Enhancing the resonance characteristics of circular patch antenna for SHF applications

DOI : 10.36909/jer.10719

Mousaab M. Nahas*

Department of Electrical and Electronic Engineering, College of Engineering, University of Jeddah, Jeddah, Saudi Arabia

*Email: mnahas1@uj.edu.sa; Corresponding Author.

ABSTRACT

Microstrip patch antenna is attractive for various applications due to its easy fabrication, low cost and small size. It simply comprises of a radiating patch and ground plane that are separated by a dielectric substrate. However, the resonance bandwidth of the microstrip antenna is still an issue that needs to be considered in research. This paper aims to enhance the bandwidth of a microstrip antenna or introduce more resonant frequencies within the Super High Frequency (SHF) band. The paper demonstrates empirical results for circular-shaped patch antenna using the High Frequency Structure Simulator (HFSS). It begins by investigating different patch sizes and substrate materials, so that an optimal preliminary design is introduced. Then, different slot shapes are inserted into the patch for significant enhancement of the resonance characteristics. As a result, new ultra-wideband (UWB) antenna designs are presented with bandwidth results reaching 15.5 GHz within the C, X, Ku and K bands. Also, new multiband antenna designs are presented with improved reflection valleys in the Ku, K and Ka bands.

Keywords: antenna; circular patch; microstrip; SHF; slot.

INTRODUCTION

Nowadays, microstrip patch antennas are widely used because they are too small, cheap and easily fabricated on a printed board (Joret et al., 2017; Singh et al., 2019). The microstrip patch antenna is simply composed of a top metallic patch, bottom ground plane and dielectric substrate in between. The metallic patch shape can have several geometry options such as rectangular, circular, triangular, elliptical, diamond etc. (Patil, 2012). In fact, the rectangular shape is commonly used due to its simplicity, and thus it has been extensively investigated by researchers (Chattopadhyay et al., 2007). Circular shape is the second simplest design and it is worth investigating extensively as well. Due to the tininess and cheapness of the microstrip antennas in general, they are used for various applications including cellular phones, satellites, missiles and radars (Emadian and Ahmadi-Shokouh, 2015; Khan et al., 2015). Typically, there are two methods to feed the microstrip antenna: contacting and non-contacting method. In contacting method, the patch is directly fed with RF power using a contacting element such as microstrip line or coaxial cable. The microstrip line can be connected to the patch directly, while the coaxial cable is connected to the ground and then extended up to the patch. In practice, the contacting method is easy to model and fabricate but it yields low frequency bandwidth. Non-contacting method involves coupling of electromagnetic field between the patch and a feedline. It results in an enhanced bandwidth but it is more expensive and difficult to model and fabricate (Kumar et al., 2013).

In general, the microstrip patch antenna still suffers from narrow bandwidth and low gain efficiency, where the bandwidth is typically ~2-5% and the gain is ~5-7 dB by single antenna (Chaudhary and Dhukaiya, 2014). This can be understood as the electromagnetic fringing occurs from two sides of the patch, which means that the antenna radiates into half plane only. If the side fringing is enhanced, the resonance characteristics of the antenna are improved, hence bandwidth and gain. To achieve this, several possible options can be done such as increasing the thickness of the dielectric substrate or reducing the dielectric constant. In practice, the substrate thickness must not exceed a certain value (that is 0.05λ) because the antenna would deliver power into surface waves instead of transverse waves, thus it stops to radiate (Nahas and Nahas, 2019). Other options involve increasing the patch dimensions such that the fringing is significantly increased (Chaudhary and Dhukaiya, 2014). Generally, the patch design plays an important role in the antenna radiation, where numerous patch shapes have already been considered by researchers to enhance the antenna radiation (Lal and Singh, 2014; Mahmoud et al., 2016). However, introducing a slot into a simple patch shape is much more practical as it is easy to model and fabricate while the fringing can improve significantly (Patil, 2012). Accordingly, many researchers have demonstrated slots in simple rectangular and circular patches, but the maximum bandwidth achieved was still comparatively low (less than 7 GHz) (AbuTarboush et al., 2009; Chitra and Nagarajan, 2013; Chatterjee, 2016; Chaouki et al., 2017; Rani and Dawre, 2010; Burcakbas et al., 2017; Bhatia et al., 2018; Shaw et al., 2018; Rajagopal et al., 2017; Sahoo et al., 2018; Parveen et al., 2019; Naik and Shet, 2018; Khattak et al., 2019; Chen et al., 2017). Nevertheless, one paper demonstrated 10.14-GHz bandwidth in a circular patch antenna using three complementary ring slots that is relatively complex (Chandra et al., 2019). Another research showed 10.38-GHz bandwidth using circular patch with defected ground where two L-shaped slits were introduced in the ground plane (Bala et al., 2019). This also added more complexity to the antenna design. A recent research has been successful in approaching 11.5-GHz bandwidth in the SHF band by investigating simple slot shapes in a rectangular patch (Nahas and Nahas, 2019). In this paper, we aim to conduct similar experiments but on circular patch due to its simple geometry beside the rectangular. Also, new simple slot shapes are involved, e.g. crescent, annulus and half annulus, as they are still uncommon and easy to model and fabricate. The work starts by conducting a parametric study to introduce a preliminary circular design that will be the base for next investigations. In specific, the parametric study examines different feeding methods, patch sizes and substrate characteristics. Having attained an optimal preliminary design, the antenna performance is intended to be further enhanced by cutting a single slot of different shapes into the patch.

PRELIMINARY DESIGN

To design a preliminary antenna, the parametric investigation commences by comparing between the microstrip and coaxial feeds using different substrate materials. Then, a sequence of empirical investigations is conducted, which mainly involves the dimensions of the circular patch and cuboidal substrate. In practice, the patch thickness variation commonly shows trivial changes on the performance (Nahas and Nahas, 2019), thus it is preferred to be fixed at minimum (0.035 mm) to ensure minimal antenna weight and fabrication cost.

Theoretically, the optimal patch radius (a) can be estimated by using the following equation:

$$a = \frac{F}{\sqrt{1 + \frac{2h}{\pi \varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]}} \tag{1}$$

$$F = \frac{8.791 \times 10^9}{f_r \sqrt{\varepsilon_r}}$$

where f_r is the resonance frequency, h is the substrate height (thickness) and ε_r is the dielectric constant. However, since we look for a broad spectral improvement rather than just a single resonance peak, the above parameters are tweaked in the simulation to attain an optimized spectrum along the entire SHF band.

As an initial observation, the microstrip line feeding yields higher bandwidth than the coaxial feeding (see, for example, Figure 1 and Figure 6 below). By running numerous simulation tests, the optimal empirical radius is explored to be ~6 mm when the feedline width is 2.8 mm and the substrate dimensions are 35 × 35 × 1.5 mm. Note that the feedline width value is important as it allows matching the line impedance to the patch input impedance without the need for additional matching element.

Table 1 summarizes the simulation results for three common substrate materials using microstrip feeding, where f_L and f_H denote the lowest and highest edge of the resonated spectrum, respectively. Since frequency bandwidth is the most interesting value among resonance characteristics, RT duroid is decided to be used next, as it obviously yields the best bandwidth in Table 1 while simultaneously maintains a very low reflection valley.

Table 1 Substrate material results for 6-mm patch radius.

Substrate Material	**f_L (GHz)**	**f_H (GHz)**	**Bandwidth (GHz)**	**Minimum Reflection Coefficient (dB)**	**Minimum Reflection Frequency (GHz)**
FR-4 Epoxy	2.8	11.5	8.7	–31	4.4
Bakelite	2.8	11.4	8.6	–26.4	4.5
RT Duroid	3.3	14.3	11	–30.7	4.3

Figure 1 shows the top-view design and complete results of our preliminary RT-duroid antenna. The results are depicted through the S11 curve that shows the power reflection coefficient versus frequency, where the resonated spectrum corresponds to reflection values ≤ –10 dB. If smaller patch radius is used in the simulation (i.e. < 6 mm), the minimum reflection frequency would be shifted upward but the total bandwidth is reduced.

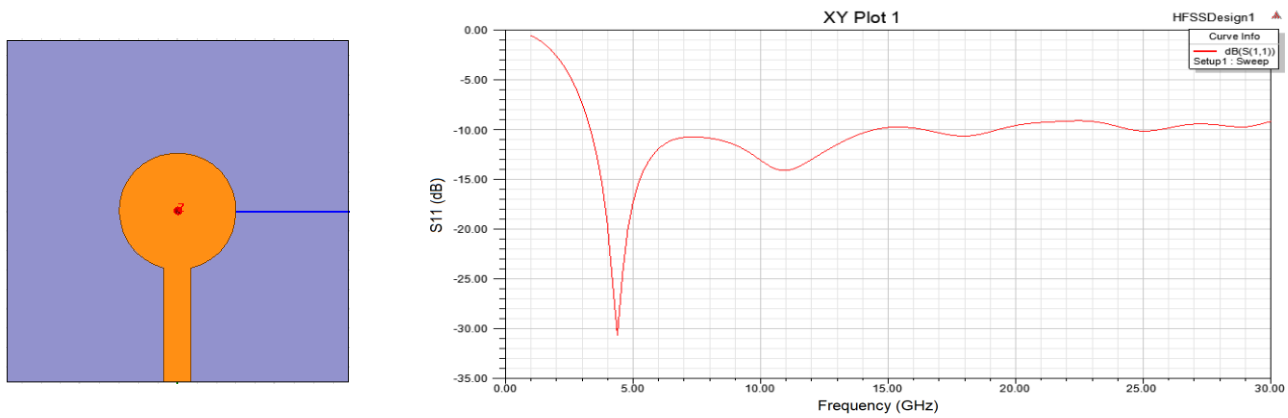

Figure 1 Design and results of the preliminary circular patch antenna.

It is obvious from Table 1 and Figure 1 that the preliminary antenna is a UWB where the frequency bandwidth reaches 11 GHz (extending between 3.3 and 14.3 GHz). According to the IEEE radio band designations, this antenna is suitable for the entire C-band (4 to 8 GHz), X-band (8 to 12 GHz) and some Ku-band (12 to 18 GHz) applications. Thus, it works effectively for satellite, Wi-Fi, cordless telephones, surveillance, radar, weather radar systems, satellite broadcast services and space shuttle communication. Nevertheless, it is most efficient for aircraft and drone altimeters since the minimum reflection reaches –30.7 dB at around 4.3-GHz frequency.

ENHANCED DESIGNS AND RESULTS

In this part, different slot designs are added to the above circular patch for further enhancement of the bandwidth and efficiency. New parametric study is performed on the slot size and position to attain the best empirical reflection characteristics. Then, we will show the results when the microstrip feedline is replaced by coaxial cable that is the second easiest feeding method in fabrication after the microstrip feeding (Kumar et al., 2013).

Microstrip Line Feeding

Figure 2 shows the antenna design and S11 results with a simple rectangular slot using the microstrip feedline characterized above. The best empirical position of the slot center is (2.5, 0, 0.035) mm, given that *x* is the vertical axis, *y* is the horizontal axis and *z* is the patch thickness that has already been fixed throughout the paper. (Note that positive *x* is towards the bottom in our view, while negative *x* would be towards the top.) In turn, the best empirical slot dimensions are 4 × 0.1 mm. As a result, the bandwidth is increased up to ~15.4 GHz but the minimum reflection becomes –28.7 dB at 4.5 GHz. Since the highest frequency reaches 18.7 GHz, this design is suitable for the entire C-band, X-band and Ku-band applications in addition to a few frequencies in the K-band (18 to 27 GHz) that can involve satellite, radar and astronomical. Nevertheless, as the minimum reflection coefficient is around 4.5 GHz, the antenna is most efficient for military communications and drone vehicle telemetry.

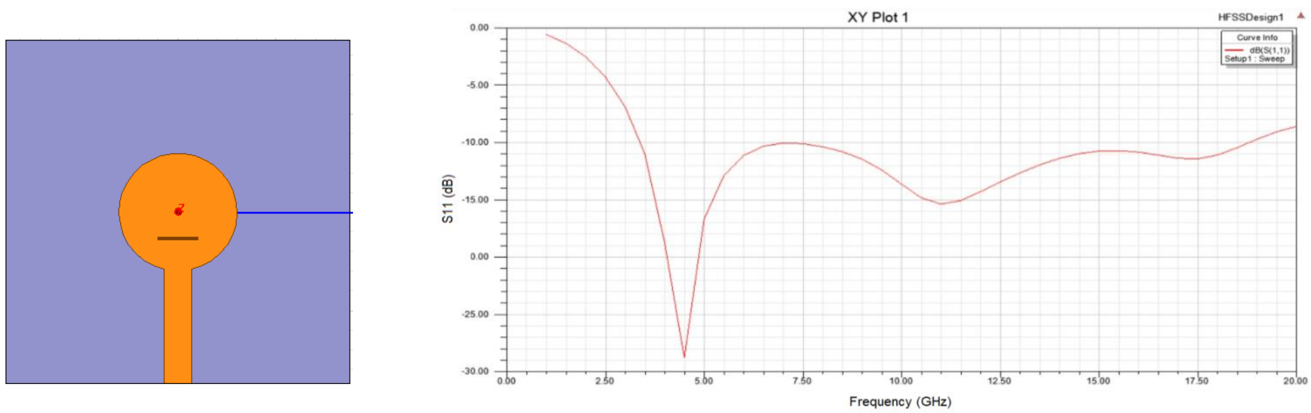

Figure 2 Circular patch antenna with a rectangular slot; design and results.

Figure 3 shows the design and results of the circular antenna with a novel crescent slot. The crescent slot was simply formed on the HFSS by drawing two arcs on top of each other, shifting one of them by 0.5 mm, linking the arcs and then cutting the in-between area. The radius of the first and second arcs as measured from the origin is 1.5 mm and 2 mm, respectively. This basically would imply that the maximum thickness of the crescent is 0.5 mm. Obviously, the bandwidth becomes 11.2 GHz that is slightly better than the preliminary antenna's (where there was no slot). Again, the antenna is suitable for applications in the C-band, X-band and part of Ku-band. Moreover, the reflection valley is reduced significantly and reached –37.5 dB at 4.4 GHz, which means the design is much more efficient in the applications related to the military communications and telemetry.

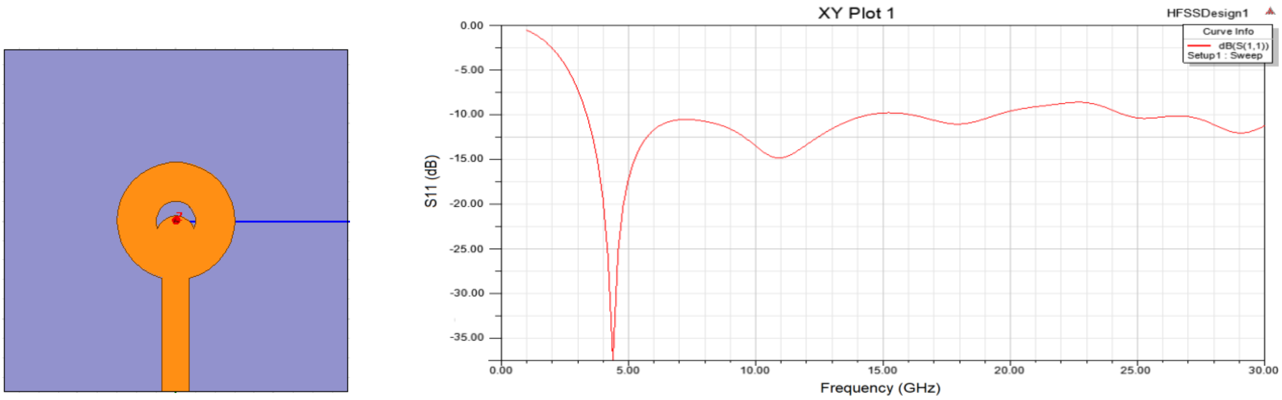

Figure 3 Circular patch antenna with a crescent slot; design and results.

Figure 4 shows the design and results of the antenna with a half annulus slot. The outer radius of the slot as measured from the origin is 2 mm while its thickness is 0.5 mm. The resulting bandwidth is 11.7 GHz and the minimum reflection coefficient is –31.3 dB at 4.3 GHz. This antenna yields better bandwidth than the crescent and preliminary designs', but again, it is suitable for operation in the same IEEE radio bands. Since the resonant peak is at 4.3 GHz, the antenna is most suitable for drone or craft altimetry applications.

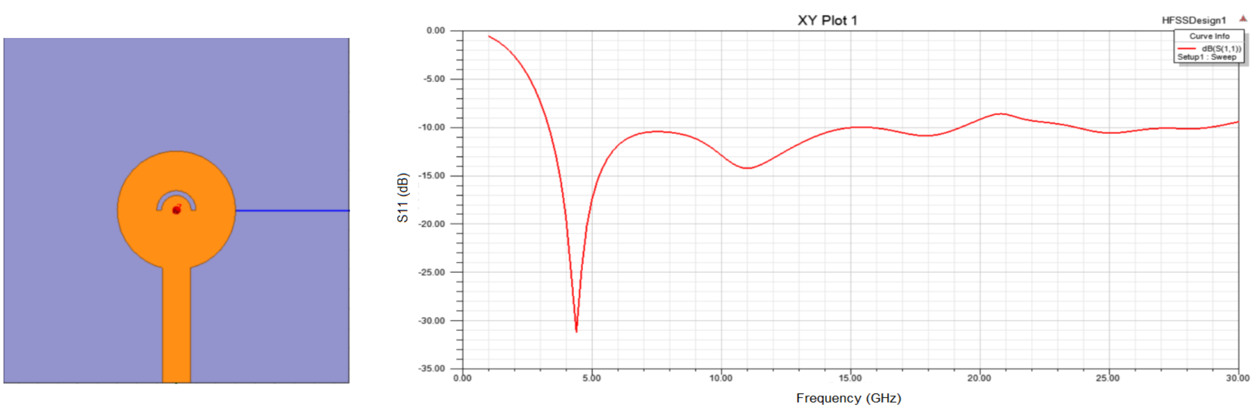

Figure 4 Circular patch antenna with half annulus slot; design and results.

Figure 5 shows the antenna design and results with a full annulus slot. The best empirical radius of the outer slot is 2.5 mm and the optimal thickness is 0.5 mm. The reflection in the results reaches –29 dB at 4.4 GHz while the bandwidth is extended up to 15.5 GHz, which slightly exceeds the value obtained before by rectangular slot. Thus, the antenna is effective in the entire C-band, X-band, Ku-band and partial K-band, but it is most suitable for the military communications and telemetry applications.

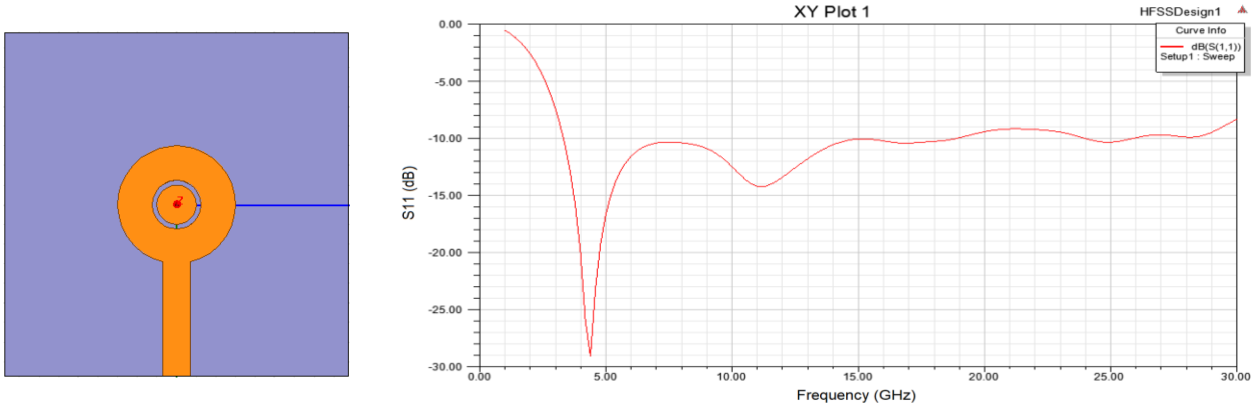

Figure 5 Circular patch antenna with an annulus slot; design and results.

Table 2 summarizes the entire results achieved for the circular antenna using microstrip line feeding. Obviously, the best designs with respect to the frequency bandwidth are the annulus-slot and the rectangular-slot designs whose bandwidth is 15.5 GHz and 15.4 GHz, respectively. In fact, these values are considered huge in the context of UWB circular patch antenna (Bala et al., 2019; Chandra et al., 2019) while very simple designs are simultaneously maintained. However, the other designs achieved above are also promising where they are all very simple and yield frequency bandwidth ≥ 11 GHz.

Table 2 Results of the circular antenna fed by a microstrip line.

Slot Design	**f_L (GHz)**	**f_H (GHz)**	**Bandwidth (GHz)**	**Min. Reflec. Coeff. (dB)**	**Min. Reflec. Freq. (GHz)**	**IEEE Radio Bands**
Without Slot	3.3	14.3	11	–30.7	4.3	C, X, Ku
Rectangular Slot	3.3	18.7	15.4	–28.7	4.5	C, X, Ku, K
Crescent Slot	3.3	14.5	11.2	–37.5	4.4	C, X, Ku
Half Annulus Slot	3.2	15	11.8	–31.3	4.3	C, X, Ku
Annulus Slot	3.3	8.8	15.5	–29	4.4	C, X, Ku, K

Coaxial Feeding

At this point the simulations are repeated using coaxial feeding instead of microstrip feeding. For comparison purposes, the patch and slots parameters are kept the same as before. The advantage of this feeding scheme is that the feed cable can be placed anywhere on the patch in order to match the impedance. However, its major drawback is that it often yields narrowband reflection valleys (Kumar et al., 2013).

Figure 6 shows the design and results of the coaxially-fed antenna without slot. It is obvious that the antenna is no longer UWB and becomes multiband, where multiple valleys occur separately and no wideband resonance is achieved. The best resonance is at 22.4 GHz where the reflection coefficient is −19.8 dB. Also, another resonance peak is observed at 16.7 GHz, but the antenna can work in the whole narrow bands 15.8-17.5 GHz and 21.4-23.5 GHz during which the reflection ≤ −10 dB. This antenna is most efficient for applications operating around 17 and 22 GHz that are in the Ku-band and K-band, respectively. The real applications of these bands were identified before.

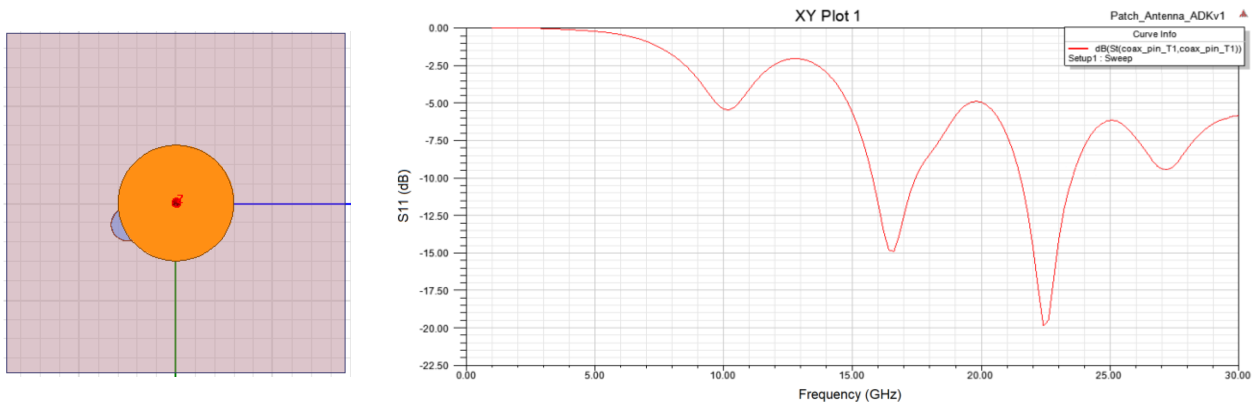

Figure 6 Coaxially-fed circular antenna without slot; design and results.

Figure 7 shows the design and results of the coaxially-fed antenna with a rectangular slot. The entire reflection curve is improved significantly, where a new reflection valley is introduced at 27.8 GHz with reflection −18.5 dB. The original two valleys obtained before are seen again but the minimum reflection coefficient is rather reduced to −22.5 dB at ~22 GHz. However, the antenna can be effective in all the narrow bands 15.7-17.6, 21.3-23.8 and 26.3-29.6 GHz. In effect, this design is most efficient for applications operating around 17 GHz (in the Ku-band), 22 GHz (in the K-band) and 28 GHz that is in the Ka-band (26.5 to 40 GHz). The Ka-band involves satellite communication and it is considered the spectrum of the future NASA communications.

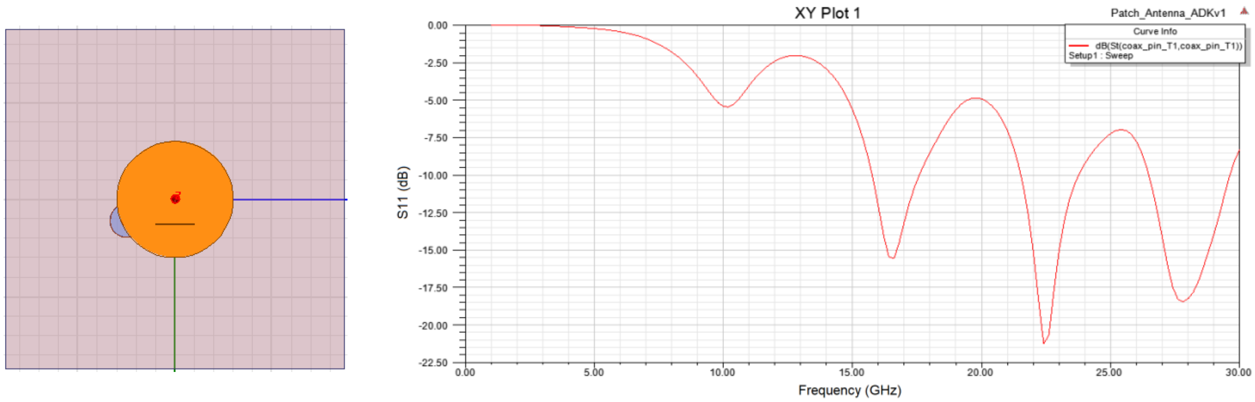

Figure 7 Coaxially-fed circular antenna with a rectangular slot; design and results.

Figure 8 shows the design and results of the coaxially-fed antenna with a crescent slot. The best reflection coefficient is –21.3 dB at 28.4 GHz. Two other resonance peaks are seen again at 16.5 and 22.6 GHz, and the antenna can operate in the narrow bands 15.8-17.4, 21.6-23.6 and 26.2-29.3 GHz. According to the reflection valleys mentioned above, the antenna is suitable for applications in the Ku, K and Ka bands.

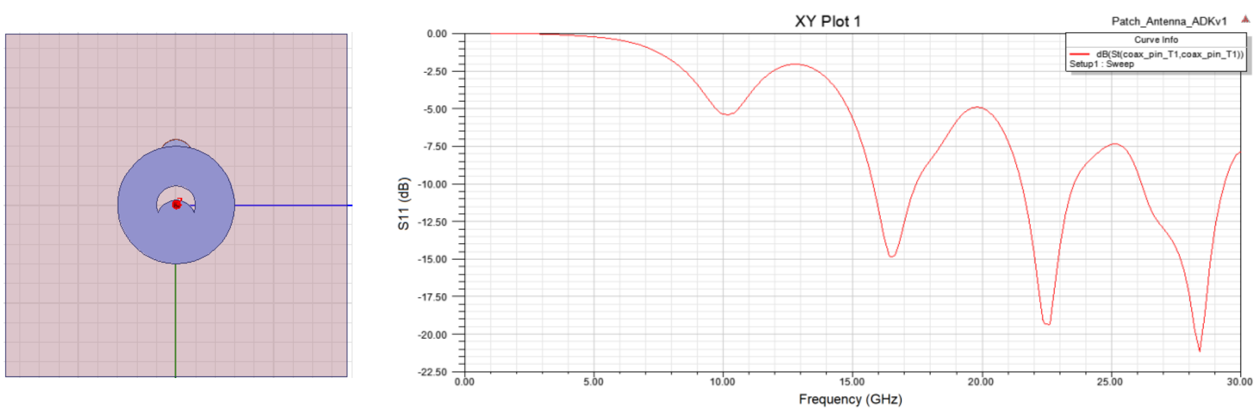

Figure 8 Coaxially-fed circular antenna with a crescent slot; design and results.

Figure 9 shows the design and results of the coaxial antenna with a half annulus slot. The best reflection in the results reaches −21.7 dB at 27.6 GHz. Other resonance peaks are obtained again at 16.6 and 22.6 GHz. Nevertheless, the antenna has continuous low reflection (≤ −10 dB) within the bands 15.6-18.1, 21.6-23.6 and 26.6-29.9 GHz. Again, this design is suitable for applications operating around 17, 23 and 28 GHz that belong to the Ku-, K- and Ka-band, respectively.

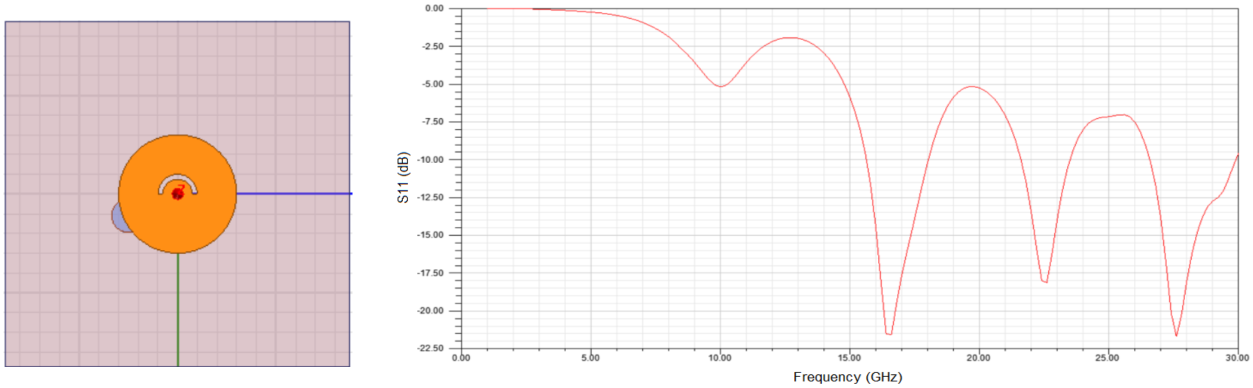

Figure 9 Coaxially-fed circular antenna with half annulus slot; design and results.

Figure 10 shows the design and results of the coaxial antenna with a full annulus slot. Clearly, the minimum reflection level is decreased considerably by this design as it reaches –28.1 dB at 22.7 GHz. However, this enhancement is at the expense of the 16-GHz valley whose reflection gets much closer to –10 dB. Furthermore, other valley is observed again at ~28 GHz with reflection –22.4 dB. In practice, the antenna is most efficient for applications operating in the Ku-band, K-band and Ka-band. It is also considered effective in the whole narrow bands 21.2-23.8 and 26.4-29.5 GHz during which the reflection curve drops dramatically below –10 dB.

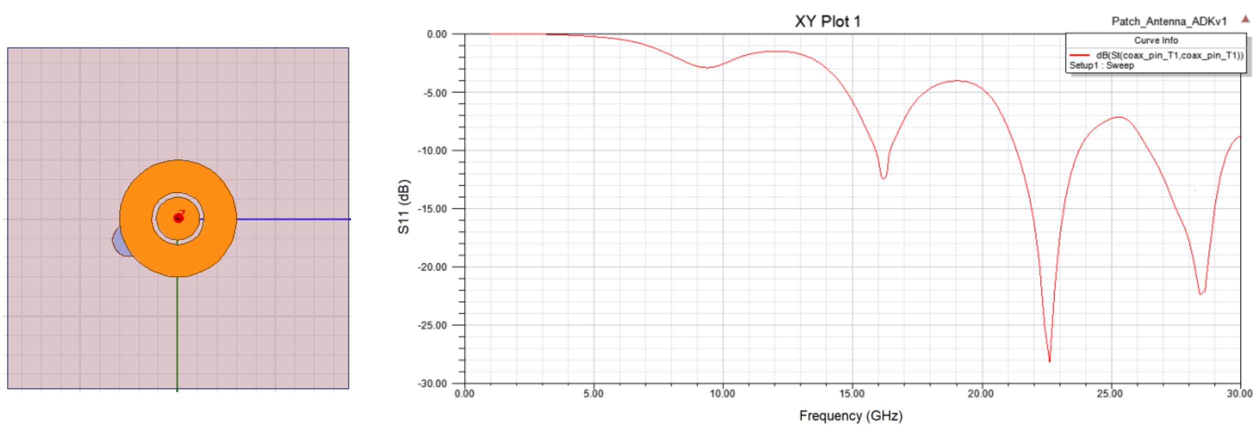

Figure 10 Coaxially-fed circular antenna with an annulus slot; design and results.

Table 3 summarizes the entire results achieved for the coaxially-fed antenna. The different designs yield almost similar performance in terms of the resonant frequencies but they show different reflection levels, where the lowest level is reached by the annulus design at ~23 GHz.

Table 3 Results of the circular antenna fed by a coaxial cable.

Slot Design	Min. Reflec. Coeff. (dB)	Min. Reflec. Freq. (GHz)	2nd Valley Freq. (GHz)	3rd Valley Freq. (GHz)	Continuous Resonance Bands (GHz)	IEEE Radio Bands
Without Slot	–19.8	22.4	16.7	---	15.8-17.5, 21.4-23.5	Ku, K
Rectangular Slot	–22.5	22.3	27.8	16.6	15.7-17.6, 21.3-23.8, 26.3-29.6	Ku, K, Ka
Crescent Slot	–21.3	28.4	22.6	16.5	15.8-17.4, 21.6-23.6, 26.2-29.3	Ku, K, Ka
Half Annulus Slot	–21.7	27.6	16.6	22.6	15.6-18.1, 21.6-23.6, 26.6-29.9	Ku, K, Ka
Annulus Slot	–28.1	22.7	28.3	16.2	21.2-23.8, 26.4-29.5	Ku, K, Ka

CONCLUSIONS

This paper investigated ways to enhance the resonance characteristics of a simple circular patch antenna using the HFSS. It began by introducing a preliminary design via optimizing the patch size and substrate material parameters. Then, further improvement was obtained by inserting different shapes of single slot into the patch. For comprehension and comparison, two contact feeding methods were involved that are microstrip line and coaxial feeding. As a main result, the microstrip line feeding showed better performance in terms of the frequency bandwidth. Moreover, it was empirically proven that inserting a slot into the circular patch would improve the antenna resonance characteristics significantly due to enhanced fringing. In specific, a UWB antenna was successfully designed with 15.5-GHz bandwidth for SHF applications in the range 3.3-18.8 GHz using an annulus slot design. In addition, a comparable performance was also obtained using a rectangular slot. The above two antennas are, therefore, suitable for applications exist in the C, X, Ku and K bands as per the IEEE radio band designations. Other successful UWB design was also obtained with 11.8-GHz bandwidth in the region

3.2-15 GHz using a half annulus slot. This antenna is suitable for applications in the C, X and Ku bands. In addition, the paper also demonstrated successful designs of multiband antenna by applying coaxial feeding along with slots into the patch. Such antennas are most efficient for operation at discrete frequencies covering applications in the Ku, K and Ka bands where reflection valleys are achieved around 17, 23 and 28 GHz, respectively. In conclusion, the UWB designs achieved primarily by microstrip feeding are the most attractive in this research, but however, all the slotted designs presented are highly recommended for fabrication.

ACKNOWLEDGMENT

The author thanks Ali Al-Yahyaoui, Madi Al-Hazmi and Mohammed Assaggaf for their great assistance during this research.

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