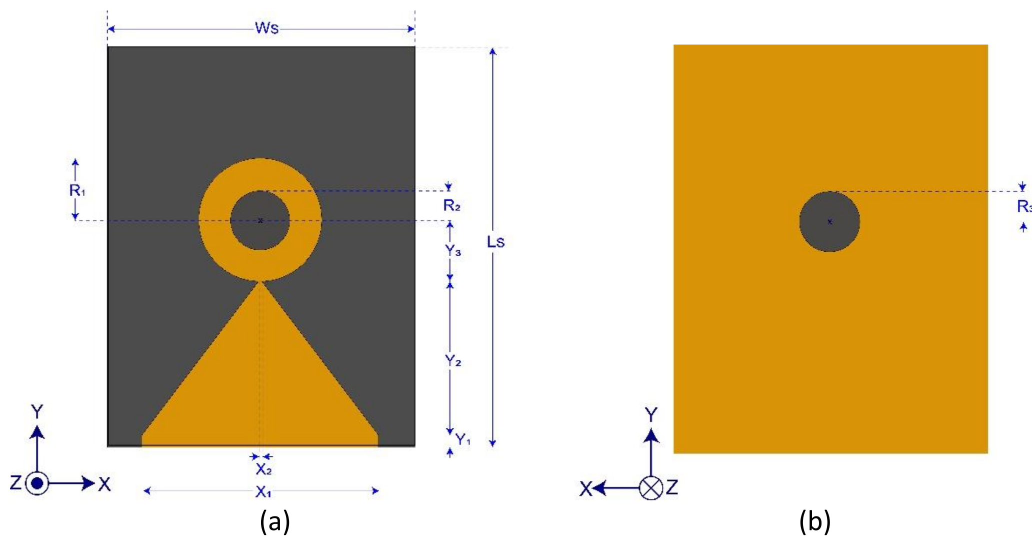
1.Introduction

Cellular communication systems have experienced a significant change in recent years, depending on technological and sociological factors. The demand for these devices has become increasingly widespread in terms of the advantages provided by the wireless and portable telephone calls. Studies have been conducted to improve quality parameters such as voice quality, bandwidth, coverage, delay, energy efficiency, reliability, and efficiency over time. Analog voice transmission was realized with 1G technology, and 2G technology provided data transmission at Kb/s levels as well as better quality digital sound transmission. In addition, features such as SMS (Short Message Service) and MMS (Multimedia Messaging Service) came with 2G. With the increasing number of mobile phone users, the demand for quality parameters has increased. These developments enabled the development of new mobile communication techniques and a fast transition to 3G technologies. 3G technologies have brought along data rates in Mb/s levels and features such as watch (VoD: Video on Demand), GPS (Global Positioning System), video chat (VC: Video Conferencing), mobile TV (MTV). 3G technology has enabled the spread of mobile internet and increased the use of social networks. However, the trend towards data traffic instead of voice traffic has increased, and the need to use 4G technologies has emerged. When looking from 1G to 4G, it is clearly seen that with the development of technology, people's demands in the field of communication are increasing day by day. Beyond this, 5G technology will allow devices to communicate with each other as well as people to communicate. In this context, it is expected that there will be a serious increase in data traffic and connection density per square kilometer in the coming years. Considering all these factors, the idle millimeter-wave frequency range (30-300 GHz) for mobile communication is considered to be used in 5G technology. In 5G technology, parameters such as high efficiency, high reliability, low latency, and increased energy efficiency are considered to be important, and studies on antenna design to meet these needs are carried out worldwide [1-3].

In the 5G system, 3.5-4.2 GHz band, defined as 6-GHz sub-band, is reserved for broadband radio services [4-5]. To achieve superior capacity in 5G applications, multiple-input multiple-output (MIMO) is one of the solutions used to create antenna arrays by maximizing spectral and energy efficiency [6-7]. In addition to MIMO antennas, recently developed Quasi-Yagi antennas can support high directionality, wide bandwidth, and low profile for 5G applications [8-9]. Direct-feeding microstrip patch antennas are relatively compact and robust structures but typically suffer from narrow bandwidths and high losses [10-12]. However, microstrip antennas to be designed with different geometries can eliminate the problem of narrow bandwidth and also provide high gain. In this article, using symmetrically located gaps on the ground and the radiator, a circular patch antenna design is proposed, which shows low side lobe level, wide bandwidth, and high gain. The design procedure of the gapped circular patch antenna is explained with the applied parametric analysis based on simulations. The proposed antenna has a gain of more than 9 dBi in the 24-28 GHz band.

2. Antenna Design

The structure of the circular patch antenna with its parameters is shown in Fig. 1. The proposed antenna consists of a microstrip tapered feed line and the radiating structure that is a circular patch with a circular gap. It has broadside radiation characteristics. Rogers RT5880 substrate with the dielectric constant of ε_r=2.2, and loss tangent of tanδ=0.0009 is selected. The dielectric thickness is 2 mm, corresponding to 0.1733λ at the center operation frequency, and the surface area is optimized to 10 mm x 13 mm. The bottom layer of the substrate, the ground, is covered with copper involving a circular gap. The center of the circular gap in the bottom layer of the substrate is in line with the center of the circular resonator at the top of the substrate. The optimal antenna parameters are summarized in Table 1.



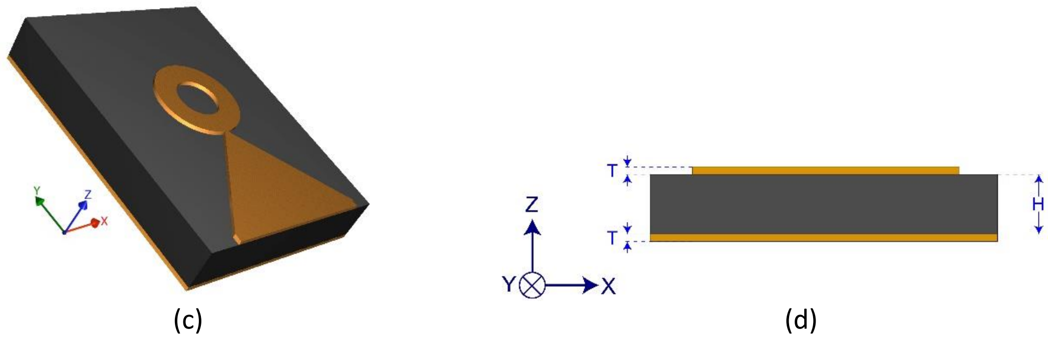


Figure 1.Antenna geometry (a) Top view, (b) Bottom view, (c)Perspective view, (c)Side view.

Table 1.Dimensions of the proposed antenna (all units are in mm)

W_s	L_s	X_1	X_2	Y_1	Y_2	Y_3	R_1	R_2	R_3	T	H
10	13	7.69	0.246	0.4	5	2	2.1	0.9	0.9	0.035	2

3. Simulation Results

The simulations of the proposed antenna are performed using a three-dimensional full-wave electromagnetic simulator CST Microwave Studio [13]. The reflection coefficient (S11) and voltage standing wave ratio (VWSR) results are shown in Fig.2 (a) and Fig.2 (b), respectively. The results show that the proposed antenna design can cover the range of 21.6-28.8 GHz (1:1.33 BW) with a reflection coefficient of less than −10 dB. It also displays the deepest S11 value of -18 dB at 24 GHz and VSWR value of 1.28 at 24 GHz.

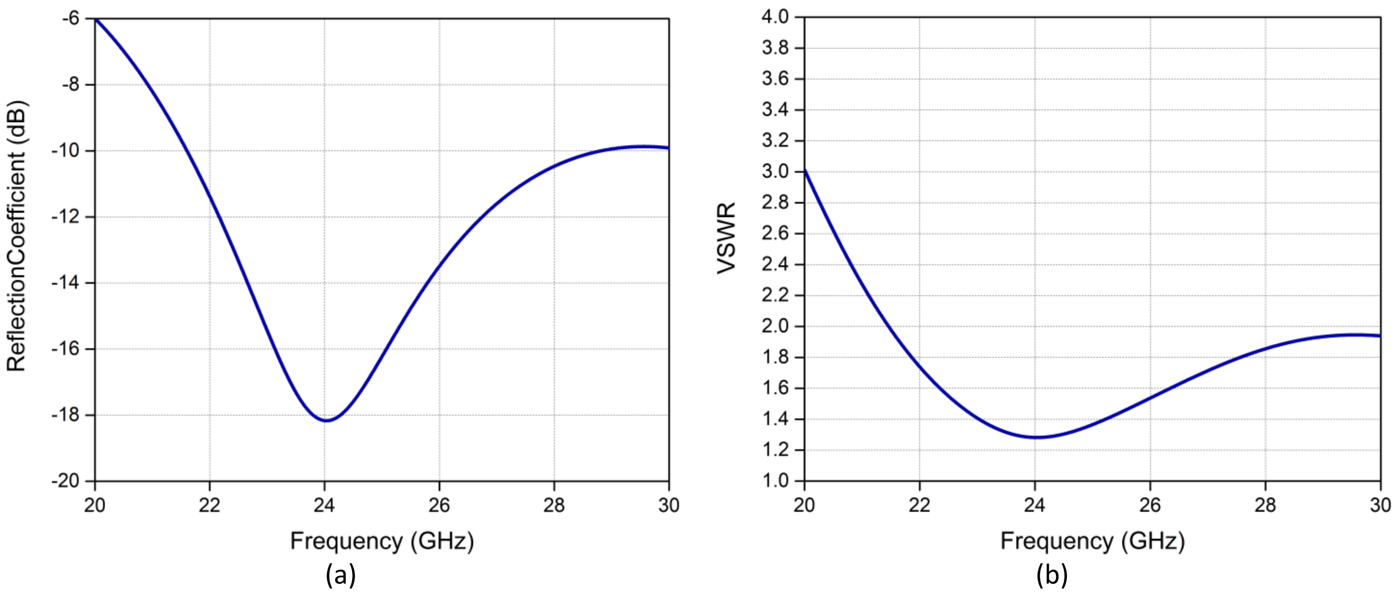


Figure 2. (a) Reflection coefficient (b)VSWR.

The parametric analysis results demonstrate that the antenna's bandwidth, gain, and efficiency can be adjusted by changing the antenna profile. Based on this outcome, various circular patch antenna versions are designed, as shown in Fig.3, and the effects are observed. First, the version-1 parameters are examined. The antenna performance and major characteristics such as gain, bandwidth, and radiation efficiency have been analyzed with variations in the parameters of X_1, R_1, Y_2, Y_3, and X_2. To obtain perfect impedance matching, the X_1 parameter, which is the width of the feed line input, was set to be an input impedance of 50 Ω.

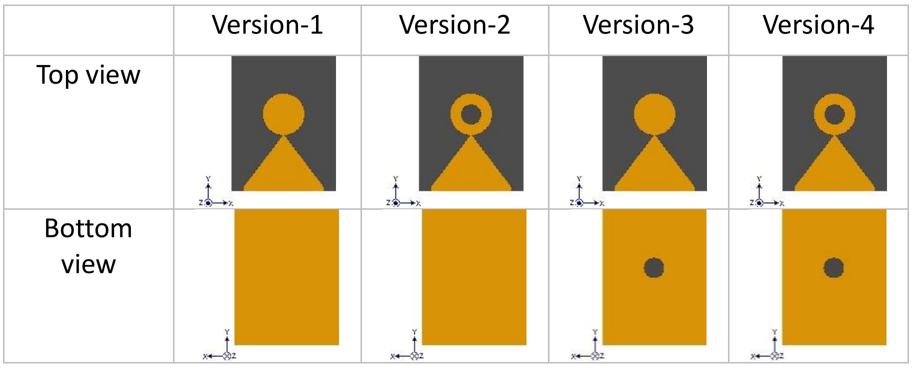


Figure 3.Top and bottom views of the studied antenna versions

The effect of parameter R_1, the radius of the circular resonator, was observed by changing it between 1.4 mm and 2.4 mm at intervals of 0.2 mm. As R_1 increases, the resonance frequency moves to a lower frequency due to the dimension of the resonator with an increase in gain and radiation efficiency. However, the E-plane side lobe level rises in this case. The effect of parameter Y_2 and Y_3, the lengths of the feed line parts, was also analyzed separately. It is observed that they pose the similar effects. When Y_2 and Y_3 increase, the antenna bandwidth, gain, and radiation efficiency decrease. Furthermore, although large Y_2 and Y_3 values lower the E-plane side lobe level, it raises the H-plane side lobe level. Finally, the effect of the X_2 was also analyzed. It has been found that the bandwidth of the antenna is not affected with any changes in the specified range of X_2, from 0.1 to 0.6 mm.

Table 2.Antenna gains at the 24-28GHz frequency band with e plane and H plane sidelobe levels for different variations of the structure.

Version	Sidelobe Level (dB)						Gain (dBi)		
	E-Plane			H-Plane					
	Frequency(GHz)			Frequency(GHz)			Frequency(GHz)		
	24	26	28	24	26	28	24	26	28
Version-1	-8.3	-10.4	-11.4	-15.4	-16.1	-18	8.187	9.127	9.456
Version-2	-9.3	-11.2	-11.7	-15.6	-16.3	-18.2	8.38	9.239	9.536
Version-3	-9	-11	-11.8	-15.1	-15.5	-17.1	8.282	9.132	9.438
Version-4 (Proposed Antenna)	-10	-11.6	-12	-15.4	-15.7	-17.3	8.446	9.241	9.496

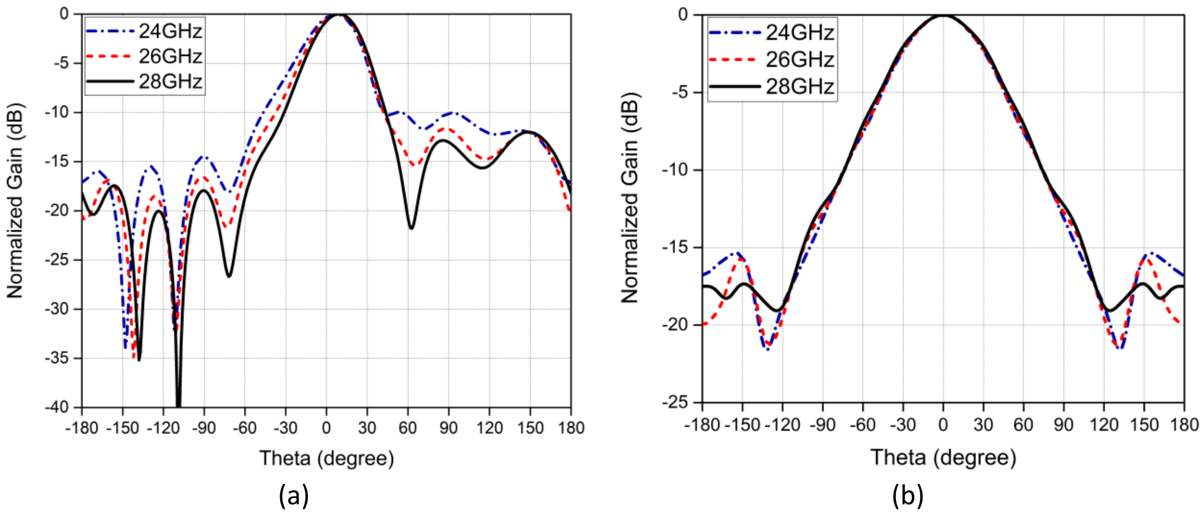


Figure 4.Simulated gain patterns of proposed antenna at 24, 26, and 28GHz (a) E-plane (b) H-plane.

In contrast to the effects of other parameters, as the X_2 value increases, the level of the E-plane side lobe and the radiation efficiency enhance, however, the gain reduces. With all these studies considered, the optimum value of X_1, X_2, Y_2, Y_3, and R_1 is selected 7.69 mm, 0.1 mm, 5 mm, 2 mm, and 2.1 mm, respectively, as shown in Table 1. However, the E-plane sidelobe level was above -10 dB after the optimum dimensions were achieved, particularly at frequencies near 24 GHz. In order to overcome this undesirable issue, a gap was first created on the resonator with radius R_2. It was observed that the etching of a circular shaped gap on the circular resonator affects the other performance parameters of the antenna beside the sidelobe level suppression. As shown in Table.2, the etching gap on the resonator, the version-2, enhances the sidelobe level and increases the antenna gain, like version-3. Nevertheless, the E-plane sidelobe level is still above −10 dB at 24 GHz. Thus, the ideal antenna design is selected as version-4 with the appropriate sidelobe levels and highest gain among the other versions.

Simulated co-polarized far-field gain patterns are shown in Fig. 4 for E-plane and H-plane at 24, 26, and 28 GHz. As shown in Fig. 4(a), the radiation peak is observed along the z-axis with a tilt of $\theta \approx 5°$. As the shape of the pattern and 3 dB bandwidth remain almost stable (Fig.4(b)), the E-plane pattern slightly changes within the 24-28 GHz band. However, we observe that 3 dB bandwidth narrows with the frequency in the E-plane. We attribute the narrowing in the bandwidth to the clear enhancement in the antenna gain (Fig.6). On the other hand, side lobe levels in both planes are approximately −10 dB below the main beam at 24, 26, and 28 GHz.

We also investigate the current behavior through the top and bottom antenna surface. Fig.5 shows the surface vector current distribution of the proposed antenna at 24 GHz to explain the antenna resonance mechanism. As shown in Fig. 5, whereas the gapped circular patch on the top layer hosts large surface electric current density, both top and bottom side gaps are the center of vortex currents.

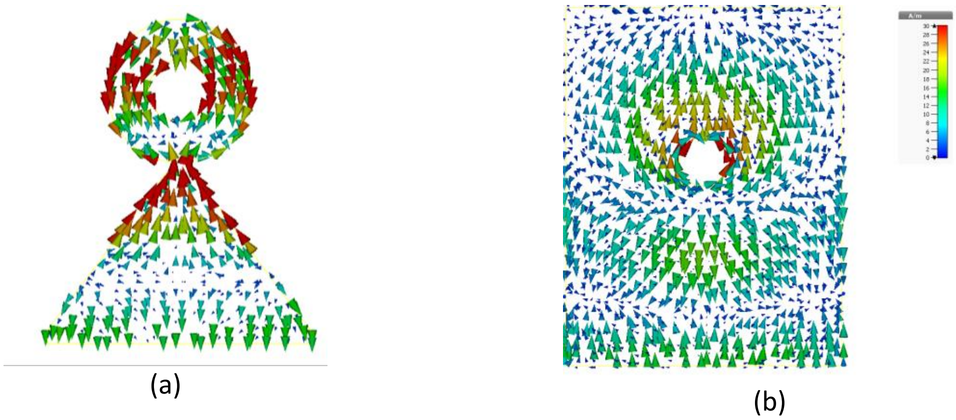


Figure 5.Surface current density distribution on the (a) top plane (b) bottom plane of the proposed antenna at 24 GHz

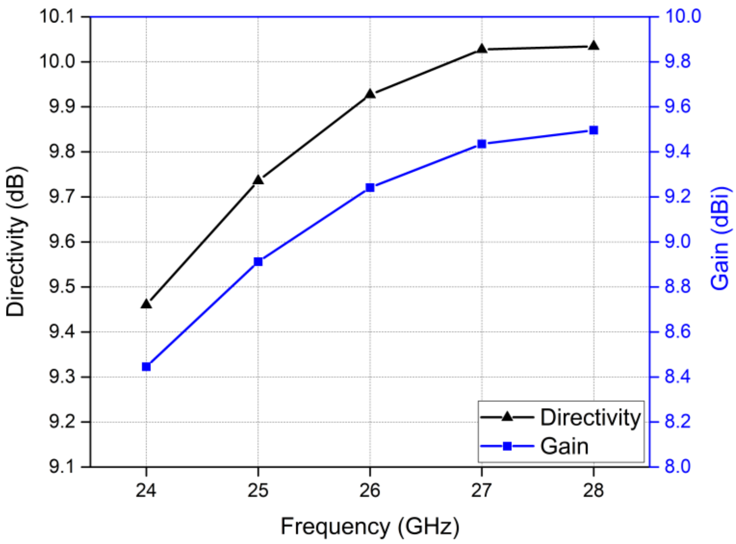


Figure 6.The directivity and gain of the proposed structure.

Fig. 6 shows the variations in the directivity of the antenna and gain depending on the frequency within the 24-28 GHz band. As shown, both figure-of-merits tend to increase with frequency. It is observed that the gain of the antenna is 8.44, 9.24, and 9.49 dBi at 24, 26, and 28 GHz, respectively.

4. Conclusion

In this paper, a new 24-28 GHz band 5G patch antenna design using circular gaps is introduced. The simulation results prove that the symmetrically located circular gaps on both top and bottom sides reduce the side lobe level under −10 dB, and enhance the gain. The proposed antenna shows 10 dB bandwidth of 21.6-28.8 GHz (1:1.33 BW), and the large gain with 8.44 dBi, 9.24 dBi, and 9.46 dBi at 24 GHz, 26 GHz, and 28 GHz, respectively. The proposed design can be a good candidate for 24-28 GHz band 5G mobile applications.

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