The sequential description of various steps involved in the synthesis of low loss dielectric resonator materials are described in this chapter. A qualitative discussion on the structural as well as microwave characterization tools to determine the dielectric constant, quality factor and temperature coefficient of resonant frequency of ceramics are given. The design, fabrication and characterization of dielectric resonator antennas are also included in this chapter. A brief introduction about the importance and applications of 3D Transmission Line Matrix simulation method and its adaptation for modeling the cavity shielded dielectric resonators and antennas are introduced.
2.1 SYNTHESIS OF DIELECTRIC RESONATORS

2.1.1 Introduction

The miniaturization of devices and the development of new components have made possible many interesting advances and innovative concepts in material fabrication technology. The focus of attention in this regard has not only been on the improved microstructure and property of the products but also in the design and development of potential engineering applications. Along with the revolutionary development of electronics in the second half of the twentieth century, the huge potential of ceramic materials has been unfolded and introduced into a fascinatingly wide spectrum of electrical and microelectronic devices and applications. Obviously, oxide ceramics cover a huge area of functionalities. Hardly any other class of materials (semiconductors, metals, polymers) offers such a broad variety of properties which can be exploited for electronic applications. Nowadays, the synthesis technique for the fabrication of electroceramic powders has generated considerable interest mainly focusing on improving the physical and electronic properties of the final ceramic products. Different methods can be applied to ceramic powder materials to form the commercial ceramic products like Dielectric resonators that are diverse in size, shape, material composition, structure and property. Hence to the shaped body of DR with desired property, the ceramic processing steps have to be carefully monitored.

Ceramics, by definition, comprise inorganic, non-metallic, non-water-soluble compounds that show ionic contributions in their chemical bonds. These are the product of solid compounds, which are formed into desired shapes initially and then hardened by the application of heat and sometimes heat and pressure simultaneously. Ceramic fabrication techniques generally include various powder processing methods with powder synthesis, forming and sintering. The powder synthesis process of ceramics involve several techniques like (a) solid state reaction methods (b) mechanical methods and (c) chemical methods. Powders with different properties can be produced using different processing methods. A careful selection of the preparation technique is necessary to prepare powders consisting of particles with specific properties to yield the bulk component. The synthesis of specific powders and the better control of chemical and
physical characteristics of ceramic powders allow obtaining improved and/or reproducible properties.

The most common method of preparing ceramic powders is by solid-state reaction methods, because it is the simplest, easier and cost effective method to make bulk amount of ceramics. However it is established that the surface area of the ceramic powder derived through solid state reaction technique is relatively lower and hence the particles can offer lesser points of contacts which are vital for effective sintering reactions to take place. In addition to that the homogeneity of particle size distribution and high temperature of formation makes the solid state ceramic techniques unpopular for the synthesis of advanced dielectric ceramics. In the mechanical methods, small particles are produced from larger ones by mechanical forces, a process referred to as comminution. The process of comminution involves operations such as crushing, grinding and milling. Mechanical treatment of ceramic powders can reduce particle size and enables to obtain nano-structured powders, which are of the main interest in the current trend of miniaturization and integration of electronic components. However this technique lacks the synthesis of phase pure ceramics, which is essential for the fabrication of DRs with optimum dielectric properties. Hence alternate chemical techniques like molten salt, precipitation, sol-gel, hydrothermal and combustion methods have been worked out in the synthesis of complex perovskite ceramics. But the sinterability of bulk ceramics prepared using chemically derived powders was found to be very poor and hence none of these techniques could fetch a higher quality factor for dielectric resonators than that obtained through solid state technique. Moreover the stringent operation conditions involved in the reaction sequence as well as the high cost of chemicals, limit the usage of chemical methods for the fabrication of DRs in industry. Hence in the present study we have employed the conventional solid state synthesis of ceramics for the fabrication of DRs, because this method lead to better dielectric properties, which is the primary interest in the fabrication of devices employing DRs.
2. 1. 2 Solid State Synthesis of Ceramics

The conventional ceramic approach involves basically four steps (a) intimate mixing of the stoichiometric oxides, (b) high temperature firing/calcination (c) intermediate grinding and (d) sintering.

On heating at high temperatures, a new material is formed (See Fig. 2.1) to reduce the free energy, at the points of contact through solid state diffusion. This new product layer (of a few Å) eventually acts as a potential barrier between the two grains and thus impeding further grain to grain material transport. This demands the need of new points of contacts to be introduced which is usually achieved though grinding or ball milling. This frequent grinding coupled with multiple calcination maximizes the product to reactant ratio.

The solid-state reaction method, which is employed in the present work, involves the following steps:

2. 1. 2. 1 Weighing of Raw Materials

The first step in the solid-state reaction method is to weigh the different oxides/carbonates which act as reactants according to the stoichiometry with due allowance to impurity and moisture content. The presence of impurities in the raw
materials can affect reactivity as well as dielectric properties of the fired ceramics. Hence very high purity oxides (> 99.9 %) are essential for obtaining phase pure compounds. Electronic balance is used to obtain accuracy up to four decimal places.

2.1.2.2 Stoichiometric Mixing

The raw materials need to be intimately mixed to increase the points of contacts between reactant oxides, which in turn act as ‘product layer formation centres’. Hence the raw materials constituting the batch must be intimately mixed. The mixing and milling eliminates agglomerates and reduces particle size. If agglomerates are present they densify more rapidly resulting in pores. During the mixing process agglomerates are broken and defects are introduced into the grains that enhance diffusion mechanism. Therefore in the present investigation, the mixture of constituent powders taken in polythene bottles were ball milled for sufficient duration in distilled water medium using Yttria Stabilized Zirconia (YSZ) balls. In the milling process, the particles experience mechanical stresses at their contact points due to compression, impact or shear with the milling medium or with other particles. The mechanical stress leads to elastic and inelastic deformation. If the stresses exceed ultimate strength of the particle, it will fracture the particles. The mechanical energy supplied to the particle is used not only to create new surfaces but also to produce other physical changes in the particle.

2.1.2.3 Calcination

Calcination is the intermediate heat treatment at a lower temperature prior to sintering. Calcination involves chemical decomposition reactions, in which a solid reactant is heated to produce a new solid plus a gas which are commonly used for the production of powders of simple oxides. The calcination conditions such as temperature, duration and heating atmosphere are important factors controlling densification during sintering. Though calcination does not yield the final phases of interest, consistent products may form during the process.
2.1.2.4 Grinding

The grinding of calcined powder helps to reduce the particle size and hence to increase the surface area to promote densification during sintering. Grinding also aids to homogenize the compositional variations that may still exist or that may arise during calcination. If the grind is coarser the ceramic can have larger intergranular voids and lower sintered density. If grinding is too fine, the colloidal properties may interfere with subsequent forming operations. Generally, grinding up to a grain size of about 5 μm is advisable. Generally for grinding purpose ball mill or agate mortar with pestle is used. In large scale production of ceramics a grinding medium is chosen that suffers very little wear.

2.1.2.5 Addition of Polymeric Binder

The main objective of adding polymer binder is to impart sufficient strength and appropriate mechanical properties for handling and shaping the ceramic during the post forming stage. The polymeric dispersions and organic binders provide the pressed ceramic powders with optimal properties for thickening abilities and mechanical strength of the pressed samples. Hence in modern ceramics technology, a narrow range of watersoluble organic binders, such as poly vinyl alcohol (PVA) or poly ethylene glycol (PEG) is most often applied to improve the rheological properties of the powder compact. The recent research trends suggest that small amount (3 – 4 wt %) of the PVA and PEG are ideal binder additives for fabrication of microwave dielectric ceramics. Optimal addition of the binder will not affect the dielectric properties as it will burn out at low temperatures (400 – 500°C).

2.1.2.6 Forming or Shaping

Forming or shaping is the process of making the powder in the desired form or shape. Various methods like dry uniaxial pressing, isostatic pressing, calendaring, extrusion, jiggering, injection moulding, slip casting, band casting, silk screening etc. are available for shaping bulk ceramic specimens. In the present study the fine powder is compacted into cylindrical specimen by uniaxial dry-pressing. Compaction is done
slowly to facilitate the escape of the entrapped air. Internal lubricants such as Stearic Acid dissolved in Propan 2-ole, was used to reduce the friction between the powder and die wall. Pressures of the range 50-150 MPa is ideal in low loss ceramic forming.

2.1.2.7 Solid State Sintering

Sintering is the heat treatment of powder compacts at elevated temperatures, where diffusional mass transport is appreciable which results in a dense polycrystalline solid\(^{14}\). The purpose of sintering is the reduction of compact porosity. The development of microstructure and densification during sintering is a direct consequence of mass transport through several possible paths and one of these paths is usually predominant at any given stage of sintering\(^{15,16}\). The normal sintering method is also termed as standard pressure sintering and is used in the present investigation. The pressed ceramic green sample is loaded over cleaned platinum plates and kept in high temperature furnaces. In this method at a certain temperature the ceramic begin to diffuse and shrinkage occurs resulting in densification\(^{17}\). Usually the sintering temperature is a little below the melting point of the ceramic. In solid state sintering mechanism, the bulk material transport can be by (i) volume diffusion, (ii) grain boundary diffusion, (iii) surface diffusion or by (iv) evaporation-condensation.

During sintering, the surface energy is reduced by transferring matter from the interior of grains to adjacent pores. Grain boundaries serve as vacancy sinks. Grain growth also takes place in parallel with densification\(^{18}\), which is favoured by reduction in the area of grain boundaries. Rapid growth of discontinuous grains during sintering will trap porosity,\(^{19}\) which in turn will deteriorate the dielectric properties. On the otherhand, if the material contains a large fraction of low-melting vitreous phases, then densification is accelerated by liquid-phase sintering\(^{20}\). For microwave dielectric resonator applications, ceramics sintered by solid-state diffusion show better quality factor.

2.1.2.8 Effect of Dopants in Sintering

Dopants can significantly affect the sintering process. They can act either as (i) substitution ions (ii) grain boundary pinning to form secondary phase or (iii) as solute
segregation to grain boundaries inhibiting discontinuous grain growth. In the first case bulk material transport is enhanced due to the introduction of vacancies when a solute of different valancy is added\textsuperscript{21}. The presence of vacancies (or defects) speed up the transport mechanism. In the second mechanism, formation of second phase particles at grain boundaries acts to pin up the grain boundaries and thereby prevents discontinuous grain growth. The third mechanism is similar to the second one, but the grain growth inhibitor is an adsorbed solute. The role and effect of dopants on the densification and microwave dielectric properties of low loss ceramics are described in detail in Chapter 3.

2.1.2.9 Liquid Phase Sintering

When a wetting liquid is present during the process of sintering, bulk viscous flow can result in volume shrinkage. When the liquid coats each grain, the material can often be sintered to a higher density at a lower temperature with less tendency for exaggerated grain growth. The liquid phase wets the surface of solid phase, partially dissolves and pulls the mass of particles together so that a large fraction of pores is filled with glass. The role and effect of glass additives on the densification and microwave dielectric properties of low loss ceramics are explained in Chapter 4.

2.2 STRUCTURAL AND MICROSTRUCTURAL CHARACTERIZATION OF DIELECTRIC RESONATORS

2.2.1 X-Ray Diffraction Methods

The structure of the powdered ceramic specimens in this investigation were analyzed by X-Ray diffraction (XRD) techniques. The X-Ray diffraction method is most useful for qualitative, rather than quantitative, analysis (although it can be used for both). An X-Ray diffractometer utilizes a powdered sample, a goniometer, and a fixed-position detector to measure the diffraction patterns of unknowns. The powdered sample provides (theoretically) all possible orientations of the crystal lattice, the goniometer provides a variety of angles of incidence, and the detector measures the intensity of the diffracted beam. The resulting analysis is described graphically as a set of peaks with percentage intensity on the Y-axis and goniometer angle on the X-axis. The exact angle and intensity
A monochromator is used to ensure a specific wavelength reaches the detector, eliminating fluorescent radiation. The resulting trace consists of a recording of the intensity against counter angle (2θ). The trace can then be used to identify the phases present in the sample. Diffraction data from many materials have been recorded in a computer searchable Powder Diffraction File (PDF/JCPDS File). Comparing the observed data with that in the PDF allows the phases in the sample to be identified. In this investigation XRD spectra were recorded using CuKα radiations employing Philips X-ray Diffractometer (Model-Expert Pro).

2.2.2 Scanning Electron Microscopic Methods

Scanning Electron Microscopic (SEM) methods were adopted in the present study to analyze the microstructure of sintered and thermally etched surface of ceramic samples. In this method, an electron beam is produced at the top of the microscope by an electron gun. The electron beam follows a vertical path through the microscope, which is held within a vacuum atmosphere. The beam travels through electromagnetic fields and lenses, which focus the beam down toward the sample. Once the beam hits the sample, electrons and X-Rays are ejected from the sample. Detectors collect these X-Rays, backscattered electrons, and secondary electrons to convert them into a signal that is sent to a screen similar to a television screen. This produces the final image. All metals are conductive and require no preparation before being used. All non-metals need to be made conductive by covering the sample with a thin layer of conductive material like gold. In this study we have used a Scanning Electron Microscope of Model S – 2400, Hitachi, Japan for the microstructural evolution of ceramic samples prepared.

2.3 MICROWAVE CHARACTERIZATION OF DRs

2.3.1 Introduction

The generally adopted methods for the measurement of dielectric and magnetic properties of materials at microwave frequencies can be classified into (i) perturbation
methods, (ii) optical methods, (iii) transmission line methods, (iv) reflection methods and (v) exact resonance methods. The choice of method or combination of methods will depend on the value of \( \varepsilon \) and loss factor, the amount of material available, the accuracy required, and whether the technique is required for research or routine measurements.

**Perturbation Technique:** The perturbation methods are highly suitable for materials of small size since the material should not alter the field configuration considerably. These techniques are suitable for dielectric constants less than 10, although this range can be extended by an exact solution of the resonator containing the specimen\(^{27}\). Hence this technique is not commonly used for DR characterization.

**Optical Methods:** Optical methods are applicable for wavelength of below one centimetre. Since this method requires large amount of material it is not suitable for DRs\(^{28}\).

**Transmission line techniques:** This technique has a serious disadvantage of the very small waveguide size used below 4 mm, which gives rise to practical difficulties\(^{29}\). More over imperfections in the sample dimensions produce errors in the measurement. It was reported that the accuracy of transmission mode measurements of the dielectric properties is more in weak coupling conditions\(^{30}\).

**Reflection methods:** In reflection methods, waves reflected from the dielectric are studied. When the dielectric constant becomes large, there occurs considerable error in the measurement of complex voltage reflection coefficient\(^{31}\).

**Exact Resonance methods:** Exact resonance method is the most accurate method as compared to the above-mentioned methods for the measurement of DRs. In this method, the exact resonant frequency of the resonator is measured using different techniques\(^{32}\). From the resonant characteristics, parameters like \( \varepsilon_r \), \( Q_e \) etc are determined. Special techniques of exact resonance methods are used in the present study, which are described in detail in the following sections.
2.3.1.1 Network Analyzer

This is the major instrument used in this investigation for the characterization of DRs and DRAs. Network Analyzer is a swept frequency measurement equipment to completely characterize the complex network parameters in comparatively less time, without any degradation in accuracy and precision. Two types of network analyzers are available, scalar and vector network analyzers. Scalar network analyzer measures only the magnitude of reflection and transmission coefficients while the vector network analyzer measures both the magnitude and phase.

Fig. 2.2 Schematic diagram of HP 8510C network Analyzer

A vector Network Analyzer consists of the following system

1) Microwave Source
2) Test Set
3) Signal Processor
4) Display Unit

The schematic diagram of the network analyzer controlled by IBM PC is shown in Fig. 2.2. The synthesized source or the sweep oscillator provides the RF stimulus. The sweep oscillator drives the network under test and two receivers. The first receiver is used to accurately measure the Reflection or input voltage to the network. The second receiver is called the Transmission channel and is used to measure the output of the network under test. The ratio of the output to the input level is displayed as dB and is the voltage gain or loss of the network. The analyzer can operate in ramp or in step mode. In the ramp mode the analyzer directs the source to sweep in a linear ramp over the frequency and in the step mode, it provides maximum precision.

2.3.2 Measurement of Dielectric Constant (\(\varepsilon_r\))

In this method developed by Hakki and Coleman\(^a\) a circular disc of material whose \(\varepsilon_r\) to be measured is inserted between two mathematically infinite conducting plates, as shown in Fig. 2.3.

![Fig. 2.3 Hakki-Coleman method for measuring \(\varepsilon_r\) by end shorted method](image1)

![Fig. 2.4 Mode charts of Hakki-Coleman giving \(\alpha_r\) as functions of \(\beta\)](image2)

If the dielectric material is isotropic then the characteristic equation for this resonant structure operating in the \(TE_{0m1}\) mode is written as
where $J_0(\alpha)$ and $J_1(\alpha)$ are Bessel functions of the first kind of orders zero and one respectively. The $K_0(\beta)$ and $K_1(\beta)$ are the modified Bessel functions of the second kind of order zero and one respectively. The parameters $\alpha$ and $\beta$ depend on the geometry, the resonant wavelength inside and outside the DR respectively and dielectric properties. Thus

$$\alpha = \frac{\pi D}{\lambda_o} \left[ \varepsilon - \left( \frac{l \lambda_o}{2L} \right)^2 \right]^{1/2} \quad (2.2)$$

$$\beta = \frac{\pi D}{\lambda_o} \left[ \left( \frac{l \lambda_o}{2L} \right)^2 - 1 \right]^{1/2} \quad (2.3)$$

where

- $l$ = the longitudinal variations of the field along the axis
- $L$ = Length of the DR
- $D$ = Diameter of the DR
- $\lambda_o$ = free space resonant wave length

The characteristic equation is a transcendental equation and hence a graphical solution is necessary. Corresponding to each value of $\beta$ there are infinite number of $(\alpha_n)$ that solves the characteristic equation. Hakki and Coleman obtained a mode chart showing the variation of $\alpha$ values as a function of $\beta$ and are shown in Fig. 2.4.
The dielectric constant of the resonator can be calculated using the mode chart parameters ($\alpha_l$ and $\beta_l$), the resonant frequency ($f_r$) and the dimensions of the dielectric puck using the equation

$$\varepsilon_r = 1 + \left( \frac{c}{\pi D f_r} \right)^2 \left( \alpha_l^2 + \beta_l^2 \right)$$  \hspace{1cm} (2.4)

The horizontally oriented E-field probes for coupling microwaves to the DRs, was proposed by Courtney\textsuperscript{34} which enabled to span a wide range of frequencies, since there is no cut-off frequency for coaxial lines. The $TE_{01}$ mode is used for the measurements since this mode propagates inside the sample but is evanescent out side the geometry of DR. Therefore a large amount of electrical energy can be stored in the high $Q$ dielectric resonators\textsuperscript{35}. However, in the open space post resonators setup, a part of electrical energy is radiated out as evanescent field and hence the axial mode number is usually expressed as $\delta$ since it is less than 1 (i.e. $TE_{01\delta}$). In the end shorted condition the $E$-field becomes zero close to the metal wall and electric energy vanishes in the air gap\textsuperscript{36}.

In the experimental setup, a Vector Network Analyzer, HP 8510 C is used for taking measurements at microwave frequencies. The HP 9000, 300 series instrumentation computer, interfaced with network analyzer makes the measurement quicker and accurate. The specimen is placed approximately symmetrical with the two $E$-probes. The resonant modes are visualized by giving a wide frequency range by adjusting the Network Analyzer. To select the $TE_{011}$ resonance from the several modes having non zero $E_z$ components, the upper metal plate is slightly tilted to introduce an air gap. As the plate is tilted the entire $TM$ modes move rapidly to the higher frequencies while the $TE_{011}$ mode remains almost stationary. It is well known that in exact resonance technique, $TE_{011}$ is least perturbed by the surroundings. After identifying the $TE_{011}$ resonant frequency or central frequency ($f_c$), the span around $f_c$ is reduced as much as possible to get maximum resolution. The 3 dB bandwidth of the curve decreases and a stage of saturation is reached when the width will remain the least possible. The coupling loops are fixed at
CHAPTER 2

this position and the centre frequency can be noted corresponding to the maxima as \( f \). By knowing the diameter ‘\( D \)' and length ‘\( L \)' of the sample \( \beta \) is calculated using equation 2.

3. From the mode chart, the value of \( \alpha_1 \) corresponding to \( \beta_1 \) value is noted. The dielectric constant \( \varepsilon_r \) is calculated using Eqn. 2.4.

### 2.3.3 Measurement of Unloaded Quality Factor (\( Q_u \))

Various methods\(^{37,38,39,40}\) are available in literature for measurement of \( Q \)-factors of microwave resonators. However, all these methods failed to account for the practical effects such as noise, crosstalk, coupling losses, transmission line delay, and impedance mismatch introduced by a real measurement system. Moreover, the microwave loss factors of DRs are affected by many other intrinsic and extrinsic factors (See section 1.2.2 of Chapter 1). Inadequate accounting of these effects may lead to significant uncertainty in the measured quality factor of the DRs. End-shorted method applied for the measurement of \( \varepsilon_r \) can also be used for measuring the unloaded quality factor (\( Q_u \)). But the quality factor measured for the \( TE_{011} \) mode using the parallel plate rod resonator is very low since there occurs losses due to conducting plates, radiation etc.

![Fig. 2.5 The cavity set up for the measurement of Q factor](image)

![Fig. 2.6 The method of calculating Q from resonant mode using Eqn. 2.5](image)

In the present study the \( Q_u \) of the DR samples are measured by using a method proposed by Krupka et al.\(^{41}\) (See Fig. 2.5). In this method, the DR specimen to be characterized is placed inside a cylindrical copper/invar cavity whose inner surface is
silver coated to reduce radiation loss. The diameter of the cavity is designed almost four times than that of the sample diameter to reduce the effect of cavity shielding. Samples with diameter/length ($D/L$) ratio of 1.8 - 2.2 is preferable to get maximum mode separation and to avoid interference from other modes. The DR specimen is kept over a quartz spacer placed at the inner bottom surface, which enables to avoid the conduction loss. The cavity is provided with a tunable upper lid. This enables to tune the height of air layer in the metallic cavity and hence more accuracy in the determination of the resonant mode and $Q_u$ can be attained and also allows to measure samples with various dimensions. Microwaves are fed into the sample using two loop coaxial antennas which provides a magnetic coupling to excite the transmission mode resonance spectrum of dielectric cylinder. The coupling is adjusted to be optimum (weak coupling for high $Q_u$ and strong coupling for lossy samples). Observe $S_{21}$ versus frequency spectrum. In principle the cavity has infinite number of modes, when excited with microwave spectrum of frequencies. $TE_{01s}$ mode is identified as the fundamental mode with least perturbation when the tunable top lid is adjusted properly. After identifying the desired mode, the lid is fine tuned to get maximum separation between $TE_{01s}$ and any nearby cavity modes, to attain maximum possible accuracy in the $Q_u$ measurement. Measure $TE_{01s}$ mode frequency and the unloaded and the 3 dB bandwidth from the resonance spectrum (See Fig. 6) to calculate the $Q$ factor as

$$Q = \frac{f_u}{\Delta f} \quad (2.5)$$

One can assume that for low loss dielectrics, the unloaded $Q$ factor is equal to loaded $Q$ factor if coupling is weak. In the microwave frequency range the dielectric loss increases with frequency and hence there exists an inverse relationship between quality factor and resonant frequency. Hence the quality factor of dielectric resonators are conventionally represented in units of $Q_u \times f$, rather than $Q_u$. 

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2.3.4 Measurement of Temperature Coefficient of Resonant Frequency ($\tau_f$)

Stability of resonant frequency with temperature is an important property of a DR to operate in microwave devices. $\tau_f$ is defined as

$$\tau_f = \frac{1}{f} \frac{\Delta f}{\Delta T}$$  \hspace{1cm} (2.6)

The unit of $\tau_f$ is part per million per degree Celsius. In order to measure $\tau_f$, DR is kept in the Hakki-Coleman end-shorted position between two copper plates. This is then kept on a hot plate and the entire system is insulated in an isothermal enclosure. The $E$-field probe is kept near the DR in such a way to get the $TE_{011}$ resonant mode excited. The setup is then slowly heated ($\sim 1^\circ$C/minute) in the range 25 to 80$^\circ$C. The probe of the thermocouple is kept just inside the isothermal enclosure so that it does not disturb the resonant frequency. Shift in the resonant frequency of $TE_{011}$ is noted at every 2$^\circ$C increment in temperature. The variation of resonant frequency is plotted as function of temperature and the $\tau_f$ is calculated from the slope of the curve using eqn. 2.6.

2.3.5 Error Calculations in Dielectric Property Measurements

The measurement of microwave dielectric properties were done with two decimal point accuracy. Usually three samples were prepared in a batch corresponding to a particular composition and the measurements were made at least twice per each specimen. The error in $\varepsilon_r$ is calculated using the root sum of squares (RSS) method. The accuracy of $\varepsilon_r$ measurement is restricted to the accuracy in measurement of resonant frequency and dimensions of the sample. Hence the possible errors in the measured value of dielectric constant of a sample of height ($L$), radius ($r$) and resonant frequency ($f_r$) given by

$$\Delta \varepsilon_r = \left[ \left( \frac{\partial \varepsilon_r}{\partial L} \Delta L \right)^2 + \left( \frac{\partial \varepsilon_r}{\partial r} \Delta r \right)^2 + \left( \frac{\partial \varepsilon_r}{\partial f_r} \Delta f_r \right)^2 \right]^{1/2}$$  \hspace{1cm} (2.7)
CHAPTER 2

If the independent sources of error corresponds to one standard deviation, then the error in $\varepsilon_r$ will also correspond to one standard deviation. The errors in unloaded quality factor ($Q_u$) and temperature coefficient of resonant frequency ($\tau_f$) were calculated using RSS method by taking partial derivative of these parameters with respect to independent variables.

2.4 DESIGN METHODOLOGY AND FABRICATION OF DRAs

The building block for dielectric resonator antenna is a block of dielectric material. Various shapes are possible for the antenna solely depending on the geometry of the DR sample. The physical dimensions and $\varepsilon_r$ of the dielectric block determines the resonant frequency of the antenna. Due to the ease of fabrication and better performance reported, in the present work investigations were mainly concentrated on cylindrical, rectangular and elliptical DRAs.

![Fig. 2.7 Geometry of a cylindrical DRA configuration](image)

The geometry of a representative DRA studied in this investigation is depicted in Fig. 2.7. The geometry comprises a dielectric disk resonator of specific shape (cylinder, ellipsoid/rectangular) synthesized through solid-state ceramic route as explained in sections 2.1 and the dielectric properties are characterized as described in section 2.3 of
this chapter. The dielectric constant and dimensions of the DR disk are controlled to operate the antenna in the desired frequency range. The DR is electromagnetically coupled with a 50 Ω microstrip feed line of width 3 mm and length $S_1 = 50$ mm, fabricated on a low loss, low dielectric constant ($e_r_{sub}$) substrate material (glass epoxy) of dielectric constant $e_r = 4.28$ and thickness $h = 1.6$ mm backed by a conducting plane.

2.5 MEASUREMENT TECHNIQUES OF ANTENNAS

2.5.1 Measurement of return loss, resonant frequency and bandwidth

Network Analyzer is calibrated to one full port and the test antenna is connected to PORT 1 of the S-parameter test set. The measured $S_{11}$ in ‘LOGMAG’ data is acquired

![Experimental setup for the measurement of return loss and resonant frequency](image)

and stored in ASCII format in the computer interfaced with the network analyzer (Fig. 2.8), using ‘MERL Soft’. The resonant frequency is determined from the dip of the return loss curve. The impedance bandwidth is measured by taking the range of frequencies
(Δf) over which the return loss is greater than or equal to 10 dB. Percentage bandwidth can be calculated using the expression \((Δf/f_c) \times 100\), where \(f_c\) is the centre frequency of the operating band.

### 2.5.2 Measurement of Radiation Pattern

Antenna radiation pattern is the spatial distribution of the electromagnetic field radiated by the antenna. Generally patterns in two-principle plane, \(E\) and \(H\) planes are taken. The principal plane patterns (co-and cross-polar) of the test antenna are measured.

![Experimental setup for the measurement of radiation pattern](image)

**Fig. 2.9** Experimental setup for the measurement of radiation pattern
by keeping the antenna in receiving mode inside an anechoic chamber. The experimental setup for the measurement of radiation pattern is shown in Fig. 2.9. HP 8510C Network Analyzer, interfaced to an IBM PC, is used for the pattern measurement. The PC is attached to a STIC 310C position controller. The test antenna is mounted on the antenna positioner kept inside the anechoic chamber at a distance \( R > \frac{2D^2}{\lambda} \) from a wideband horn antenna (transmitter), where \( D \) is the maximum dimension of the antenna and \( \lambda \) is the wavelength. The test antenna and the transmitting antenna are connected to Port 2 and Port 1 of the network analyzer respectively.

Radiation patterns of the antenna at multiple frequency points can be measured in a single rotation of the test antenna by using MERL Soft. The positioner will stop at each step angle and take S21 measurement at different frequency points in the operating band. The process will repeat till it reaches the stop angle. The entire measured data is stored in ASCII format and can be used for further processing. The different radiation pattern characteristics like half power beam width, cross-polar level etc. are obtained after the analysis of the radiation pattern.

2.5.3 Measurement of Gain

The setup for the measurement of gain is the same as that used for pattern measurement. The relative gain of the new antenna is measured with a standard circular patch antenna operating at the same frequency and fabricated on the same substrate. The standard circular microstrip antenna is kept inside the anechoic chamber and connected to Port 2 of the Network Analyzer. The test antenna in the transmitting mode is connected to Port 1. The antenna is bore-sighted and a THRU RESPONSE calibration is performed in the Network Analyzer and stored in the CAL SET. This is the reference gain response. The standard antenna is now replaced with the test antenna and the plot displayed on the Network Analyzer will directly give the relative gain of the test antenna with respect to the standard circular antenna.
2.6 SIMULATION OF DRs AND DRAs

2.6.1 Introduction

The traditional process for solving EM (Electromagnetic) problems was to build a prototype, accumulate performance test data by subjecting the prototype to various experiments, correct deficiencies, and retesting, which normally require several cycles. With the advent of 3D-EM (Three Dimensional Electro-Magnetic) simulation techniques, these problems became efficient and simplified. However, these methods were generally not economically feasible since they required the use of supercomputers as well as a substantial knowledge of EM theory and advanced numerical techniques. During the last decade, the three dimensional electromagnetic simulation capabilities have significantly advanced due to the tremendous progress in computer hardware technology combined with an improvement in numerical techniques. Most of the electromagnetic problems can now be analyzed and understood by 3D-EM simulation which is performed by solving Maxwell's equations numerically. Recent advances in computer hardware technology and EM simulation algorithm enabled to visualize 3D EM wave propagation, even with personal computers. The following are very important criteria to be considered when selecting a 3D-EM software tool: (i) Consistently reliable results (ii) Relatively short computational time, compatible with the development schedule (iii) Simplicity of operation, particularly the ease of CAD input and mesh generation (iv) Compatibility with the requirements (v) Compatibility with other CAD tools and (vi) Versatility and expandability. Various numerical methods have been used to solve different EM problems. These methods include mode matching technique, the finite element method (FEM), the finite-difference method (FDM), the finite-difference time-domain method (FDTD), the moment method (MoM) and Transmission Line Matrix (TLM) method. Each method has got its own advantages and deficiencies and hence a single method can not be used to solve all the problems related with EM wave propagation. In this work the 3D TLM technique has been employed to describe the interaction of EM wave with dielectric resonators and the characteristics of DRAs.
2.6.2 Transmission Line Matrix (TLM) Method

Transmission Line Modeling (TLM) or Transmission Line Matrix Modeling (TLM) is a general numerical simulation technique suitable for solving field problems. In 1971, Johns & Beurle have introduced the principles of TLM time domain methods in electromagnetics. Subsequently, this method was pioneered by the microwave engineering community. Its main application has been in electromagnetics, but it has also been applied to thermal or diffusion problems as well as acoustics. The TLM method belongs to the general class of differential time-domain numerical modeling methods.

The basic approach of the TLM method is to obtain a discrete model which is then solved exactly by numerical means; approximations are only introduced at the discretisation stage. This is to be contrasted with the traditional approach in which an idealized continuous model is first obtained and then this model is solved approximately. For electromagnetic systems, the discrete model is formed by conceptually filling space with a network of transmission-lines in such a way that the voltage and current give information on the electric and magnetic fields. The point at which the transmission-lines intersect is referred as a node and the most commonly used node for 3-dimensional work is the symmetrical condensed node. At each time step, voltage pulses are incident upon the node from each of the transmission-lines. These pulses are then scattered to produce a new set of pulses which become incident on adjacent nodes at the next time step. Each 3D node is the combination of three shunt and three series nodes. The three shunt nodes represent the E-field, and the three series nodes represent the H-field in the three coordinate directions as shown in Fig. 2.10 (a). To accommodate discontinuities such as metallic boundaries and slabs of dielectric or magnetic material, open-circuited and short-circuited stubs of admittance $Y_0$ and impedance $Z_0$ are added to shunt and series nodes respectively. The 3D node is further equipped with stubs of infinite length and normalized characteristic admittance $G_0$ to facilitate any dielectric losses which may be required. The 3D geometry of a problem is set up by connecting many such 3D nodes together. The relationship between the incident pulses and the scattered pulses at each node is determined by the scattering matrix, which is set to be consistent with the
following set of Maxwell's equations. Additional elements, such as transmission-line stubs, can be added to the node so that different material properties can be represented.

\[
\frac{\partial H_x}{\partial y} - \frac{\partial H_y}{\partial z} = \varepsilon_r \varepsilon_0 \frac{\partial E_x}{\partial t} + \sigma E_x \tag{2.8}
\]

\[
\frac{\partial H_y}{\partial z} - \frac{\partial H_z}{\partial x} = \varepsilon_r \varepsilon_0 \frac{\partial E_y}{\partial t} + \sigma E_y \tag{2.9}
\]

\[
\frac{\partial H_z}{\partial x} - \frac{\partial H_x}{\partial y} = \varepsilon_r \varepsilon_0 \frac{\partial E_z}{\partial t} + \sigma E_z \tag{2.10}
\]

\[
\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial z} = -\mu_r \mu_0 \frac{\partial H_x}{\partial t} \tag{2.11}
\]

\[
\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial x} = -\mu_r \mu_0 \frac{\partial H_y}{\partial t} \tag{2.12}
\]

\[
\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial y} = -\mu_r \mu_0 \frac{\partial H_z}{\partial t} \tag{2.13}
\]

In these equations, the following equivalences apply:

- \( E_x = \) the common voltage at shunt node \( E_x \)
- \( E_y = \) the common voltage at shunt node \( E_y \)
- \( E_z = \) the common voltage at shunt node \( E_z \)
- \( H_x = \) the common current at series node \( H_x \)
- \( H_y = \) the common current at series node \( H_y \)
- \( H_z = \) the common current at series node \( H_z \)

\( \varepsilon_0 \) and \( \mu_0 \) are the permittivity and permeability of free space, \( \varepsilon_r \) and \( \mu_r \) are their relative values and \( \sigma \) is the conductivity. It should be noted that the values of \( \varepsilon_r, \mu_r, \) and \( \sigma \) can assign values depending on the material properties.
For the purpose of analysis, any of the six electromagnetic field components is excited by introducing impulses at various points in the network model. The impulses travel along the ideal TEM lines and are scattered at the individual nodes. In this way the time-domain propagation of all six EM field components is obtained simultaneously. A solution of any (or all) of the field components is available anywhere within the geometry of the problem. The output consists of a stream of impulse amplitudes corresponding to the output impulse function for the particular field component under consideration. Finally, the Fourier transform of this function is taken to yield the response to an excitation varying sinusoidally with time.

In general, models can be described as low, medium or high loss systems. For low loss systems, the spectral content of the truncated time series is required since the amplitude of any resonances will increase in proportion to the number of time steps (tending to infinity in the limit). For high loss systems, in which the signal effectively decays to zero within the simulation time, the actual spectral content of the complete time series is obtained. Moderately damped systems present a problem since an excessive number of time steps would be required for the signal to decay significantly. In this case, the spectral content of the truncated time series is obtained as an estimation of the spectral content of the complete time series.

One of the advantages of TLM is that the core algorithm is very straightforward. Each time step can be divided into two processes: scatter and connect. During the "scatter" stage, voltage pulses incident on the node are scattered to produce a new set of outgoing voltage pulses. During the "connect" stage, voltage pulses are transferred to the adjacent nodes. It is possible to combine both processes together but it is simpler to consider them separately. Nowadays 3D-TLM methods are popular measurement technique because of their accuracy, efficiency and ability to provide broadband data over a wide frequency range. In the present investigation, we have used a Computer Aided Simulation (CAD) package named Micro-stripes based on 3D-TLM techniques.
Aided Simulation (CAD) package named Micro-stripes 6.5\textsuperscript{56} based on 3D-TLM techniques.

![Diagram of Micro-stripes](image)

Fig. 2.10 Schematic diagram of various steps involved in the simulation using Micro-stripes 6.5

Micro-Stripes is a complete software tool for the 3D electromagnetic analysis and design of devices and structures required in the high frequency range. The design process follows five easy steps: (i) Define the geometry using a versatile and intuitive solid modeler based on the ACIS kernel, or import the geometric model from another CAD package (ii) Assign the material properties to the geometry (iii) Choose the type of excitation (e.g. port or plane wave) (iv) Definition of the results indented to obtain and (v) Let the efficient processing of time domain solver based on the TLM to yield the results. Examples for various processes involved in the simulation process using Micro-stripes is shown in Fig. 2.10 (b) to 2.10 (d). The geometric structure for simulation was made using solid modeler based on ASCis Kernel plotting software. Fig. 2.10 (b) shows the main application window from which all the tools of the CAD can be accessed.
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Projects are created using this window, and system designs held within the projects are studied. The advanced build module provided allows the 3D solid modelling, which is used to create the geometry or import it from other CAD tools. Most industry standard CAD formats can be imported. Within Build the electromagnetic parameters and results required are set. Material properties like conductivity, relative permittivity and dielectric loss as well as excitation mechanisms can be assigned properly. TLM has multigrid mesh capability to assign isotropic as well as anisotropic properties of different materials. The mesh size can be manually assigned or it can be automatized. Fig. 2.10 (b) and 2.10 (c) shows the model of a three dimensional geometric structure (Cavity and Hakki-Colemann set up) for the measurement of microwave dielectric properties of a dielectric resonator (See Chapter 5, Section 5.3.1.2) designed using Micro-stripes 6.5.

To run the simulation program, the Build module of Micro-stripes divides the model and space it occupies (the work space) into a large number of spatial elements or cells. These cells are small rectangular blocks arranged on a Cartesian mesh. The accuracy and time step of simulation depends on cell size. The duration for the process can be reduced by lumping or multigriding. The 3D-TLM simulator considers the EM field to be uniform within each cell. It is therefore necessary for the cells to be small on the scale of distance over which the field varies. Build chooses the default cell-size to be $1/10^6$ of the free space wavelength at the requested maximum model frequency. Auto-mesh facility takes into account the material properties and reduces the cell-size within dielectric bodies. Build sets a sensible default duration. Build monitor the response after every multigriding analysis and display a graph of the time-domain response which is updated as the simulation proceeds. Simulation terminates after completing all the time domain truncation and verifying the results with the input given by the user.

TLM has the feasibility for the calculation and displaying of field distributions (Electric, Magnetic fields, surface currents, power flows, power densities, power loss densities and SAR) at specified frequencies after a single run. This enables the resonant mode identification of DRs and DRAs. Two such examples are illustrated in Figs. 2.10 (d). After finishing the simulation, the graph plotter of TLM provides a view of time and frequency domain results assigned to it. In this thesis TLM method was adopted for the
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simulation of transmission mode resonance spectra of cavity shielded and end-shorted
dielectric resonators (See Chapters 5 and 6) to predict their microwave dielectric
properties. In addition the simulation technique was also applied to simulate the antenna
characteristics (See Chapter 8) and to identify the excited modes of DRA.
2.7 REFERENCES


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