Institut für Hochfrequenztechnik
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Studienarbeit

Circular polarized 60 GHz antennas

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1. INTRODUCTION

Many multimedia applications for high speed data wireless transmissions (around Gb/s or multi-Gb/s) are used in indoor systems (<10m). Some examples of them are the Ethernet Gigabit (1.25 Gb/s), the wireless high-speed download and the wireless transfer of high-definition video (2-20Gb/s). These high transmission rates cannot be implemented in the traditional frequency bands dedicated for the typical wireless systems, since they obtain an important degradation of service and the bandwidth is not enough for the data rate. For this reason, the Federal Communications Commission (FCC) has introduced recently 7 GHz of bandwidth, without license, in the band of 60 GHz. It is mainly due to the appearance of the atmospheric attenuation (10 to 15 dB/Km), since the presence of the oxygen affects in a bandwidth of 8 GHz (approximately) over the 60 GHz band; So the band of 60 GHz is not suitable for long distances (more than 2 Km). However, it is possible to dedicate completely in indoor wireless applications (<50m), where the atmospheric attenuation does not have any significant impact.

This high bandwidth allows high speeds of data transmission and a new range of ultra-high rates of the wireless communications systems. In consequence, the wireless high-definition multimedia interface (wHDMI) and "Kiosk-downloading" are some applications with a high volume of information. It is important to highlight that wHDMI will offer an important improvement in the WLAN incorporated in the systems of portable computer (laptops, PDAs, etc …).

On the other hand, " Kiosk-downloading " is a possible solution to transfer, in a short time, DVD's movies from a server (kiosk) to a portable device such as iPods or PDAs. For example, the download of 120 minutes of a DVD would take 10 minutes with a rate of 54 Mb / s, whereas with this new technology would only take 13 seconds for a 2 Gb / s rate, and for 6 Gb / s rate it would only takes 4 seconds.

In spite of the quantity of publications and the interest related to the 60 GHz band, it is possible to observe that the data rates of WLAN and WPAN increase periodically. For example, in 1999 the standard 802.11.b was allowing a maximum speed of 11Mb/s and in 2007 the rate was coming until 300Mb/s through the support to the project 802.11.n. Therefore, in 2011 it is possible to anticipate that a rate of a few Gb/s will be offered.

Therefore, in order to satisfy the increasing demand of bandwidth, many enterprises and research institutions are investigating in new technologies to solve or at least to cover it temporally. For example, in March, 2005, the Group of Tasks 3C (TG3c) in IEEE802.15 was formed to coordinate the normalization of the 60 GHz band [12].

In order to contribute something to this investigation topic, this project is dedicated to the study of different antennas capable of working at the 60 GHz band and with the addition value of being circular polarized.

2. CIRCULAR POLARIZED MSA

In a communication system that uses circularly polarized radiation, the rotational orientations of the transmitter and the receiver antennas are unimportant in ratio to the received signal strength. With linearly polarized signals, on the other hand, there will be very weak reception if the transmitter and receiver antenna orientations are nearly orthogonal. Also in CP, after reflection from metallic objects, the sense of polarization reverses from *left-hand CP* (LHCP) to *right-hand CP* (RHCP) and vice versa to produce predominantly orthogonal polarization [1,2,3]. The system then tends to discriminate the reception of such reflected signals from other signals arising from direct paths. Therefore, CP is useful for a number of applications, such as radar, communication, and navigational systems.

2.1 Linear, Circular, and Elliptical Polarizations

The polarization of an electromagnetic wave may be linear, circular, or elliptical. The instantaneous field of a plane wave, traveling in the negative *z* direction is given by

$$E(z,t) = e_x(z,t)\hat{x} + E_y(z,t)\hat{y}$$

The instantaneous components are related to their complex counterparts by

$$E_x(z,t) = E_x \cos(\omega_t + \beta_z + \phi_x)$$

And

$$E_y(z,t) = E_y \cos(\omega_t + \beta_z + \phi_y)$$

Where E_x and E_y are the maximum magnitudes and ϕ_x and ϕ_y are the phase angles of the *x* and *y* components, respectively, ω is the angular frequency, and β is the propagation constant.

For the wave to be linearly polarized, the phase difference between the two components must be

$$\Delta_\phi = \phi_y - \phi_x = n\pi \text{ , where } n = 0, 1, 2, \ldots$$

The wave is circularly polarized when the magnitudes of the two components are equal ($E_x = E_y$) and the phase difference $\Delta\phi$ is an odd multiple of $\pi/2$, or in other words,

$$\Delta\phi = \phi_y - \phi_x = \begin{cases} +(2n + 1/2)\pi \text{ for RHCP} \\ \text{or} \\ -(2n + 1/2)\pi \text{ for RHCP} \end{cases}$$

If Ex, Ey or $\Delta\phi$ does not satisfy these formulas, then the resulting polarization is of elliptical shape. The performance of a circularly polarized antenna is characterized by the AR, which is defined by the difference of the major axis and the minor axis.
In other words, the difference of the input power of the two components.

$$AR = \frac{Major\_axis}{Minor\_axis} = \frac{OA}{OB}$$

Where

$$OA = \left[\frac{1}{2} \left\{ E_x^2 + E_y^2 + \left[E_x^4 + E_y^4 + 2E_x^2 E_y^2 \cos(2\Delta\phi) \right]^{\frac{1}{2}} \right\} \right]^{\frac{1}{2}}$$

And

$$OB = \left[\frac{1}{2} \left\{ E_x^2 + E_y^2 - \left[E_x^4 + E_y^4 + 2E_x^2 E_y^2 \cos(2\Delta\phi) \right]^{\frac{1}{2}} \right\} \right]^{\frac{1}{2}}$$

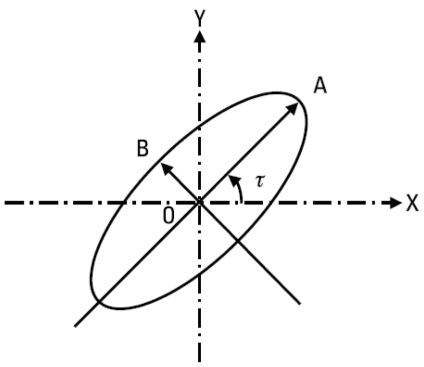


Figure 2.1 Elliptically polarized wave [2].

The tilt angle τ of the ellipse is given by

$$\tau = \frac{\pi}{2} - \frac{1}{2} \tan^{-1} \left[\frac{2E_x E_y}{E_x^2 - E_y^2} \cos(\Delta\phi) \right]$$

In general, an antenna will radiate an elliptical polarization [figure 2.1], which is defined by three parameters: axial ratio, tilt angle and sense of rotation. When an axial ratio is ∞, the polarization becomes linear with the tilt angel defining the orientation. Sense is not applicable in this case. The quality of the linear polarization in usually indicated by the level of the cross polarization. When the axial ratio is 0dB, a perfect circular polarization (CP) results and the tilt angle is not applicable. The axial ratio is generally used to specify the quality of the circularly polarized waves where generally an AR between 0 and 3 db is acceptable for the majority of the applications [4,5].

2.2 Various types of circular polarized antennas

A microstrip patch antenna is one of the most widely used radiators for circular polarization generation. Various shapes for microstrip antennas capable of circular polarization operation have been reported in literature. The next figure 2.2 shows some of these patches, including square, circular, pentagonal, equilateral triangular, ring, and elliptical shapes. However, square is the most used because it is easy to fabricate and has best performance [1,4].

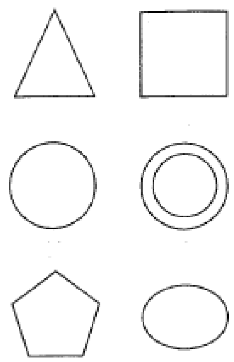


Figure 2.2 Various types of circularly polarized microstrip antennas [5].

Typically, two types of feeding schemes with only a single patch can accomplish the task. The first type is a dual-orthogonal feed, which employs an external power divider network. The other one is a single-point feed for which an external power divider is not required.

2.2.1 Dual-orthogonal fed for circularly polarized patch

The fundamental configuration of a dual-orthogonal fed circularly polarized patch using an external power divider are shown in the figure 2.3. The dual-orthogonal feeds exited two orthogonal modes with equal amplitude but in phase-quadrature. Several power divider circuits that have been successfully employed for CP generation include the quadrature hybrid, the ring hybrid, the Wilkinson power divider, and the T-junction power splitter. The quadrature hybrid splits the input into two outputs with equal amplitude but 90º out of phase. Other types of dividers, however, need a quarter-wavelength line in one of the output arms to produce 90º phase shift at the two feeds. Consequently, this produces extra losses and extra spurious radiation which is very bad in high frequencies.

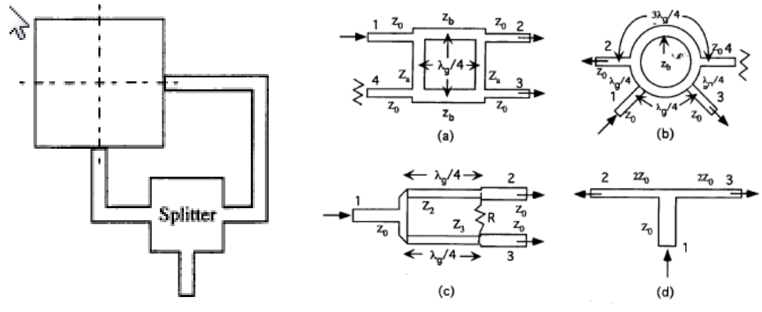


Figure 2.3 Typical dual-fed configuration and power dividers [5]: (a) Quadrature hybrid, (b) Ring hybrid(c), Wilkinson power divider, (d) T-junction power divider.

2.2.2 Singly fed circularly polarized patch

Instead of dual feed, various single feed MSA configurations can be used to generate CP. Some of the single-feed CP configurations that are obtained by modifying the square MSA are shown in the figure 2.4. These are diagonally fed nearly square, square with stubs and notches along the two opposite edges, corner-chopped squares, squares with a diagonal slot, among others.

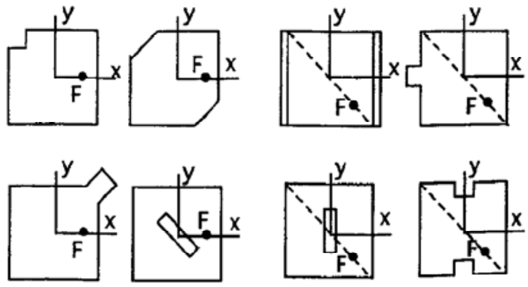


Figure 2.4 Various types of microstrip patch perturbations for circular polarization generation [5].

The dimensions of the MSA are modified such that the resonance frequencies $f\,1$ and $f\,2$ of the two orthogonal modes are close to each other. The antenna is excited at a frequency $f\,0$ in between the resonance frequencies of these two modes, such that the magnitudes of the two excited modes are equal. Also, the feed-point location is selected in such a way that it excites the two orthogonal modes with phase difference of +45° and -45° with respect to the feed point as we can see in the figure 2.5, which results in phase quadrature between the two modes. These two conditions are sufficient to yield CP.

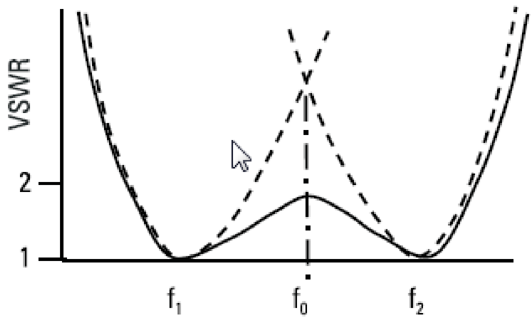


Figure 2.5 The two orthogonal modes generated for a single fed configuration [2].

3. HFSS STUDY OF PROPOSED ANTENNAS FOR 60 GHZ

Among all the possible options before mentioned for obtaining a kind of patch antenna with circular polarization, we have chosen the squared patch antennas with a singular fed for designing and manufacturing them. As we said before the antennas with double fed are rejected, due to the fact they have an extra section of line. This increment of section in the high frequencies, especially in the band that we are going to use, generates a few losses, spurious radiation and their design and manufacture are more complex.

3.1 Design of corner-truncated antenna and slotted antenna

Inside the possibilities of this type of patch, we have chosen two different kinds, since they seemed to be easy to design and manufacture. The first one of them is the called "corner - truncated antenna", which consists of a squared patch with two opposite corners cut in an angle of 45 º. The main reason of this design is for creating two orthogonal nodes with exactly the same amplitude but with a phase difference of 90º between them and in this way we can achieve our desired circular polarization.

The second designed antenna is the "slotted-patch antenna". This one consists of another square patch, but this time with a slot inserted diagonally in the center of the patch, which generates 2 orthogonal nodes with the same amplitude and with a phase difference of 90 º between them, as in the previous kind of antenna.

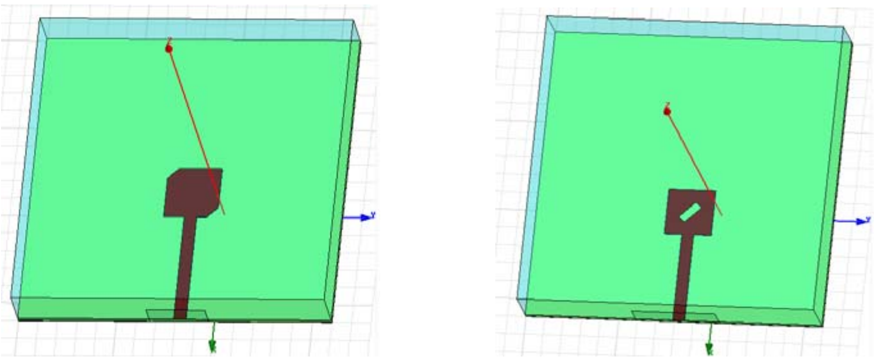


Figure 3.1 corner-truncated antenna and slotted patch antenna design.

Due to the easy design of these antennas, it is very difficult to obtain a good matching of the antenna and an acceptable axial ratio to be considered circularly polarized (AR <3dB) simultaneously. This is because we can only modify the size of the patch (that we cannot change too much since the resonance frequency depends on this parameter) and the depth of the cut of the corners in case of the "corner - truncated antenna" or the dimensions of the slot in case of "slotted-patch antenna".

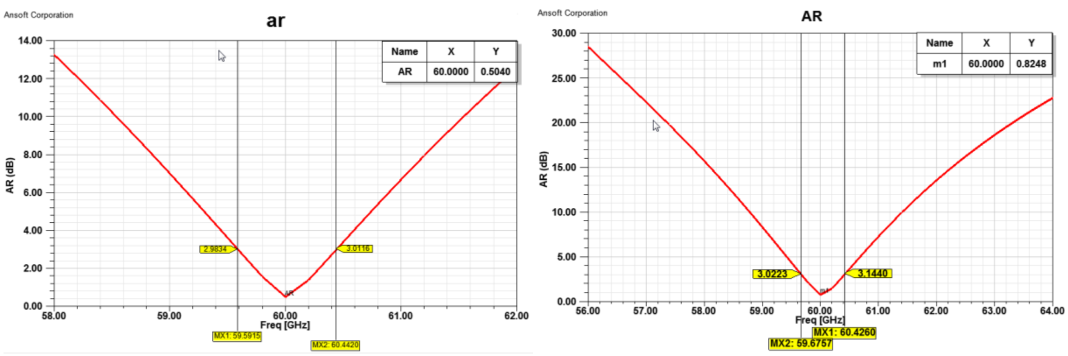
In case of "corner - truncated antenna" we improve our axial ratio as we increase the depth of the cut, but simultaneously we are getting worse the matching of the antenna and vice versa.

In reference to the "slotted-patch antenna", when we make narrower and longer the slot, we are improving the matching of the antenna, but in the other hand we are getting worse the AR. And if we try to make it wider and shorter we have the opposite effect.

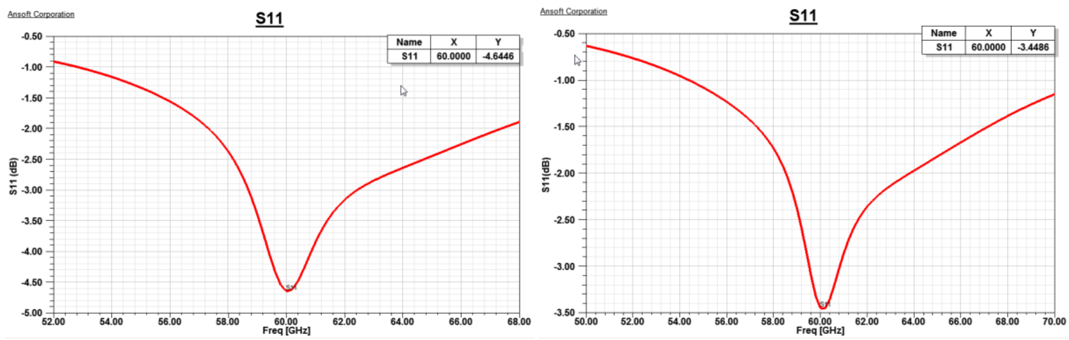
We have to highlight that these two antennas are designed for a circular polarization to left handed, but if it is wished to change to the rights handed, the only thing that it is necessary to do is to turn the slot towards the other diagonal or to change the chosen of the two cut corners for their opposites.

For all the previous reasons and with the intention of being able to see, compare and quantify all these parameters, we have designed 3 different models for each one of these antennas. The first one them will be optimized to obtain a good matching with the higher possible bandwidth. The second design will be optimized to obtain the minimal value of AR in our frequency of interest and the last one will be an intermediate design with the minimal matching acceptable value of 12dB, to see the best AR that could be managed to this type of simple antennas and also to be able to see better the progression of the values of S11 and AR in reference to the 2 previous cases.

In the first case, there are shown the results of the simulations of both antennas optimized to obtain the minimal value of axial ratio (figure 3.2). As we can observe in the following plots we have achieved a minimal AR value (in both cases) of around 0.5 dB in our frequency of interest of 60 GHz and with a bandwidth near to 1 GHz (AR <3 dB) , so we can say that it is achieved a good circular polarization. However, if we focus on the S11 graphics we can appreciate that the adaptation values of the antenna are around -5dB, which are inacceptable because it supposes a great loss in the total power delivered to the antenna.



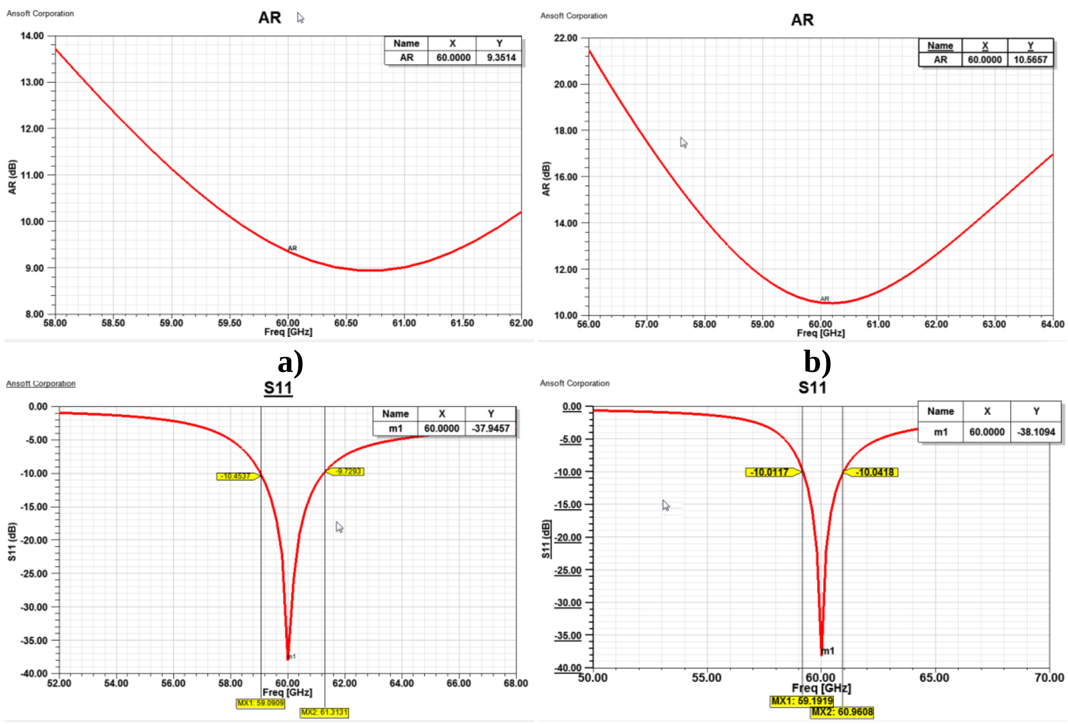
a) b)



c) d)

Figure 3.2 Axial ratio of (a) corner-truncated patch antenna, (b) slotted patch antenna, and S11 parameter of (a) corner-truncated patch antenna, (d) slotted patch antenna.

In the second case, we see the values obtained of the antennas, which are optimized to have the best possible matching. As we can see, the values of the S11 graph achieve widely with the requirements of an adapted well antenna, since we have a minimal value in our frequency of interest of approximately -40 dB and an available bandwidth in both antennas of approximately 2 GHz, more than the threshold required to fulfill with our specifications. Nevertheless, when we observe the results of the plots related to the axial ratio, we can see that the values are unacceptable to be able to consider it to be circular polarized; because the axial ratio is higher to 10 dB, when it should be lower than 3 dB.



c) d)

Figure 3.3 Axial ratio of (a) corner-truncated patch antenna, (b) slotted patch antenna, and S11 parameter of (a) corner-truncated patch antenna, (d) slotted patch antenna.

At last, with the intention to be able to see how the AR's values and the S11 changes related to the both previous cases, an intermediate case was designed. In the following graphs we can see clearly that the AR and the matching of the antenna are dependent, if we try to improve one of them the other parameter get worse considerably. We can observe it in the case that is depicted, which has a minimal value of S11 acceptably of 12 dB, without scarcely bandwidth and the AR's value still does not manage to be the acceptable, since we remain in approximately 5 dB-6 dB when the minimal value to be considered to be circular polarized they are 3dB.

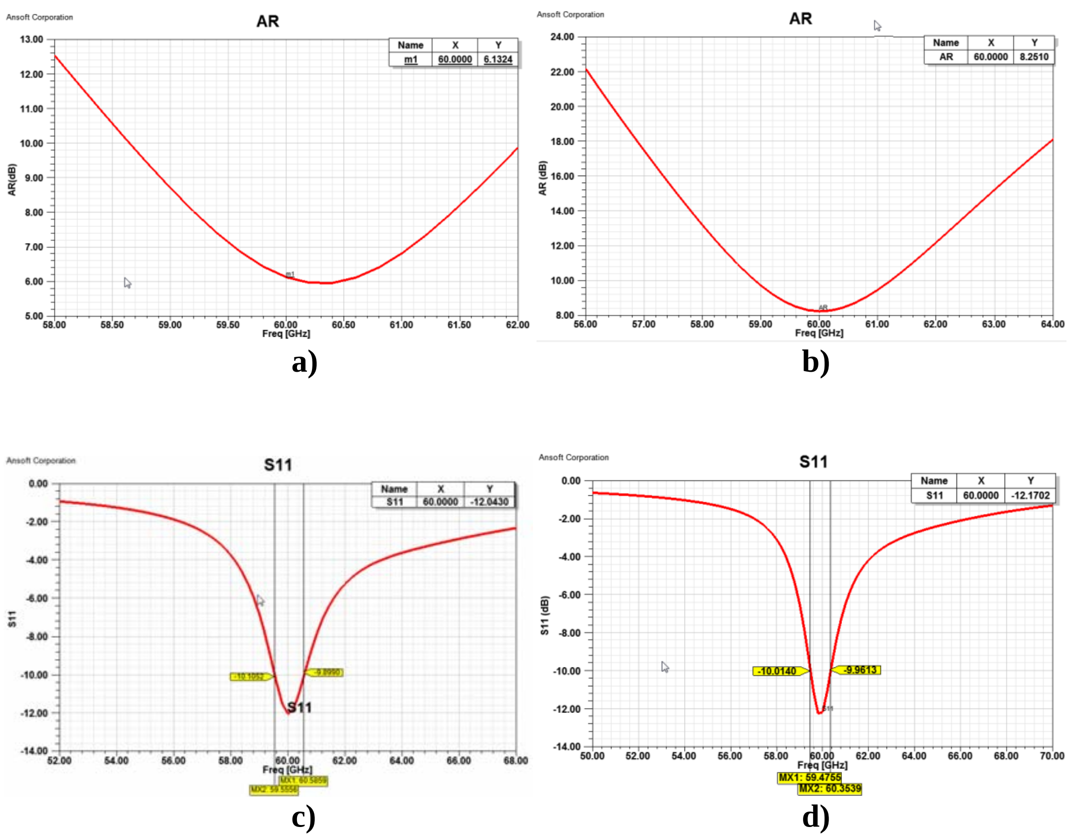
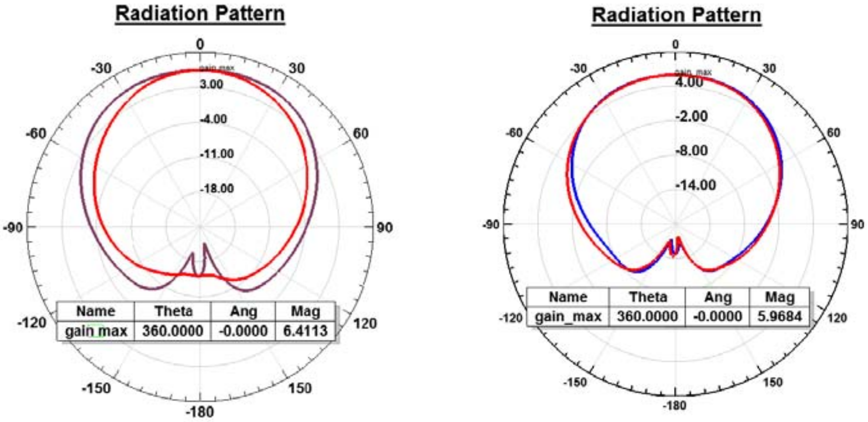


Figure 3.4 Axial ratio of (a) corner-truncated patch antenna, (b) slotted patch antenna, And S11 parameter of (c) corner-truncated patch antenna, (d) slotted patch antenna.

Concerning to the rest of the important characteristics of the antenna, which are the gain and the radiation diagram, we have to highlight that they are practically equal to a square normal patch with linear polarization, with a gain of approximately 5 dB-6 dB and with a radiation diagram, whose principal lobe is centered in ϕ =0º with a beamwidth at 3 dB of approximately 60 º.



a) **b)**

Figure 3.5 Radiation pattern of (a) corner-truncated patch antenna, (b) slotted patch antenna.

3.2 Improvement of the antennas

In order to try to improve the previous antennas to be able to obtain a good level of matching and an acceptable value of the axial ratio, we have tried a couple of methods that possibly might solve this problem.

3.2.1 Corner truncated patch Antenna with insets

Normally, to improve the matching of a square standard patch, the most advisable improvement is to insert a couple of insets in the entry of the line to the patch, since the input impedance of the patch in the edge is of 180 Ω – 300 Ω and in the center is of 0 Ω [2]. This technique reduces the impedance to 50 Ω, which will help the antenna to obtain a prefect matching.

Therefore, we took the antenna "corner - truncated antenna" optimized to obtain the best axial ratio and we incorporated 2 insets for changing its size and depth with the main purpose of improving the matching without getting worse the AR. However, as we can observe in the following results, we still continue having the same problem. This is due to the fact that technique improves a bit the matching of the antenna, but at the same time distorts the 2 orthogonal nodes that generate the circular polarization and for this reason the value of the axial ratio gets worse. In addition the design is very dependent on the size of the insets, so the manufacture would be still more complicated.

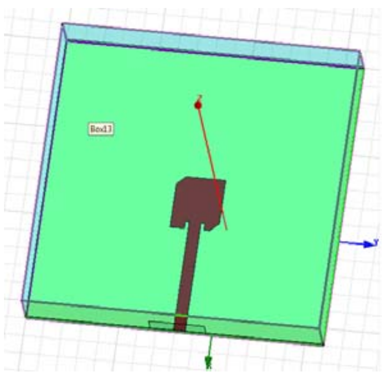
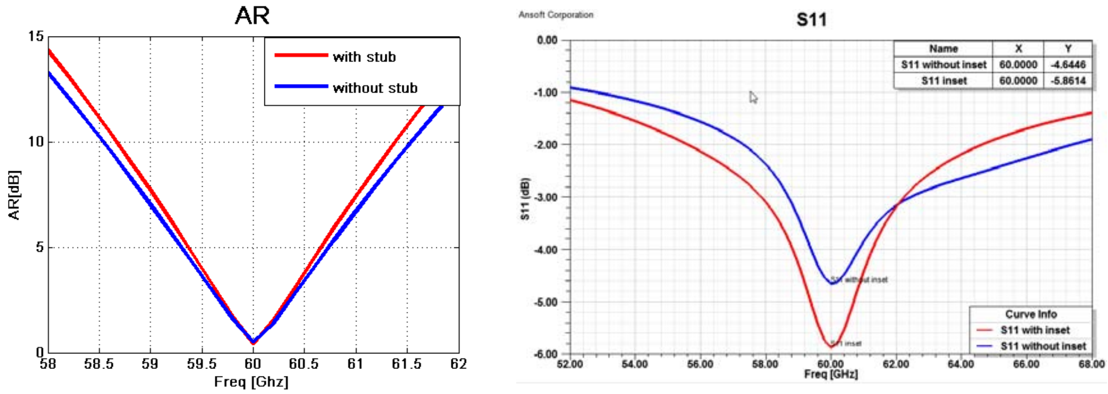


Figure 3.6 Corner-truncated patch antenna with insets design.



a) b)

Figure 3.7 Differences between corner-truncated patch array with and without insets for (a) axial ratio and (b) S11 parameter.

3.2.2 truncated patch Antenna with insets and stub

On the other hand, we found in a paper the design of a patch antenna supplied from a corner with a stub in the opposite corner, which according to the results that it was showing, it could obtain simultaneously a good matching and a good value of axial ratio that is was what we are searching for obtaining.

Furthermore, we decided to implement this idea in our design of the "corner - truncated antenna", in which we add a stub in the opposite side to supply with the hope to improve our antenna.

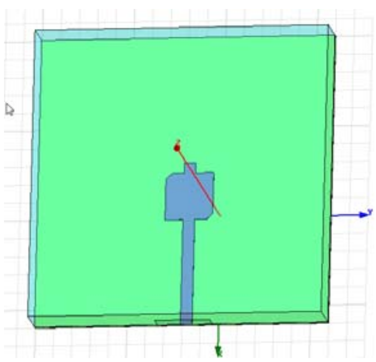


Figure 3.8 Corner-truncated with stub design.

Nevertheless, we could not obtain acceptable results with this type of design and for it, we decided to try a last design, mixing these last two options and the results is shown in the following figure 3.9. But once again we met the same problem, when the matching was improved, the axial ratio got worse and vice versa.

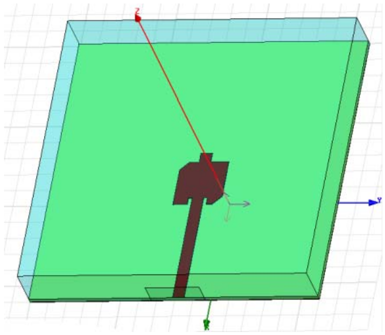
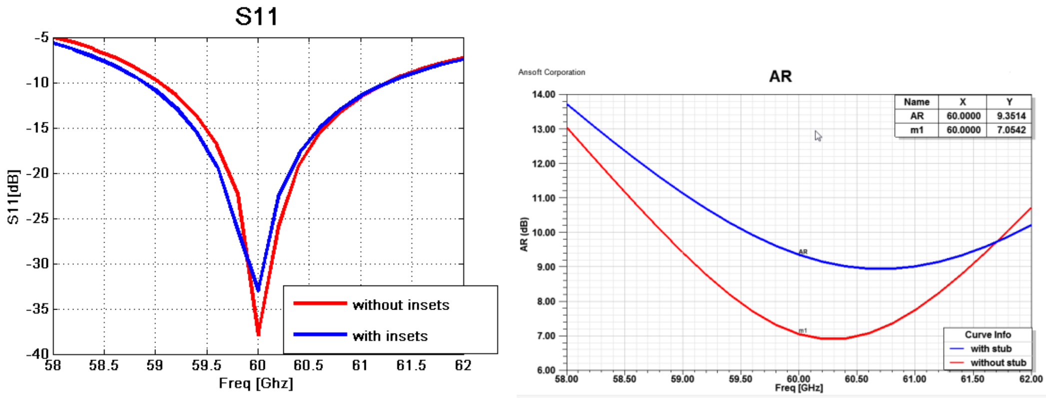


Figure 3.9 Corner-truncated with insets and stub design.



a) **b)**

Figure 3.10 Differences between corner-truncated patch antenna with insets and stub and without stub for (a) S11 parameter and (b) Axial ratio.

Apart from all of this, the manufacture of these antennas is more complicated, since the model is very dependent on the width and depth of the insets and on the length of the stub. So the results after its manufacture would be affected seriously.

3.3 Circular vs. linear polarized patch antenna

Finally, before of manufacturing and measuring the designed antennas, we have realized a comparative study between our circular polarized antennas with one standard linearly polarized patch. The main goal is to be able to see the differences of the most significant parameters between both antennas.

As we can observe in these figures, the fact of changing the polarization do not make any change neither the value of the gain nor the form of the radiation diagram, keeping them practically equal in both polarizations.

In reference to the antenna matching, it depends more on the optimization of the design, but we can say that both can have also a similar matching.

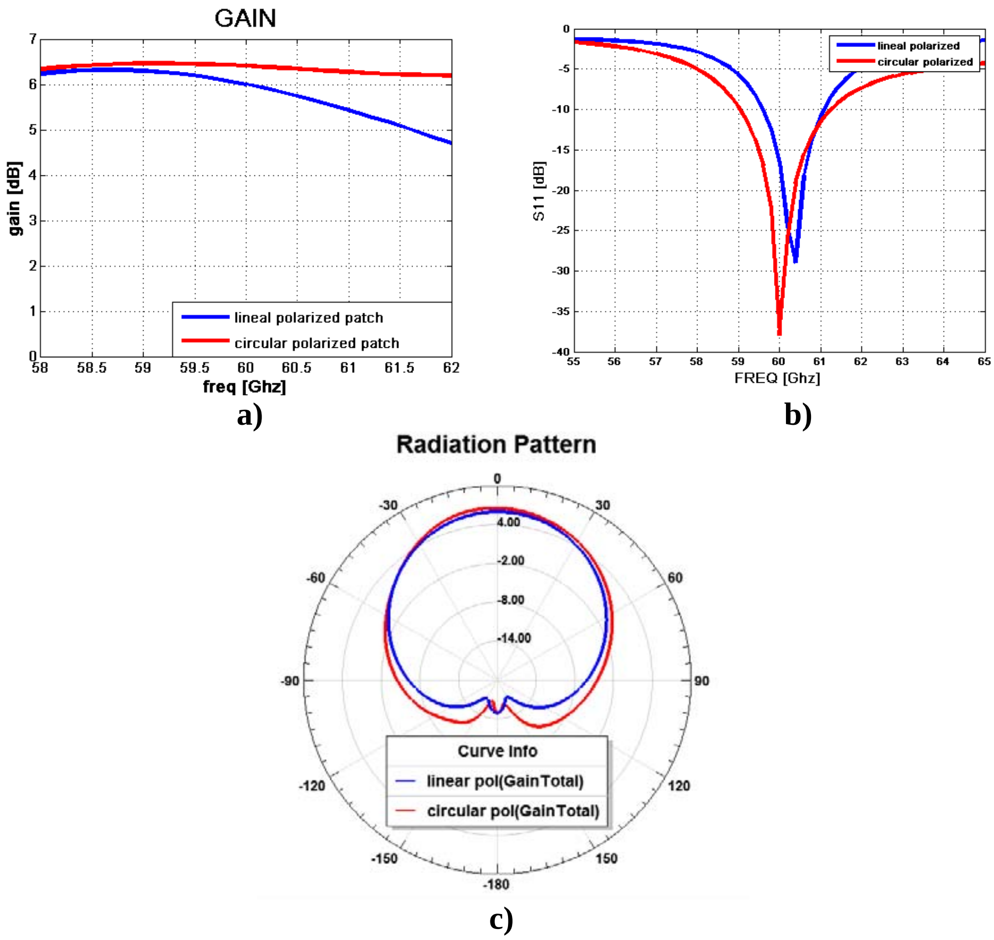


Figure 3.11 Differences between linear and circular polarization for (a), total gain of the antenna, (b) S11 parameter, (c) radiation pattern.

To be able to see the differences between both polarizations, we have to focus on the graph of the axial ratio, where theoretically, the value of a circular polarized antenna has to be close to 0 dB, whereas the value of the linearly polarized one has to tend to infinite. As we can see in the graph, the simulations show as the linearly polarized one has a value about 50 dB, more than the threshold that allow us to consider an antenna to be linear and our circular polarized antenna keeps close the value of 0 dB.

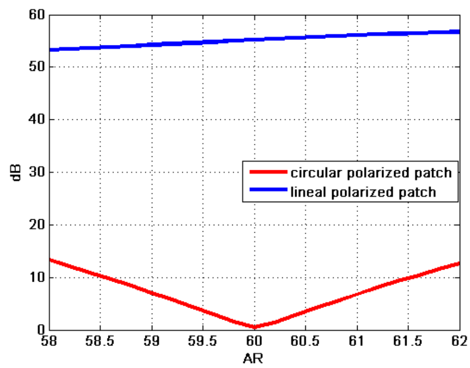
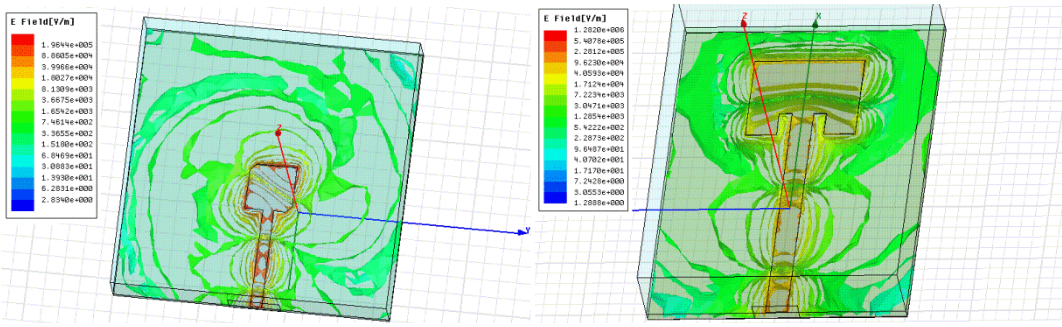


Figure 3.12 Axial ratio differences between linear and circular polarization.

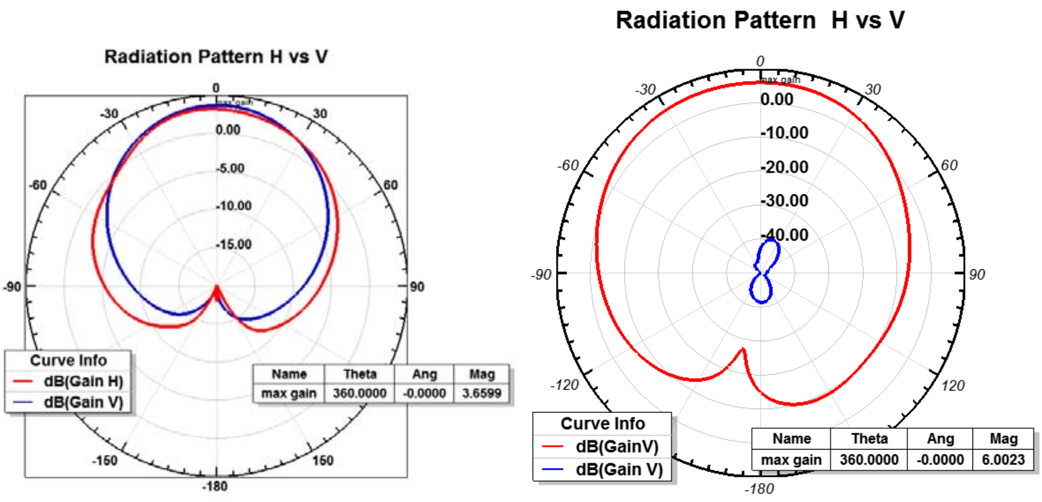
We can also find another difference if we represent the surface waves of both antennas. If we could see them in movement, we would see like in case of our circular polarized antenna, the waves turn circular to left sides while in case of the linearly polarized one, the waves only move in linear direction horizontal.



a) **b)**

Figure 3.13 Surface waves for (a) circular polarized patch antenna, (b) lineal polarized patch antenna.

Finally, we can also see very well the difference between both polarizations if we represent the radiation diagram in the horizontal plane and in the vertical plane. As we can see, in case of the linearly polarized one, as it has to be theoretically, it only transmits power in one of the two planes, in this case in V plane. Whereas in the case of the circular polarized antenna, we can see clearly in the radiation diagram of both planes that each one of them has the same form and amplitude. That is a necessary characteristic to fulfill with the requirements of a circular polarization.



a) **b)**

Figure 3.14 Radiation patter for the vertical and horizontal plane for (a) circular polarization, (b) linear polarization.

3.4 Measured vs. simulated of exemplary single antennas

Once finished all the designs, we are going to fabricate and measure the antennas with the support of our measure system.

About all the models before designed, I fabricated at least an antenna of every type to corroborate if their results coincided with their simulations. Later, I manufactured some more antennas that were obtaining better results.
In short, the fabricated antennas were:

- Two models of "corner - truncated antenna". One of them, optimized to obtain the best AR value and other one designed to obtain the best matching.
- Two models of "slotted antenna". This time both models were focused to obtain the best possible AR. We manufactured two times the same antenna because this design is very difficult to realize due to the overeating of the central slot, which affects seriously over the results.
- And finally, one model for the antenna with insets and other one for the antenna with stub, since the results were not very positives and their manufacture is more complex. This is due to the fact that the design is very dependent on the size of the stub and on the insets.

Next we will see the graphs of the more illustrative results that our measurement system allows us to measure. The rest of the results of all the antennas will be able to be seen by us in the appendix.

As we can see in this first plot, where the S11 value is represented, the resonance frequency of our antenna, which should be centered on 60 GHz, is shifted to the higher frequencies. This phenomenon happens due to the fact that the size of the manufactured antennas is smaller than the size of the antennas simulated, whose main reason is the overeating in the manufacture (an antenna of patch squared with a smaller size in general means a higher frequency).

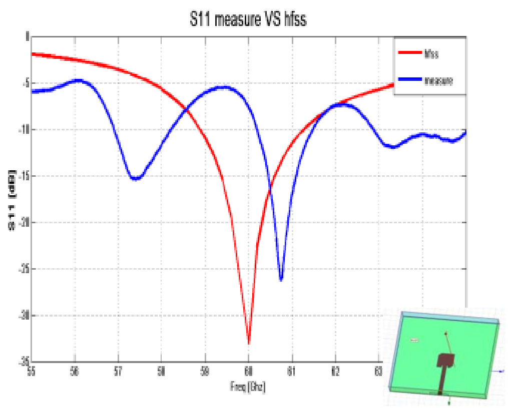


Figure 4.1 S11 parameter of the simulation and the measurement for the corner-truncated antenna with insets.

Therefore, in order to be able to better difference the results of the antennas manufactured in reference to the simulated ones, we have measured them under the microscope to be able to obtain the real size and after we have simulated again the antennas with the real obtained values. As we can see in this another graph, where we have incorporated the S11 value of the re-simulation, we can see clearly how the resonance frequency comes closer to the manufactured antenna. Thus, now we can compare better the differences between the simulations and the measurement of the antennas.

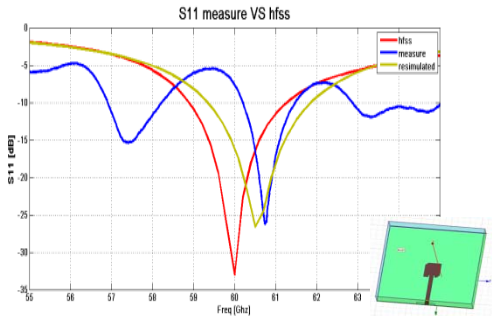


Figure 4.2 S11 parameter of the simulation, the resimulation and the measure for the corner-truncated antenna with insets.

According to the antenna's gain, the process to obtain the results of the measurements is realized firstly with the system calibrated and with the system not normalized and for this reason the gain values are approximates. Also we have to highlight that we can only measure the antenna's gain in the vertical plane and later in the horizontal plane. As we see in the figure 4.3, the antenna's power in both planes is practically the same one, around our frequency of interest of 60 GHz, which is an indispensable requirement to obtain a circular polarization. About the acceptable bandwidth, it is close 2 GHz (when the difference between Gv and Gh are under 3dB).

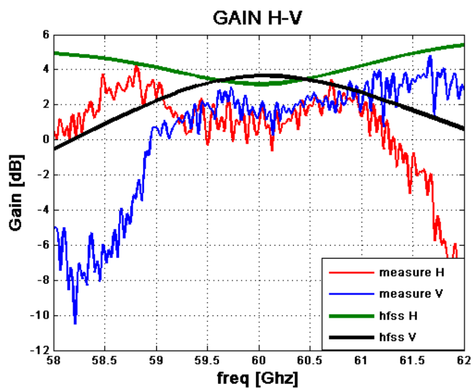


Figure 4.3 Gain of the antenna for the horizontal and vertical plane for the corner-truncated antenna optimized to achieve to best AR.

Also we can represent the form of the radiation diagram of the antennas. Our measurement system just allows us to measure between 90 º and -90 º, but it is enough to be able to compare the results. As this figure shows, where we compare the result of the simulation with the result obtained through the measurement, how the main lobe of the graph keeps close ϕ =0º and the form of the diagram is very similar in both cases.

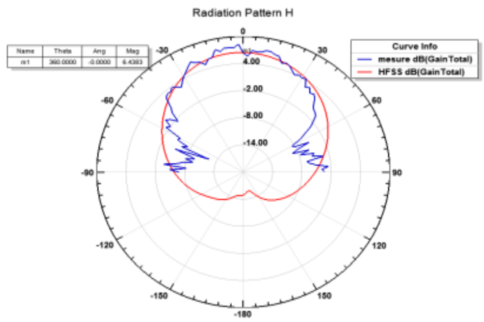


Figure 4.4 Radiation pattern of the simulation and the measure antenna.

Now we come to the most important point, where we will be able to see clearly if our antenna is really circular polarized or not.

The next case especially corresponds to the "corner-truncated antenna" optimized to obtain the best value of axial ratio. After measuring all the manufactured antennas, we can conclude that this one is the best in reference to AR, due to the fact that it is the simplest of manufacturing and almost it has not been affected by the overeating. So it keeps the resonance frequency close to 60 GHz that are what we are wishing.

The following figure corresponds to the radiation diagram in reference to the frequency and the angle in the H plane as in the V plane. Theoretically, an antenna is circular polarized when the power is equal in both the planes in the same point, but a priori, these two radiation diagram seem to be in cross-polarization as it success in a linearly polarized antenna. But if we focus on our interest frequency of 60 GHz, where we have the best matching and for this reason fewer power loss, and in our main lobe, which is close to ϕ =0º and where is the maximum gain; we can see how in this place, the antenna's power is practically the same and for this reason we can conclude that this antenna is has a good circular polarization in the point that we are talking about.

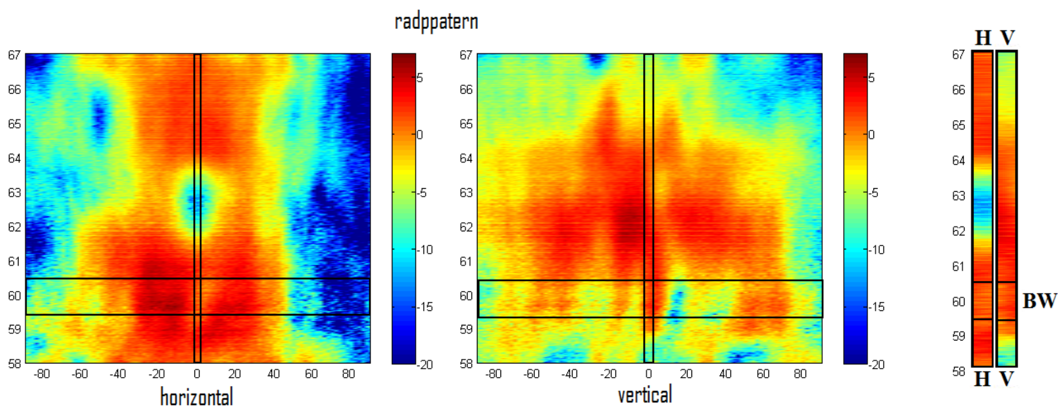


Figure 4.5 Measured radiation pattern.

As we cannot see with accuracy the value of gain of both planes in the following picture, we have calculated the difference of these values to be able to obtain the graph of the AR and the results is depicted in the following figure, which corresponds to the AR depending on the frequency for ϕ=0º. We can appreciate a 2 GHz bandwidth about 60 GHz (AR <3dB) where we can say that this antenna works with a good circular polarization. These results even overcome the obtained through the simulations, in which the bandwidth was not overcoming 900 MHz, as we can observe in the figure.

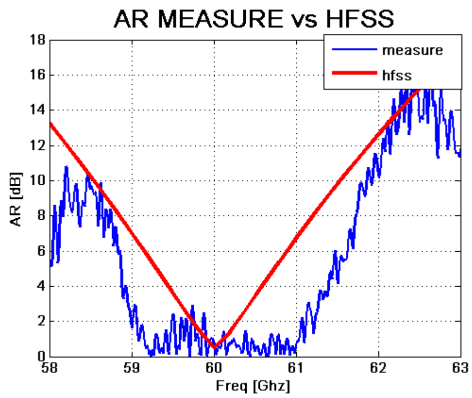


Figure 4.6 Axial ratio for measured and simulated antenna.

In summary, we can say that this antenna, which we have manufactured, has all the characteristics necessary for being considered as a patch antenna with circular polarization that works at 60GHz.

4. CIRCULAR POLARIZED PATCH ARRAY

The previous solutions can be used in a great majority of applications; nevertheless, the gain of these antennas is typically not sufficient for overcome path loss. For instance, WiHDTV needs approximately 12 dB for its correct functioning and for this reason the design of an array is necessary in order to increase the gain of our antenna and thus to be able to achieve a the minimum power level required by applications as WiHDTV [12].

The design of this array consists of 4 patches, which are enough to obtain the minimal gain necessary for our application. They are placed in parallel by a separation of an half wavelength, in order that the secondary lobes created by the array stay under a reasonable level of approximately 10 dB of difference (SLL> 10dB). A Wilkinson divisor is the responsible of distributing the power in an equal way to each of the patches and supply them with the same phase to keep the main lobe of our radiation diagram close to $\phi = 0^{o}$.

As a result of the high complexity of the manufacture of these arrays, due to the thinness of Wilkinson's lines, we have only focused on the simplest antennas. Those are the "corner – truncated" and "slotted patch antenna", which are those that showed the best results after their manufacture and were less affected by the overeating.

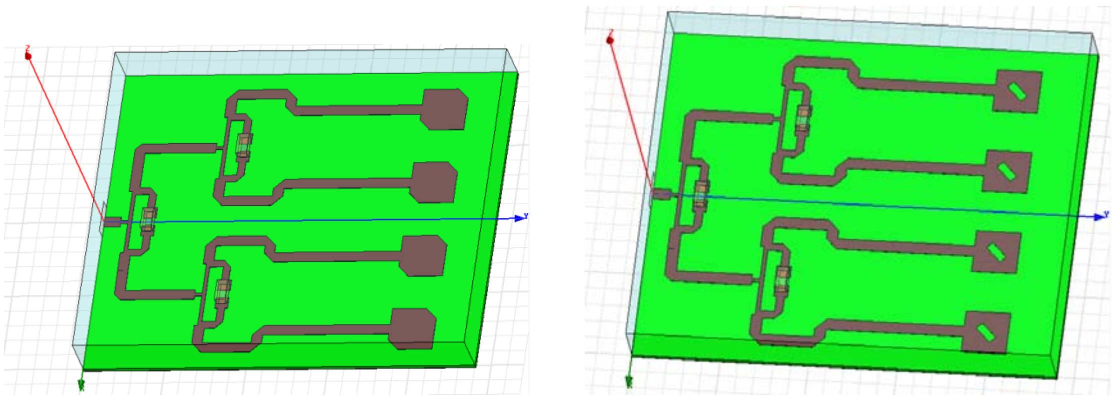
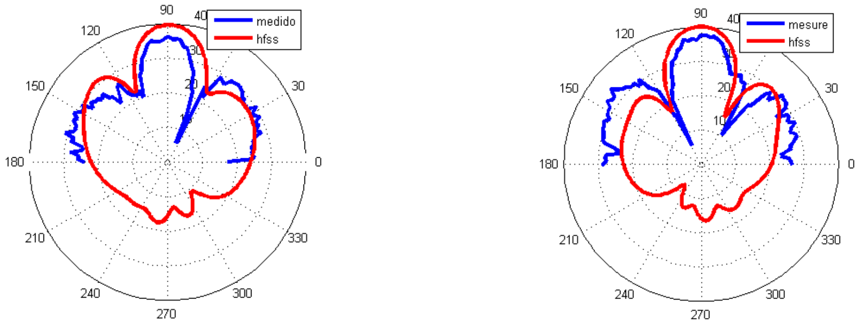


Figure 5.1 Corner-truncated array antenna and slotted array antenna design.

Once obtained the results of the simulations and the real measures, we can see that we have achieved some requirements such as the main lobe of the radiation diagram keeps closer $\phi = 0^{o}$ and the secondary lobes, which are created due to the array, are under a reasonable level. Also, we can see how the beamwidth to 3dB has been reduced to approximately 30 º.



a) **b)**

Figure 5.2 Radiation pattern for the measured and simulated antenna for (a) corner-truncated patch antenna, (b) slotted patch antenna.

Concerning to the resonance frequency to the matching of the array, it is shifted to higher frequencies (around 63 GHz) due to the overeating, as it happened in the previous case. And once again, we have to realize the same process as before, which consists of redoing the simulation with the real size of the antenna. The results come closer enough.

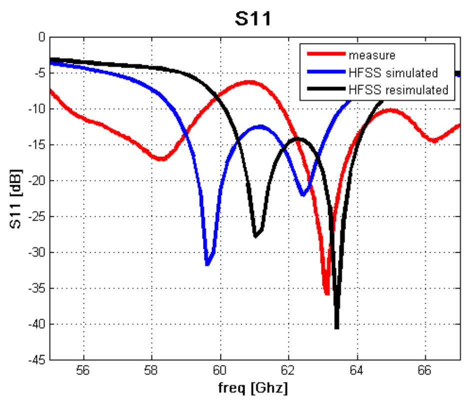


Figure 5.3 S11 parameter for measured, simulated and resimulated for the corner-truncated path array.

In reference to the gain, with our array we were trying to obtain a value approximately 10-12 dB to fulfill with the requirements for our application and as we can see in the following figure, in 60 GHz more or less we are inside the range of gain, which we were expecting to obtain.

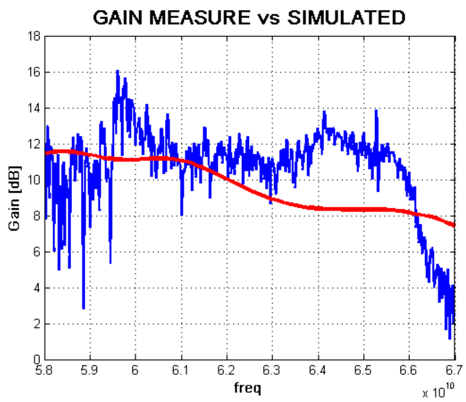


Figure 5.4 Total gain for measured an simulated antenna.

About the manufactured antennas, which show the best results related to have a good circular polarization are the “slotted antennas”. In this kind of antennas, the resonance frequency was shifted to 65.5 GHz due to the overeating and curiously for this frequency is where less power we lose, so it is where we obtain the best results.

Once again, we have to focus on the 2D radiation diagram and we can observe that it seems to be in cross-polarization as it takes places in the simple antenna. However, if we look at the frequency of 65.5 GHz, the antenna has the best matching, for ϕ =0º is where we have the main lobe with the highest gain and for this point is where the gain of the antenna is more similar in both planes. It can be better seen in the other picture, where the power of both planes is represented, both the measure and the simulated one. Also we can observe clearly that the point where the matching is optimum, the gains are approximately equals and for this range the antenna has a good circular polarization as we can see in the graph of the AR.

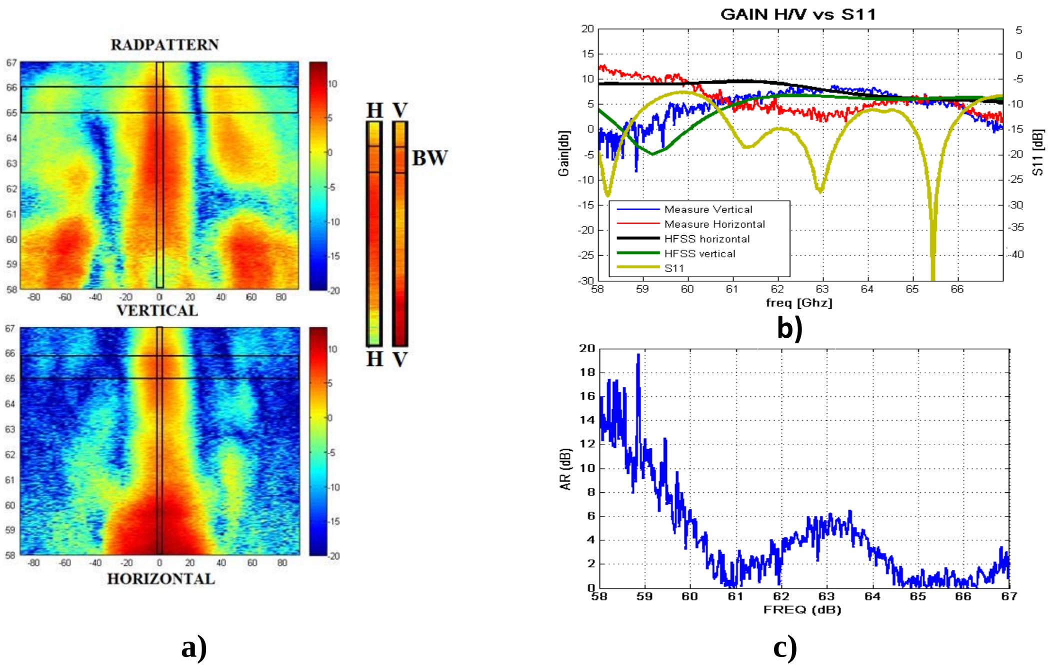


Figure 5.5 (a) Measured radiation pattern, (b) S11 parameter and G_H and G_V for measured and simulated antenna, (c) measured Axial Ratio.

Finally we can say that we have designed an array of 4 patches with a gain of approximately 11 dB and with an almost perfect circular polarization, but due to the complexity of the manufacture, this antenna works in its full performance at the frequency of 65.5 GHz.

5. FUTURE STUDY

Finally, we have realized a design of an array of 16 elements with the intention of increasing furthermore the antenna's gain, since the previous case was just in the margin of the minimal acceptable power, and another purpose would be for being able to see the results that might achieve this type of configuration in a not so far future.

This array, as we can see in the figure, consists of 16 patches distributed along 4 parallel columns, whose distance between them is of $\lambda/2$ as in the previous case, but with 4 patches in each Colum separates $\lambda_{eff}/2$. The reason of it, is due to the fact that we want to keep the main lobe near $\phi=0^{o}$ and also we want to have a second lobe under a reasonable level, as we explained in all the previous cases.

The type of the chosen patch is the "slotted patch", since they show the better AR's results in the array designed previously. Besides, to the last patch of every column we have introduced a couple of insets at the line input, since it improves enough the matching without significant distort in the AR's value.

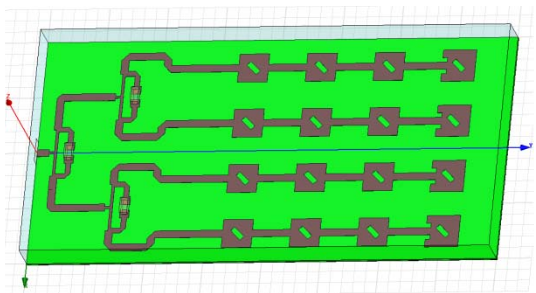
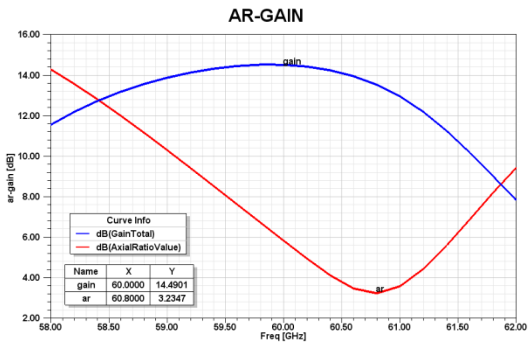
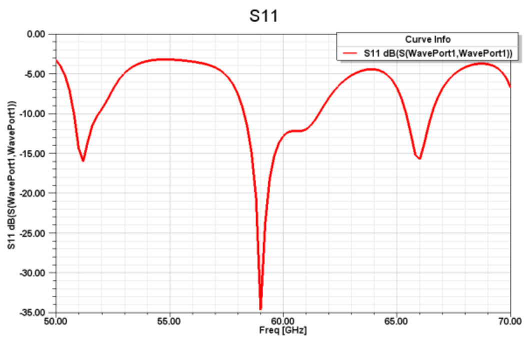


Figure 6.1 Slotted patch 4x4 array antenna design.

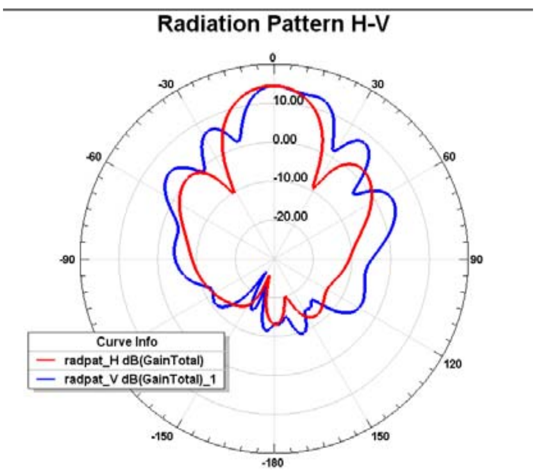
About the simulations results we can observe the main lobe of the radiation diagram keeps close to $\phi=0^{o}$ in both planes. As we also see gain's graph, for this type of configuration, the gain has achieved the 14 dB-15 dB values, which are higher than the threshold acceptable for almost any application.



a)



b)



c)

Figure 5.2 (a) Axial ratio, (b) S11 parameter, (c) radiation pattern.

Finally, we want to suggest some future investigations. One of them is to investigate more this array for to be able to optimize and antenna that can achieve a good matching in our interest frequency of 60GHz, and also try to reduce as much as possible the AR to achieve a perfect circular polarization. At last, to manufacture it and measure it to be able to compare the results obtained with the simulations and be able to quantify how much these improvements are related to the studied antennas.

6. CONCLUSIONS

In conclusion, we can say that we have studied theoretically what is the circular polarization, saw the different shapes to generate this polarization, and finally, choose the best option. This antenna is a square patch with single feed. I have discarded the square antennas with double feed because it incorporate an extra section line, that in high frequencies, introduce extra losses, spurious radiation and the fabrication is more difficult.

After the design in HFSS, I fabricated and measured the antennas, however, the fabricated antennas don’t have the same size and normally are smaller than the antennas designed in HFSS because the overeating, and the resonance frequency is shifted to higher frequencies. For this reason I redesigned to compare better the differences of the simulation and the measurement.

As show the results, we can say that we have only a little bit difference between the simulations and the measurement, and the most important, we have demonstrated that our antennas are circularly polarized in our band of interest.

Later, we have seen the design of an array with 4 elements, the differences with the measurement and as the gain of the array increase from 5-6dB in the case of the single antenna, to 10-12dB in the case of this array keeping more or less the same axial ratio.

7. ANNEX

7.1 Corner-truncated with insets

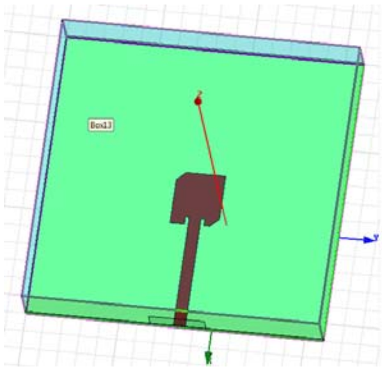
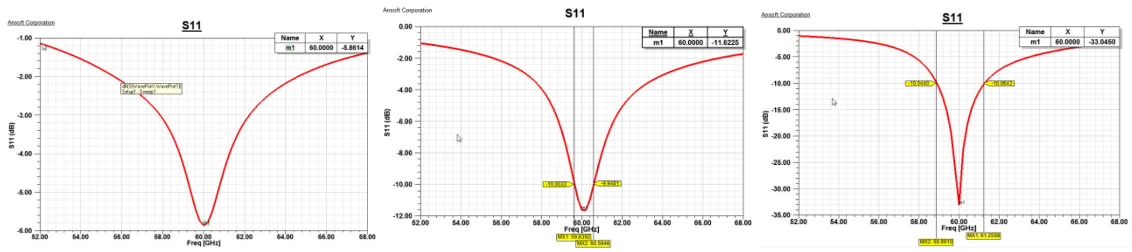
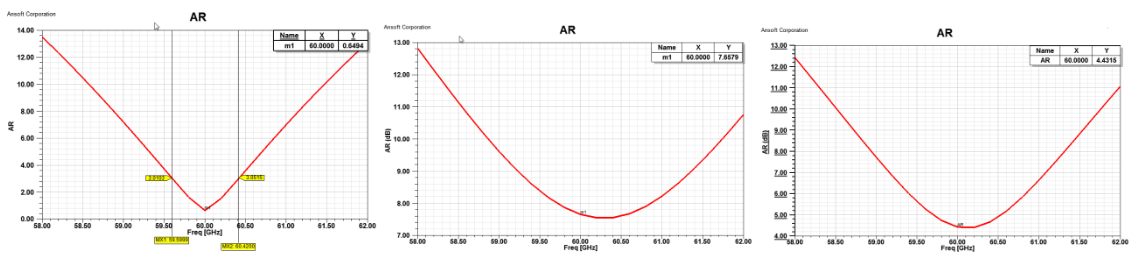


Figure 7.1.1 Corner-truncated patch antenna with insets design.



a) b) c)

Figure 7.1.2 S11 for corner-truncated patch antenna with insets (a) optimized to achieve good axial ratio, (b) intermediate value, (c) optimized to achieve good matching.



a) b) c)

Figure 7.1.3 AR for corner-truncated patch antenna with insets (a) optimized to achieve good axial ratio, (b) intermediate value, (c) optimized to achieve good matching.

7.2 Corner-truncated antenna with insets and stub

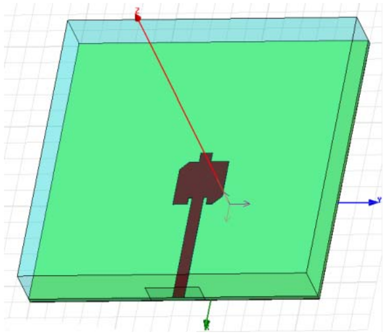
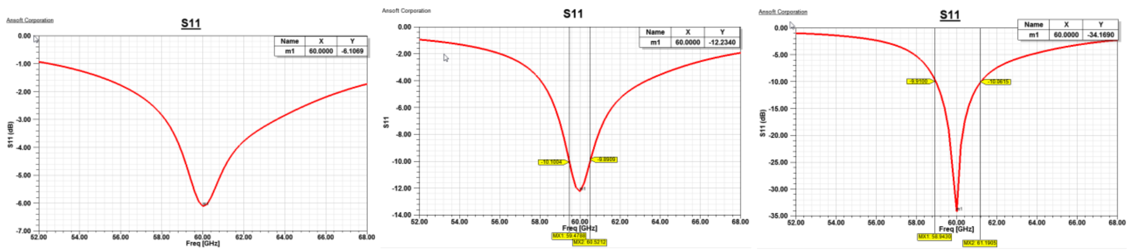
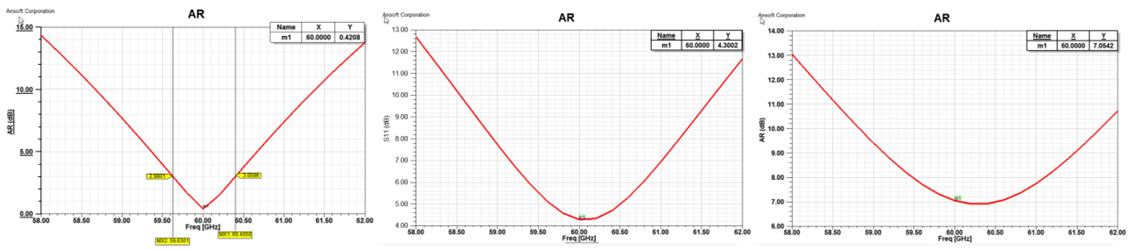


Figure 7.2.1corner-truncated patch antenna with insets and stub design.



a) **b)** **c)**

Figure 7.2.2 S11 for corner-truncated patch antenna with insets and stub (a) optimized to achieve good axial ratio, (b) intermediate value, (c) optimized to achieve good matching.



a) **b)** **c)**

Figure 7.2.3 AR for corner-truncated patch antenna with insets and stub (a) optimized to achieve good axial ratio, (b) intermediate value, (c) optimized to achieve good matching.

7.3 Measured radiation pattern and axial ratio of single antennas.

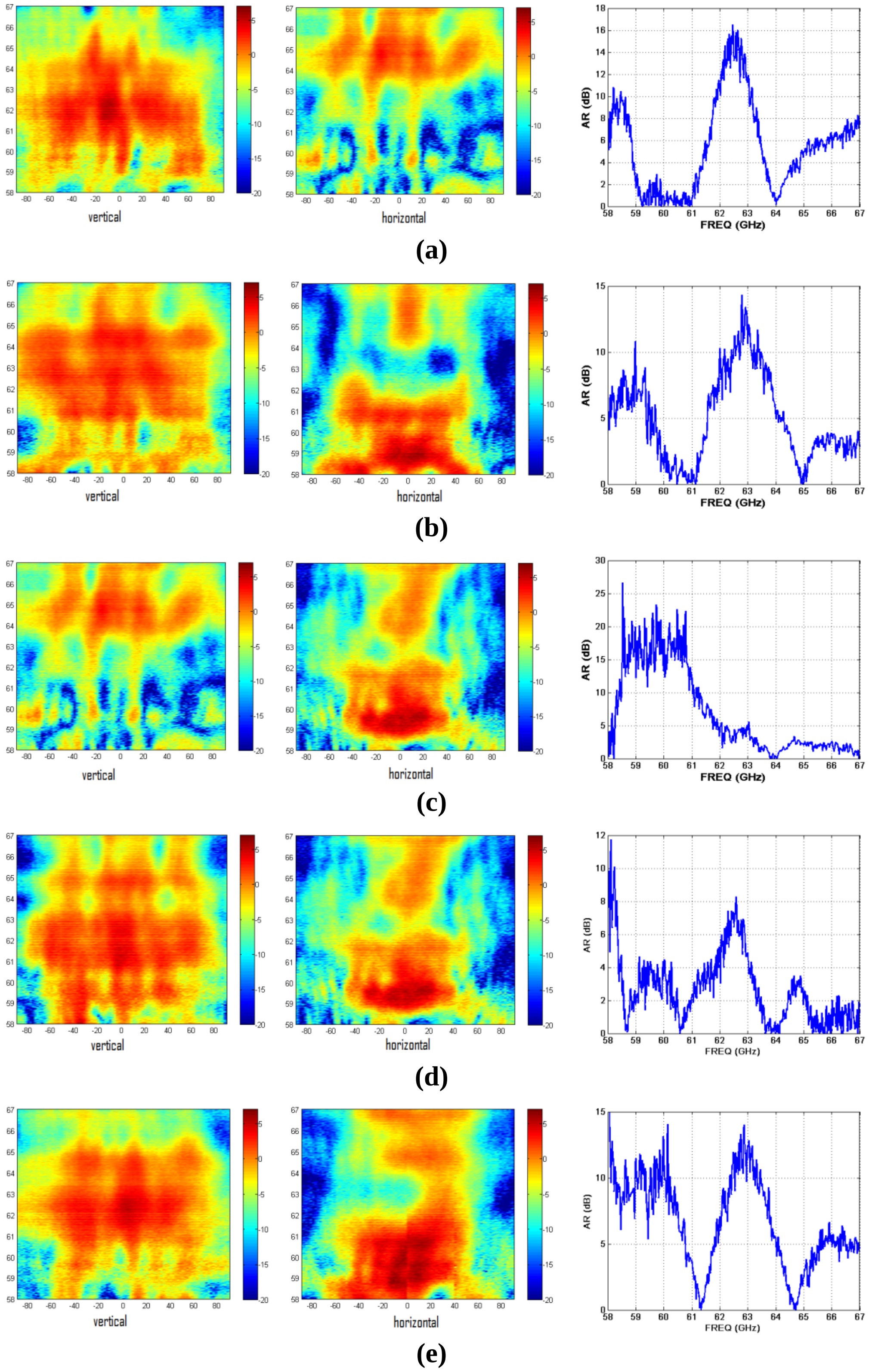


Figure 7.3.1 Measured radiation pattern and axial ratio for (a) corner-truncated patch antenna optimized to achieve good matching, (b) corner-truncated patch antenna optimized to achieve good AR, (c) corner-truncated patch antenna with insets optimized to achieve good matching, (d) slotted patch antenna optimized to achieve good AR, (e) corner-truncated patch antenna with insets and stub optimized to achieve good matching.

7.4 Measured radiation pattern and axial ratio of arrays.

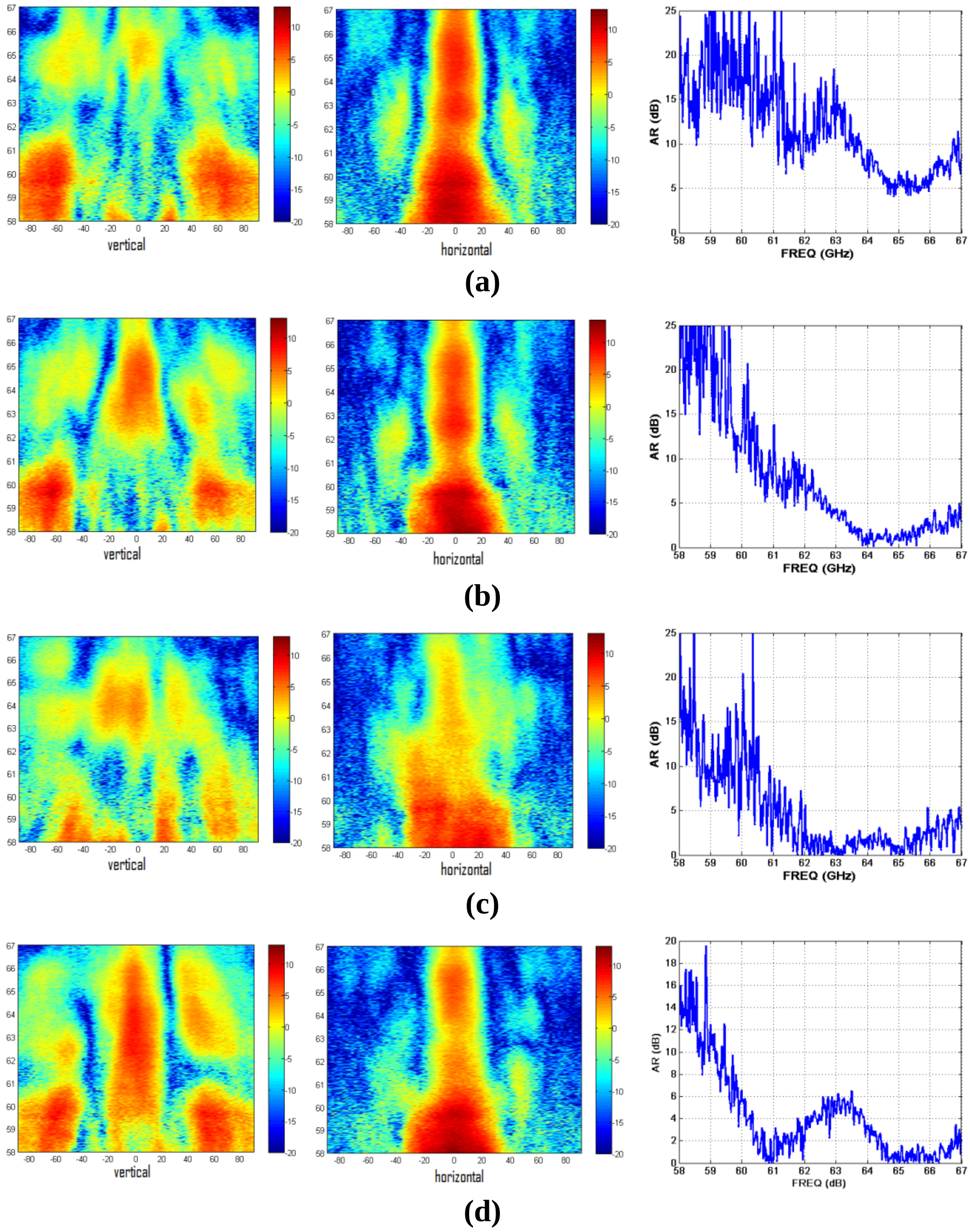


Figure 7.4.1 Measured radiation pattern and axial ratio for, (a) corner-truncated patch array optimized to achieve good matching, (b) corner-truncated patch array optimized to achieve an intermediate value of matching and AR, (c) corner-truncated patch array optimized to achieve good AR, (d) slotted patch array.

8. LITERATURE

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