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Performance Study on Modern Ultra Wideband Monopole Antennas

Abdelhalim Mohamed and Lotfollah Shafai
*University of Manitoba
 Canada*

1. Introduction

The proposed use of ultra wideband (UWB) technology in communication services has motivated the research towards more design and performance studies of modern UWB antennas, (FCC, 2002). Interference of UWB antennas with the existing technologies, phase centre stability of modern UWB antennas, low cross-polarization UWB antennas, high gain directional UWB antennas with stable phase centre, symmetrical E- and H- Plane patterns and single or double linear polarization patterns are some of the important research topics nowadays. Monopole disc antennas, with circular, elliptical and trapezoidal shapes, have simpler two-dimensional geometries and are easier to fabricate compared to the traditional UWB monopole antennas with three-dimensional geometries such as spheroidal, conical and teardrop antennas. These disc monopole antennas can be designed to cover existing and upcoming UWB communication applications, (Honda et al., 1992) & (Hammoud & Colomel, 1993).

In this study, different square, circular and elliptical disc monopole antenna geometries are designed and analysed for both omnidirectional and directional applications. The feeding structure is optimized to have a maximum impedance bandwidth starting at 3 GHz. One of the general principles of small-element antenna design is the outline design equivalence one. It states that an outline of a planar antenna element performs approximately like the original planar one, (Mohamed & Shafai, 2007) and (Schantz, 2005). In this chapter, a study is made on the gradual removal of metal from the interior of all studied antennas while keeping the impedance and radiation characteristics unchanged. The minimum metal width that could be achieved is about 50% from the total radiator area. The effect of implementing a notch close to the feeding structure on impedance bandwidth is also studied. It is found that implementing notches close to the trident-feeding strip structure did not increase the impedance bandwidth of circular and elliptical antennas. Further, implementing a notch decreased the impedance bandwidth of the square monopole antenna. On the other hand, removing metal from the interior structure of the square, circular and elliptical monopoles gives the same impedance bandwidth for square and circular monopole but increased the bandwidth of the elliptical one. The circular and elliptical monopole antennas with metal removed showed better omnidirectional behaviour at higher frequencies.

The performance of a UWB quasi-circular monopole, with rectangular and trapezoidal ground planes was studied, (Wu et al., 2010). It was shown that antenna with trapezoidal

ground plane has significantly improved radiation performance, compared with the one with rectangular ground plane. The second part of this study investigates the effect of different ground plane sizes on the performance of these antennas. This includes the effect on impedance bandwidth and radiation pattern curves.

In the last part of this study, a UWB Yagi monopole antenna over a ground plane is designed and analyzed to work over the whole UWB communication band. The antenna is relatively small in size and the driven element is based on a square or circular radiator shape with some modifications, (Wong et al., 2005).

This study will help to characterize UWB monopole antennas with better performance to be used in the existing and upcoming UWB communication applications that need both omnidirectional and directional monopole type antennas.

2. UWB Monopole antennas

Spheroidal, conical and teardrop monopole antennas are some of the traditional UWB antennas with excellent electrical characteristics. However, they are three-dimensional structures, and difficult to fabricate. Monopole disc antennas, with circular, elliptical and trapezoidal shapes, can also provide UWB impedance bandwidths, but have simpler two-dimensional geometries and are easier to fabricate. In 1992, Honda and others proposed a circular monopole TV antenna operating at 90-770 MHz, (Honda et al., 1992). These antennas can be designed to cover both existing and upcoming UWB communication applications, and have omnidirectional radiation patterns over the entire frequency of operation, (Hammoud & Colomel, 1993). In 2010, both simulated annealing algorithm and the finite element method were used for profile optimization in planar UWB monopole antennas for minimum return losses, (Martinez-Fernandez et al., 2010).

In this chapter, square, circular and elliptical monopole antennas with trident feeding strip based on the square plate monopole antenna first introduced by Wong, (Wong et al., 2005) are designed and analyzed. The proposed designs cover the frequency band between 3 to 19 GHz. The effect of metal removal from the interior structure of the radiator and implementing notch in the bottom end on the impedance bandwidth and radiation pattern of these antennas are also studied.

2.1 Impedance bandwidth and radiation pattern

Impedance bandwidth is that characteristic that distinguishes a UWB antenna from a narrow band one. The lower and upper frequencies are determined based on the 10 dB return loss bandwidth criterion. An antenna is considered well matched when its return loss is greater than or equal to 10 dB. This return loss represents the impedance mismatch level of this antenna. Techniques to increase the bandwidth and control the lowest frequency of operation have been used including geometry changes, loading effects, using shorting post or feeding the antenna with different feeding schemes. A physical interpretation of the bandwidth increase of these antennas using the theory of characteristic modes was given by Ferrando-Bataller et al., 2006. The idea is to enhance the modes that give the current distributions that support the radiation. In the case of monopole antennas, it was found that the first three modes J1, J2 and J3 are enough to characterize the antenna behaviour. J1 mode supports the radiation in the lower frequency band while J3 supports radiation in the upper band. When the monopole antenna is placed vertically over a horizontal ground plane,

modes J1 and J3 will give vertical current distributions on the antenna surface, while mode J2 will give horizontal currents parallel to the ground plane. In this case, it will be useful to suppress mode J2 to reduce cross polarization component. Monopole antennas have an omnidirectional radiation pattern in the H-Plane and monopole-like radiation pattern in the E-plane. This makes monopole antennas good candidates for communication applications. There are some shortcomings with existing UWB antenna designs which include high cross polarization components especially at higher frequencies, angular dependence of the E-plane patterns and deterioration in the H-plane patterns.

2.2 Square monopole antennas

Square monopole antennas are simple antennas to be built and have radiation characteristics that are suitable for certain UWB applications. It is an omnidirectional antenna with impedance bandwidth, which depends on the antenna design parameters. These design parameters include height, width and distance from the ground plane. To increase the bandwidth of this square monopole antenna, Wong introduced the trident-shaped feeding strip to feed the square monopole, (Wong et al., 2005). Wong's optimum design parameters for the trident-shaped feeding strip gave a 10 dB bandwidth of 10 GHz with the lower frequency of 1.376 GHz. Wong used a square monopole of $40 \times 40 \text{ mm}^2$ over a $150 \times 150 \text{ mm}^2$ ground plane, all strip widths used were 2mm. Based on this idea, a square monopole antenna with trident-shaped feeding strip is designed to work over the frequency band starting from 3GHz. The square monopole side is scaled down to 16 mm over a $120 \times 120 \text{ mm}^2$ ground plane. The optimum strip dimensions for this antenna are $t = 7 \text{ mm}$, $d = 1 \text{ mm}$, $h = 3 \text{ mm}$ and all strip widths are 1.5 mm. Simulation results of this antenna show an omnidirectional radiation pattern over the frequency band from 3GHz to 19.5 GHz. The optimized feeding structure resulted in a well matched traveling mode by enhancing modes J1 and J3 which support vertical currents on the radiator surface. To study the effect of implementing a notch close to the feeding structure, a rectangular notch of height 2mm and width 3.75mm is implemented at each lower side of the square monopole. Fig. 1 shows different configurations for the square monopole antenna along with the return loss curves. It was expected that implementing such a notch in the feeding region would increase the bandwidth of the antenna. But as can be seen from Fig. 1d, the 10dB higher frequency edge of the impedance bandwidth was decreased from 19.5 GHz to 15 GHz. This is due to the fact that implementing a notch along with the feeding type did not help in supporting current mode J3 at higher frequencies. Radiation patterns at different frequencies show no significant effect of implementing such a notch.

To further study the performance of this antenna, gradual metal removal was done from the interior monopole area. It was proven that by removing the metal from the interior radiator of an ultra wideband circular monopole antenna with a single feeding strip, a loop ultra wideband monopole antenna is achieved keeping the radiation characteristics of the antenna unchanged, (Mohamed & Shafai, 2007). With this square monopole design, $8 \times 8 \text{ mm}^2$ metal area was removed from the radiator as shown in Fig. 1c. The impedance bandwidth of the resulting antenna gives the same impedance bandwidth from 3 to 19.5 GHz with omnidirectional radiation pattern over the entire frequency bandwidth. Fig. 2 shows its E-plane and H-plane at different frequencies and different planes. It is clear that this antenna keeps its radiation characteristics at higher frequencies.

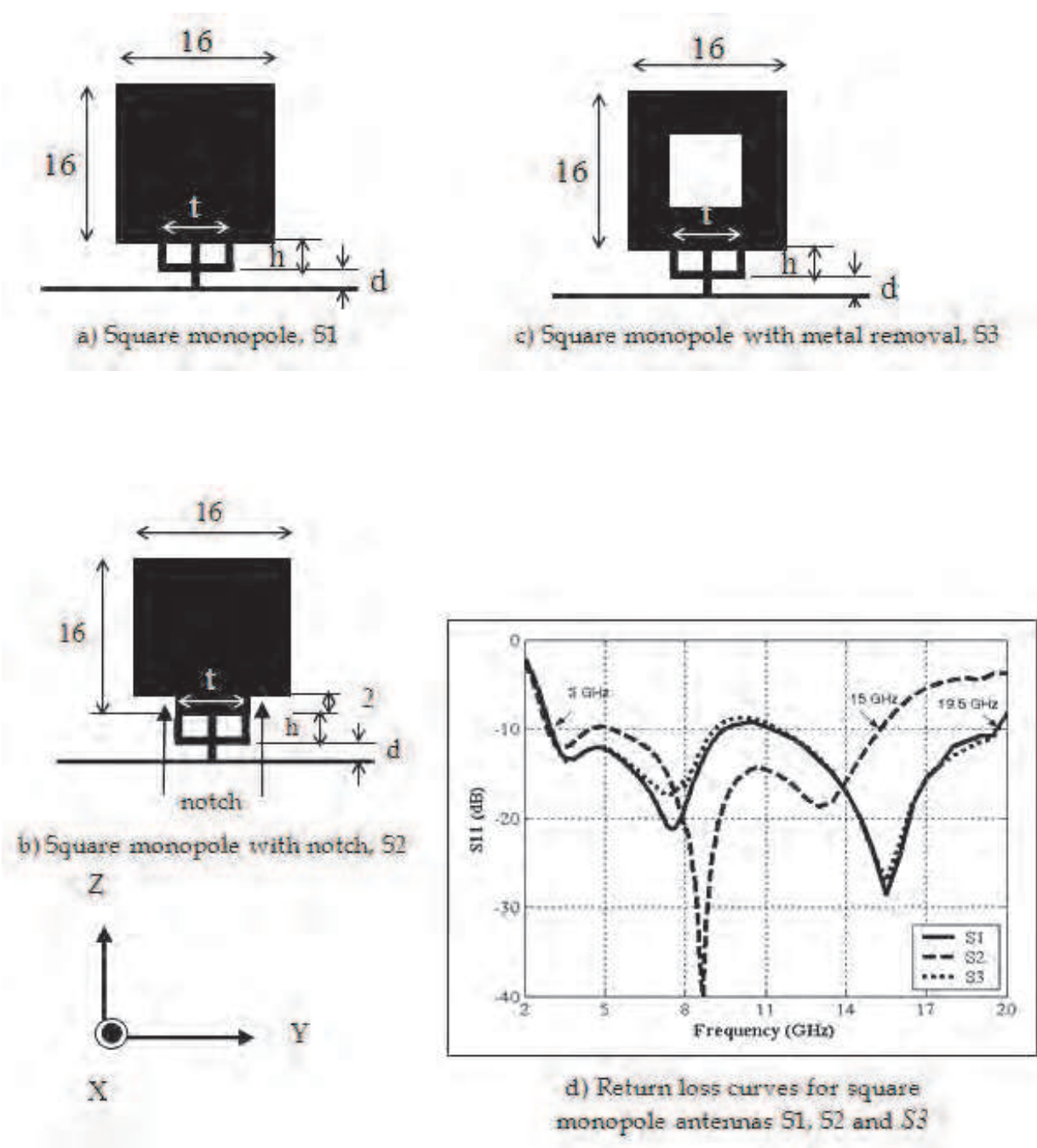


Fig. 1. Square monopole antenna with trident-feeding strip and different configurations

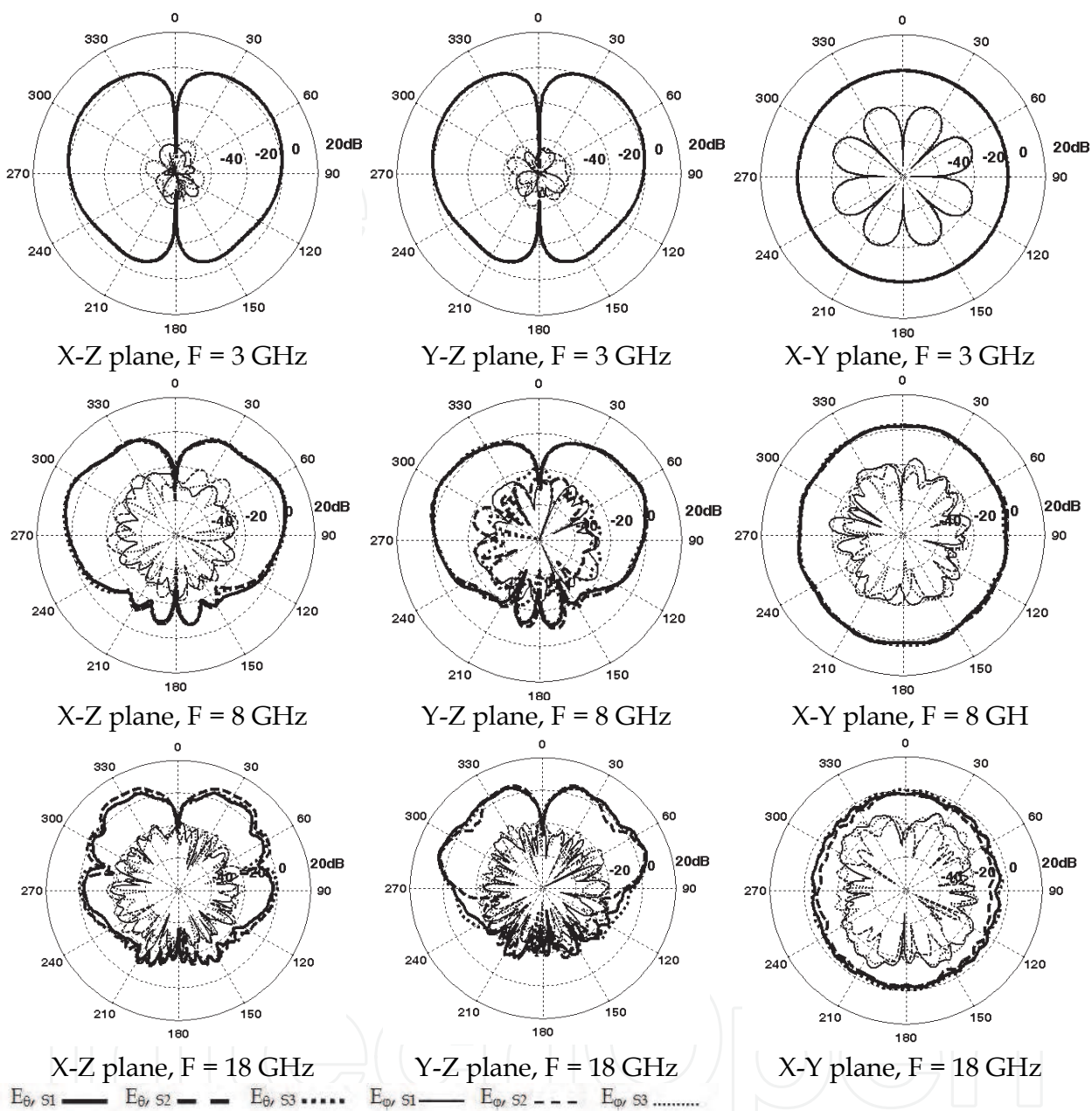


Fig. 2. Radiation patterns for three square monopole antennas S1, S2 and S3 at different frequencies

2.3 Circular monopole antennas

The second antenna to be studied is the circular monopole antenna known by its gradual bevelling near the feeding area. For the sake of comparison between this antenna and the square one, the height of the antenna, the trident-feeding strip configuration and the ground plane dimensions are kept the same. Antenna dimensions are given in Fig. 3 where *t*, *h*, and *d* are the same as those in the square monopole one. Fig. 3a, b and c show different circular

monopole configurations. In Fig. 3b and 3c, the same notch and metal removal approach used with the square monopole antenna design are implemented. The metal removed here is a circle of radius 4 mm. It is noted from the return loss curves shown in Fig 3d that the notch has a negligible effect on the circular monopole antenna. Similarly, the metal removal effect which made a circular loop monopole, gives almost the same impedance bandwidth of 130.58%, as the circular monopole.

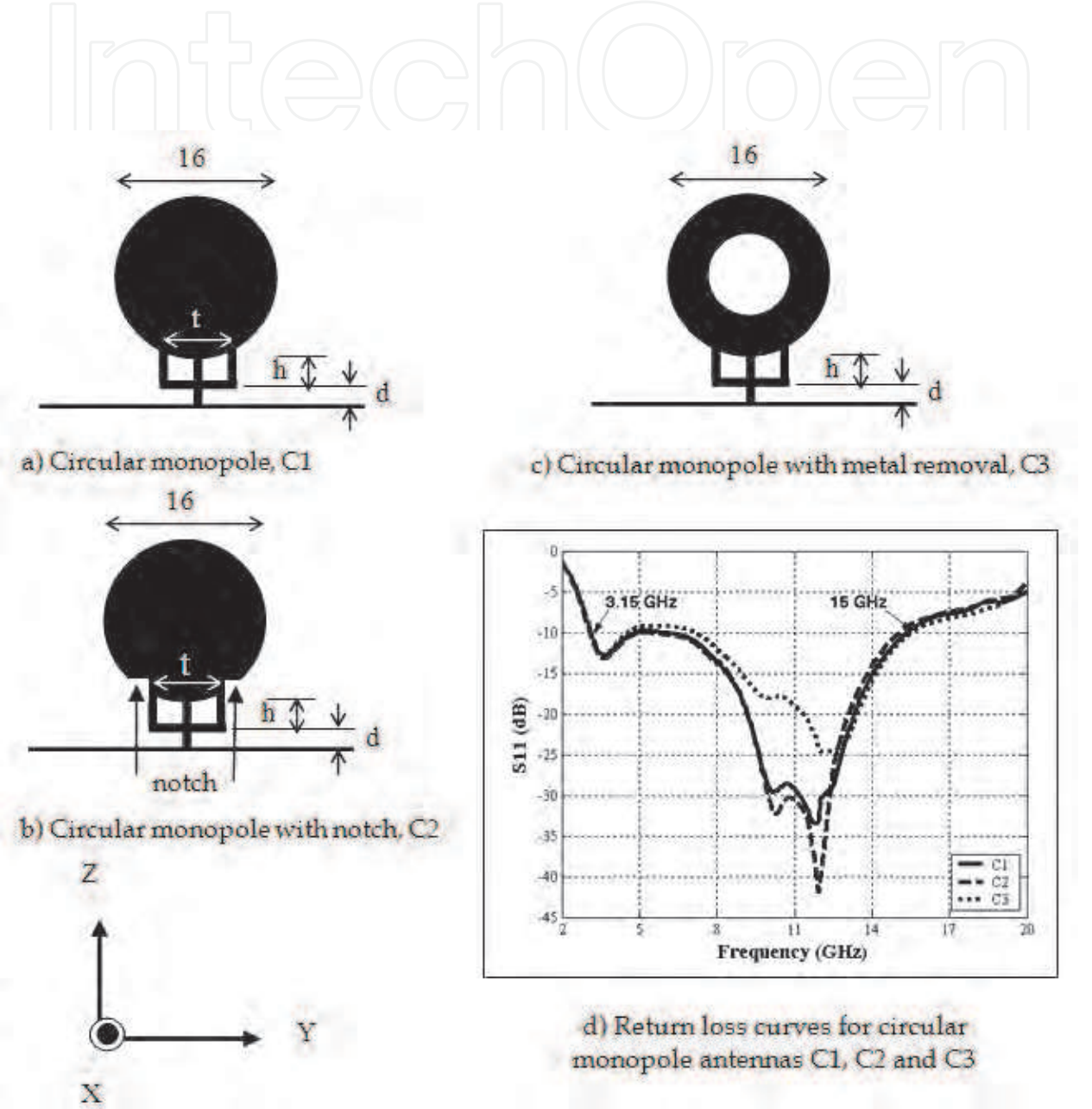


Fig. 3. Circular monopole antenna with trident-feeding strip and different configurations

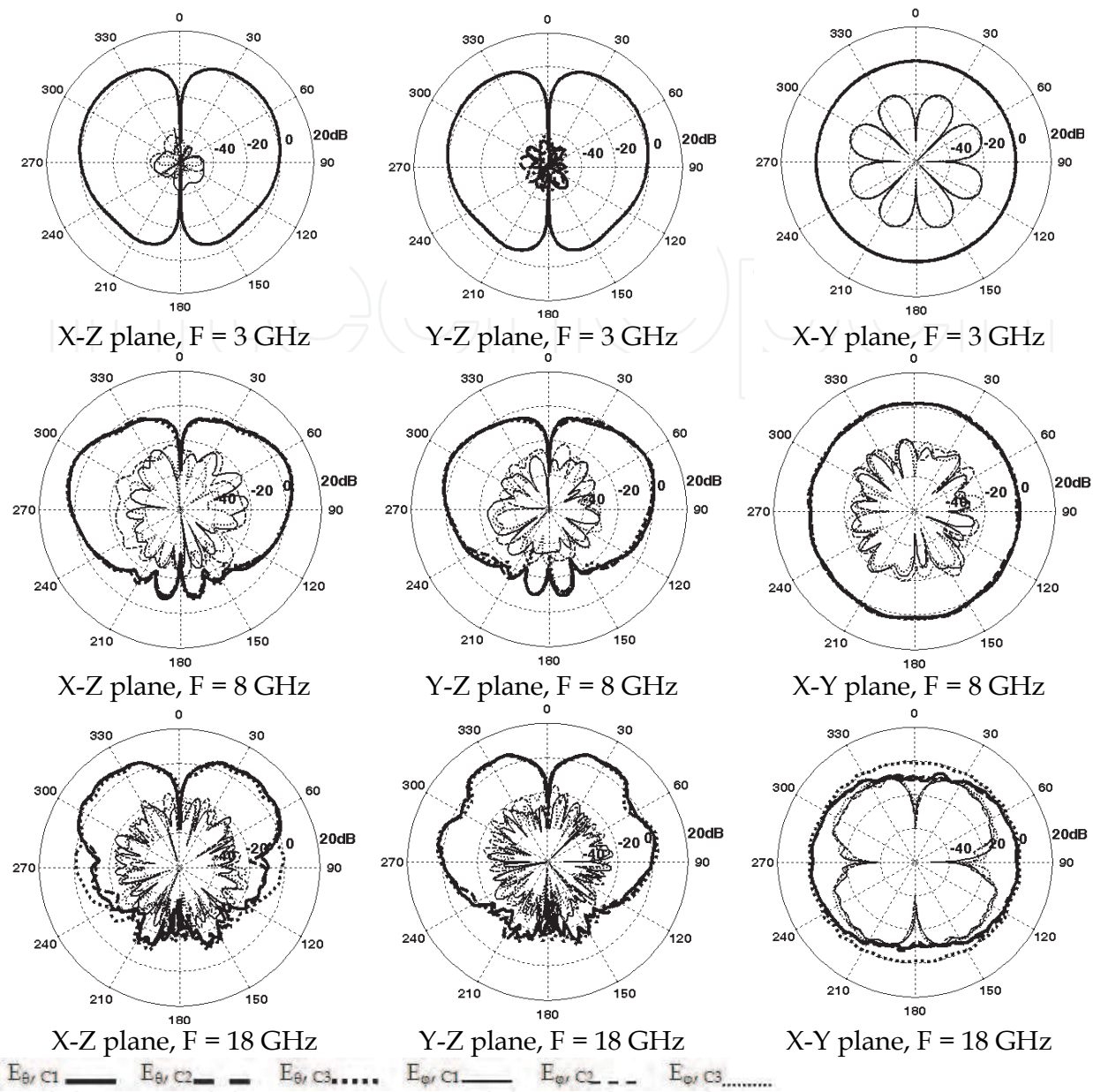


Fig. 4. Radiation patterns for three circular monopole antennas C1, C2 and C3 at different frequencies

The E and H-plane curves are shown in Fig 4. The circular monopole antenna with different configurations shows an omnidirectional radiation pattern over the frequency band of operation. The circular loop monopole antenna shows a better omnidirectional behaviour at higher frequencies. While implementing notches near the feeding region does not have a significant effect on the radiation patterns curves of these antennas.

2.4 Elliptical monopole antennas

The third antenna to be studied is the elliptical monopole antenna with trident-feeding strip. The same feeding structure and ground plane used for square and circular monopole are used here. The height of the elliptical monopole, which is the minor diameter, is 16 mm and the major diameter is 20 mm, as seen in Fig. 5. The notch implemented at the lower edge

reduced the upper frequency limit from 16.5 to 15.5 GHz. On the other hand, removing metal from the elliptical monopole by cutting an ellipse of minor 8mm and major 10 mm has increased the upper frequency limit to 17 GHz.

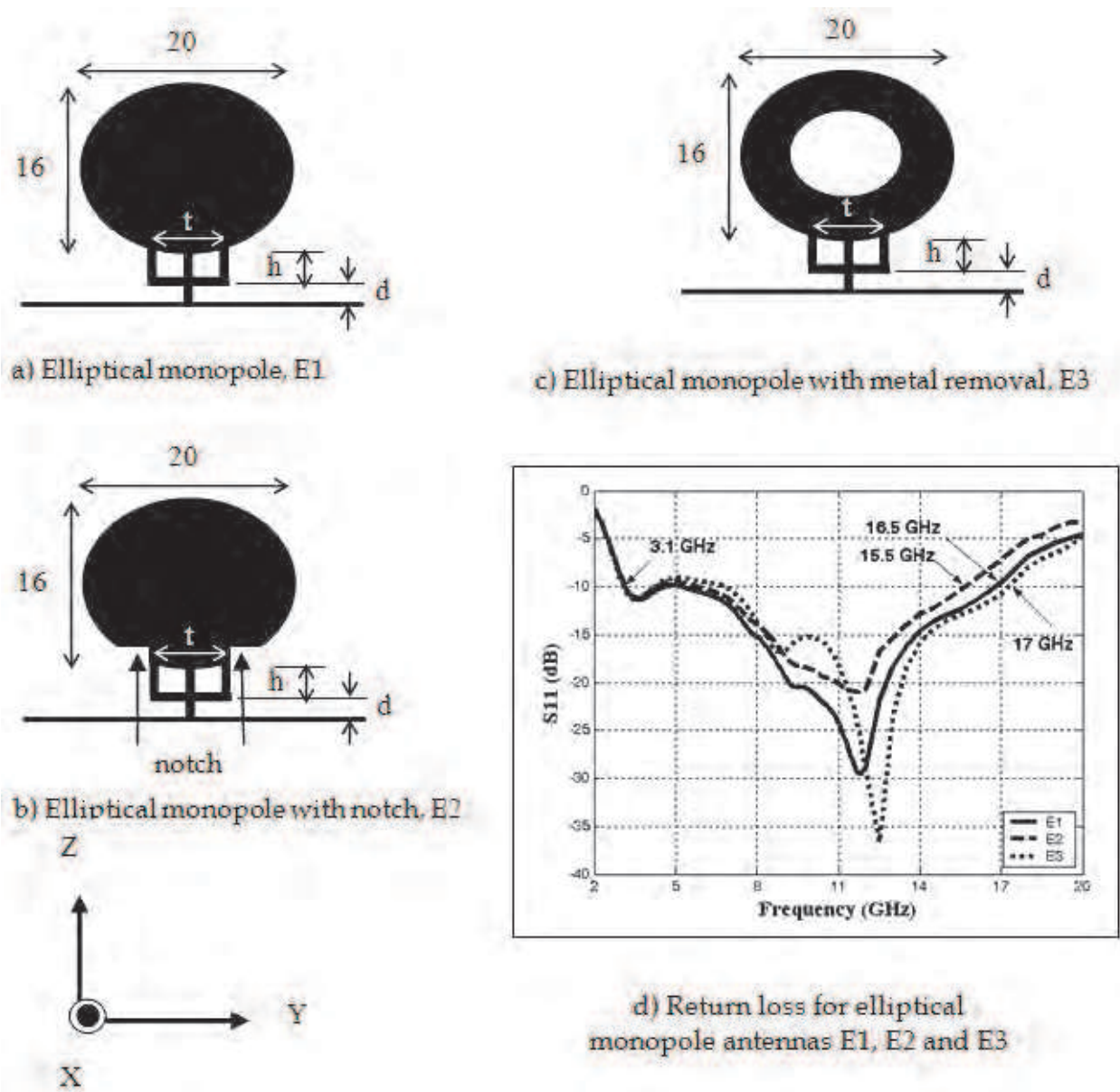


Fig. 5. Elliptical monopole antenna with trident-feeding strip and different configurations

Radiation patterns for the elliptical monopole antenna with different configurations at different frequencies and different planes are shown in Fig. 6. All the elliptical antenna configurations show omnidirectional pattern with low cross polarization. There is no effect of the notches or the metal removal on the radiation patterns at lower frequencies. While at higher frequencies, the elliptical monopole with metal removal has a better omnidirectional behaviour.

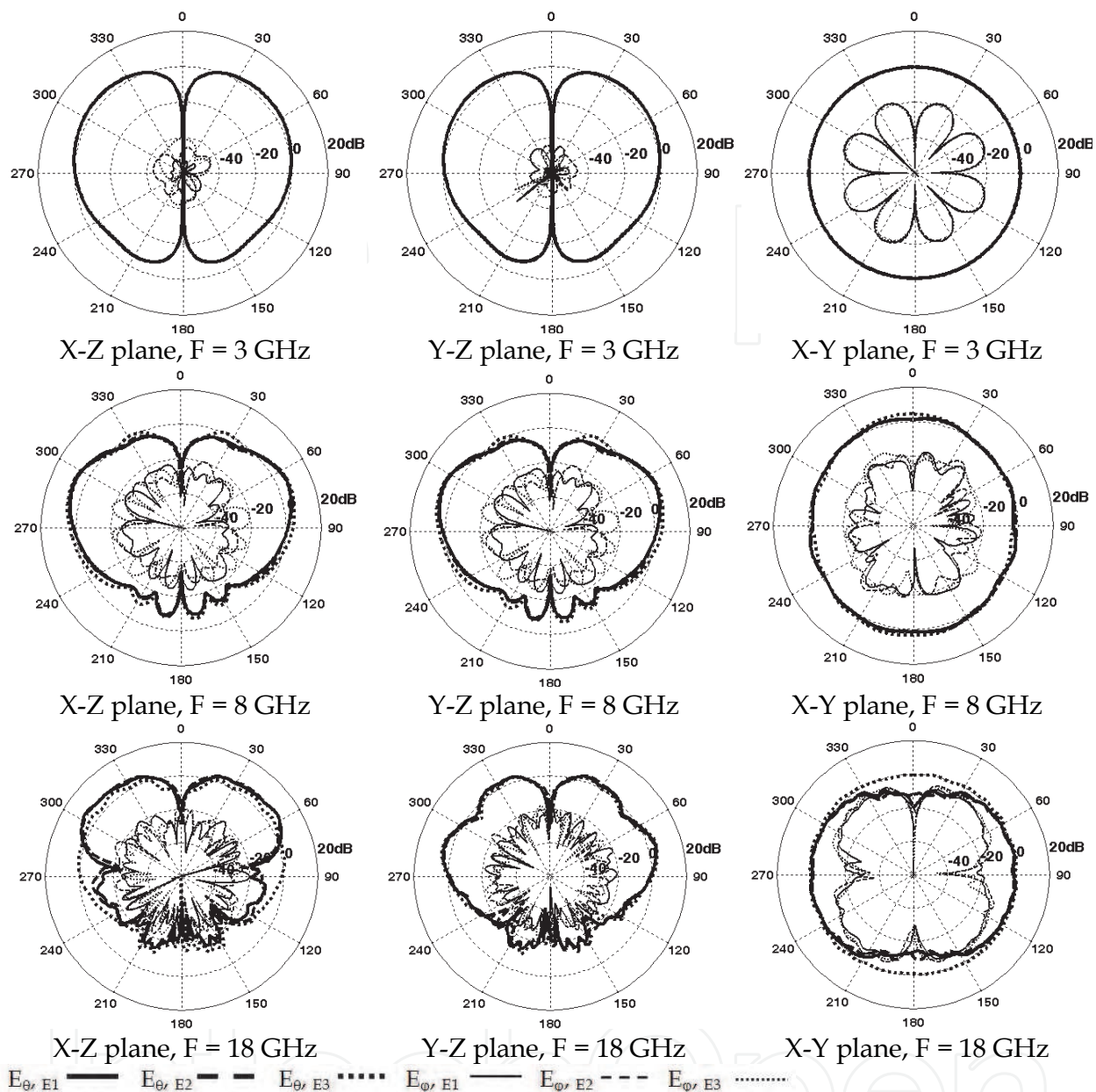


Fig. 6. Radiation patterns for three elliptical monopole antennas E1, E2 and E3 at different frequencies

3. Ground plane effect on the performance of UWB monopole antennas

Throughout the study done in section 2 of this chapter, the ground plane chosen for all monopole antennas was a square metal plate with area of 120x120 mm². The effect of a ground plane with this size appears in the results of the square, circular and elliptical monopole antennas. Using monopole antenna with height 16 mm and trident feeding strip over the ground plane and different geometries gave 10-dB impedance bandwidth with lower frequency of 3 GHz and upper frequency between 15 and 19.5 GHz. The radiation pattern curves of these antennas are monopole-like patterns with maximum radiation at the

E-plane around $\theta=60^\circ$ and omnidirectional radiation pattern at the H-plane. Although the studied antennas so far satisfied the UWB communication applications regarding the impedance bandwidth and radiation pattern curves, the small height of the antenna over the ground plane affects the lower frequency band of operation. Also, the size of the ground plane was fixed throughout the study with total area of $120 \times 120 \text{ mm}^2$. To further investigate the performance of such monopole antennas, the size of the ground plane is modified and different slots are implemented to study their effects on the antennas performance. The square monopole antenna with trident feeding strip designed in section 2, is used to illustrate the effect of the ground plane size on its performance. Antenna parameters of interest in this study are the return loss curves and radiation pattern curves. Simulation results indicate that by optimizing the ground plane size of UWB monopole antennas, the lower frequency edge of the impedance bandwidth can be reduced from 3 GHz to 2.1 GHz. On the other hand, this reduction in ground plane size will have an effect on the radiation pattern of the antenna. It is found that, by implementing a square slot in the original size of the ground plane, the frequency reduction in the lower edge of the impedance bandwidth can be maintained as well as the wanted radiation patterns. The radiation pattern is a monopole like pattern with the peak gain shifted to around $\theta = 60^\circ$ above the horizon, because of the existence of the finite ground plane. The effect of the ground plane size on the peak gain angle θ is also investigated. Fig. 7 shows the square monopole antenna used in this study, while Fig. 8 shows the return loss curves for this antenna with different ground plane sizes.

As can be seen from Fig. 8, the square monopole antenna with $20 \times 20 \text{ mm}^2$ square ground plane has a UWB impedance bandwidth that starts at 2.1 GHz. This reduction of the lower edge of the bandwidth from 3 to 2.1 GHz is achieved without increasing the monopole height. The higher edge of the impedance bandwidth extends to almost 20 GHz for all cases.

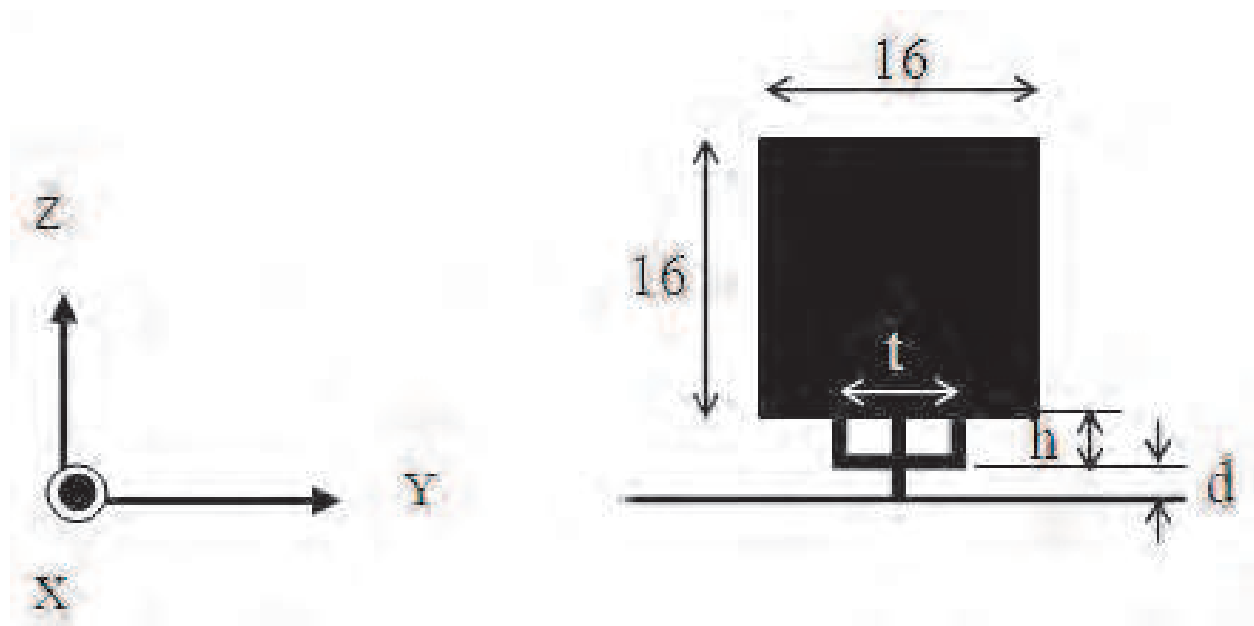


Fig. 7. Square monopole antenna with trident-feeding strip and different ground plane sizes. Optimized parameters values are: $t=7\text{mm}$, $h=3\text{mm}$, $d=1\text{mm}$, and all strip widths = 1.5mm

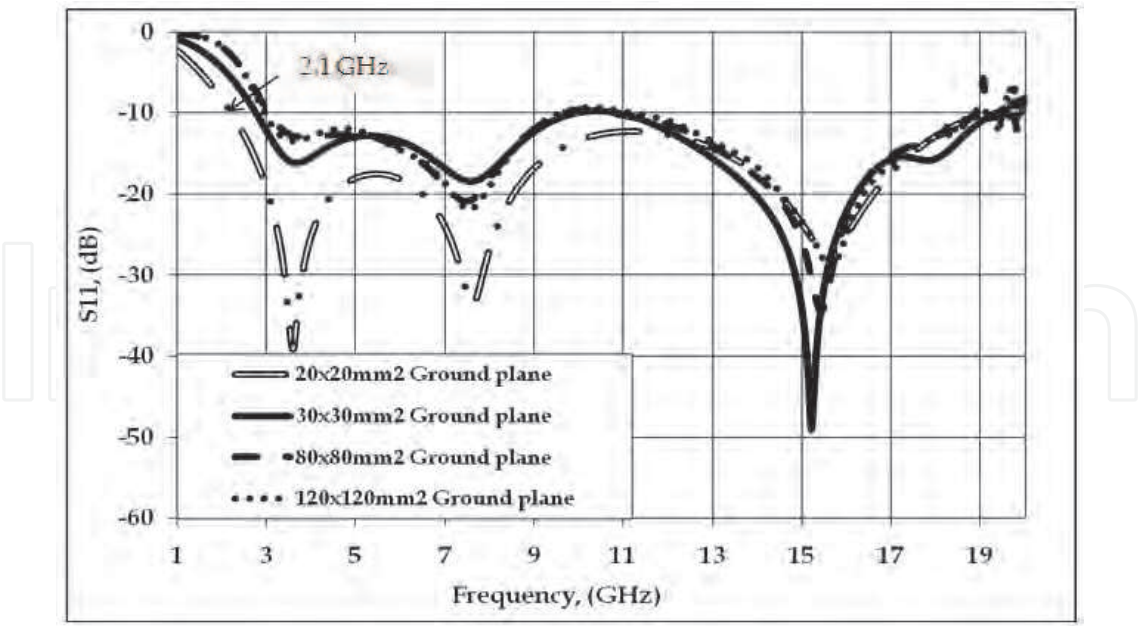
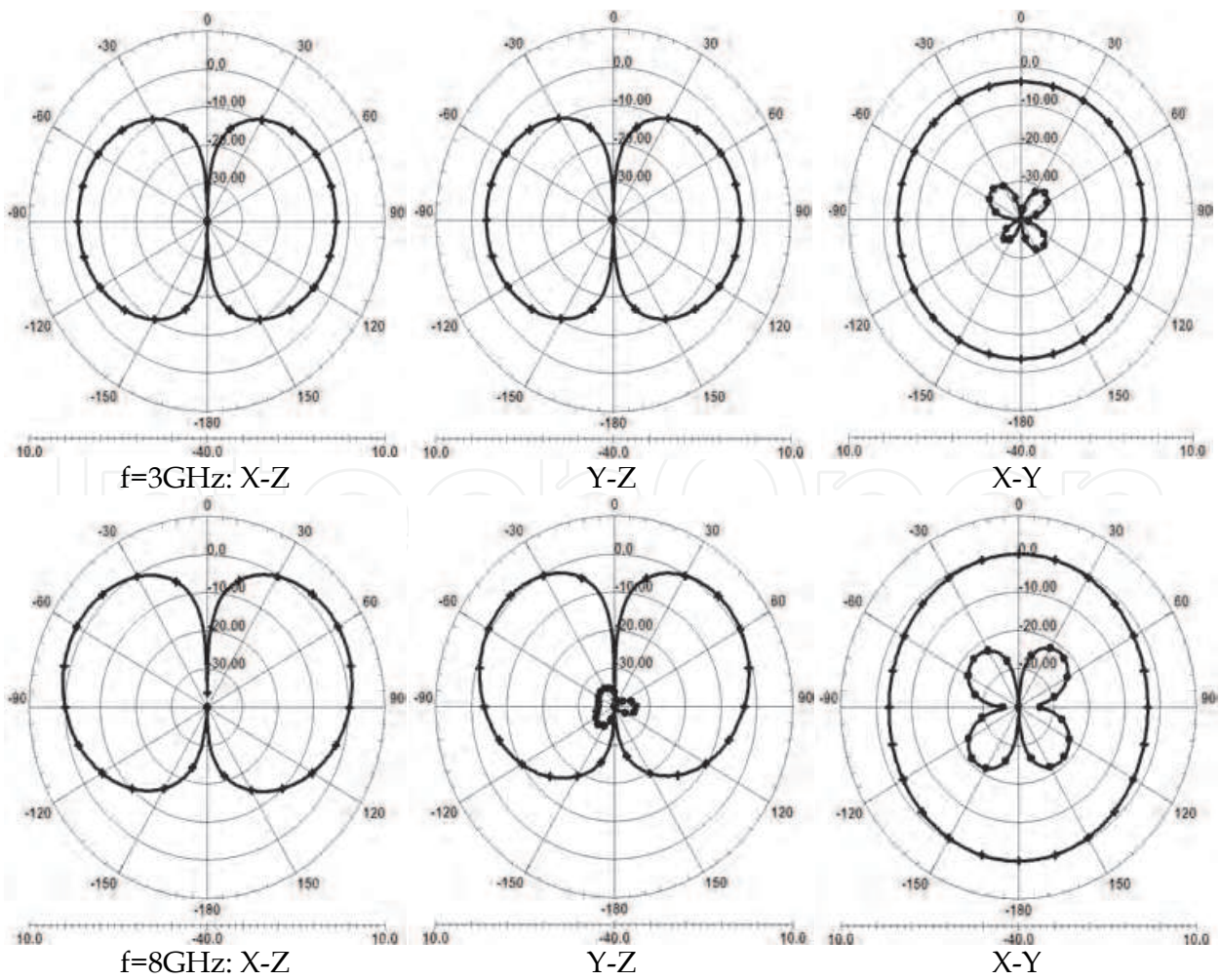


Fig. 8. Return loss curves for the square monopole antenna in Fig. 7 with different ground plane sizes.



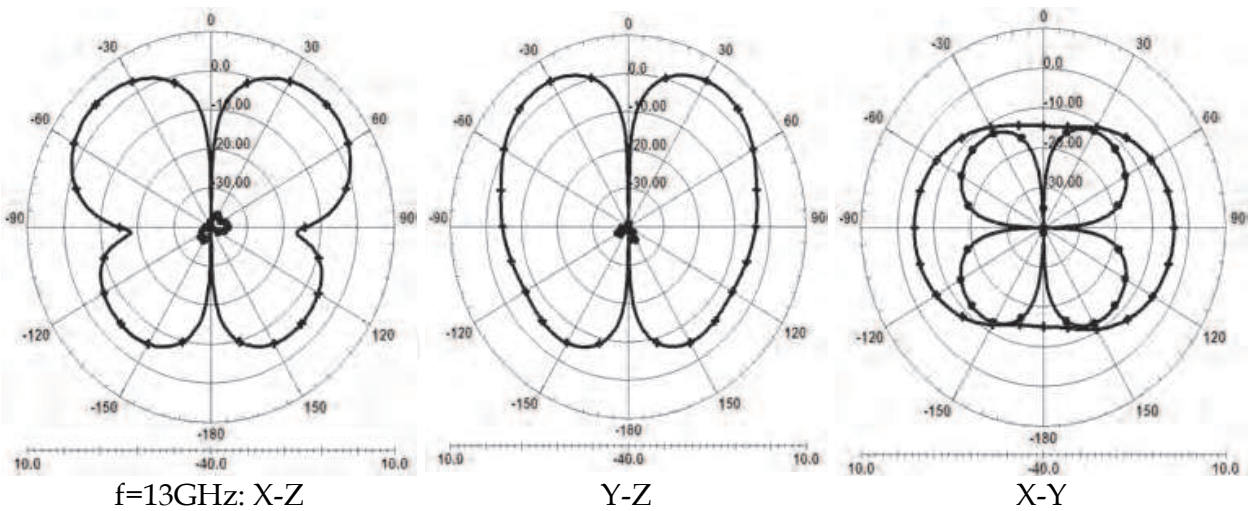


Fig. 9. Radiation patterns for the antenna shown in Fig. 7 with 20x20 mm² ground plane

To show the effect of the ground plane size on the radiation pattern curves, radiation pattern curves at different frequencies are discussed. Fig. 9 shows E and H-plane curves at different planes and frequencies of 3, 8 and 13 GHz with 20x20mm² ground plane. While in section 2, Fig. 2 shows E and H-plane curves for the same antenna and same planes but with 120x120mm² ground plane size. As can be seen from Fig. 9, Fig. 2 and other simulated results, the effect of the small ground plane size is realized at lower frequencies. The gain is reduced at the maximum angle of radiation. Another attempt is done to further decrease the ground plane size and compensate for the effect of its small size on the radiation pattern. Square slots of different widths and at different distances from the origin are introduced within the ground plane. The study showed no significant effect on the radiation pattern curves of the antenna. However by having a 20x20mm² small ground plane and increasing the height of the antenna to only 30 mm, the lower frequency edge was reduced from 2.1 to 1.4 GHz and the gain was increased at the direction of maximum radiation. Fig. 10 shows the return loss curve for the antenna in Fig. 7 but with height of 30 mm, while Fig. 11 shows E and H-plane curves for the antenna in Fig. 7 with a height of 30 mm at different frequencies and different planes.

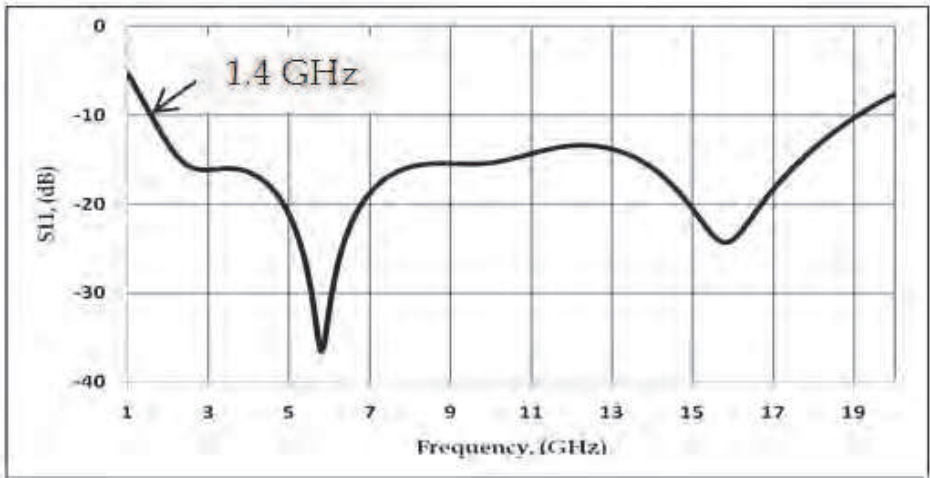


Fig. 10. Return loss curve for antenna in Fig. 7 with total height of 30mm instead of 20mm

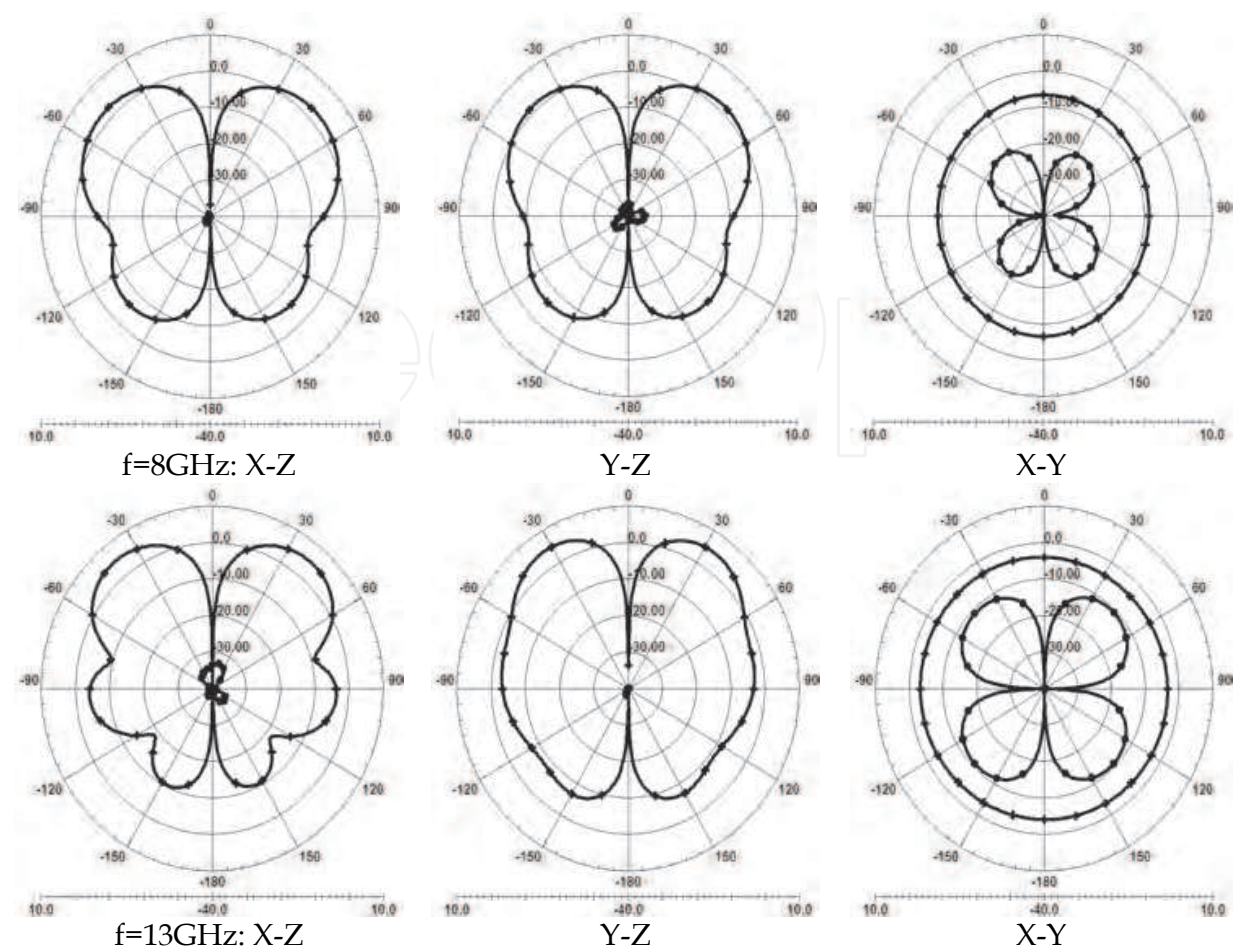


Fig. 11. Radiation Patterns for the antenna with return loss curve shown in Fig. 10

The study in section 3 showed that, the ground plane size can be reduced to 20x20 mm² to have a lower frequency edge of 2.1 GHz with some deterioration in the radiation pattern curves of the antenna. Also the total height of the antenna can be increased from 20mm to 30 mm to compensate for the change in the radiation pattern and to further reduce the lower frequency edge to 1.5 GHz. In section 4, this square monopole antenna with the trident feeding strip will be used to design a UWB Yagi monopole antenna over a ground plane.

4. UWB Yagi monopole antenna

In the last part of this study, a UWB Yagi monopole antenna over a ground plane is designed and analyzed to work over the UWB communication band. The antenna is relatively small in size and the driven element is based on the square monopole antenna with trident feeding strip designed in section 2. The first step in designing such a Yagi monopole is by having a driven element and one reflector, possibly of the same shape as the driven element, and at different distances on The Y-axis from it. The second step is to optimize the ground plane size for the best impedance bandwidth. The third step is to design a slot in the square ground plane to isolate the effect of the reflector on the impedance bandwidth. Fig. 12 shows Yagi monopole antenna with a 1 mm wide square slot at 10mm distance from the centre of the ground plane. The distance between the driven element and the reflector is d, while the ground plane size is GxG mm². Simulation results

show better performance of such antenna with the slot in the ground plane, between the radiator and the reflector. Then the reflector is moved on the Y-axis behind the driven element to optimize the maximum impedance bandwidth. It is clear from Fig. 13 that the antenna has the maximum impedance bandwidth with lower frequency of about 3GHz when the reflector is at a distance $d=20\text{mm}$ from the driven element. Fig. 14 shows some of the radiation pattern curves of this antenna for illustration purpose. Simulation results indicate a good performance of this Yagi monopole antenna with only one reflector and no directors as a directional UWB monopole antenna for communication applications.

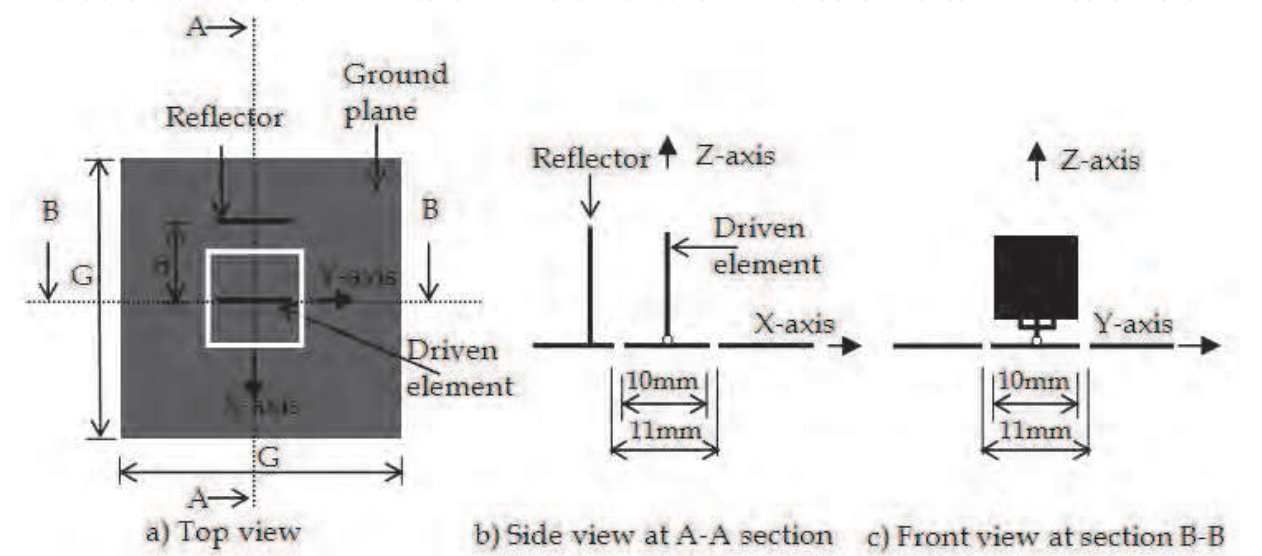


Fig. 12. Yagi monopole antenna with $G \times G \text{ mm}^2$ ground plane. One driven element and one reflector at distance d from the driven element. Driven element has same parameters as those in Fig. 7. 1mm slot at distance 10mm from the ground plane centre.

Directors can be used in front of the radiators to further increase the directive gain of this antenna. It is found that by using only one director of the same shape as the driven element with 4mm reduction in height and at 20mm distance, directive gain increased. However, this antenna needs more investigation for minimizing the back lobe level.

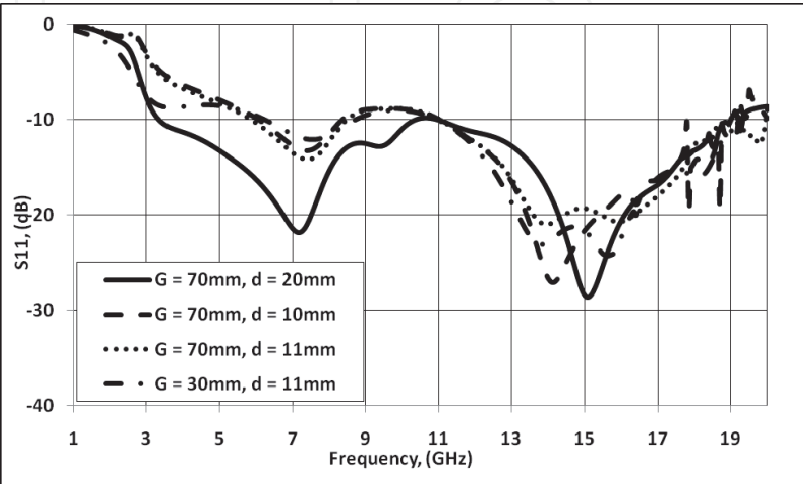


Fig. 13. Return loss curve for Yagi monopole antennas in Fig. 12

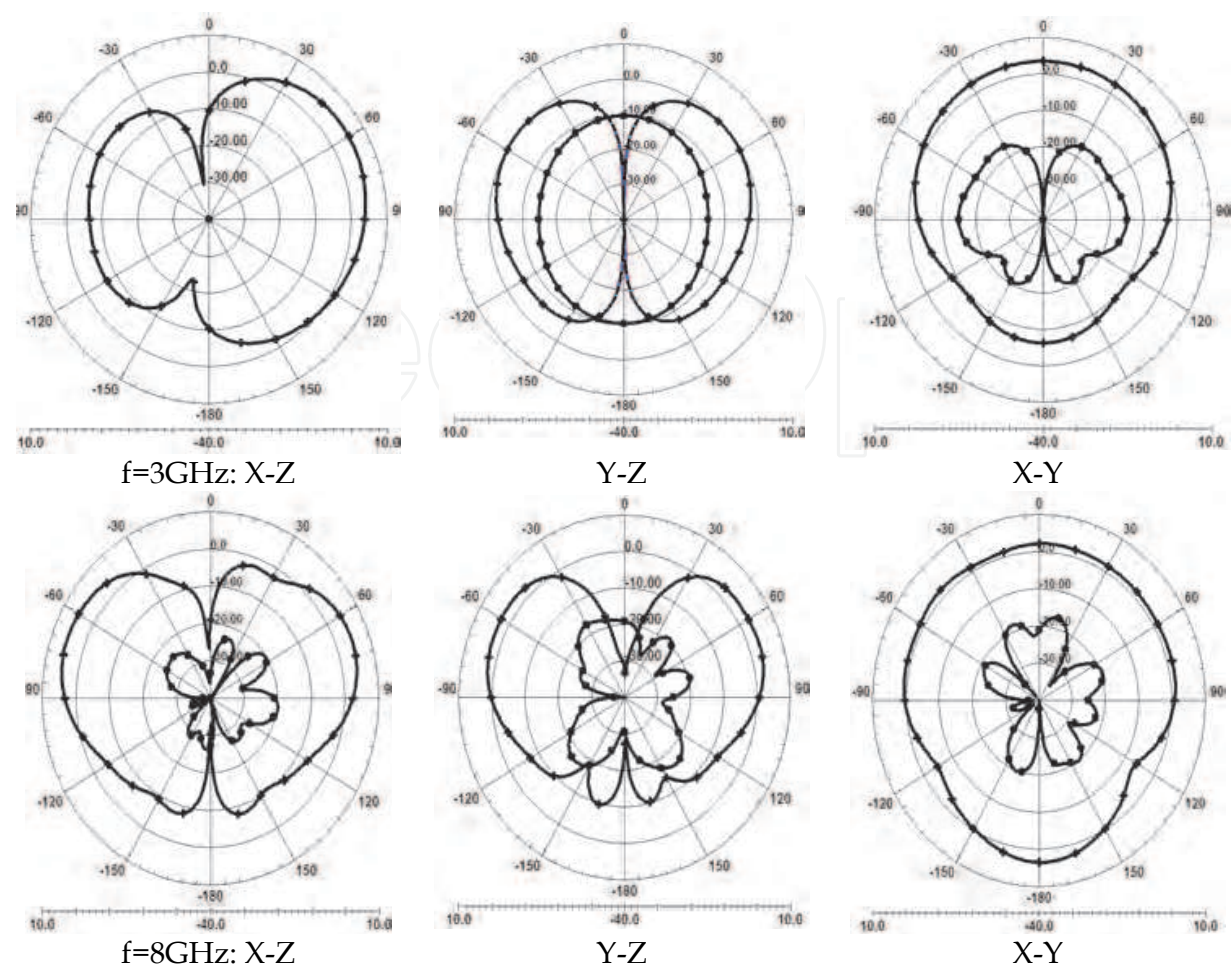


Fig. 14. Radiation patterns for the antenna shown in Fig. 12, $G=70\text{mm}$, $d=20\text{mm}$

Note also that, the trident feeding was used for the single element to improve its impedance bandwidth. This is not necessary for all elements of the Yagi antenna. The reflector and the directors, could have other shapes, such as a simple square monopole of proper size. More research is needed to determine the optimum parameters for satisfactory front to back ratios over the entire band. The example given here was to show the possibility of beam shaping using additional elements, while keeping the wide impedance bandwidth of the antenna.

5. Building and testing some of the studied monopole antennas

To verify the performance of the antennas studied in section 2 through section 4, some of those antennas have been built and tested at The University of Manitoba Antenna Lab. All antennas modelled so far were considered as metal plates mounted vertically over a horizontal ground plane. Metal was considered perfect conductor during simulation processes using Ansoft-HFSS software, a finite element method full wave solver, (Ansoft, 2011). However to overcome the problem of deformation in the planar shape of the metal plates when mounted on the ground plane, each antenna was etched on a $22 \times 22 \text{ mm}^2$ substrate with 0.8mm thickness and permittivity $\epsilon_r = 2.5$. This configuration also solved the problem of soldering the metal plate to the connector without damaging it. Ground plane used in the measurements was a sheet of Aluminium because of its light weight and capability of keeping its flatness. Fig. 15 shows one of the designed antennas after being

mounted on the Aluminium ground plane and connected to The Vector Network Analyzer for return losses measurements.

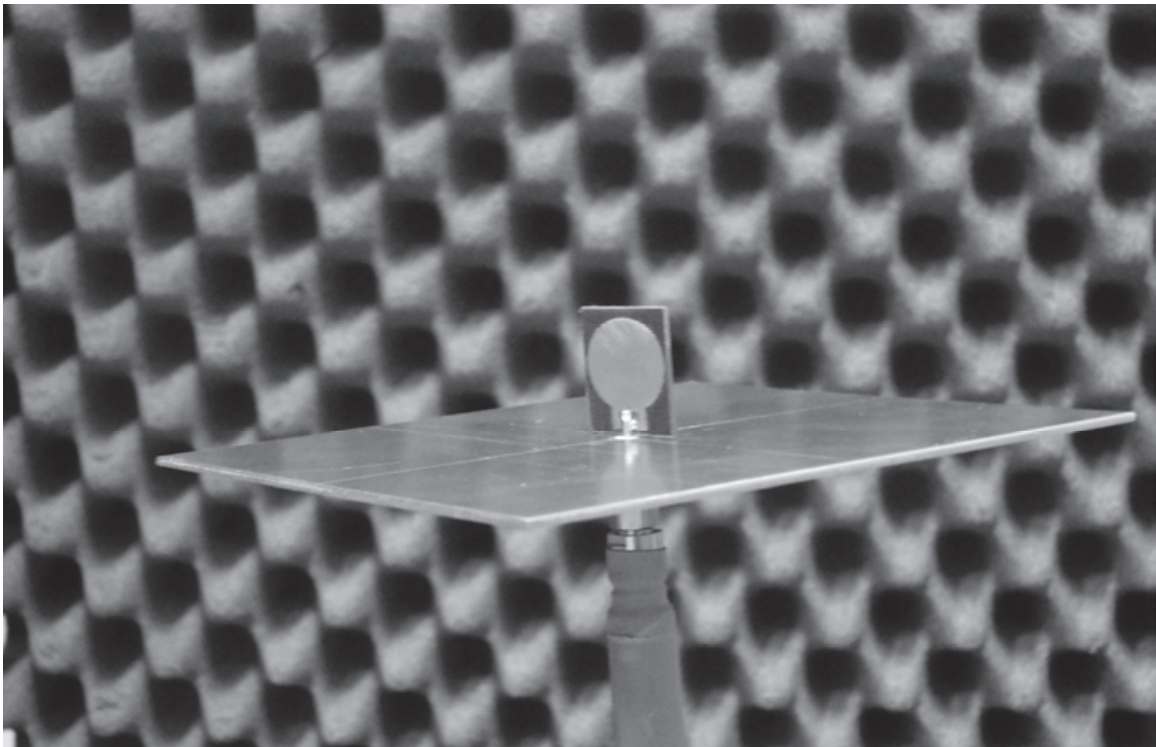


Fig. 15. Circular monopole antenna mounted on a 120x120mm² Aluminium ground plane and ready to be tested at University of Manitoba Antenna Lab using Anritsu 37397C Vector Network Analyzer



Fig. 16. Square monopole antennas of Fig. 1a and Fig. 1c etched each on a 22x22mm² substrate with $\epsilon_r=2.5$, height=0.8mm. Antennas are compared to the Canadian Dollar Coin before being mounted on the Aluminium ground plane

Fig. 16 shows the square monopole antenna with trident feeding strip with and without central metal removal, studied in Section 2.2. Metal plates are etched on a 22x22mm² single sided metal. Fig. 17 shows the return loss curves of both antennas after being mounted on a 120x120mm² Aluminium ground plane. Measured results are compared to simulated ones. As can be seen, there is a good agreement between measured and simulated return loss

curves regarding lower frequency edge and resonance frequencies. There is a shift in some resonance frequencies and the upper frequency edge. Same notations can be seen also in the circular monopole antenna with and without central metal removal shown in Fig. 18 and their return loss curves shown in Fig. 19. Elliptical monopole antennas with and without central metal removal are shown in Fig. 20 and compared to the Canadian Dollar Coin to show their sizes. The Return loss curves of the two elliptical monopole antennas are shown in Fig. 21.

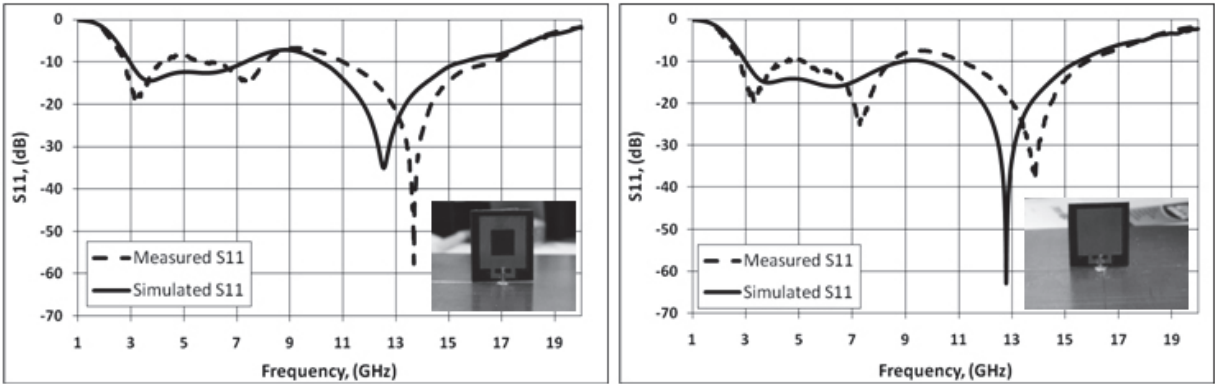


Fig. 17. Return loss curves for the square monopole antennas shown in Fig. 16



Fig. 18. Circular monopole antennas of Fig. 3a and Fig. 3c etched each on a 22x22mm² substrate with $\epsilon_r=2.5$, height=0.8mm. Antennas are compared to the Canadian Dollar Coin before being mounted on the Aluminium ground plane

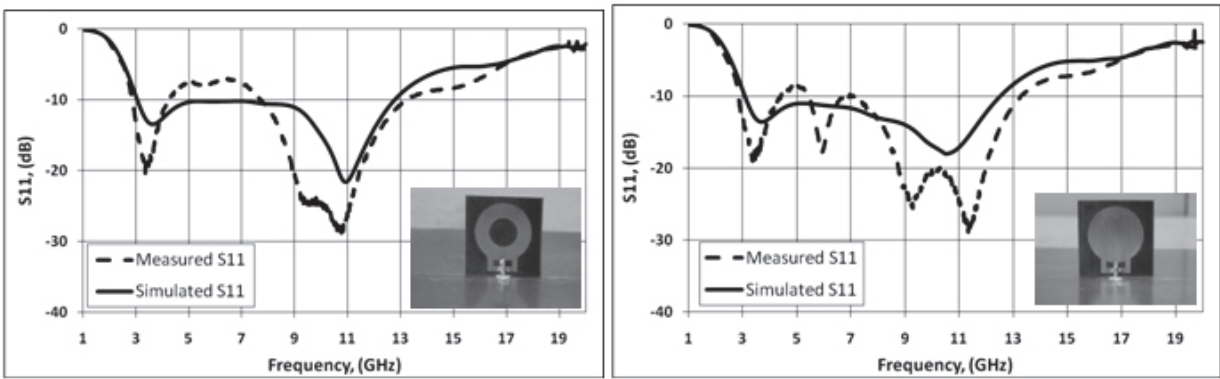


Fig. 19. Return loss curves for the circular monopole antennas shown in Fig. 18

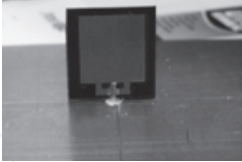
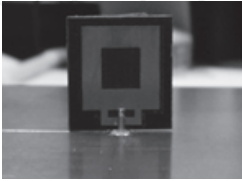
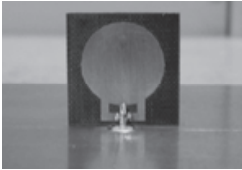
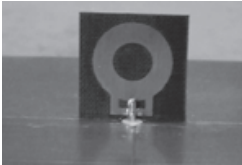
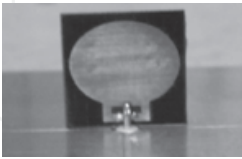
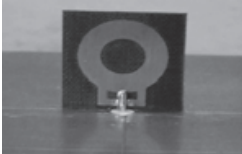
Maximum group delay (ns) measured over the entire frequency band, 3 to 20 GHz	
<div>Square monopole antenna</div> <div></div>	0.2325 ns
<div>Square monopole with central metal removal</div> <div></div>	0.2406 ns
<div>Circular monopole antenna</div> <div></div>	0.3154 ns
<div>Circular monopole with central metal removal</div> <div></div>	0.2811 ns
<div>Elliptical monopole antenna</div> <div></div>	0.2377 ns
<div>Elliptical monopole with central metal removal</div> <div></div>	0.2703 ns

Table 1. Maximum group delays measured over the frequency band, 3-20 GHz



Fig. 20. Elliptical monopole antennas of Fig. 5a and Fig. 5c etched each on a 22x22mm² substrate with $\epsilon_r=2.5$, height=0.8mm. Antennas are compared to the Canadian Dollar Coin before being mounted on the Aluminium ground plane

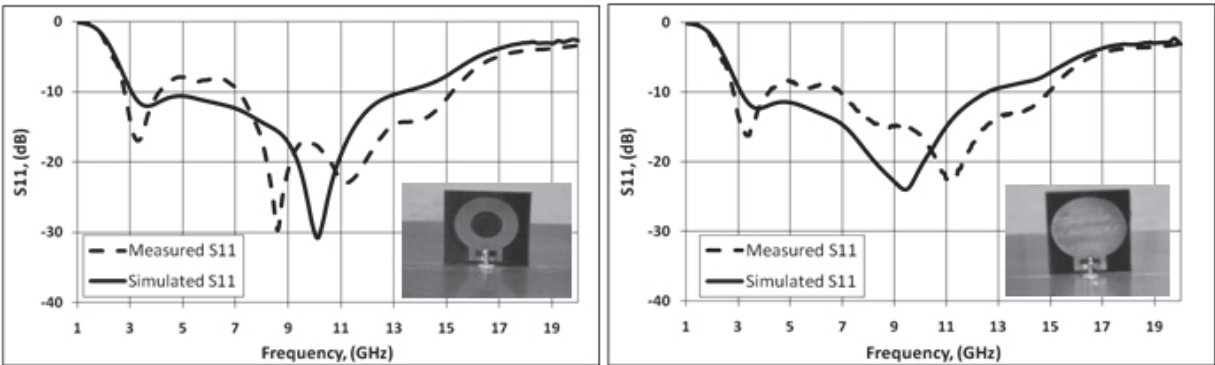


Fig. 21. Return loss curves for the elliptical monopole antennas shown in Fig. 20

To further understand how the signal transmitted or received from these antennas will be distorted; the group delay curves of the tested antennas are measured. Table 1 shows the maximum group delay of each antenna over the entire frequency band of operation, from 3 to 20 GHz. As can be seen from Table 1, all monopole antennas tested have group delay less than 0.5 ns which is less than that of the circular disc monopole with single strip feed, (Gue et al., 2007).

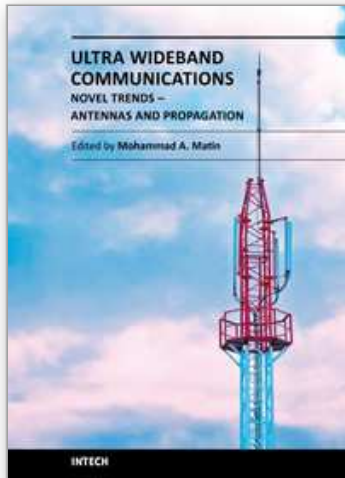
6. Conclusion

In this chapter, different UWB monopole antennas were studied. Square, circular and elliptical monopole antennas showed UWB impedance bandwidth that covered the existing defined ultra wideband communication band 3.1 to 10.6 GHz, and extended beyond that to 19.5 GHz for future applications. It was found that implementing notches close to the trident-feeding strip structure did not increase the impedance bandwidth of circular and elliptical antennas. Further, implementing a notch decreased the impedance bandwidth of the square monopole antenna. On the other hand, removing metal from the interior structure of the square, circular and elliptical monopoles gave the same impedance bandwidth for square and circular monopole and increased the bandwidth of the elliptical one. The circular and elliptical monopole antennas with metal removed showed better omnidirectional behaviour at higher frequencies. Some of the studied monopole antennas were built and tested. Antennas were etched on a substrate to keep their planar shape and

then mounted on an Aluminium ground plane. Return loss curves showed good agreement between measured and simulated ones. Radiation pattern measurements will also be done to confirm simulation results. The size of the ground plane was optimized to decrease the lower edge of the impedance bandwidth and slots were implemented to isolate the effect of this small ground plane on the radiation pattern of the antenna. Also, a UWB Yagi monopole antenna over a 70x70mm² ground plane was designed to cover the existing and upcoming communication applications. Both reflectors and directors were used to enhance the directivity of the antenna and decrease the back lobe levels. The future work on this UWB Yagi monopole will study how to minimize back lobe levels and determine the phase centre location at different frequencies and different planes.

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This book explores both the state-of-the-art and the latest achievements in UWB antennas and propagation. It has taken a theoretical and experimental approach to some extent, which is more useful to the reader. The book highlights the unique design issues which put the reader in good pace to be able to understand more advanced research.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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