CHAPTER 8

DESIGN OF AN APERTURE COUPLED RECTANGULAR DIELECTRIC RESONATOR ANTENNA ARRAY HAVING MUTUALLY COUPLED AND LOADED MIDDLE ELEMENT USING DOPED BaTiO$_3$ CERAMICS

8.1 Introduction

The ferroelectric properties viz. high dielectric constant, variability of dielectric constant with applied field etc. which are exploited in technological devices such as fabrication of high value capacitors, tuneable circuit components etc. have been described in Chapter 1 and listed in Table 1.1. One of the applications where the high values of dielectric constant may be used is in the field of developing miniaturized microwave components such as dielectric resonator antennas.

An antenna is defined as that part of a transmitting or receiving system which is designed to radiate or to receive electromagnetic waves in efficient and desired way. The combination of antenna and its feed line is termed as antenna system. An antenna is usually connected to a transmision line and works as a transformer of voltage/current to electric/ magnetic fields or vice versa. How to best make this connection, to design the antenna and to choose the material for fabrication of the antenna so that the signal being fed to the antenna is radiated in space in an efficient and desired way, is a very challenging subject. This becomes much more so since the performance of a well designed isolated antenna may be quite different than when it is installed in the actual system such as a mobile hand set. In some systems, the antenna is now no longer just a simple transmitting/receiving device, but a device which is integrated with other parts of the system to achieve better performance [Huang et al.(2008), Schelkunoff et al.(1952), Kraus (1988)]. There, knowledge of overall behaviour of the material, which the antenna is made of, would be highly useful.

In several applications antennas are mounted on some platform such as aircraft, truck, jeep or any other vehicle and protrude out .This makes them highly undesirable specially for military operations and, therefore, small size low profile (i.e. of relatively low heights) antennas are looked for. Recent development of 5G technologies aimed at increasing data rate by orders of magnitude have pressed the need for antennas having large band width so as to accommodate large number of channels, high gain, small size and temperature independent performance. This has lead to intensive efforts for better designs as well as for search of materials that may be used for fabrication of antenna [Keyrouz et al.(2017)].

The traditional microwave antennas have increased losses in the metallic body at higher frequencies and suffer from narrow bandwidth and reduced radiation efficiency [Keyrouz et al. (2016)]. In the last three decades a new kind of antenna research has gained momentum, known as dielectric resonator antenna (DRA). It was realized as early as in 1939 by Richtmyer (1939) that open dielectric resonators radiate into free space but the practical feasibility appeared after the work of Long et al. (1983) in 1983 where it was shown that the dielectric resonators, well known from microwave circuits, can in fact become very efficient antennas if properly excited.

Usual antennas almost always use a metal for radiation where as a DRA uses no metal at all except for a ground plane. It consists only of high permittivity and low loss material . Therefore, dielectric materials with suitable characteristics namely high relative permittivity , low loss tangent $tan\delta$ of the order of 10^{-2} and below and very low temperature coefficient of resonance frequency are of utmost importance for developing DRAs. Search for such novel materials or arrangements mimicking this behaviour together with refined antenna designs constitutes a very hot topic of research and development at present [Keyrouz et al. (2016); Yaduvanshi et al. (2016)].

During development of materials for antenna the main focus is to reduce the loss. The dielectrics having higher losses are discarded. Ceramic systems studied in the present work have losses in around 0.1 to 0.4. In order to explore the possibility of using these in development of antenna , design and simulation of rectangular dielectric resonator antenna (RDRA) was pursued with a view to propose a suitable design where these materials may be utilized. The results of our preliminary studies on design of RDRA using relative permittivity (ε_r) equal to 40 and to resonate at 10 GHz are presented in this chapter. Effect of loss on its performance are described.

8.2 General Ideas

A two pronged approach is useful for design and development of a DRA. In one, workable geometrical designs of antenna are looked for by taking into consideration the available materials . The resonance frequency and the modes that could be supported by the resonator, besides the properties of the material, heavily depend upon the shape and size and the way the structure is excited. In the other, the material of which the body of the resonator is to be fabricated , is looked at. The material properties such as dielectric permittivity, permeability and loss govern the band width and gain (radiation efficiency) of the antenna. After, suitable materials have been chosen , the two steps mentioned above go hand in hand. By using same design an antenna can be used at different frequencies by changing the material or vice versa [Keyrouze et al.(2016); Min et al. (2006)].

The main dimension of a DRA is proportional to the wavelength in the dielectric medium , $\lambda_0 / \sqrt{(\mu_r \varepsilon_r)}$, where λ_0 is the free-space wavelength at the resonant frequency, ε_r and μ_r are respectively the dielectric permittivity and magnetic permeability of the material [Huitema et al.(2012); Sadiku (2007)]. For a dielectric material, $\mu_r \approx 1$ and the dimension is proportional to $\lambda_0/\sqrt{\varepsilon_r}$. DRA's made using a dielectric of permittivity ε_r would have size reduced by a factor $\sqrt{\varepsilon_r}$. Thus, DRA dimensions can be decreased (i.e. DRA is miniaturized) by using a dielectric with higher value of ε_r.

Higher values of ε_r are easily achieved in ferroelectrics, such as those obtained from $BaTiO_3$ with substitutions at Ba or Ti sites (e.g. Barium Strontium Titanate). [Moulson et al.(2003), Gevogian (2009)] . A detailed account of various useful microwave ceramics has been given by Sebestian (2008, 2017). The gain (efficiency) of an antenna depends upon inter-segment matching being satisfied in the design. The antenna is exposed to air (free space) on one side (radiating side) and connected to a signal source on some other rear side through a transmission line. While connecting the antenna to a feed line which has its other end further connected to a source , typically of 50 Ω output impedance , optimum impedance matching has to be achieved for maximum power transfer. This is accomplished by utilizing transmission line concepts [Kraus et al.(1980); Sadiku (2007)].

A Dielectric Resonator Antenna consists of block of a ceramic material of various sizes and shapes , such as spherical, hemispherical , cylindrical , rectangular, cylindrical ring, conical, filleted , triangular etc., mounted on a metal surface called the ground plane. Out of all these shapes , the Rectangular Dielectric Resonator Antenna (RDRA) offers maximum flexibility of design as the dimensions (length *a*, width *b* and height *d*) can be independently varied and suitably tailored to match the desired operating specifications of frequency, band width, gain etc. for a given dielectric material [Keyrouz et al. (2016); Petosa et al. (2010); Mongia et al. (1997); Yaduvanshi et al. (2016); Petosa et al. (2003); Huitema et al. (2012); Sebastian (2008)]. In what follows the basics of designing of RDRA are summarized .

8.3 Basics of Design of RDRA

Design of RDRA essentially involves estimation of its dimensions for given resonance frequency, dielectric permittivity of the material and the modes to be excited. The modes (the patterns of electric and magnetic fields, **E** and **H**) that can exist in a DRA are obtained by using the so called dielectric wave guide model (DWM) which treats a DRA as a wave guide having its cross section same as that of the DRA (say *a* x *b*) , filled with the dielectric having no metallic walls and truncated in the direction of propagation by a length (say *d*) . It has been shown that rectangular DRA's support the so called nonconfined modes for which the boundary condition $\mathbf{E} \cdot \mathbf{n} = 0$ is to be satisfied at all the surfaces of the resonator, where **E** denotes the electric-field intensity and **n** denotes the normal to the surface of the resonator. [Mongia et al. (1997); Yaduvanshi et al. (2016)].

The basic equations of electromagnetism (the Maxwell equations) are solved using these boundary conditions and expressions for field components are derived. The dominant mode is TE^{Z}_{111} where the superscript indicates the direction of propagation and the subscripts indicate the number of half wavelengths in the x, y and z directions . It has also been shown that lowest order non confined modes radiate like magnetic dipoles [Mongia et al. (1997)]. The Maxwell equations can be solved analytically only for some well defined wave guide shapes such as cylindrical and rectangular assuming that losses are negligible [Kraus et al.(1980); Sadiku (2007)] . For other situations numerical methods are adopted. Computer programmes involving various algorithms, such as Ansys HFSS (High Frequency Structure Simulator) software utilizing finite element method, have been developed which are readily available and are being widely used. By utilizing these softwares, study of the performance of antennas of any desired designs have become possible by using simulation.

For compactness and maximum power transfer lowest mode (also called the dominant mode) is preferred. By solving Maxwell equations using DWM for a RDRA, relations for the field components H_z and E_z are given as

$$H_z = \frac{k_x^2+k_y^2}{j\omega\mu_0} A\cos(k_x x)\cos(k_y y)\cos(k_z z) \qquad \ldots(8.1)$$

$$E_z = 0 \qquad \ldots(8.2)$$

where k_x , k_y and k_z denote the wave numbers along x, y and z directions respectively and A is an arbitrary constant [Mongia et al. (1997)]. The field components H_x, H_y, E_x and E_y are derived from H_z [Sadiku (2007); Kraus et al (1980); Mongia et al. (1997)].

The values of k_x and k_y for the dominant $TE^z{}_{111}$ mode are given as

$$k_x = \frac{\pi}{a} \qquad \ldots(8.3)$$

$$k_y = \frac{\pi}{b} \qquad \ldots(8.4)$$

The wave numbers k_x, k_y and k_z satisfy the equations

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_r k_0^2 \qquad \ldots(8.5)$$

and

$$k_z \tan\left(\frac{k_z d}{2}\right) = k_{z0} \qquad \ldots(8.6)$$

where

$$k_{z0} = \sqrt{[\ (\varepsilon_r - 1)\, k_0^2 - k_z^2\ ]} \qquad \ldots(8.7)$$

and k_0 is the wave number in free space. Equation (8.6) is also known as transcendental equation and arises from the continuity condition of the fields at the surface of the RDRA normal to the direction of propagation.

Using Equation (8.6), d can also be expressed as

$$d = \frac{2}{k_z} \tan^{-1}\left(\frac{k_{z0}}{k_z}\right) \qquad \dots (8.8)$$

For TE^z_{111} mode values of a, b and d lie between $\lambda/2$ and λ and $d < b < a$, λ being the wavelength in the guide [Mongia et al. (1994); Okaya et al. (1962)].

The resonator parameters can be computed in the following way. For a given value of dielectric constant (ε' used in earlier sections), the wavelength in the material of the RDRA is calculated by using $\lambda = \lambda_0/\sqrt{\varepsilon_r}$ where λ_0 is the free space wavelength for frequency f_0. The values of a and b are chosen so that $\lambda/2 < a < \lambda$, $\lambda/2 < b < a$ and $\lambda/2 < d < b$ (to have only TE_{111} modes) . For given resonator dimensions a and b , dielectric constant ε_r (= ε' used in earlier chapters) and resonance frequency f_0, the values of k_x and k_y are first obtained from Equations (8.3) and (8.4). These are used to get the value of k_z from Equation (8.5) which is then used in Equation (8.6) or (8.8) to calculate the value of d. In actual practice the RDRA is usually placed on a large ground plane to avoid back radiations. Then, by making use of image theory, the dimension along the normal to the ground plane is made equal to half of that for the isolated RDRA [Mongia et al. (1997)]

Several feeding techniques exist for coupling of the RDRA to a microwave power source. These are named as probe feeding, microwave strip transmission line feeding, coplanar wave guide feeding and slot feeding [Keyrouz et al. (2016)]. The feed ends are so located and oriented near the DRA's that the emanating field lines enforce the field patterns of the desired modes in the DRA. Due to design simplicity and better coupling , the slot feeding , also known as aperture coupling, is very popular and involves a slot in the ground plane. The guided wave propagating along the microstrip transmission line is coupled, through the slot (aperture) , to the resonant modes of the dielectric resonator. In this, the RDRA is centrally placed on a large ground plane supported by a substrate (e.g. FR4, dielectric constant 4.4, thickness (h) = 1.6 mm) having a printed microstrip line on the other side and usually extending upto the middle of the bottom of the RDRA or a little beyond. The ground plane also possesses an etched aperture of certain length and width oriented at right angles to the microstrip beneath the RDRA. For matching the microstrip line to a 50 Ω microwave power source , the width of the line can be estimated by using the relations given in Equations (8.9- 8.11) for calculating its characteristic impedance Z_0 [Sadiku (2007)]. The line width , its length extending beyond the aperture, size of the aperture, dimensions of the DRA etc are optimized to achieve desired performance by using simulation softwares such as HFSS.

8.4. Design of RDRA Array

An aperture coupled single RDRA (having dimensions ‘a’ , ‘b’ and ‘d’ along x, y and z directions respectively) is first designed. The design essentially involves the estimation of the dimensions of the resonator for given values of relative dielectric permittivity and resonance frequency. An idea of how these estimates were obtained is now given. The values of resonance frequency and ε' were taken as 10 GHz and 40 respectively. The value of the wavelength , λ, in the dielectric is given as

$$\lambda = \frac{2\,\pi}{\sqrt{\omega^2\ \mu\varepsilon}} = \frac{c}{f\sqrt{\varepsilon}} = \frac{3x10^8}{3x10^9\sqrt{40}}\ \mathrm{m} = 4.74\ \mathrm{mm}$$

We assume that dimension along x is ‘a’, along y is ‘b’ , along z is ‘d’.

For dominant TE^z_{111} mode , values of a and b were chosen such that $\lambda/2 < a < \lambda$, $\lambda/2 < a < \lambda$ and $b < a$. Here , $\lambda/2 = 2.37$ mm. Therefore , tentative values for a and b were chosen as a = 4.5 mm and b = 3.5 mm. Now, with the given values f_0 = 10 GHz, a = 4.5 mm , b = 3.5 mm , ε' = 40, value of 'd' was calculated by using Equations (8.3) to (8.8) iteratively. A small computer program was written for this purpose. The program yields 'd' = 3.02 mm. So, we get the values as a = 4.5 mm, b = 3.5 mm , d= 3.02 mm for ε = 40 and f_0 = 10 GHz. Number of combinations of a, b and d are possible that satisfy the above requirements.

Now , design of feed line is described. A microstrip line on a FR4 (permittivity = 4.4, thickness = 1.6 mm) substrate was chosen for coupling the RDRA to a 50 Ω source. The corresponding width of the strip was estimated by using relations given by Equations (8.9) – (8.11) [Sadiku (2007)]

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}} \ln\left(\frac{8h}{w} + \frac{w}{4h}\right) \quad , \quad \frac{w}{h} \leq 1 \qquad \text{...(8.9)}$$

$$Z_0 = \frac{1}{\sqrt{\varepsilon_{eff}}} \frac{120\,\pi}{\left[\frac{w}{h} + 1.393 + 0.667 \ln\left(\frac{w}{h} + 1.444\right)\right]} \quad , \quad \frac{w}{h} \geq 1 \qquad \text{...(8.10)}$$

where w is the width of microstrip line placed on a substrate of relative dielectric permittivity ε_s and height h.. ε_{eff} is the effective dielectric permittivity given by

$$\varepsilon_{eff} = \frac{(\varepsilon_s + 1)}{2} + \frac{(\varepsilon_s - 1)}{2\sqrt{1 + 12\,h/w}} \qquad \text{...(8.11)}$$

The desired width comes out to be 3.08 mm. A ground plane of dimensions 45mm x 45mm was chosen on the other side of which the strip resides. An aperture/slot of length L_s and width W_s located at the centre of the ground plane was used for aperture coupling. One RDRA element was centrally placed on the aperture. The microstrip extended beyond the aperture to facilitate stub tuning. The parameters were optimized to give maximum bandwidth at resonance frequency of 10 GHz. A single RDRA is schematically shown in Figure 8.1 (where L=a, W=b and H=d). The reflection coefficient and gain obtained by HFSS for the same are shown in Figure 8.2. The dimensions and other details are given in Table 8.1.

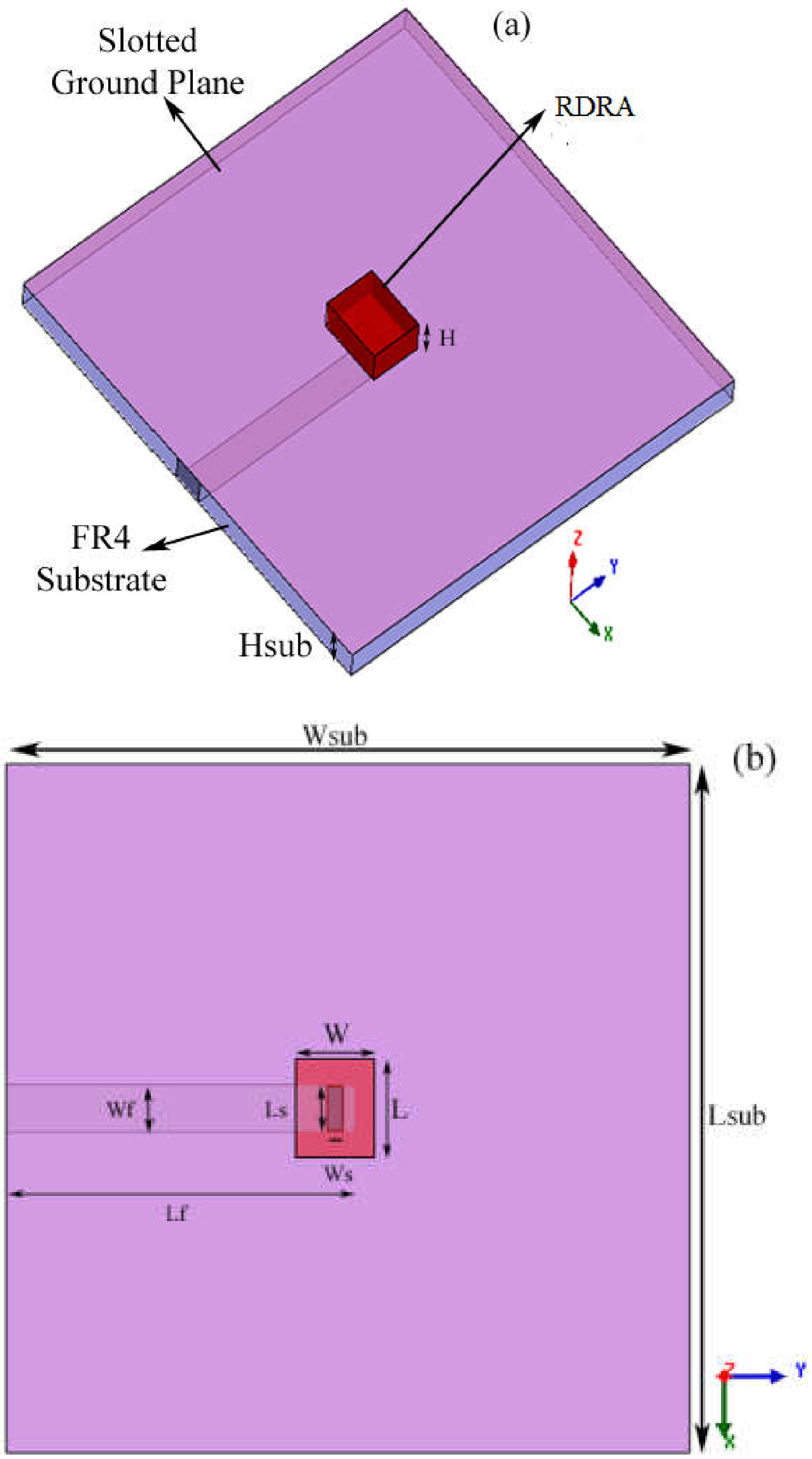


Figure 8.1: Schematic diagram of aperture coupled RDRA (a) 3-D view and (b) top view.

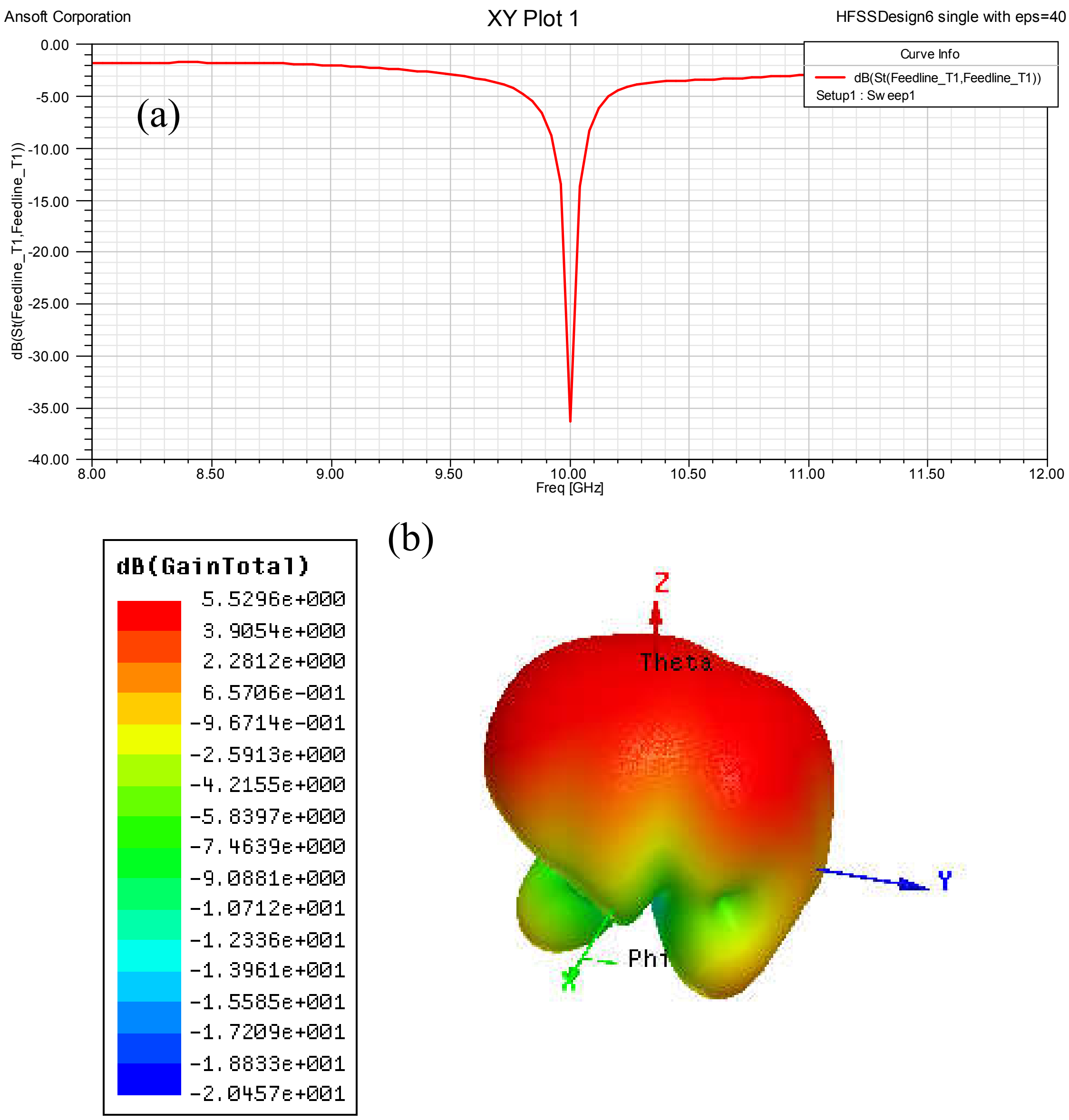


Figure 8.2: (a) Variation of reflection coefficient with frequency and (b) gain for single RDRA.

Table 8.1: Optimized values of parameters for the proposed antenna comprising substrate of length L_{sub} and width W_{sub} with height H_{sub}, RDRA of length L (= *a*) and width W(=*b*) with height H(=d), microstrip feed line of length L_f , width W_f, aperture/slot of length L_s and width W_s, the input impedance being 50 Ω.

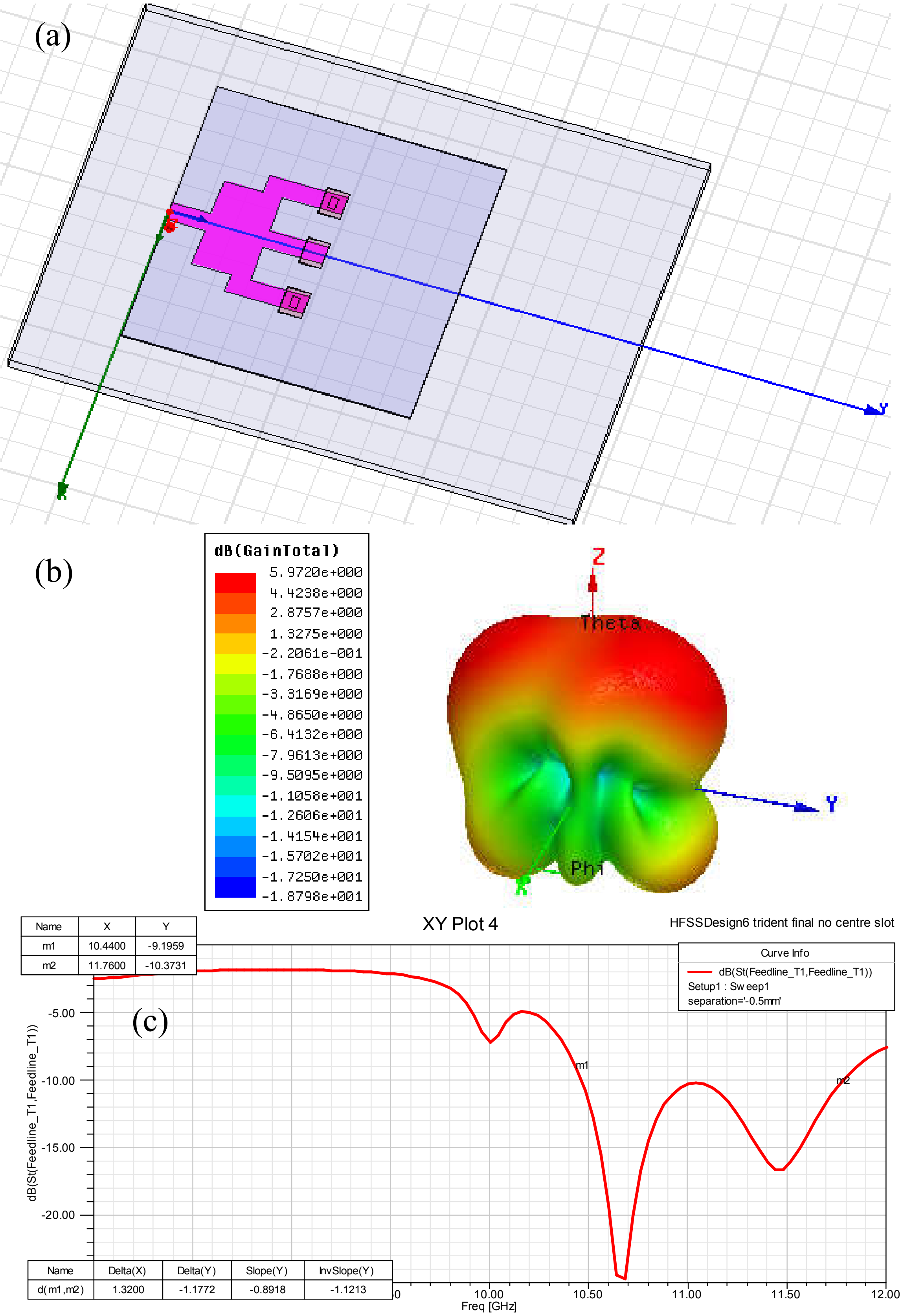
Parameter	$\mathbf{W_{sub}}$	$\mathbf{L_{sub}}$	$\mathbf{H_{sub}}$	**W**	**L**	**H**	$\mathbf{W_s}$	$\mathbf{L_s}$	$\mathbf{W_f}$	$\mathbf{L_f}$
Size(mm)	45	45	1.6	4.5	3.5	1.5	1	1.9	1	23

For designing the array, two more similar RDRA's , apertures and microstrip lines were made which were placed on each side of the middle RRDA. These strips were joined together and further connected to the 50 Ω source through a matched line. The design of the array is schematically shown in Figure 8.3. The three 50 Ω microstrip lines give an impedance of 16.67 Ω at the joint. In order to match this with the 50 Ω source a quarter wavelength section having impedance of √(50*16.67) Ω was designed which was achieved by using a wider strip (15 mm) as shown in Figure 8.3.

8.5 Results and Discussion

The performance of the system was studied by using Ansys HFSS simulation software . Effect of increasing the value of loss in the elements on bandwidth, gain and shape of the far filed pattern was observed. The results are summarized in Table 8.2.

It is seen that for case (i) the bandwidth for a single RDRA remains same but gain and shape deteriorate when the loss is increased from 0.001 to 0.1. For case(ii) , i.e. when all the elements are aperture coupled and loss tangent increases from 0 to 0.1 in all the three elements, the bandwidth slightly increases , the gain decreases heavily by 62 % and the shape of the far field pattern also deteriorates. For case (iii) , when the outer elements are aperture coupled and the middle element is mutually coupled to the neighbouring elements , the band width slightly increases from 1.32 GHz to 1.36 GHz as the loss in middle element only is increased from 0 to 0.1. The gain decreases from 5.97 dB to 5.81 dB (i.e. deteriorates only by 2.7 %). Also, in this case , the far field pattern remains almost same as loss is increased. It may be mentioned that in case (iii) , the outer elements are maintained lossless and only the middle element is made lossy.



Name	X	Y
m1	10.4400	-9.1959
m2	11.7600	-10.3731

Name	Delta(X)	Delta(Y)	Slope(Y)	InvSlope(Y)
d(m1,m2)	1.3200	-1.1772	-0.8918	-1.1213

Figure 8.3: (a) Design, (b) Variation of reflection coefficient with frequency and (c) gain for aperture coupled array of three RDRAs with middle element parasitic.

It indicates that low cost, easily preparable but slightly lossy (tan δ ~0.1) materials may also be used in conjunction with low loss dielectrics in development of antennas by applying the present RDRA design with some trade off with gain . The present study indicates that ferroelectrics such as $Ba_{1-x}Sr_xTiO3$ (x = 0.35) having ε_r and tan δ around 40 and 0.1 respectively [Chapter 5] in the microwave X-band may be used for the fabrication of the middle element. This is a preliminary report. Further work with some more designs is needed. However, our findings of enhanced bandwidth when loss is raised agree with that reported by Zivkovic (2012) where enhanced bandwidth of wire antenna was achieved by loading it with a lossy epoxy (tan δ~0.05).

Table 8.2: Variation of bandwidth and gain in RDRA arrangements with loss

Design Arrangements	**loss**	**Band width (GHz)**	**Maximum gain**	**Shape**
1.Single RDRA	0.0	0.14	5.53	Apple
	0.001	0.14	5.26	Apple
	0.01	0.14	4.82	Deformed
	0.1	---	-4.48	Deformed
2.Array of Two RDRA’s	0.0	0.97	5.20	Apple
	0.001	0.97	4.97	Apple
	0.01	0.92	3.18	Apple
	0.1	1.04	2.90	Deformed

Table 8.2(contd.): Variation of bandwidth and gain in RDRA arrangements with loss

Design Arrangements	**loss**	**Band width (GHz)**	**Maximum gain**	**Shape**
3.Array of three RDRA's (all aperture coupled)	0.0	1.34	2.55	Deformed
	0.001	1.35	2.34	Deformed
	0.01	1.37	1.84	Deformed
	0.1	1.4	1.58	Deformed
4.Array of three RDRA's (middle parasitic	0.0	1.32	5.97	Apple
	0.001	1.33	5.69	Apple
	0.01	1.32	5.92	Apple
	0.1	1.36	5.81	Apple

8.6 Conclusions

Design of an aperture coupled RDRA array comprising three elements of permittivity equal to 40 is proposed for microwave X-band operation . When the outer elements are aperture coupled and the middle one is parasitic the band width slightly increases by 3% (from 1.32 GHz to 1.36 GHz) and gain decreases only by 2.7 % (from 5.97 dB to 5.81 dB) as the loss in middle element is increased from 0 to 0.1 keeping the outer elements loss less. The far field pattern remains almost same as loss is increased. It indicates that low cost, easily preparable but slightly lossy (

$\tan\delta \sim 0.1$) materials, such as $Ba_{1-x}Sr_xTiO3$ ($x = 0.35$) ceramics having ε_r and $\tan\delta$ around 40 and 0.1 studied in the present work may be used in conjunction with low loss dielectrics in development of antennas by applying the present RDRA design with some trade off with gain .