A Design Rule for Inset-fed Rectangular Microstrip Patch Antenna

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Abstract: - In our paper, an inset-fed microstrip patch antenna has been designed and the dependency of resonant frequency on the notch gap and the feed line geometry has been studied. Our study suggests that a narrower notch resulted in better impedance matching. A design rule has also been formulated and presented the performance of the proposed design.

Key-Words: - Inset-fed, microstrip antenna

1 Introduction

Microstrip patch antennas have been widely used particularly since they are lightweight, compact and cost effective. The input impedance of these antennas depends on their geometrical shape, dimensions, the physical properties of the materials involved, the feed type and location. Therefore, a subset of antenna parameters can be adjusted to achieve the "best" geometry for matching of a particular resonance. The inset-fed microstrip antenna provides a method of impedance control with a planar feed configuration [1-2]. The experimental and numerical results showed that the input impedance of an inset-fed rectangular patch varied as a Cos^4 function of the normalized inset depth [1]. A more recent study proposed a modified shifted Sin^2 form that well characterizes probe-fed patches with a notch [3]. It is found that a shifted Cos^2 function works well for the inset-fed patch [4][5]. The parameters of the shifted cosine-squared function depend on the notch width for a given patch and substrate geometry.

In our paper, we have analyzed the characterization of resonance frequencies as a function of notch width for an inset microstrip feed. An approximate formula is introduced to describe the resonance frequency that is then implemented in the design of notch width for inset-fed antennas to achieve better impedance matching.

2 Basic Characteristics of Microstrip Patch

The microstrip patch is designed such that its pattern maximum is normal to the patch (broadside radiator). This is accomplished through proper choice of the mode (field configuration) of excitation beneath the patch. End-fire radiation can also be accomplished by judicious mode selection. The ones that are most desirable for antenna performance are thick substrates whose dielectric constant is in the lower end of the range. This is because they provide better efficiency, larger bandwidth, loosely bound fields for radiation into space, but at the expense of larger element size [6]. Thin substrates with higher dielectric constants are attractive for microwave circuitry because they require tightly bound fields to minimize undesirable radiation and coupling, which lead to smaller element sizes; however, because of their greater losses, they are less efficient and have relatively smaller bandwidths [6]. Since microstrip antennas are often integrated with other microwave circuitry, a compromise has to be reached between good antenna performance and circuit design.

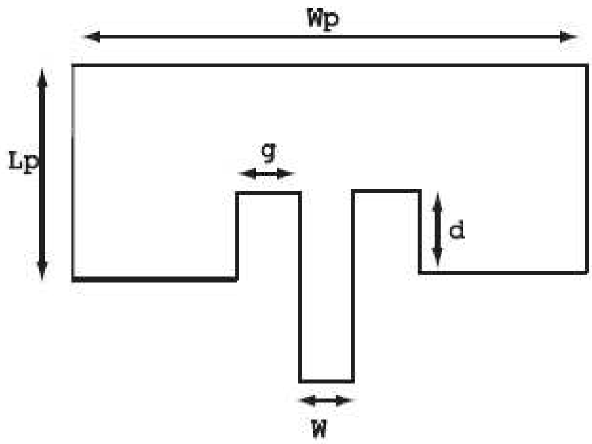

Fig.1: Geometry of inset-fed microstrip patch antenna

Table 1: Physical dimensions of inset-fed microstrip patch antenna

Operating frequency, f in GHz	10
Dielectric constant, ε_{reff}	2.2
Length of the patch, L_p in µm	9064
Width of the patch, W_p in µm	11895
Position of inset feed point, d in µm	3126
Width of the microstrip feed line, W in µm	2150

Often microstrip antennas are referred to as patch antennas. The radiating elements and the feed lines are habitually photo etched on the dielectric substrate. The radiating patch may be square, rectangular, thin strip, circular, elliptical, triangular or constituting any other configuration. Square, rectangular, thin strip and circular microstrip patch configurations are the most common because of their ease of analysis, fabrication, and their attractive radiation characteristics, especially the low cross-polarization radiation. There are many configurations that can be used to feed microstrip antennas. The four most popular feeding techniques are the microstrip line, coaxial probe, aperture coupling and proximity coupling [6] [7-13]. In our paper, we have chosen inset feed microstrip line with rectangular microstrip patch.

3 Patch Geometry

Fig.1 shows the patch geometry of an inset-fed rectangular patch, where the notch width 'g' is located symmetrically along the width of the patch.

The dimensions of the different parameters have been approximated using the procedure discussed in [14] and the final values are determined through extensive numerical simulations which are shown in Table 1. The value of 'g' is changed with the ratio of 'W/10', 'W/15', 'W/20', W/25', 'W/30' W/35' and 'W/40' where W is the width of microstrip feed line.

Table 2: Performance analysis as a function of notch width

Performance Properties	$W/10$	$W/15$	$W/20$	$W/25$	$W/30$	$W/35$	$W/40$
-10dB Bandwidth (GHz)	.65	.69	.83	.95	1.0	1.04	1.1
Antenna gain (dB)	7.167	7.028	6.921	6.842	6.781	6.734	6.695
S_{11} (dB)	-23.5	-24	-55	-34	-29	-26	-24.5

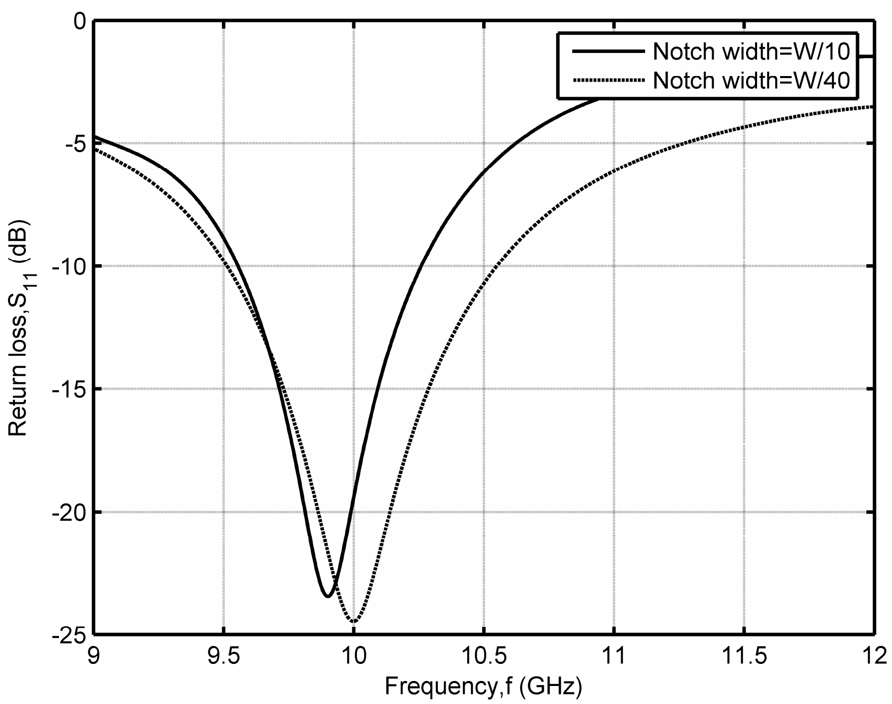

Fig.2: Return loss as a function of Notch width, g

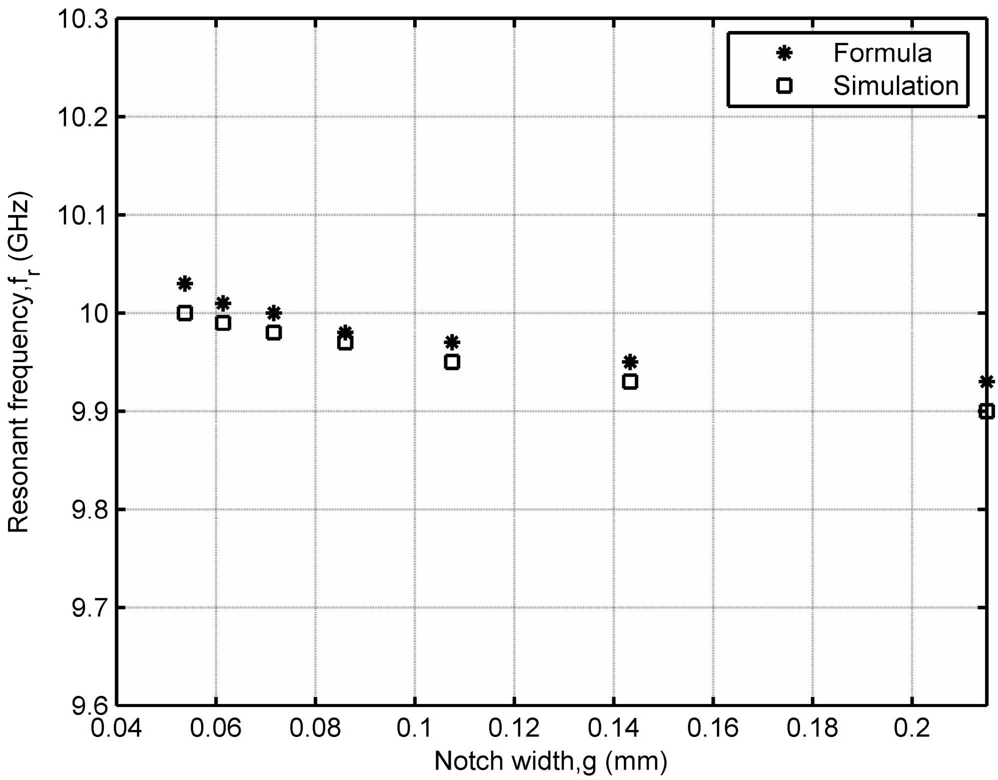

Fig.3: Resonant frequency comparison between proposed formula and simulation

4 Design Analysis

It was observed that with a decrease in notch width, the resonant frequency shifts away from 10 GHz. There is a resonance shift of 0.06 GHz and the bandwidth is increased about 46.2% when notch width is decreased from W/10 to W/40.

The -10dB bandwidth is shown in Fig.2 and the optimized results for this design are tabulated in Table 2 which is analyzed for 10 GHz operating frequency to find the resonant frequency with the change of notch width. An equation has been formulated for the resonant frequency which depends on notch width. The equation has been given in (1)

$$f_r = \frac{v_0}{\sqrt{2\times\varepsilon_{eff}}}\frac{4.6\times10^{-14}}{g}+\frac{f}{1.01} \qquad (1)$$

Where, f_r = Resonant frequency, ε_{eff} = Effective dielectric constant, v_0 = Velocity of Electromagnetic wave, $3X10^{11}$ mm/s, g = Notch width, mm, f = Operating frequency in GHz.

The resonant frequency, f_r is calculated using our proposed equation as a function of g where g varies from 0.054 mm to 0.215 mm. Fig.3 shows the calculated and simulated resonant frequency as a function of g that proves the validity of the proposed equation.

5 Design Procedure

We adopt the design strategy of keeping the return loss minimum at the resonant frequencies as close as possible and striving to achieve -10dB return loss over the impedance bandwidth. Our design procedure is based on the existing literature and analysis of the notch width discussed earlier and the goal of this procedure is to provide a good first-pass design.

In practice, the dielectric constants of the material are not free variables, since discrete values depend on the dielectric material used. Therefore, it is convenient to choose the parameters ε_r in advance and vary other parameters. A further constraint must be placed on the thickness as common laminates are available only with a certain thickness. To account for this constraint, we initially allow a continuous choice of h. On finding an optimum, this thickness value is rounded to an available thickness and then optimization resumes with the available h. In this case, there are several parameters required for the optimization problem, which is time consuming. Therefore the dielectric constant and thickness above the ground plane are set to constant values that provide a good impedance match for inset-feed patch structure.

The design procedure assumes that the specified information includes the dielectric constant of the substrate (ε_r) and the height of the substrate (h) and is stated as below:

1. Specify the center frequency and select a substrate permittivity ε_r and a substrate thickness h

$$h \geq 0.06 \frac{\lambda_{air}}{\sqrt{\varepsilon_r}}$$

2. Calculate W_p as [7]

$$W_p = \frac{v_o}{2 f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} \qquad (2)$$

3. Calculate ε_r using the following common equation found in [15]

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[1 + 12 \frac{h}{W_p} \right]^{-1/2}$$

for $W_p / h > 1$ (3)

4 ΔL is the normalized extension of the length and given as

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{reff} + 0.3)\left(\frac{W_p}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W_p}{h} + 0.8\right)} \qquad (4)$$

5. Calculate the value of L_p and Z_0 as

$$L_p = \frac{v_o}{2 f_r \sqrt{\varepsilon_{reff}}} - 2\Delta L \qquad (5)$$

6. Calculate the notch width, g

$$f_r = \frac{v_0}{\sqrt{2 \times \varepsilon_{eff}}} \frac{4.6 \times 10^{-14}}{g} + \frac{f}{1.01}$$

To obtain the desired resonance f_r at the operating f i.e $f_r = f$

The above equation will become

$$f = \frac{v_0}{\sqrt{2 \times \varepsilon_{eff}}} \frac{4.6 \times 10^{-14}}{g} + \frac{f}{1.01}$$

Rearranging the equation,

$$f - \frac{f}{1.01} = \frac{v_0}{\sqrt{2 \times \varepsilon_{eff}}} \frac{4.6 \times 10^{-14}}{g}$$

$$\text{Or, } f\left(1 - \frac{1}{1.01}\right) = \frac{v_0}{\sqrt{2 \times \varepsilon_{eff}}} \frac{4.6 \times 10^{-14}}{g}$$

$$\text{Or, } \frac{.01 f}{1.01} = \frac{v_0}{\sqrt{2 \times \varepsilon_{eff}}} \frac{4.6 \times 10^{-14}}{g}$$

$$g = \frac{v_0}{\sqrt{2 \times \varepsilon_{eff}}} \frac{4.65 \times 10^{-12}}{f} \qquad (6)$$

7. Calculate the value of Z_0 as

$$Z_o = R_{in} \cos^2\left(\frac{\pi}{L_p} d\right) \qquad (7)$$

Where, d is the inset distance from the radiating edge, and R_{in} is the resonant input resistance when the patch is fed at a radiating edge. The inset distance (d) is selected such that Z_0 is equivalent to the feed line impedance. The notch width 'g' is located symmetrically along the width of the patch. The dimensions of the different parameters have been approximated using the above equations.

5.1 The resonance input resistance R_{in} calculation:

A rectangular microstrip patch can be represented as an array of two radiating slots, each of width W_p, height h and separated by a distance L_p. Each slot is equivalent to a parallel equivalent admittance Y with conductance G and susceptance B. The equivalent circuit transmission model of a microstrip patch antenna is shown in Fig. 4.

The conductance of a single slot can be obtained using the following equation

$$G_1 = \frac{1}{120\pi^2} \int_0^{\pi} \left[\frac{\sin(\frac{k_o W_p}{2} \cos\theta)}{\cos\theta} \right]^2 \sin^3 \theta d\theta \quad (8)$$

Ideally the two slots should be separated by λ/2 where λ . is the wavelength in the dielectric substrate. But in reality, the separation of slots is slightly less than λ/2 because the length of the patch is electrically longer than the actual length due to fringing [14]. The mutual conductance G_{12} can be calculated using [16]

$$G_{12} = \frac{1}{120\pi^2} \int_0^{\pi} \left[\frac{\sin(\frac{k_o W_p}{2} \cos\theta)}{\cos\theta} \right]^2 * J_o(k_o L_p \sin\theta) \sin^3 \theta d\theta \quad (9)$$

Where J_0 is the Bessel function of the first kind of order zero. The mutual conductance obtained using equation (8) is small compared to the self conductance. Taking mutual effects into account between the slots, the resonant input impedance can be calculated as [16]

$$R_{in} = \frac{1}{2(G_1 + G_{12})}$$

The inset feed introduces a physical notch, which in turn introduces a junction capacitance. The physical notch and its corresponding junction capacitance influence the resonance frequency. As the inset feed-point moves from the edge toward the centre of the patch the resonant input impedance decreases monotonically and reaches zero at the centre. When the value of the inset feed point approaches the centre of the patch, the $\cos^2\left(\frac{\pi}{L_p} d\right)$ varies very rapidly; therefore the input resistance also changes rapidly with the position of the feed point which is shown in Fig 5. To maintain very accurate values, a close tolerance must be preserved.

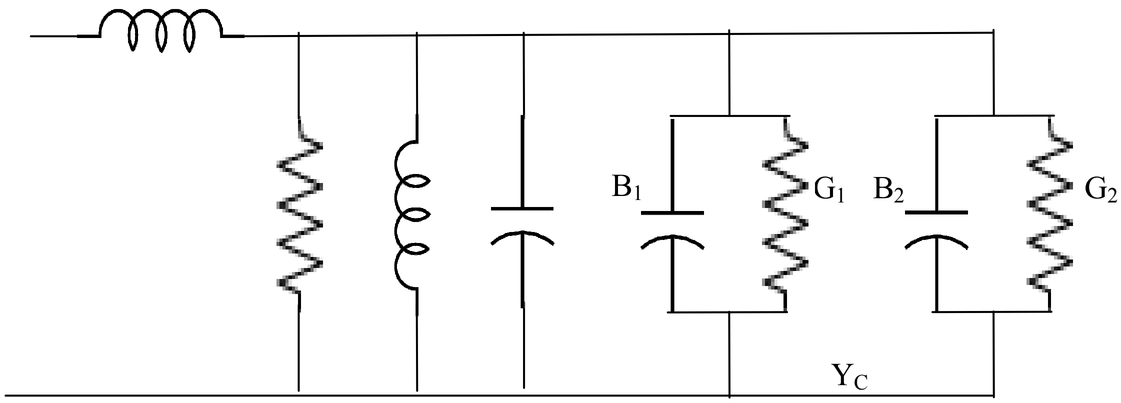

Fig.4 Equivalent circuit of Inset fed microstrip patch antenna

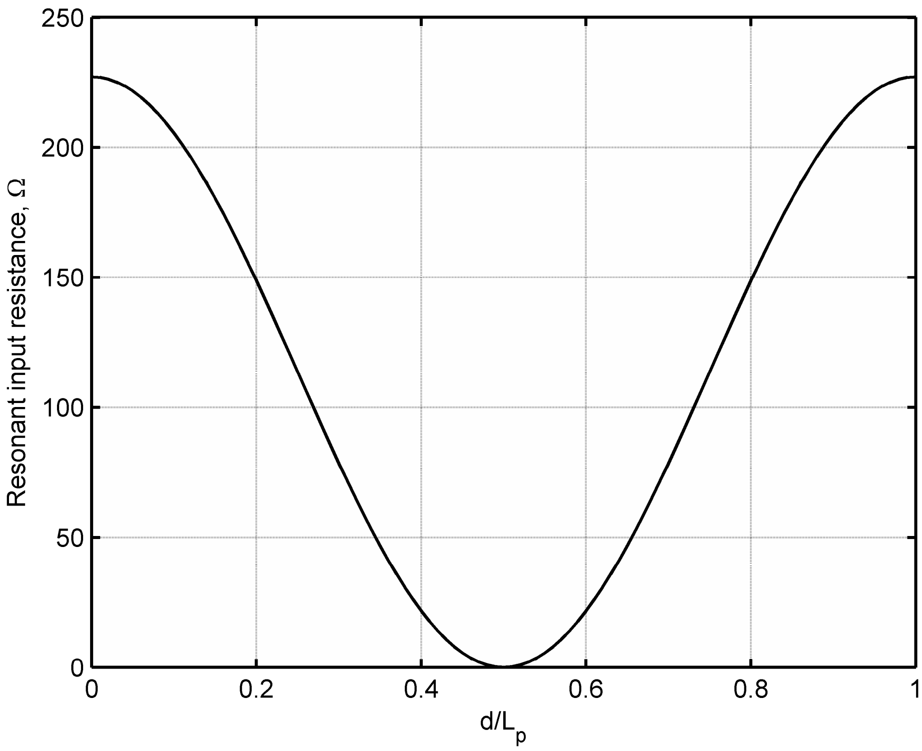

Fig.5 Inset-fed distance and variation of input impedance

6 Design Example

The design is intended to operate 9 GHz resonance frequency. The -10dB bandwidth is shown in Fig.6.

This example demonstrates that while the design procedure can do a good job of producing an antenna with designated resonant frequencies, it does not necessarily give a design with good bandwidth characteristics, which are still largely a function of dielectric thickness and feed point position.

The radiation pattern at 9 GHz is shown in Fig.7 (a) (YZ) and Fig.7(b) (XZ). Simulations are performed for fixed notch width and depth. Increasing either the notch width or depth results in a greater disturbance of the patch currents. The narrowest notch width is found to have the smallest cross-polarization, although the cross polarization is not

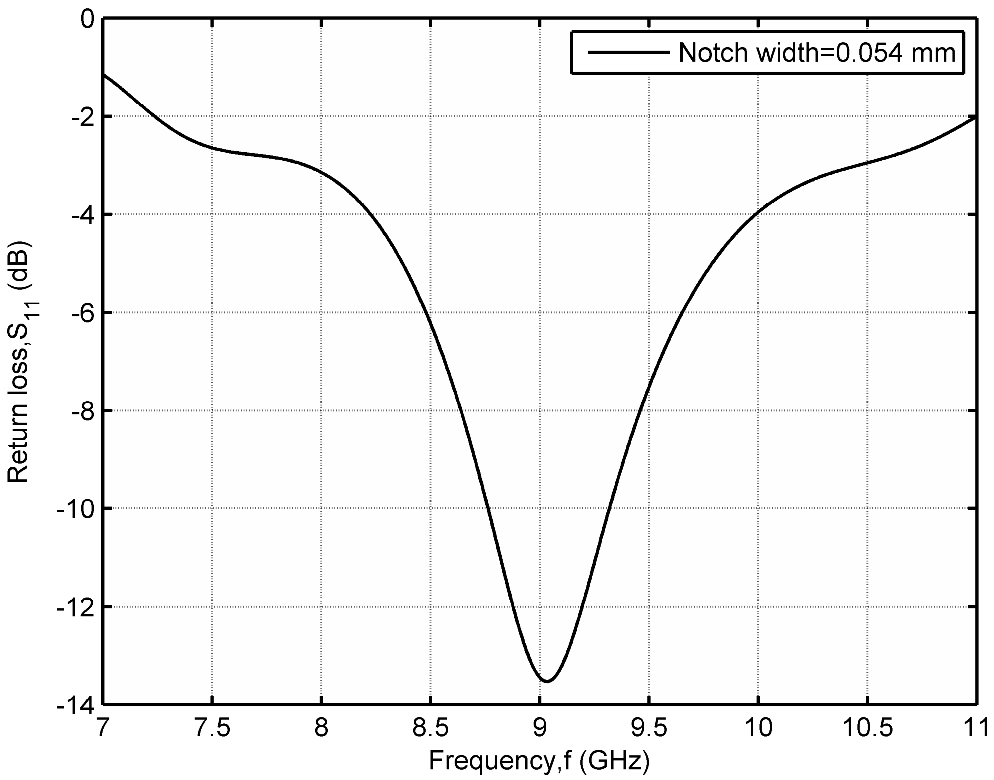

Fig.6: Return loss

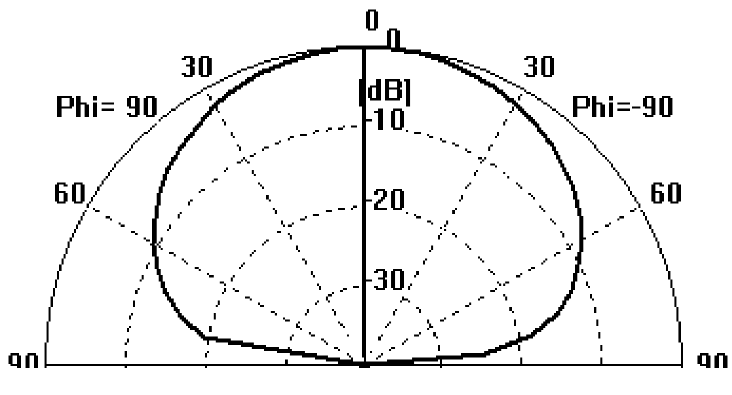

Fig.7: Radiation pattern at 9 GHz (a) YZ plane

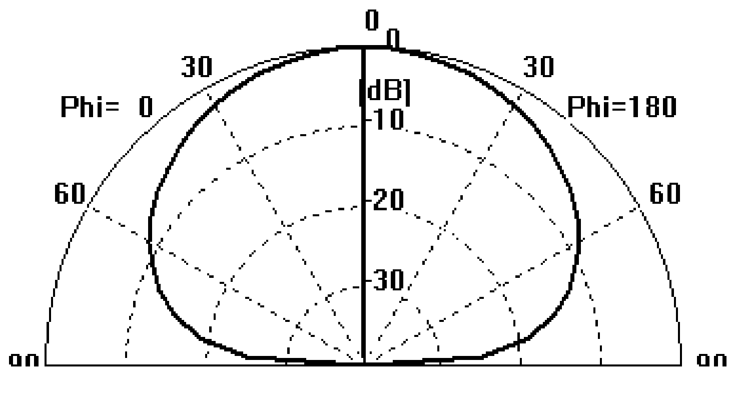

Fig.7 Radiation pattern at 9 GHz (b) XZ plane

too much sensitive to the notch width for a fixed input resistance. In the previous work, piecewise sinusoidal basis pulse functions were used in the vicinity of the contact point between a semi-infinite microstrip line and the patch surface for an inset-fed patch [17]. A large current fluctuation was found at the contact point [18], which would be expected to result in cross-polarization.

7 Conclusion

A formula has been proposed in our paper to find the values of resonant frequency within the given ratio of notch width for the antenna to obtain the best possible match (minimum S_{11}) to a feeding 50 ohm microstrip line. It is found that the proposed formula works well with a maximum deviation of 0.2% from the simulation. The design procedure has also been presented here which will provide an excellent starting point for antenna designers that give better results than simple guesses or cut and try techniques.

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