

Bandwidth and Efficiency Enhancement of Rectangular Patch Antenna for SHF Applications

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Abstract—The microstrip patch antenna is used in various communication applications including cellular phones, satellites, missiles, and radars, due to its several attractive features such as small size and weight, low cost, and easy fabrication. The microstrip patch antenna consists of a top radiating patch, a bottom ground plane, and a dielectric substrate in between. The patch can have different shapes, the rectangular patch being the most commonly used. In practice, the microstrip antenna suffers from narrow bandwidth and low gain efficiency. This paper aims to enhance the bandwidth and efficiency of a rectangular-patch antenna using the High-Frequency Structure Simulator (HFSS). Initially different patch sizes and substrate materials are investigated and optimal antenna parameters are achieved. Then, the antenna performance is further enhanced by inserting single and double slot designs into the patch. Two cost-effective feeding methods are involved in the investigation. The antenna is designed to operate in the Super High Frequency (SHF) band.

Keywords—microstrip patch antenna; microwave; SHF; slot

I. INTRODUCTION

Among various antenna structures, the microstrip patch antenna is the most widely used nowadays because it can be easily installed (due to its low size, weight and cost) and fabricated on a printed circuit board [1, 2]. The microstrip patch antenna is simply a metallic patch placed on a dielectric material and supported by a ground plane. There are different shapes that can be used for the patch, including rectangular, square, circular, triangular, semicircular, elliptical, diamond, hexagonal and bowtie [3]. However, the rectangular patch is the most common antenna geometry which has been extensively investigated [4]. Due to its simplicity and other advantages, the microstrip antenna is used for various applications including aircrafts, spacecrafts, satellites, missiles and mobile phones [5, 6]. Typically, the antenna is fed by two methods: contacting and non-contacting. Contacting method is more attractive because it is easy to model and fabricate and simple to match the impedance. It uses either inset or probe feeding techniques. The inset feeding uses a microstrip line connected to the patch directly, while the probe feeding involves a coaxial cable connected to the ground and extended up to the patch. However, the main disadvantage of the contacting method is that it yields a low frequency bandwidth.

Non-contacting method involves the coupling of an electromagnetic field between the patch and the microstrip line. Although it results in better bandwidth, it is less attractive due to its high cost and difficulty of modeling and fabrication [7].

In effect, the microstrip patch antenna still suffers from narrow bandwidth and low gain efficiency especially in rectangular shape. The bandwidth is typically around 2-5% while the gain is 5-7dB by single patch [8]. The reason is that electromagnetic fringing occurs from two sides of the patch only, thus the antenna radiates into half plane. Such fringing must be increased to enhance the antenna performance. There are several possible techniques to achieve this, for example, increasing the height (thickness) of the dielectric substrate. However, the thickness must not exceed 0.05λ , above which the antenna stops to radiate due to delivering the power into surface waves instead of transverse waves. Other options involve reducing of the dielectric constant or increasing the patch width from which the fringing takes place [8]. In fact, the patch width ultimately controls the radiation pattern as it is inversely proportional to the input impedance and directly proportional to the bandwidth. In contrast, the patch length has no significant contribution to the radiation and it is typically fixed at $\sim\lambda/2$. However, its optimal value depends on the patch width and substrate parameters. Since the patch design, in general, plays important role in the antenna radiation, different patch shapes have been considered to enhance the antenna bandwidth and efficiency [9, 10], though introducing a slot into a simple patch shape is much more practical as it is very easy and can enhance the antenna fringing significantly [3]. Therefore, many studies have demonstrated slots in simple rectangular patch, but the maximum bandwidth achieved is still relatively low ($< 5\text{GHz}$) [11-18].

This paper intends to further enhance the bandwidth and gain of the rectangular patch antenna. Various design options and their simulation results are demonstrated using the 1-30GHz frequency range to include the entire SHF band. A parametric study is initially performed to introduce a preliminary design, which involves different feeding methods, patch sizes and substrate materials. Then, the antenna performance is enhanced by cutting different slot designs into the patch using one and two slots.

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II. PRELIMINARY DESIGN

The preliminary design is based on a parametric study that commences by comparing the inset and coaxial feeding methods using the FR-4 epoxy substrate. Then, it goes through a sequence of empirical investigations including patch thickness, patch width, patch length, feedline width, substrate dimensions, and substrate material. As a result, the inset feeding yields higher bandwidth than coaxial feeding (see, for example, Figure 1 and Figure 5). The patch thickness has a negligible effect on the performance, thus 0.035mm is decided to be used to ensure minimal antenna weight. However, the other parameters affect the radiation where the optimal empirical patch length and width are found to be 6mm and 9mm respectively. These values are in a very good agreement with the calculated ones using 10GHz operation frequency in the following equations [17, 18]:

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

$$Length(L) = \frac{c}{2f_o\sqrt{\epsilon_{eff}}} - 0.824h \left(\frac{(\epsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\epsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \right) \quad (2)$$

where ϵ_r is the dielectric constant, h is the substrate height, f_o is the operation frequency and ϵ_{eff} the effective permittivity that is given by:

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2} \left(\frac{1}{1+12(\frac{h}{W})} \right) \quad (3)$$

The best inset feedline width is empirically ~2.8mm and the optimal substrate dimensions are 35x35x1.5mm. Finally, different common substrate materials are compared including Bakelite and RT duroid. The detailed results of the comparison are shown in Table I. Since frequency bandwidth is the most important parameter to consider in our research, RT duroid is decided to be used. However, the minimum reflection coefficient is reasonably low with such a dielectric.

TABLE I. DIELECTRIC MATERIAL RESULTS

Substrate material	f_l (GHz)	f_h (GHz)	Bandwidth (GHz)	Minimum reflection coefficient (dB)	Minimum reflection frequency (GHz)
FR-4 Epoxy	3.7	10.1	6.4	-32.4	6
Bakelite	3.68	10.1	6.42	-27	6.1
RT Duroid	4.4	12	7.6	-30.2	6.2

Figure 1 shows the top-view design and results of our preliminary antenna using the optimal parameters obtained above. The results are depicted through the S11 curve that shows the power reflection coefficient vs frequency. Typically, the acceptable performance corresponds to ≤ -10 dB reflection. It is obvious that the antenna is ultra-wideband (UWB) where the frequency bandwidth reaches 7.6GHz. According to the IEEE radio band designations, this antenna is suitable for the C-band (4 to 8GHz) and X-band (7 to 11.2GHz) applications, which involve satellites, Wi-Fi, cordless telephones,

surveillance, radar, and weather radar systems. It is most efficient for the next Wi-Fi generation [19] since the minimum reflection coefficient reaches -30.2dB at around 6GHz frequency.

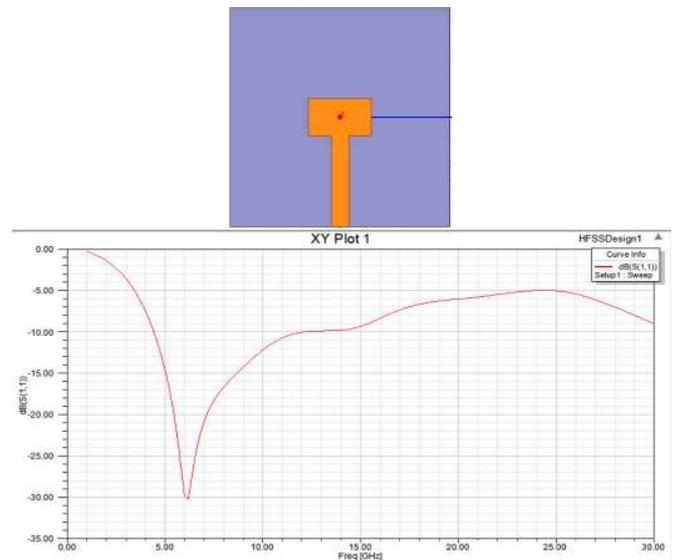


Fig. 1. Design and results of preliminary rectangular patch antenna

III. ENHANCED DESIGNS AND RESULTS

In this part, slot(s) is (are) added to the patch for further bandwidth and efficiency enhancement. Another parametric study is performed on each slot design, including size and position, such that the best design is empirically obtained. Single and double slots of the same shape are investigated respectively. Finally, the inset feedline is replaced by a coaxial cable for comparison. This is because coaxial feeding is the second easiest feeding method in fabrication after the inset method [7].

A. Inset Feeding

This section presents several slotted designs and their S11 results using inset feeding. Figure 2 shows the antenna design and results with a U-slot. The position of the slot center is (-2.5, 0) mm, given that x is the vertical axis, y is the horizontal axis, and negative x is towards the top in our view. The slot width and length are 0.25 and 8mm respectively, while each arm is 1.2mm long. As a result, the bandwidth is increased up to ~9.8GHz but the minimum reflection becomes -27.7dB at 6.4GHz. This design is suitable for C-band, X-band and some Ku-band (12 to 18GHz) applications where the higher frequency exceeds 14GHz. Again, it is most efficient for the next Wi-Fi generation since the minimum reflection coefficient is still around 6GHz.

Figure 3 shows the antenna design and results with a rectangular slot. The position of the slot center is (-1, 0) mm, while the slot length is 5.5mm and its width is 0.25mm. Obviously, the bandwidth is enhanced to 11.5GHz where the higher frequency reaches ~16.2GHz. This antenna can operate in the C-band, X-band and most of the Ku-band which involves satellite broadcast services, space shuttle communication and

International Space Station (ISS) communication. Moreover, the minimum reflection of this design is reduced down to -41dB at 7GHz, which allows excellent operation in the next Wi-Fi generation band.

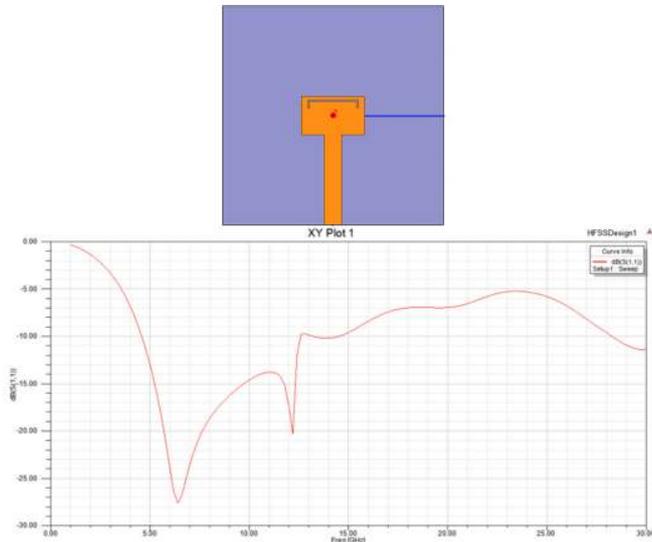


Fig. 2. Rectangular patch with U-slot. Design and results

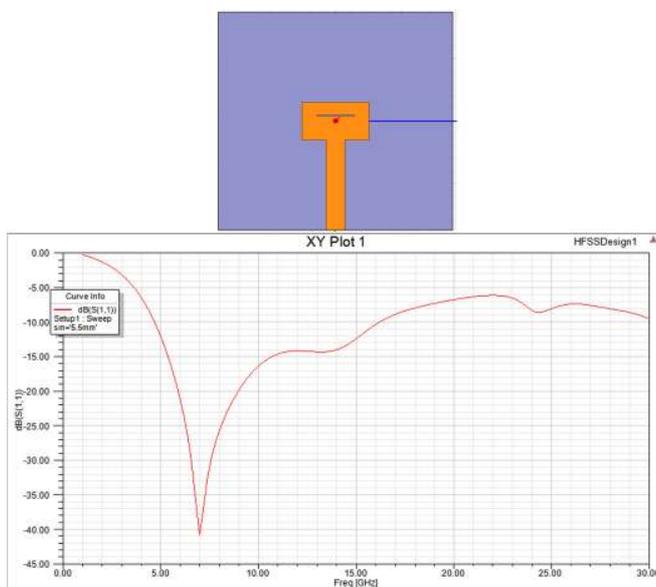


Fig. 3. Rectangular patch with rectangular slot. Design and results

Figure 4 shows the antenna design and results with double rectangular slots. The central position of slot 1 is (-1, 0) mm, the length is 5mm and the width is 0.25mm. The position of slot 2 is (-1.7, 0) mm, the length is 9mm and its width is 0.1mm. The resulting bandwidth is 10.2GHz since the higher frequency becomes less than 15GHz. The minimum reflection coefficient is -25.5dB at 6.2GHz. Again, this antenna has peak resonance at the next Wi-Fi generation band, and it is generally suitable for applications of the C-band, X-band and Ku-band.

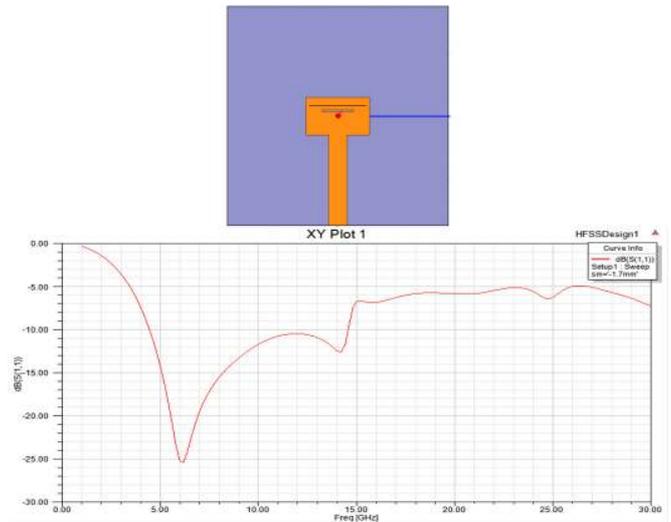


Fig. 4. Rectangular patch with double rectangular slots. Design and results

In addition, the same procedure is repeated for a rectangular patch with double U-slots. The first slot has the same dimensions and position of the one shown in Figure 2. The second slot is located around the origin and its width and length are 0.25mm and 2.5mm respectively. Again, the arm length is 1.2mm. As a result, the bandwidth is reduced to 7.1GHz and the minimum reflection becomes -25dB at 6GHz. These values are worse than those of the preliminary design although they cover frequencies in the X-, C- and Ku-bands. This degradation can be understood as some fringing field components cancel each other, resulting in significant reduction of the overall radiation.

Table II summarizes the results achieved for the rectangular antenna using inset feeding. Obviously, the best design is corresponding to the single rectangular slot where the bandwidth reaches 11.5GHz and the minimum reflection coefficient drops down to -41dB at 7GHz. However, other successful designs are achieved with double rectangular slots and single U-slot antenna, where the bandwidth is 10.2 and 9.8GHz respectively.

TABLE II. RECTANGULAR PATCH FED BY INSET FEEDLINE RESULTS

Slot design	f_l (GHz)	f_h (GHz)	Bandwidth (GHz)	Min. ref. coef. (dB)	Min. ref. freq. (GHz)	IEEE radio bands
Without slot	4.4	12	7.6	-30.2	6.2	C, X
U-slot	4.7	14.5	9.8	-27.7	6.4	C, X, Ku
Double U-slots	6.3	13.4	7.1	-25	6	C, X, Ku
Rectangular slot	4.7	16.2	11.5	-41	7	C, X, Ku
Double rectangular slots	4.4	14.6	10.2	-25.5	6.2	C, X, Ku

B. Coaxial Feeding

In this part, the simulation results of using coaxial cable instead of inset feedline are shown. For comparison purposes, the antenna parameters and slots position and size are the same as before.

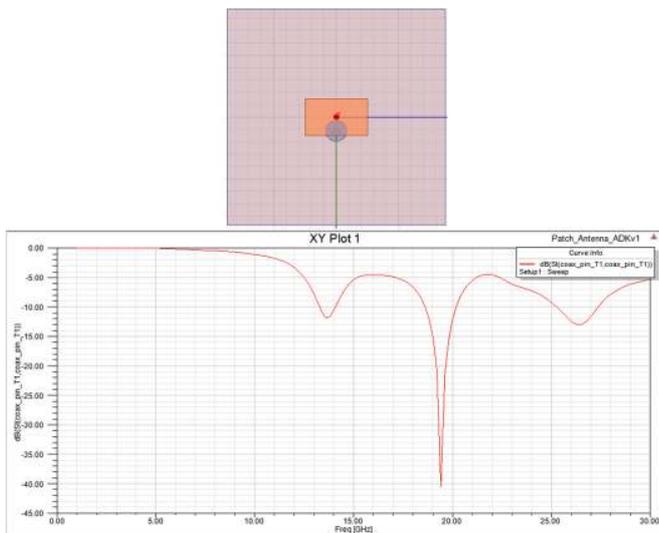


Fig. 5. Coaxially-fed rectangular patch without slot. Design and results

Figure 5 shows the design and results of the coaxially-fed antenna without slot. It is obvious that the antenna is no more UWB and becomes multiband, where peak resonance occurs discontinuously for a few specific frequencies at which reflection ≤ -10 dB. The best resonance is at 19.3GHz where the reflection coefficient reaches -40.3 dB. However, other resonance peaks are observed around 13.7GHz and 25.2–27.3GHz with acceptable reflection coefficient values. This antenna is most efficient for applications operating around 19GHz which belongs in the K-band (18 to 27GHz), which involves satellite, radar, and astronomical applications. The antenna can also operate at other frequencies in the same band including 25.2–27.3GHz. It is also suitable for Ku-band applications operating around 14GHz.

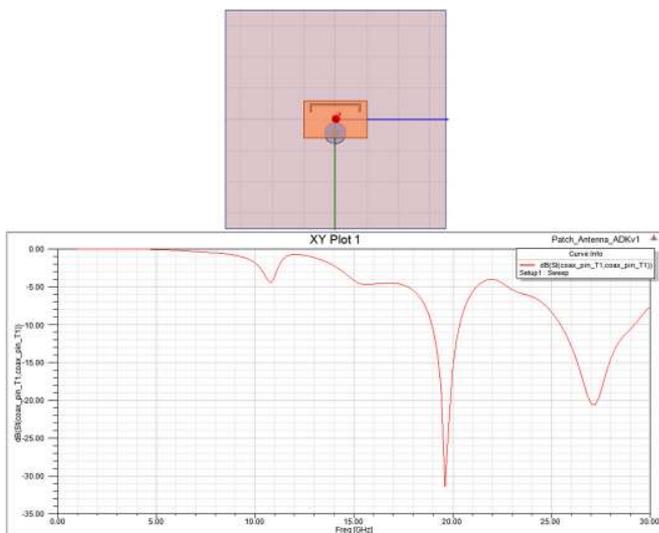


Fig. 6. Coaxially-fed rectangular patch with U-slot. Design and results

Figure 6 shows the design and results of the coaxially-fed antenna with U-slot. The best resonance is observed at 19.6GHz where the reflection is -31.4 dB. Moreover, the

acceptable reflection is also seen between 25.5 and 29.1GHz where a reflection valley of -20.6 dB is observed at 27.2GHz. Again, this design is most efficient for applications operating around 19GHz in the K-band. However, the resonance is expanded to include frequencies in the Ka-band (26.5 to 40GHz), which is used for satellite communications and is also considered as the future spectrum for NASA communications.

Figure 7 shows the design and results of a coaxial patch antenna with a rectangular slot. The best reflection in the results reaches -38 dB at 13GHz. Other resonance peaks are obtained at 19.4 and 26.1GHz where the reflection is -26.8 and -29.8 dB respectively. However, the antenna has continuous low reflection (≤ -10 dB) between 24.6 and 28GHz. Obviously, the results are enhanced by this design as the antenna becomes efficient for applications operating around 13GHz in the Ku-band, 19GHz in the K-band and 26GHz in the Ka-band. It is also suitable for operation between 24.6 and 28GHz.

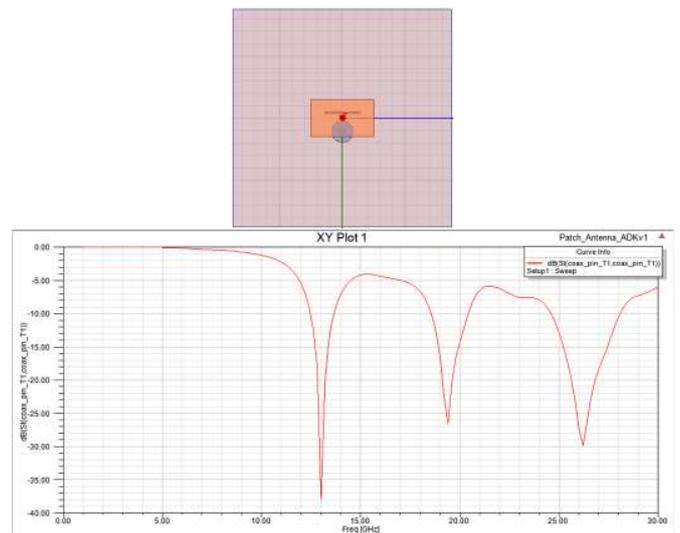


Fig. 7. Coaxially-fed rectangular patch with a rectangular slot. Design and results

Figure 8 shows the design and results of a coaxial patch antenna with double rectangular slots. As a result, resonance peaks are observed at 19.7 and 26.6GHz whose reflections are -26.3 and -22.7 dB respectively. Moreover, the antenna has an acceptable reflection in the 24.5–28.9GHz range. This antenna is efficient for applications at 19.7 and 26.6GHz which are in the K- and Ka-band respectively. It is also suitable for any application between 24.5 and 29GHz.

The same procedure is repeated for a coaxially-fed patch with double U-slots. Unfortunately, the reflection never drops below -10 dB, hence no resonance is observed. This is due to field opposition and cancellation that arises from the slots.

Table III summarizes the results achieved for our coaxially-fed antenna. The best multiband design is corresponding to the single rectangular slot where three reflection valleys are obtained at 13, 19.4 and 26.1GHz. An additional operating band is also seen between 24.6 and 28GHz.

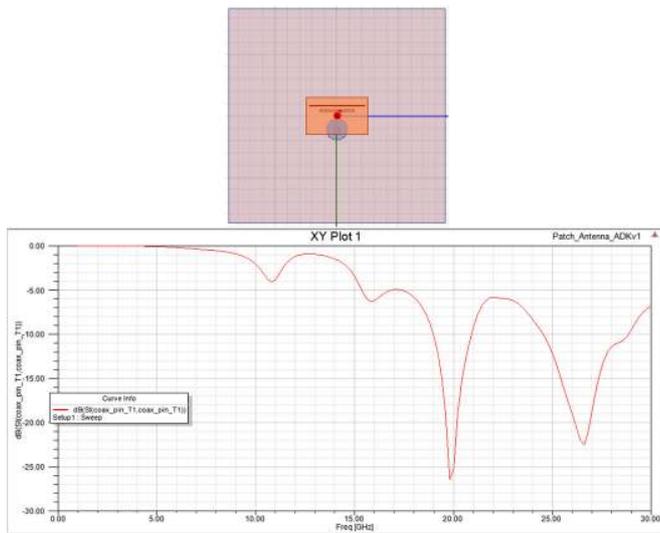


Fig. 8. Coaxially-fed rectangular patch with double rectangular slots. Design and results

TABLE III. RECTANGULAR PATCH FED BY COAXIAL CABLE RESULTS

Slot design	Min. ref. coef. (dB)	Min. ref. freq. (GHz)	2nd res. (GHz)	3rd res. (GHz)	Additional resonance (GHz)	IEEE radio bands
Without slot	-40.3	19.3	-	-	13.7, 25.2-27.3	Ku, K
U-Slot	-31.4	19.6	27.2	-	25.5-29.1	K, Ka
Double U-slots	-	-	-	-	-	-
Rectangular slot	-38	13	19.4	26.1	24.6-28	Ku, K, Ka
Double rectangular slots	-26.3	19.7	26.6	-	24.5-28.9	K, Ka

IV. CONCLUSIONS

This paper explored ways for enhancing the bandwidth and efficiency of a simple rectangular patch antenna using HFSS. At first, a preliminary design was introduced via optimizing the patch size and substrate material parameters. Further improvement was obtained by inserting different shapes of single and double slots into the patch. A comparison of two feeding methods was also carried out using inset and coaxial feeding. The results showed that the inset feeding is a better option as far as the frequency bandwidth is concerned. However, it was also proven that inserting slot(s) would improve the overall antenna performance significantly. In specific, a UWB antenna was successfully designed for SHF applications with 11.5GHz bandwidth using a single rectangular slot. Other UWB designs were also obtained with 10.2 and 9.8GHz bandwidth using double rectangular slots and single U-slot respectively. These designs are suitable for

applications in the C-, X- and Ku-band. In addition, successful designs of multiband antenna using coaxial feeding along with a slotted patch were shown. Such antennas are efficient for operation at discrete frequencies, where the best design covers applications in the Ku-, K- and Ka-bands operating around 13, 19 and 26GHz respectively. They are also suitable for applications between 24.6 and 28GHz. However, the UWB results achieved by inset feeding are the most attractive ones in this research.

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