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Investigations on Dielectric Slab Antenna and its Performance Improvement in Broadband Communication

Singha Roy Pritam[1] and Guha Moumita[2*]

[1]Department of Electronics, Pacific University, Udaipur, Rajasthan-313003, India
[2]Department of Electronics, Govt. Textile College, Berhampore, Murshidabad-742101, India

ABSTRACT

Usage of dielectric antennas is well established in the higher frequency ranges due to their low loss, improved performance, low cost and ease of fabrication. Directivity and return loss of a dielectric slab antenna may vary according to its length, characteristics of the feed matching section and also permittivity of the dielectric substrate. Computer simulated results are presented for rectangular dielectric slab antenna which is mounted on a rectangular wave guide launcher. Dielectric and dielectric loaded antennas are nowadays finding increasing usage in microwave and millimeter wave frequency ranges because of several advantages as enlisted below. In these paper characteristics of a rectangular dielectric slab as radiator is investigated especially with respect to matching with its launcher. Some novel measures are also suggested to improve the performance of the radiators.

KEYWORDS: Dielectric Slab Antennas, Taper, Electromagnetic simulation, Modes.

***Corresponding Author:**

Pritam Singha Roy

Department of Electronics, Pacific University, Udaipur,

Rajasthan-313003, India

E-mail: prittam.pritam@gmail.com

INTRODUCTION

A rectangular metallic wave guide is used as wave launcher to the radiating slab. For efficient impedance matching a tapered dielectric section is introduced within the launcher. Different parameters are varied and their effects are studied on the impedance and radiation characteristics of the slab antenna. Parameters investigated include length and taper type of the matching section as well as length and dielectric constant of the antenna itself. Several noteworthy observations can be made from the results reported herein regarding the trends of variation of different antenna characteristics with these parameters. A metallic post in the taper matching section can gives better impedance matching and directivity of rectangular slab dielectric antenna. Further pyramidal taper and pyramidal truncation in the front aperture of the rectangular slab antenna are reported in this chapter, both of which gives improvement in impedance matching and directivity further.

Theoretical Back-bone for Dielectric Slab Antennas

The solid rectangular dielectric waveguide, henceforth simply called the dielectric waveguide, is possibly one of the simplest dielectric antennas. This is particularly true if one thinks of the standard metallic rectangular waveguide operated in the TE_{10} mode as the feeder (or launcher). Fig 3.1 shows a possible configuration of such an antenna where the external dielectric waveguide dimensions are the same as the internal dimensions of the metallic waveguide[1,2].

Unlike metallic walls, boundary conditions at dielectric walls do not require the tangential component of the electric field to vanish. One is thus led to expect improved radiation pattern symmetry for the dielectric waveguide. Additionally, since the field in the dielectric waveguide extend beyond the dielectric boundaries, increased directivity (compared to the waveguide free end) should also be expected. The first work on the dielectric waveguide antenna, then commonly referred to as the polyrod antenna, is attributed to G.C. Southworth[3]in 1940. A few years later in a paper[4] describing the work done from 1941 to 1944 at Bell Telephone Laboratories, Holmdel, New Jersey, Mueller approached the design of a dielectric waveguide antenna of uniform rectangular cross section by “establishing analogies with array theory, coupled with existing knowledge about transmission in uniform dielectric wires ”.

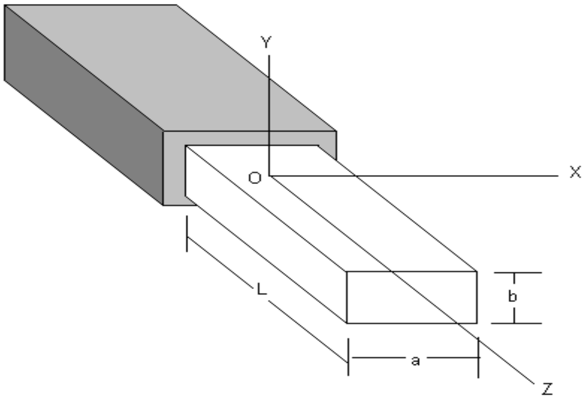

Figure.1: Dielectric waveguide antenna excited by a rectangular metallic waveguide.

Further work on dielectric waveguide antennas had to wait for a better description of the fields in the dielectric. In 1969 Marcatili[5] presented an approximate solution of Mawell's equations for an infinite dielectric waveguide of rectangular cross section, based on a rectangular coordinate system, which describes the fields in terms of cosine functions inside the dielectric and decaying exponentials outside. The concept of "effective dielectric constant", put forward by Mclevige[6] , while keeping the simplicity of application, extends and improves Marcatill's results, particularly near the cutoff region.

Taking Marcatili's expressions for the fields inside a dielectric waveguide, Sen[7-11] applied both the equivalence theorem and the two aperture theory to derive the radiation pattern of a dielectric waveguide antenna.

Field Equations

Consider an infinite lossless dielectric waveguide, a prism with rectangular cross section, with permittivity ε_1 and permeability μ_0 immersed in otherwise free space with constants ε_0 and μ_0, and a coaxial system of rectangular coordinates as shown in Figure 1.

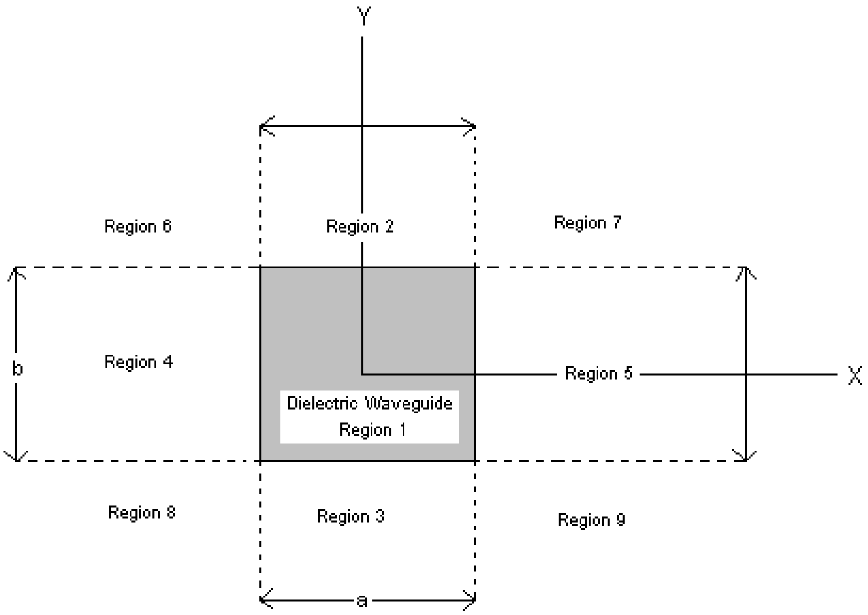

Figure 2:Cross section of the dielectric waveguide antenna.

In Figure 2 we represent the waveguide cross section and regions inside and outside the dielectric wave guide. Taking for the fields an $exp(j\omega t)$ time dependence it is possible to write the electric and magnetic fields E andin terms of an electric vector potential $\vec{F}$ and a magnetic vector potential $\vec{A}$ as

$$\vec{E} = -\frac{1}{\varepsilon_r}\times\vec{F} - j\omega\vec{A} + \frac{1}{j\omega\varepsilon\mu}\nabla(\nabla.\vec{A}) \tag{3.1}$$

$$\vec{H} = -\frac{1}{\mu}\times\vec{A} - j\omega\vec{F} + \frac{1}{j\omega\varepsilon\mu}\nabla(\nabla.\vec{F}) \tag{3.2}$$

where the vector potentials $\vec{A}$ and $\vec{F}$ are chosen according to the excitation.

In the dielectric waveguide we may derive two basic sets of modes: one with a linearly polarized transversal electric field and the other with a linearly polarized transversal magnetic field. In each case these modes may be either symmetric(even) or anti symmetric (odd) with respect to coordinate axes X and Y. It is instructive to point out that there is no simple and exact solution on the field equations in a dielectric waveguide. Take for instance (Figure 3.2), the boundary between regions 1 and 2,

where y= + b/2 and |x| <= a/2, where we must have

$$\varepsilon_0 E_{y2} = \varepsilon_r E_{y1} \tag{3.3}$$

On the other hand on the boundary between regions 1 and 4

$$E_{y4} = E_{y1} \tag{3.4}$$

On the corner, where regions 1, 2, and 4 meet, (3.3) and (3.4) must hold simultaneously, which means that the electric field cannot be continuous at this point. This behavior makes it impossible to get simple analytical solution to field equations. Even approximate (numeric) solutions converge slowly at this point.

Besides breaking down when the fields in the dielectric waveguide extend far away from the dielectric, that is when the dielectric cross section dimensions are small compared to the free space wavelength. A better description of the main transversal field component is obtained if we impose the continuity of the normal component of the electric displacement on the dielectric boundaries at $y = \pm b/2$; we do this at the cost of the continuity of the longitudinal electric field.

INVESTIGATION ON DIELECTRIC SLAB ANTENNA THROUGH SIMULATION

Simulations and experimental observations where possible are carried out in the X-band of frequencies[3]. Several noteworthy observations can be made from the results reported herein regarding the trends of variation of different antenna characteristics with the different antenna parameters like length of radiating slab, impedance matching inserted portion and the dielectric constant of the material. For example the beam tends to spread i.e. beam width increases with increase in the length of the matching section, whereas side lobes appear and gradually their levels tend to rise with increase in the radiating slab length beyond a certain limit.

All these investigations have been carried out in the form of electromagnetic simulation using HFSS (High Frequency Structure Simulation Software which is finite elements based simulation software marketed by An soft Corporation, USA).

The structure investigated is shown in Figure.3 along with the co-ordinate system used.

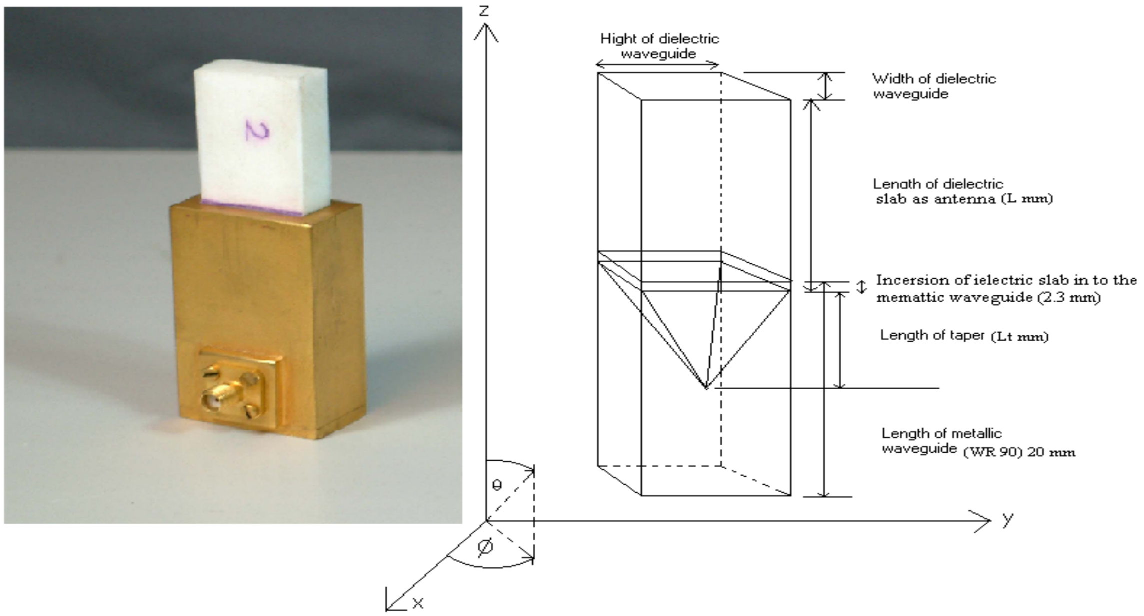

Figure 3: Schematic diagram of dielectric slab antenna.

Comparison of Results for Different Types of Taper

Rectangular dielectric waveguide antennas are commonly used for power transmission at microwave frequencies. There physical dimensions are regulated by the signal being transmitted. Here we chosen X-band frequencies for example and the dielectric slab is fed by a metallic rectangular waveguide, as EIA WR (90). The outer side dimensions are 25.4 cm wide and 12.7 mm high, and its inside dimensions are 22.86 mm wide and 10.16 mm high. Taper length of the dielectric slab is varied from 12 mm to 48mm, radiating slab length of the dielectric antenna is varied from 12 mm to 84mm and the dielectric constant of the dielectric slab is also varied from 2 to 12 in simulations. The dielectric slab is 2.3 mm inserted inside the metallic waveguide for mechanical support.

It is observed that rather than E-Plane or H-plane tapering sections, pyramidal taper of same length gives better radiation pattern and reduced return loss as viewed from the launcher wave guide. Figures.4 (a,b) through 6 (a,b) show this comparison for a typical case.

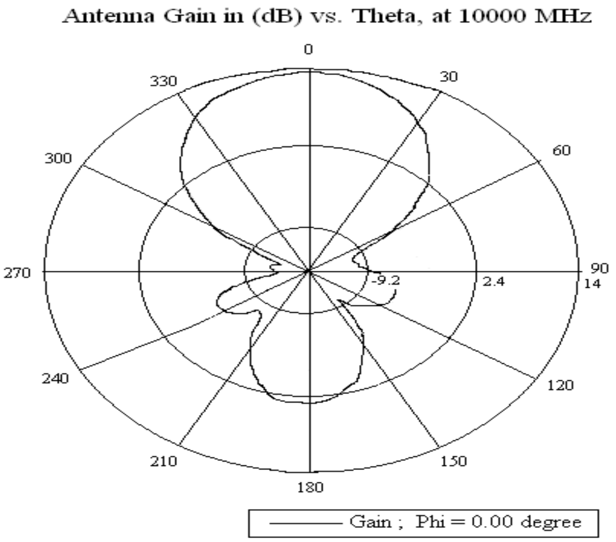

Figure 4 (a) Radiation Pattern (H-plane taper) at ϕ=0 deg. at 10 GHz

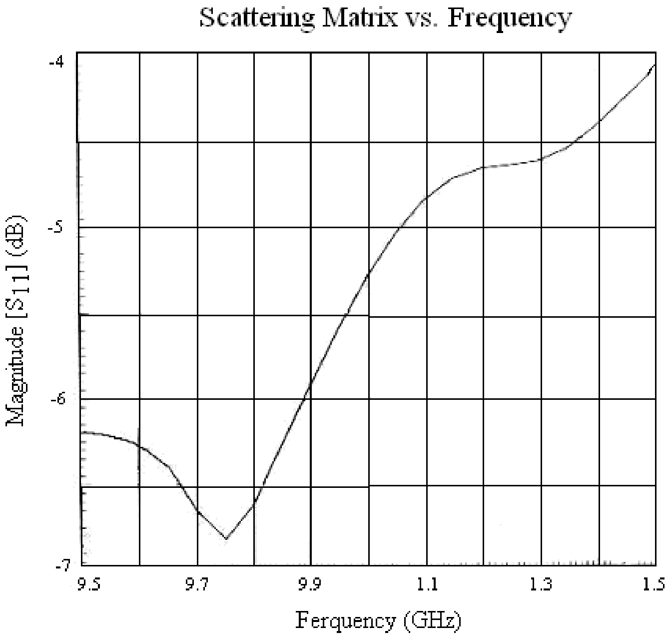

Figure 4 (b)Return Loss in dB (H-plane taper) for 9.5 to 10.5 GHz

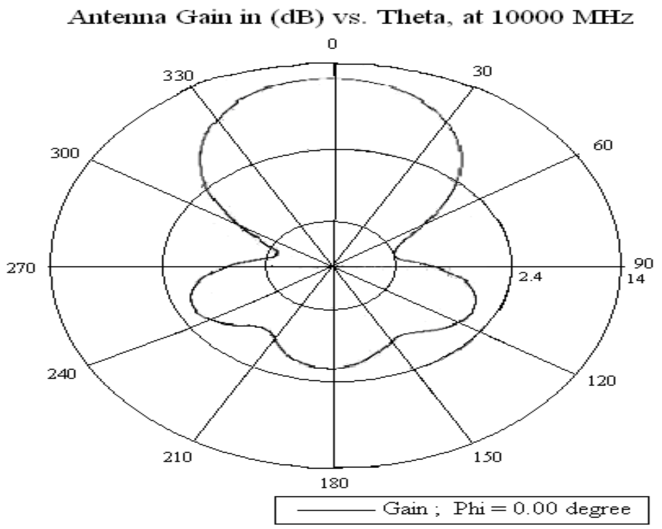

Figure 5 (a)Radiation Pattern (E-plane taper) at ϕ=0 deg at 10 GHz

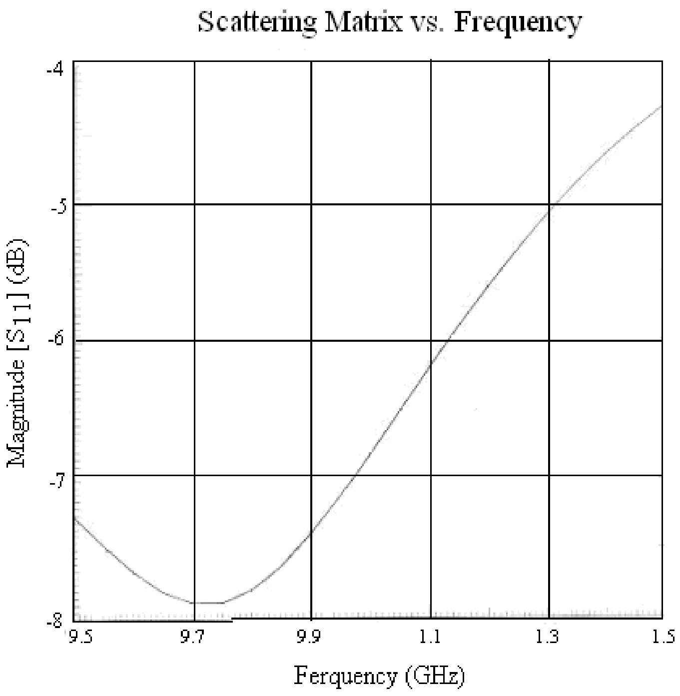

Figure 5 (b)Return Loss in dB (E-plane taper) for 9.5 to 10.5 GHz

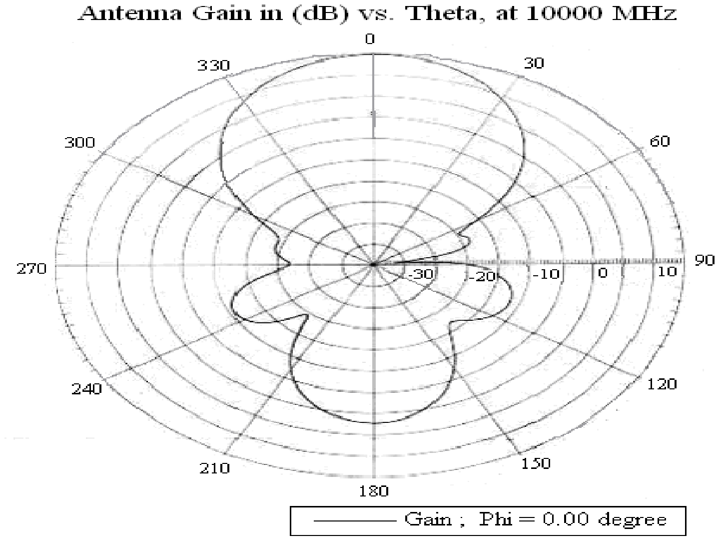

Figure 6 (a)Radiation Pattern (Pyramidal taper) at ϕ=0 deg at 10 GHz

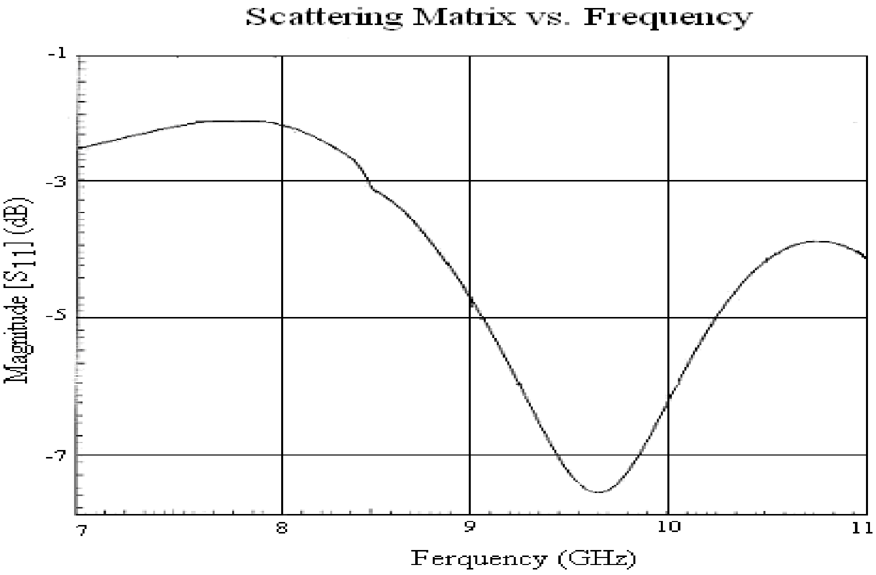

Figure 6 (b)Return Loss in dB (Pyramidal taper) for 7 to 11 GHz

Comparison of Results for Different Lengths of Taper

It is studied that as the taper length increases, corresponding matching with the launcher wave guide is improved since the taper characteristic impedance varies slowly over a wider range. Further, the beam tends to spread i.e. beam width increases with increase in the length of the matching section but the side lobes gradually tend to get reduced. Table 1 summarizes the antenna radiation characteristics for three typical values for length of the matching section.

Table 1: Study for radiation characteristics of antennas for different length of taper matching section (Lt)

Parameters	**Lt** = 17.7 mm	**Lt** = 26.55 mm	**Lt** = 35.4 mm
3dB beam width	45^{o}	40^{0}	45^{0}
Front/back ratio in dB	18.78	22.92	29.02
Side lobe level	-25.54 dB	-27.5 dB	-29 dB

Comparison of Results for Different Antenna Lengths

It is studied from the simulated results that if length of the antenna increases, the directivity increases but at the cost of increased side lobe level. This can be explained in terms of additional radiation from the sides, top and bottom in addition with the front aperture of the dielectric slab. Here we length of matching section is 17.5 mm, dielectric constant (DK) of the slab antenna is 4. Three typical cases of radiation pattern are shown in Figures. 7 through 8. Since the antenna impedance is not affected much by its length variation, corresponding information is not presented. It is also observed that the antenna impedance (matching performances) is not affected much by its length variation.

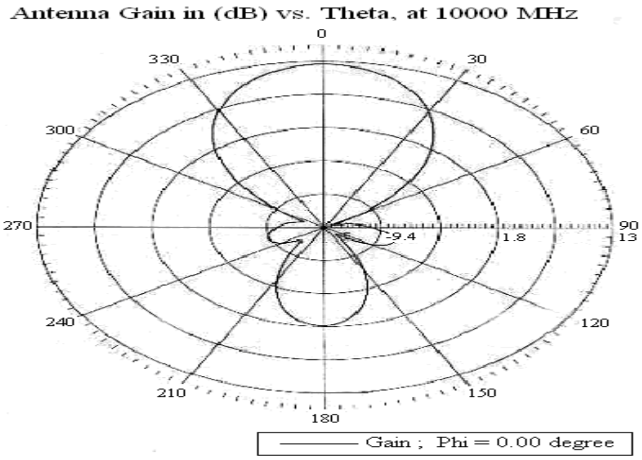

Figure.7:Radiation Pattern for length of the slab = 16 mm at ϕ=0 deg. (10 GHz)

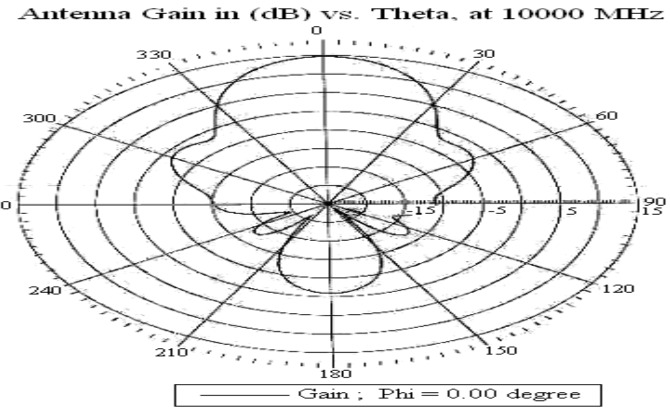

Figure.8:Radiation Pattern for length of the slab = 32 mm at ϕ=0 deg. (10 GHz)

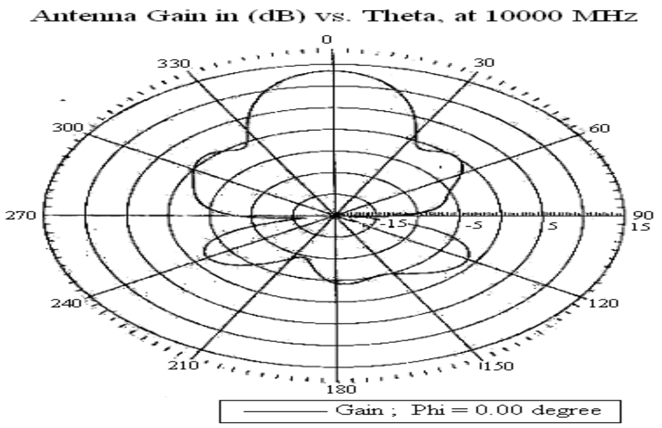

Figure .9: Radiation Pattern for length of the slab = 36 mm at ϕ=0 deg. (10 GHz)

RESULTS AND DISCUSSION

A rectangular dielectric waveguide antenna with pyramidal matching section using Teflon (dielectric constant 2.4) is designed to resonate at 10GHz and simulated for operation in the X-band.

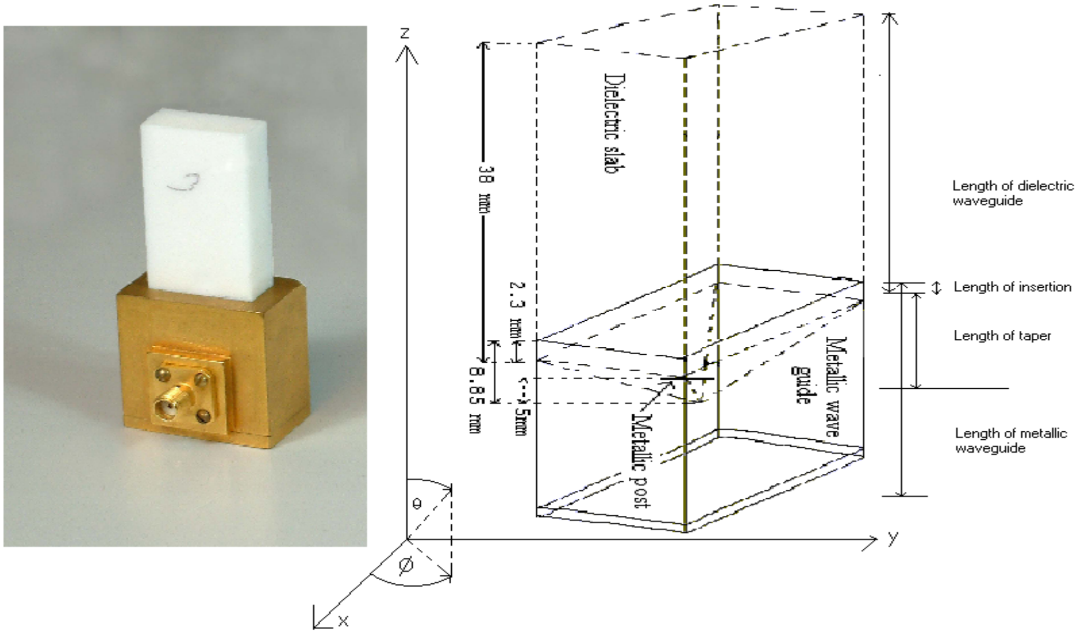

Figure .10:Dielectric slab antenna with reactive loading

It is fed by a standard WR 90 X-band metallic waveguide. After introduction of a metallic post and optimizing its position as well as physical parameters, the antenna shown in figure.10 results. Figure 11 depicts the return loss for the antenna with and without introduction of the post, whereby the antenna performance is found to improve drastically showing an improvement in return loss from –8.4 dB to –20.4 dB (V.S.W.R. 1.2:1).

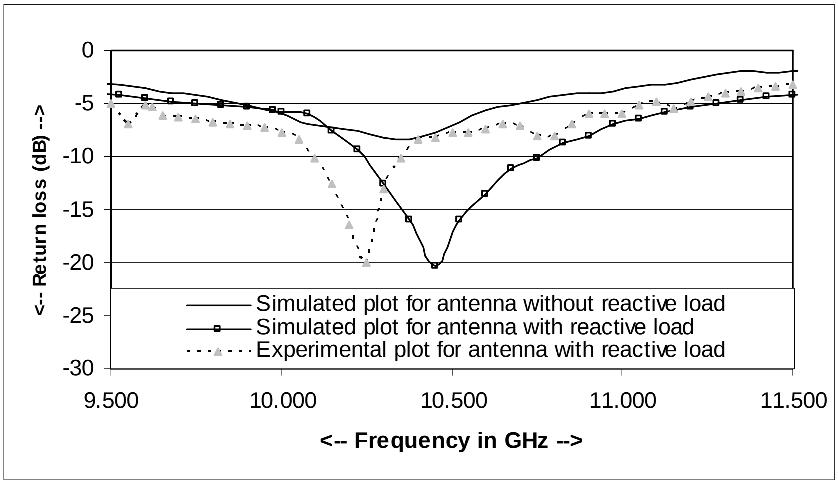

Figure.11:Simulated and measured return loss plots without and with reactive loading

Measurements on the fabricated prototype using Vector Network Analyzer (Agilent Technologies, VNA-E5071B) yields a minimum return loss of –20.1 dB with about 200 MHz shift in the resonant frequency, in close agreement with the simulated result.

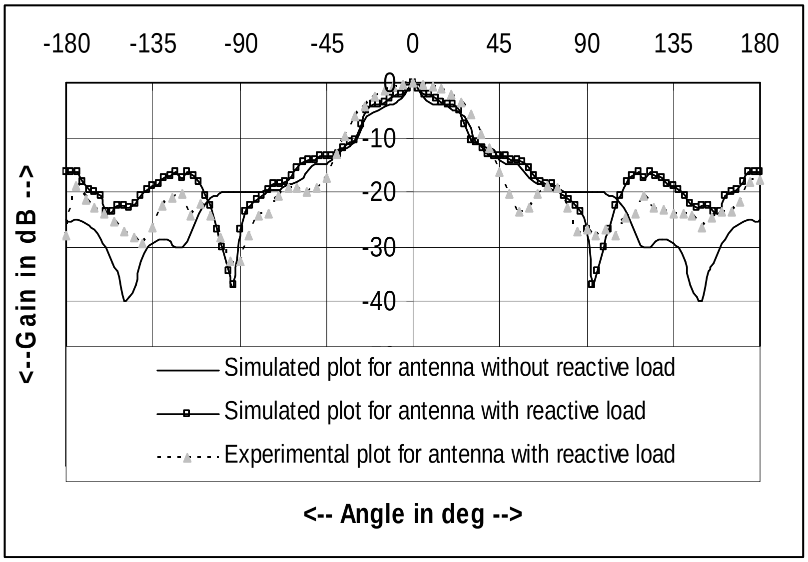

Figure.12:Simulated and measured E-plane radiation without and with reactive loading

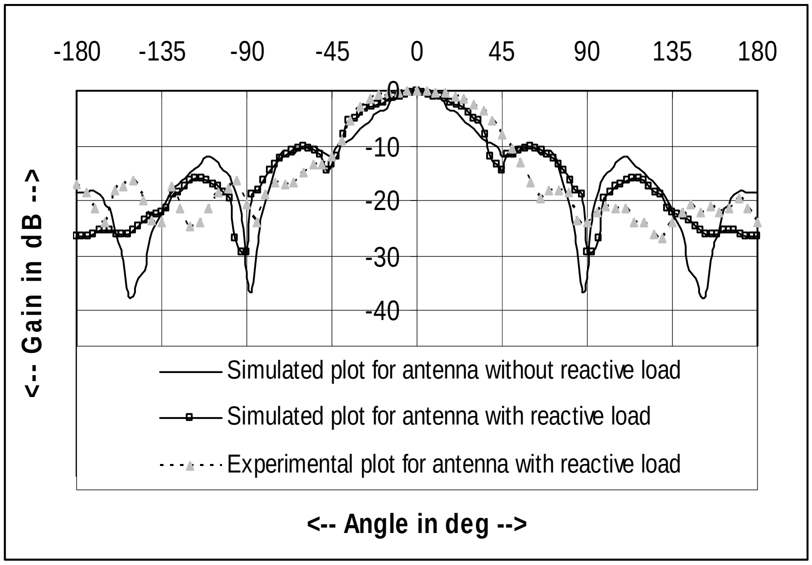

Figure13:Simulated and measured H-plane radiation for without and with reactive loading

Measured radiation patterns for the same show front to back ratio of nearly 18 dB with a 3 dB beam width of 30^0 in the E plane & 36^0 in the H plane. These patterns along with their simulated counterparts are shown in Figures. 12 and 13.

From these figures we find that there is practically negligible discrepancy between the simulated and measured patterns.

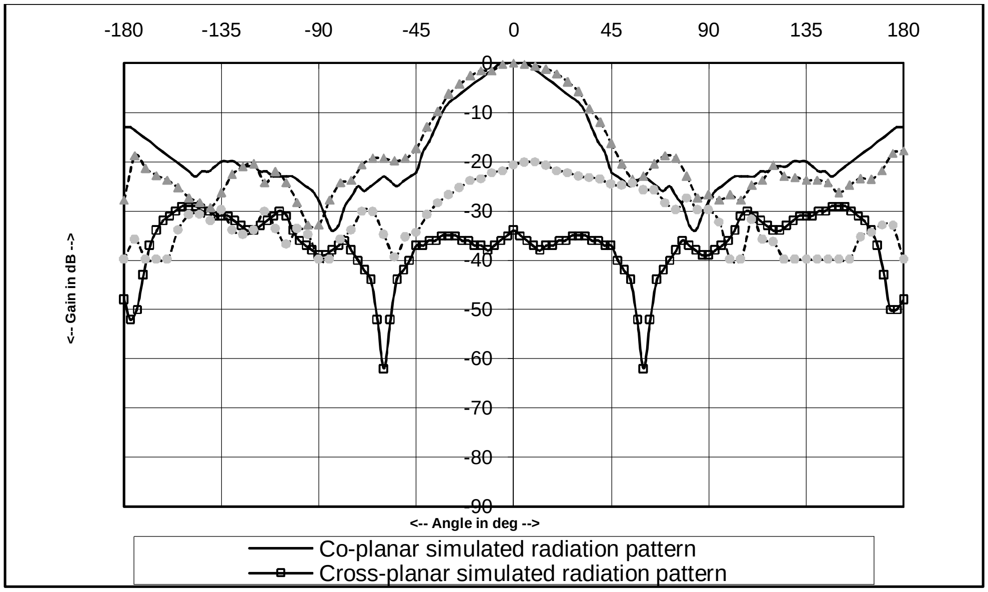

Figure.14:Simulated and measured co and cross-planar radiation with reactive loading

CONCLUSION

It is observed that return loss behavior can be dramatically improved by inserting a shorting post within the feed matching section of a rectangular dielectric waveguide antenna. The post acts as a reactive load and is able to scatter the wave propagating along the guide and control the propagation characteristics and field pattern from the aperture end. However, the bandwidth obtained with post loaded dielectric waveguide antenna is quite small (~1%) because of the high degree of frequency sensitivity of the load. From our studies it has been also observed that tapers in both wave launching and free space radiating edges are useful in simultaneous impedance matching and improvement of the radiation pattern. The introduction of pyramidal taper in the front radiating face with adjustable properties (length and base area of the introduced pyramidal taper section) can give similar directive beam without undesirable increase in length and at the same time it shows dual frequency operation. An appropriate approach of truncation in the front radiating edge with adjustable properties (length and base area of the truncated pyramidal hollow section) can give improved directive beam without undesirable increase in length and at the same time huge improvement in bandwidth and impedance matching. All these give our proposed antenna competitive advantage for trans-receiver applications over standard dielectric slab antennas.

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