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Analysis Performance of Singly-Fed Circularly Polarized Microstrip Antenna for Wireless Communication

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Graphical abstract

Circularly polarized (CP) microstrip antenna limitation in gain, impedance and axial-ratio bandwidths

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Consideration about application targets and specifications, materials to be used, and methods to choose the type of antenna software

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The design of CP and large-bandwidth microstrip antenna is done gradually, by firstly truncating one tip, then truncating the whole three tips, and finally modifying it into a pentagonal patch structure and adding an air-gap to obtain larger bandwidths of impedance, gain and axial ratio

Abstract

The circularly polarized (CP) microstrip antennas, both of singly- and doubly-fed types, possess inherent limitation in gain, impedance and axial-ratio bandwidths. These limitations are caused mainly by the natural resonance of the patch antenna which has a high unloaded Q-factor and the frequency-dependent excitation of two degenerative modes (TM01 and TM10) when using a single feed. Many applications which require circular polarization, large bandwidth, and good performance, especially in the field of wireless communication, are still difficult to be designed by using antenna software. Some consideration to take will include the application target and design specification, the materials to be used, and the method to choose (formula, numerical analysis, etc). This paper explains and analyzes the singly-fed microstrip antenna with circular polarization and large bandwidth. This singly-fed type of microstrip antenna provides certain advantage of requiring no external circular polarizer, e.g. the 90^0 hybrid, as it only needs to apply some perturbation or modification to a patch radiator with a standard geometry. The design of CP and large-bandwidth microstrip antenna is done gradually, by firstly truncating one tip, then truncating the whole three tips, and finally modifying it into a pentagonal patch structure and adding an air-gap to obtain larger bandwidths of impedance, gain and axial ratio. The last one antenna structure results in a novelty because it is a rare design of antenna which includes all types of bandwidth (impedance, gain, and axial ratio) being simultaneously larger than the origin antenna. The resulted characteristic performance of the 1-tip (one-tip) antenna shows respectively 1.9% of impedance bandwidth, 3.1% of gain bandwidth, and 0.45% of axial-ratio bandwidth. For the 3-tip (three-tip) step, the resulted bandwiths of respectively impedance, gain, and axial ratio are 1.7%, 3.3% and 0.5%. The pentagonal structure resulted in the bandwith values of 15.67%, 52.16% and 4.11% respectively for impedance, gain, and axial ratio.

Keywords: Circularly polarized; microstrip antenna; singly-fed; tip truncating; air-gap

1.0 INTRODUCTION

The circularly polarized (CP) microstrip antennas, both of singly- and doubly-fed types, possess inherent limitation in gain, impedance and axial-ratio bandwidths. These limitations are caused mainly by the natural resonance of the patch antenna which has a high unloaded Q-factor and the frequency-dependent excitation of two degenerative modes (TM01 and TM10) when using a single feed [1]. In order to achieve enhanced gain, impedance and CP bandwidths, several singly-fed single-element patch antenna designs use air-layer or foam substrate for minimizing the unloaded Q-factor [1],[2]. Another way to increase the antenna bandwidth is performed by using stacked patches and electromagnetically coupled patch configurations, as presented in [3],[4].

One of the most common techniques for calculating the unknown current of the patch antenna is the *Method of Moments*. This method discretizes the integral into a matrix equation which can then be solved. This discretization can be considered as dividing the antenna surface into a number of small elements. From the current distribution, the S-parameters, radiation pattern and any other parameters of interest can be obtained.

The accuracy of the simulations using such this kind of software package is very high. Since the calculations are performed over discretized space, the accuracy of the solution is dependent on the grid size. As the grid size is decreased, the accuracy will be increased, although reaching the solution will become more computationally expensive [5].

A generalized formula to express the electrical current potential at the surface of a conductor can be written as [6]:

$$L(q)=\phi \tag{1}$$

where ***L*** is a linear operator, ***q*** an unknown variable, and ***Φ*** is a known function such as forced term or source term. ***q*** can be discretized into q_n and can be approximated as follows:

$$q=\sum_n f_n q_n \tag{2}$$

where f_n is the expansion functions. By substituting it into (1), the following expression is obtained:

$$\sum_n q_n L(f_n)=\phi \tag{3}$$

Then, in order to create the equation at the node ***i***, weighting functions w_m are placed on both sides of the equation and by integration on the surface of the conductor, it leads to the following equation:

$$\sum_n q_n \iint_{Sc} L(f_n) w_m dS=\iint_{Sc} \phi\, w_m dS \tag{4}$$

By applying the previous equation to the whole unknown discretized nodes with ***m = 1, 2,…,*** a system of equation is obtained as follows :

$$[C]\{q\}=\{\Phi\} \tag{5}$$

Here, each C_{mn} and Φ_m terms, respectively factor of **[C]** and **{Φ}**, is equal to:

$$C_{mn}=\iint_{Sc} L(f_n) w_m dS \tag{6}$$

$$\Phi_m=\iint_{Sc} \phi\, w_m dS \tag{7}$$

In equations (6) and (7), the particular choice of $w_n=f_n$ is known as the Galerkin's method. In addition, the method which consists in applying the Dirac delta function ***δ*** at the node ***m*** of w_m is called the point-matching method.

There are several ways to choose the expansion functions and the weighting functions, leading to a change in the accuracy of the calculation. However, the method of integral equation is largely used because the point-matching method is the easiest one to treat. As equations (6) and (7) are isomorphic to the calculation of moments, this technique is called the Method of Moments.

The antenna analysis using the Method of Moments is based on the calculation of the magnetic vector potential ***A*** and the electric scalar potential ***Φ***, assuming the electric current on the antenna, or the density of current, to be an unknown variable. Let assume from here that the dependence in time is sinusoidal. ***A*** and ***Φ*** can be calculated from the following equations by assuming that current flows on the antenna and the sources are electric charges:

$$A=\mu\iint_V J\phi\, dV \tag{8}$$

$$\phi=\frac{1}{\varepsilon}\iint_V \rho\varphi dV \tag{9}$$

where ***μ*** is the magnetic permeability, ***ε*** the permittivity, ***Φ*** the elementary solution, and ***V*** the region of the antenna. In three dimensional problems, the elementary solution is given by:

$$\varphi=\frac{1}{4\pi r}\exp(-jkr) \tag{10}$$

Considering ***J*** and ***ρ*** not being independent, from the Gauss's Law we have:

$$\nabla\cdot D=\rho \tag{11}$$

and from the time differential of the density of magnetic flux ***B***, i.e. from the equation that expresses the divergence of Ampere's Law and ignoring the current charges :

$$\nabla\cdot J+\nabla\cdot\frac{\partial D}{\partial t}=0 \tag{12}$$

to which ***ρ*** is connected. From the equation of the electric continuity, the following equation can be obtained:

$$\rho=-\frac{\nabla\cdot J}{j\omega} \tag{13}$$

When ***J*** and ***ρ*** conform to the upper equation, the obtained expressions of ***A*** and ***Φ*** satisfy Lorenz's gauge.

The strength of electric field ***E*** is derived from ***A*** and ***Φ***:

$$E=-j\omega A-\nabla\phi \tag{14}$$

Finally, at the surface of the antenna, i.e. the surface of a perfect conductor where the tangential component of ***E*** tends to zero, the following equation needs to be used in order to create the system of equations:

$$-n\times E=n\times E_0 \tag{15}$$

where ***n*** is the normal direction, E_0 the outer electric field. By substituting (14) into (15), the next equation is obtained:

$$j\omega A+\nabla\phi=n\times E_0 \tag{16}$$

Depending on the number of feed points necessary to excite the CP waves, the circularly polarized (CP) antennas are classified into singly-fed and doubly-fed types. The singly-fed type is especially useful because it requires no external circular polarizer such as the 90^0 hybrid, as it only needs to apply some perturbation or modification to a patch radiator with a standard geometry [7]. For example, the CP radiation of an equilateral triangular antenna with a truncated tip [8] is achieved by cutting the correctly-sized section from the tip of an equilateral-triangular patch (Fig.1). In this case, for left-hand circularly polarized (LHCP) the probe-fed is located in the left-half of the triangular patch.

In this paper, an antenna will be designed by embedding the cutting of each tip of an equilateral-triangular patch and also the pentagonal antenna using air-gap for circular polarization and enhancing bandwidth of antenna with a simple configuration (Fig.1.a, Fig.1.b, Fig.2.a, Fig.2.b). Hence, the new phenomena occur, in the case Is > Ip (Fig.1.b and Fig.2.a), probe-fed LHCP and right-hand circularly polarized (RHCP) are located on the right- and left-half of the triangular patch, respectively. In the case Is < Ip, the RHCP and LHCP can be obtained suitably with the previous rule [3], but in the case Is = Ip, both RHCP and LHCP could not operate, as only linear polarization can be obtained. In this case, the function of two-truncated tips with length Is is as a switch to move variation of polarization, if the probe feed exists on the same place. In addition, the function of Is or two of triple truncated tips can also affect the bandwidth of axial ratio. It makes the axial ratio bandwidth become wider and smoother than without it (Fig.3).

Moreover, a new model is also to be designed (Fig.2.b). Another shape of pentagonal like a kite has been proposed by Weinschel [9] with the characteristic of antenna parameter similar to a new model of pentagonal antenna. The new model of pentagonal antenna owns technical depth design with analysis of the method of numerical analysis based on method of moment as explained previously. This is a novelty because its rare that a design of antenna includes all types of bandwidths (impedance, gain, and axial ratio) being simultaneously larger than the previous antenna.

2.0 ANTENNA CONFIGURATION

2.1 Comparison of Circularly Polarized (CP) Techniques

Fig. 1.a and Fig. 1.b show the configuration of antenna design, for 1-tip truncation and 3-tip truncation, respectively. The triangular patch has a side length of a = b and uses a conventional substrate with relative permittivity 2.17 and loss tangent 0.0009. In Fig.1.a, the antenna is fed using a single probe which is located on the left side of LHCP. In the LHCP of Fig.1.b the fed is located on the right side. In addition, there are three small triangular tips, two of which are of the same side length Is. It is used to excite more magnitude current path around this area which is moving to y-direction and x-direction, hence increasing the bandwidth of axial ratio. The other triangular tip has a side length of Ip that if it combines with loci of feeding in the right side of triangular patch owing to perturbation, so that the effective excited patch surface current path in the y-direction is slightly longer than that in the x-direction, which gives the y-directed resonant mode a resonant frequency slightly smaller than that of the x-directed resonant mode [10]. That is, the dominant mode (TM10 mode) of the triangular patch could be separated into two near-degenerate orthogonal resonant modes of equal amplitudes and 90^0 of phase difference for LHCP operation. In the same manner, for the case in Fig.1.b, owing to the truncated-tip perturbation and fed located in the left side of triangular patch, the effective excited patch surface current path in the y-direction is slightly shorter than that in the x-direction. It gives in the y-directed resonant mode a resonant frequency which is slightly larger than that in the x-directed resonant mode that are equal amplitudes and 90^0 of phase difference for RHCP operation [11].

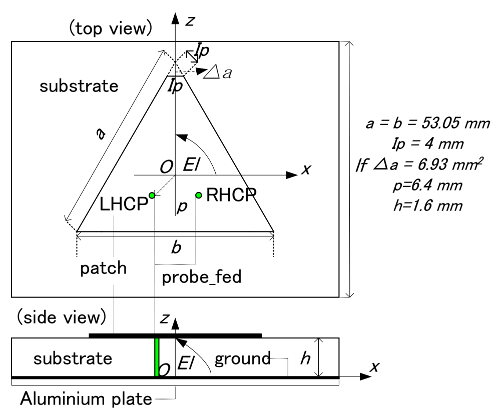

Figure 1(a) Configuration of 1-tip truncation antenna (c1) – Comparison of circularly polarized technique

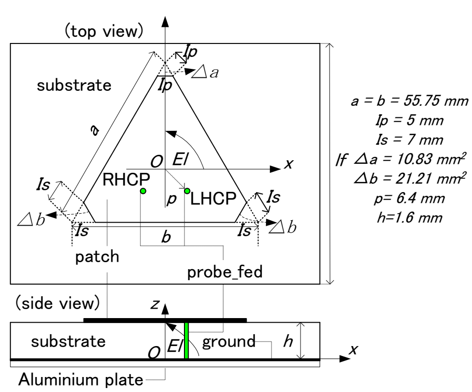

Figure 1(b) Configuration of 3-tip truncation antenna (c3) - Comparison of circularly polarized technique

2.2 Comparison of Larger Bandwidth Techniques

Fig. 2.a and Fig. 2.b show the configuration of antenna design, for triangular of 3-tip truncation and pentagonal antenna, respectively. Both antennas are using a conventional substrate (relative permittivity 2.17 and loss tangent 0.0009) and fed by a coaxial probe to avoid the elliptic degradation by unwanted radiation from the feed network. Fig.2.a shows the last antenna design with poor bandwidth of antenna, which has a side length of a = b and a fed is located on the right side relatively to central coordinate (null potential) for LHCP.

Fig.2.b shows the new model design of pentagonal antenna using air-gap whose angle ∠θ is 45^0. The shape of such pentagonal can be prescribed completely using two parameters c/a and b/a. The pentagon becomes a rectangle when c/a = 0, an isosceles triangle when c/a = 1. It is important to enhance the bandwidth, its position of c/a is 0 < c/a < 1 or in the others word the patch shape should combine two or more shapes in becoming one (pentagon = triangle + rectangle). In this case, by only combining two shapes for getting wide bandwidth of antenna is not enough, to match impedance 50Ω and to be smooth impedance, axial ratio and gain bandwidth, so the antenna are added the dimensions of antenna, air gap and feeding location which must be chosen correctly (Fig.2.b). They are used to excite more than one mode where each of mode degenerates two frequencies closed, hence much of the magnitude currents paths around this area move to y-direction and x-direction which are perpendicular to each other, hence increasing the bandwidth of axial ratio [12].

For LHCP, the feeding is located on the left side from null potential. In this case, there are occur 3 modes at the frequency operation of 2.4925, 4.5 and 6.8 GHz, but only a good radiation characteristic obtains in the first mode of 2.4925 GHz. This mode is dominant modes (TM01 and TM10), owing to the shape perturbation (pentagonal) using air-gap and feeding location at the left side of pentagonal, hence the effective excited patch surface current path in the y-direction is slightly shorter than that in the x-direction. It gives at the y-directed resonant mode a resonant frequency which is slightly larger than that at the x-directed resonant mode that are equal amplitudes and 90^0 of phase difference for LHCP operation [13].

In this paper, the method of moment (Ensemble version 8 software) is employed to simulate the model with an infinite ground plane. Consideration of the efficient thickness of the antenna (see Fig. 1.a) allowed either the substrate thickness for triangular patch to be defined with the single substrate or single layer (h = 1.6 mm). The 3-tip truncation antenna result (c3) is compared to the 1-tip truncation (c1) to know the improvement of performance of each other. Moreover, consideration of the efficient thickness of the antenna (Fig.2.b) allowed either the substrate thickness for pentagonal patch to be defined with the single substrate or single layer using air-gap (h1 = 1.6 mm and h2 = 7.4 mm). The pentagonal antenna result (antenna 2) is compared to the 3-tip truncation (antenna 1) also to know the improvement of performance of each others.

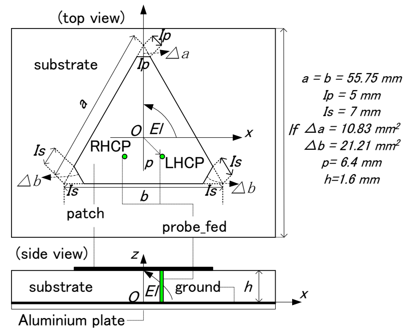

Figure 2(a) Configuration of the 3-tip truncation antenna (c3 or 1) - Comparison of larger bandwidth techniques

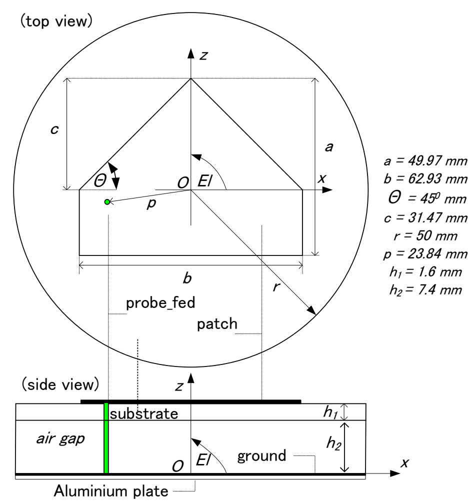

Figure 2(b) Configuration of the pentagonal antenna (2) – Comparison of larger bandwidth techniques

3.0 RESULTS AND DISCUSSIONS

3.1 Comparison Results of Circularly Polarized (CP) Techniques

Figure 3 to Figure 6b indicate the results of simulation of the truncated antenna c3, and c1, in the case of frequency characteristic, S-parameter, input impedance and elevation plane. Fig. 3 shows the value of gain and axial ratio (Ar) for simulation of 3-tip truncation antenna (c3) and the 1-tip truncation (c1) at the resonant frequency of 2.5025 GHz. The results of antenna c3 are 6.8 dBic and 0.42 dB, while antenna c1 are 6.7 dBic and 2.4 dB, respectively. In addition, the bandwidth of axial ratio antenna c3 is wider than that of antenna c1 by about 30.07% (ΔW c3 = 0.0143 GHz being compared to ΔW c1 = 0.01 GHz).

Fig. 4 shows the relationship between the reflection coefficient (S-parameter) and frequency for the simulation of Rx antenna. From this figure, it can be seen that the S-parameter of the new model antenna c3 at the resonant frequency is better than the previous antenna c1 of -17.9 dB and -11.84 dB, respectively. But, the bandwidth of S-parameter antenna c3 is narrower than that of antenna c1. It is caused by loci of feeding antenna c3 which is not optimized yet on the place of patch antenna bieng compared to that of the antenna c1. Moreover, it is also the effect of perturbation area on both of the below patches of antenna (ls) and upper patches of antenna (lp) which can reduce the bandwidth of *S*-parameter.

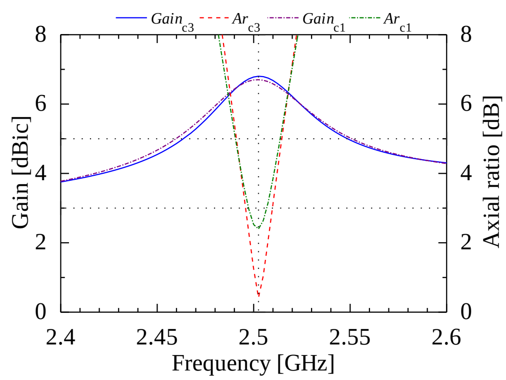

Figure 3 Gain and axial ratio vs. frequency

Fig. 5 depicts the input impedance characteristic of Rx. This figure shows that the real part of simulation is different from each other, but in the case of antenna c3 the real impedance is approaching 50Ω at the operation frequency. Moreover, the reactance part of the antenna c3 is better than antenna c1 that closed to 0 Ω at the resonant frequency.

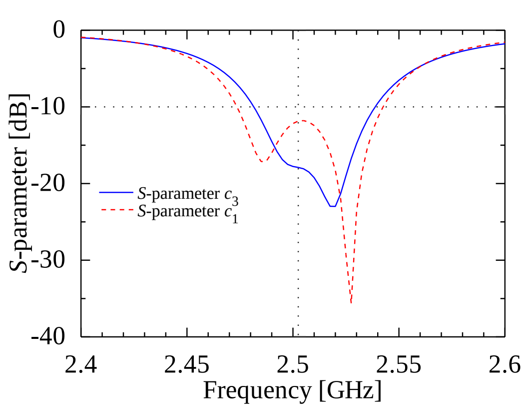

Figure 4 S-parameter

For coaxial-fed antennas, the input impedance is dependent on the feed position. The variation of input resistance at resonance with feed position essentially follows that of the cavity field. For the lowest mode, it is usually large when the feed is near the edge of the patch and decreases as the feed moves inside the patch. Its magnitude can vary from tens to hundreds of ohms. By choosing the feed position properly, an effective match between the antenna and the transmission line can be obtained.

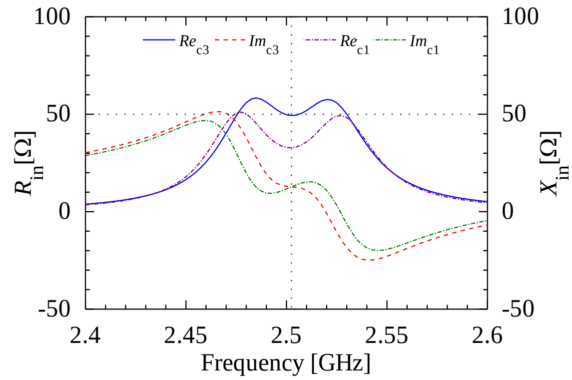

Figure 5 Input impedance

Figure 6a and 6b depict the relationship between gain-axial ratio and elevation angle at Az=0⁰ and 90⁰. At the elevation of 90⁰ the maximum gain of c1 and c3 are about 6.68 dBic in both of azimuth angles, respectively. But, it different for axial ratio, especially in x-z plane are about 2.8 dB for c1 and 0.29 dB for c3, respectively. The effect of using truncated tip in both 1-tip and 3-tip models result mostly difference of azimuth angles, especially for axial ratio.

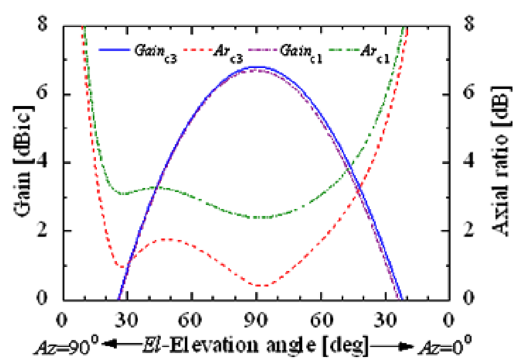

Figure 6(a) x-z plane

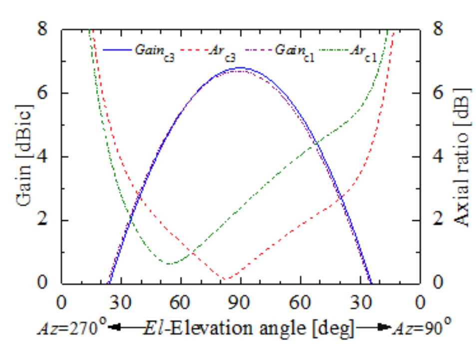

Figure 6(b) y-z plane

3.2 Comparison Results of Larger Bandwidth Technique

Figure 7 to 11 show the results of simulation between the pentagonal antenna 2 and the 3-tip truncation antenna 1, in terms of frequency characteristic, S-parameter, input impedance and elevation plane. Fig. 7 shows the value of gain and axial ratio (Ar) from the simulation of the new model antenna or pentagonal antenna (2) at the resonant frequency 2.4925 GHz and of the previous antenna or hexagonal (1) at the resonant frequency 2.5025 GHz. The results of antenna 2 are 8.74 dBic and 0.06 dB, whereas those of the antenna 1 are 6.8 dBic and 0.42 dB, respectively. In addition, the bandwidth of axial ratio antenna 2 is wider than antenna 1 by about 8.2 times (∆W 2 = 4.11% being compared to ∆W 1 = 0.5 %).

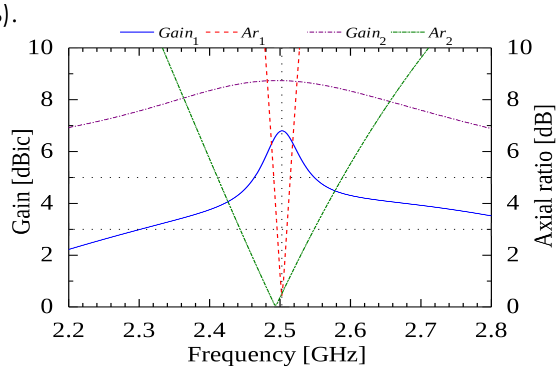

Figure 7 Gain and axial ratio vs. frequency

Figure 8 shows the relationship between the reflection coefficient (S-parameter) and frequency for the simulation of Rx antenna. From this figure, it can be seen that the bandwidth of S-parameter of a new model antenna 2 is wider than the previous antenna 1 by 15.67% and 1.7%, respectively. It is caused by the new shape of perturbation on antenna like a pentagonal where the area square is larger than the previous antenna of about 2154.3 mm² and 1292.58 mm², respectively. In addition, it is also the effect of air-gap and location of feeding which is matched with the configuration of antenna to yield the target's fulfillment. Moreover, the value of S-parameter at the resonant frequency of antenna 1 is slightly better than that of antenna 2, which is -17.9 being compared to -15.03 dB.

Figure 9 depicts the input impedance characteristic of Rx. This figure shows that the real and reactance part of simulation are similar of each other, but in the case of antenna 2 where its covered frequencies for real and reactance impedance are not closed to 50 Ω and 0 Ω, they are located wider over the frequency operation range than compared with antenna 1.

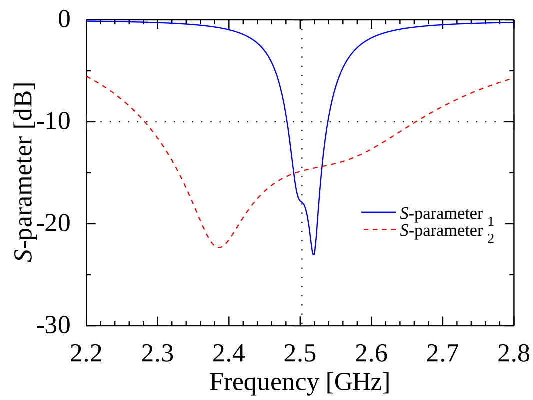

Figure 8 S-parameter

For coaxial-fed antennas, it can slightly effect toward the resonant frequency, axial ratio, S-parameter and input impedance which is dependent on the feed position. By choosing the feed position properly, an effective match between the antenna and the transmission line can be obtained.

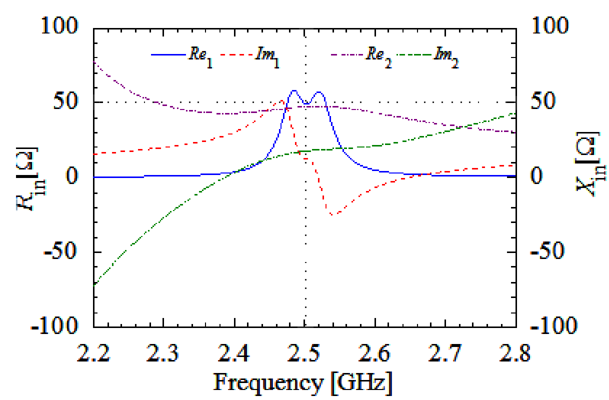

Figure 9 Input impedance

Figure 10 and 11 depict the relationship between gain-axial ratio and elevation angle at Az=0^0 and 90^0. At the elevation 90^0 the maximum gain-axial ratio of 1 and 2 are about 6.68 dBic - 0.29 dB and 8.87 dBic - 0.07dB in both of azimuth angles, respectively. The effect of truncating 3-tip, pentagonal antenna shape and air-gap of both azimuth angles and elevation angle are strong difference in terms of both gain and axial ratio values.

4.0 CONCLUSIONS

In order to obtain a circular polarization, compact, small, and simple configuration, the truncated-tip antenna and pentagonal antenna have been studied. Comparison of the resulted characteristic performances, especially in terms of bandwidth of the axial ratio, the pentagonal antenna excels the truncated-tip antenna. The better performance is obtained owing to the new-shape of pentagonal antenna using air-gap and the good choice of feeding position.

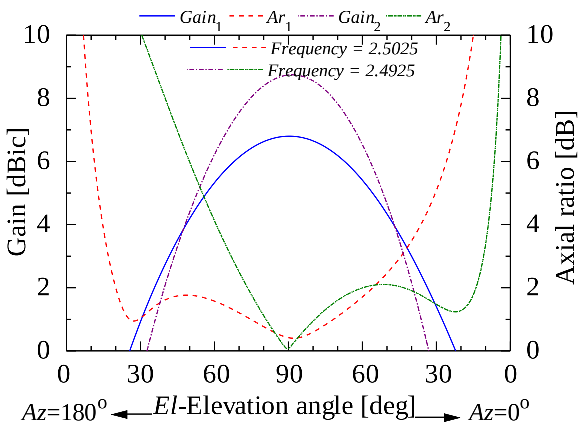

Figure 10 Elevation in x-z plane

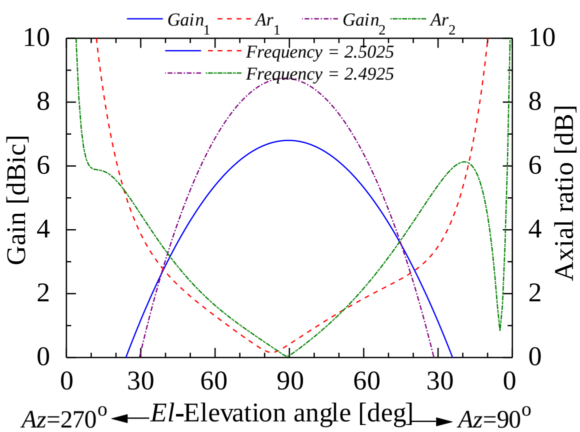

Figure 11 Elevation in y-z plane

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