CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The dielectric resonator antenna (DRA) has attracted much attention in the last three decades for wireless communication. The utility of DRAs can be enhanced by utilising different microwave dielectric materials for their design and development. In the DRA structure, the ceramic materials can find its place either as an antenna resonating element and/or as a substrate. The resonating element should possess low tan delta, dielectric constant ranging from 5 – 50, nearly zero temperature coefficient of resonant frequency. On the contrary, the requirement for a dielectric material for its application as substrate is low dielectric constant, low tan delta, low coefficient of thermal expansion (< 20 ppm/^{o}C), no reactivity with electrode material, good thermal conductivity etc. Both these material constraints for the resonator as well as for the substrate are met by the Low Temperature Co-fired Ceramic (LTCC) materials. So, the present investigation focuses on the development of different LTCC materials for the design and fabrication of DRAs. A layout showing requirement of LTCC material for dielectric resonator antenna application is shown in Figure 1.1.

1.1 Antennas

1.1.1 Emergence of antennas

The presence of electromagnetic waves was first demonstrated by German Physicist Heinrich Hertz in 1887, which later resulted in the emergence of antenna and other electromagnetic devices and systems. Since then, many simple but efficient antennas were developed which lead to the growth of radio-frequency technology. With the invention of optical fibre communication, most of the researchers got interested in its development with fast pace during 1980s. In the early 1990s, the success of the second-generation (2G) mobile phone opened the new scope for the telecommunication industry. Many new RF communication standards, patents and papers have been reported and developed over the last three decades. Thus wireless communication engineers are striving hard in order to build a wireless world.

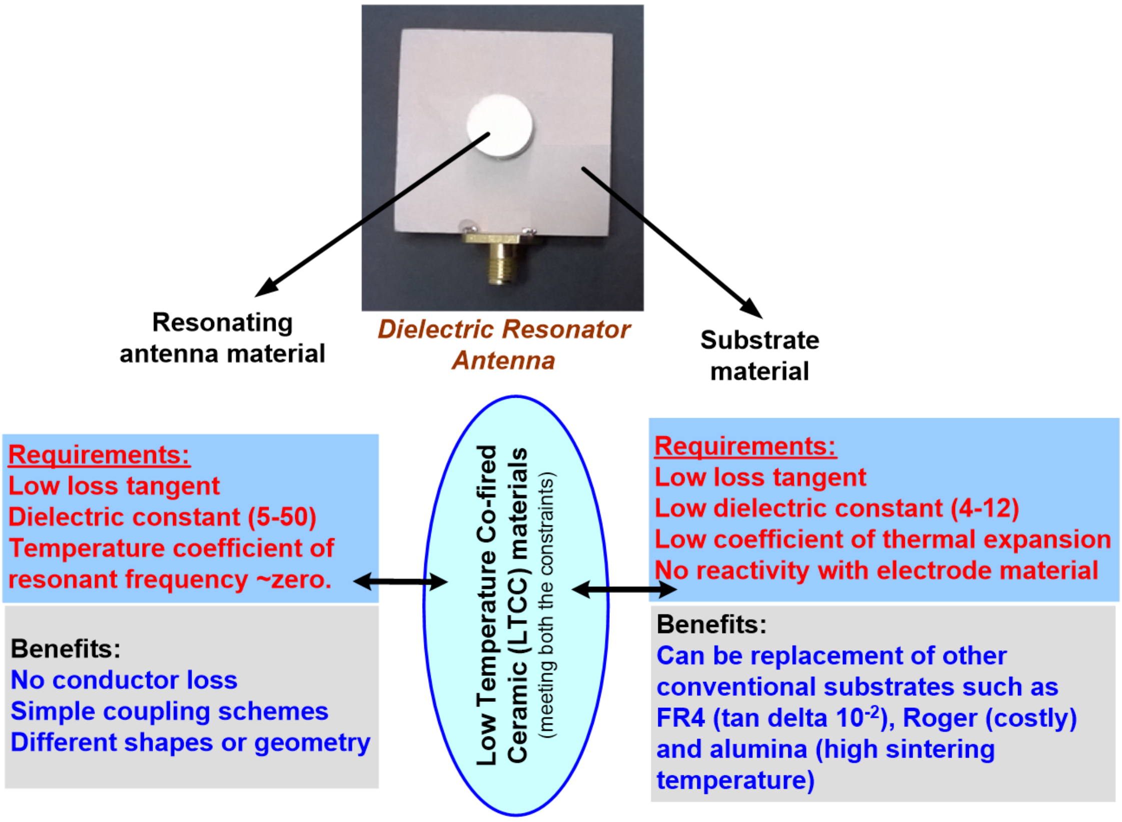


Figure 1.1 Layout showing LTCC material for DRA.

Antenna engineering enjoyed a very successful period during 1940–1990s. The introduction and technological advances of some new elements of radiation, such as aperture antennas, reflectors, microstrip antennas and dielectric resonator antennas were responsible for its success. A major factor in the success of antenna technology has been the advances in computer architecture and numerical computation techniques. Today antenna engineering is deliberated as a truly fine engineering art.

The antenna can be defined as “a means for radiating and receiving radio waves” [IEEE (1969, 1974, 1983)]. In other words, the antenna is the transitional structure between the free-space and a guiding device. It is a necessary building block of any wireless system.

There are many books covering fundamental aspects of development of antennas [Aharoni (1946); Silver (1949); Kraus (1950, 1988, 2002); Fradin (1961); Briggs and Roberts (1964, 1968); Collin and Zucker (1969); Balanis (1982, 1997, 2005); Bahl and Bhartia (1980); Bhartia et al. (1991); Garg et al. (2001); Gupta and Benella (1988); Lee and Chen (1997); Guha and Antar (2011); Kiely (1953); Anderson (1971); Chatterjee (1985); Luk and Leung (2003); Petosa (2007); Yaduvanshi and Parthasarathy (2016)].

Antennas can be broadly categorized into (i) three dimensional (3D) antennas and (ii) planar antennas. Various types of 3D antennas have been developed and brought to use in practice. For instance, the classical dish-like reflector antennas, which are very giant in size kept in a plain field and another one is the fishbone-like Yagi Uda antenna that once was used for the television transmission and reception. Some other examples of 3D antennas are wire antennas, horn antennas, dielectric resonator antennas, travelling wave antennas, parabolic reflective antennas, cassegrain antennas etc. In the modern wireless communication, either planar or low profile antennas are required. This enables them to get easily embedded into the mounting bodies for enhancing portability. Both the planar microstrip antennas and low profile dielectric resonator antennas have been under investigation for the last four decades for modern wireless communication applications such as digital cellular networks, mobile broadcasting systems, navigation systems, satellite communication systems, radar, millimetre wave automotive sensors and surveillance systems.

1.1.2 Microstrip antennas and technology

The concept of microstrip technology dates back to 1952 [Greig and Engleman (1952)]. It has been popular for microwave and millimetre wave applications since the 1970s, it recently showed tremendous growth in wireless communications as well as space-borne/airborne applications. The basic microstrip configuration is very similar to a printed circuit board (PCB) used for low frequency electronic circuits. It constitutes a low loss thin substrate coated with copper film on both sides. Printed transmission line and patches are etched out on one side of the microstrip board and the other copper-clad surface is used as the ground plane. In between the ground plane and microstrip structure, a quasi-Transverse Electro-Magnetic (TEM) electromagnetic wave is launched and allowed to spread. Rigorous study has been performed on different types of microstrip antennas. Some of the unique features of microstrip antennas such as low profile, low cost, light weight, ease of fabrication and suitability to conform on curved surface etc. have made it attractive since its early phase development. Various textbooks for the microstrip antennas have been published [Bahl and Bhartia (1980); Bhartia et al. (1991); Garg et al. (2001); Gupta and Benella (1988); Lee and Chen (1997); Guha and Antar (2011)]. But microstrip patch antenna has some drawbacks such as narrow bandwidth for electrically thin substrates, more ohmic losses at higher frequency, presence of surface waves with less radiation efficiency in case of electrically thicker substrates, spurious feed radiation, poor polarization purity and low dielectric strength. Hence these cannot handle much output power when compared to other antennas.

1.1.3 Dielectric resonator antennas (DRAs)

DRA consists of a dielectric resonator, which is a piece of dielectric material that is designed to function as a resonator for radio waves, generally in the microwave and millimetre wave bands. DRA is a resonant antenna fabricated from a low loss, low to medium permittivity dielectric ceramic material of different shapes mounted on a ground plane and fed by different feeding structures such as coaxial probe, slot, waveguide or microstrip line etc.

As compared to a microstrip antenna, the DRA has several advantages. The DRA provides wider bandwidth because the microstrip antenna radiates through only two narrow radiation slots whereas the DRA radiates through the whole surface except the grounded part. Another attractive advantage of DRA over microstrip antenna is the avoidance of surface waves and negligible conductor loss due to which DRA provides higher efficiency. Richtmyer (1939) was first to prove theoretically that the open dielectric resonators radiate into free space. However, Long et al. (1983) and McAllister et al. (1983) have first reported the systematic study and experimental demonstration on the microwave DRAs. Since then, DRA technology has become an emerging field of interest in the microwave domain. DRA also provides higher dielectric strength and therefore has higher power handling capacity than microstrip patch antenna (MPA). Certain remarkable features of DRAs are listed below.

- Wider impedance bandwidth as compared to microstrip antenna because it radiates through the whole antenna surface except the ground part while microstrip antenna radiates only through two narrow radiation slots.
- Higher efficiency
- Avoidance of surface waves

- Light weight, small volume, and low profile configuration
- Design flexibility (various resonator shapes such as hemispherical, rectangular, cylindrical, triangular etc.)
- Compatibility with different excitation techniques such as coaxial feed, microstrip line feed, aperture coupled microstrip feed etc.
- Ease of fabrication
- Wide range of dielectric constant (5–50)
- Low production cost

1.1.4 Bandwidth enhancement Techniques in DRAs

By choosing proper feeding structure and DRA configuration, bandwidth can be increased. There are various bandwidth enhancement techniques used for DRA, such as optimizing the feed mechanism and the DRA parameters (geometry and dimension), using stacked dielectric resonators in DRA designs, introduction of air gap between the ground and dielectric resonator, changing the dielectric constant of dielectric resonator and use of parasitic coupling with different resonators.

1.1.5 Applications of DRAs

Different types of DRAs for wireless communication systems have been evolved rapidly during the recent decades. Most antennas for modern wireless communications are simple in structure but usually supported by finite dielectric substrates and are mounted inside small mobile devices. The dielectric resonator antenna (DRA) is an interesting alternative for the microstrip patch antenna for satellite communication, radar and navigation applications. The material selection and the design of DRAs to satisfy the application requirements are the challenging tasks. Different applications of DRAs in the X– band include primary feed for reflector in satellite communication, transmitter or receiver in radars for weapon control military aircrafts, in weather navigation system, in mapping of ocean currents in harbour area, in capturing multi-spectral images to study the type of terrains or water bodies in earth sciences, in observing coastal and harbour traffic, in microwave radiometer to get the information of climate parameters like rain rate, ice morphology and ocean wind speed.

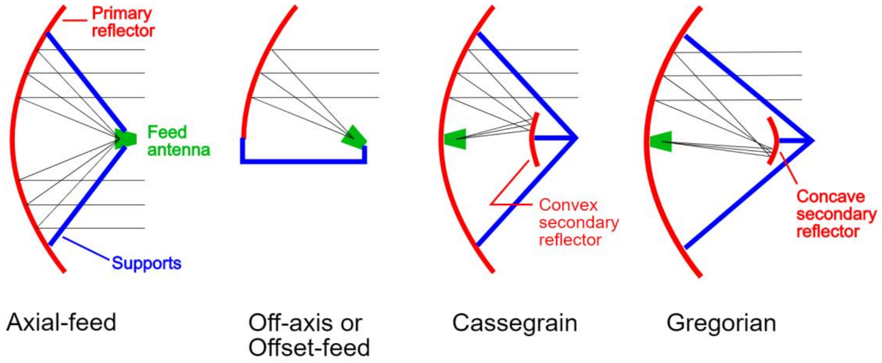


Figure 1.2 Different types of parabolic antenna feed [www.commons.wikimedia.org].

1.1.6 Recent development pertaining to DRAs

Petosa and Ittipiboon (2010) wrote a historical review article on the research carried out on DRAs. The achievable performance of DRAs designed in the last three decades for the compactness, wide impedance bandwidth, low profile, linear or circular polarization, or high gain are illustrated. The latest developments in the dielectric resonator antenna arrays and fabrication techniques are also examined. Unlike many other resonant antennas, the same resonant frequency can be maintained by changing the aspect ratio of different shapes of DRA for a given dielectric constant. A tall, thin DRA can have the same resonant frequency (but may not have the same bandwidth) as that of the low profile, wide DRA. This permits most of the antenna researchers certain degree of flexibility in shaping the DRA to meet the specific requirements.

Kumar and Gupta (2014) investigated the performance analysis of different DRAs designed for wide impedance bandwidth, low profile, compactness, and high gain. Their investigation provides a comprehensive review of the radiation characteristics of dielectric resonator antennas of different shapes, such as cylindrical, rectangular, hemi-spherical, ring and hybrid shape. The versatility in choice of shape, radiation patterns, bandwidths, relative permittivity and size enables a whole spectrum of operating frequency range (1–100 GHz) for the DRAs.

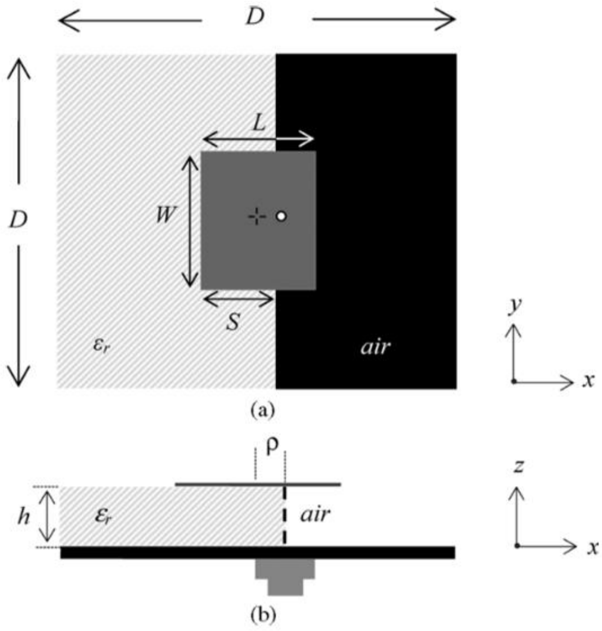
Ullah et al. (2015) published a review paper in which the current state of the art of LTCC-technology-based antennas. All realizable features of the LTCC-based antennas, such as compactness being lightweight and high-speed functionality for portable electronic devices are illustrated. Different techniques used by researchers for broad band, multiband designs, and fabrication of LTCC-based antennas are also presented in this paper.

Some textbooks on dielectric resonator antennas have also been published [Kiely (1953); Anderson (1971); Chatterjee (1985); Luk and Leung (2003); Petosa (2007); Yaduvanshi and Parthasarathy (2016)]. Gangwar and his group have done work on wide variety of dielectric resonator antennas including multiband DRAs, ultra-wide band DRAs, circularly polarized antennas, antenna arrays and also used different feeding techniques for excitation of different modes in the dielectric resonator elements [Sharma et al. (2015, 2016a, 2016b, 2016c, 2016d, 2017a); Gupta et al. (2016, 2017); Sahu et al. (2017); Rajan et al. (2015); Sharma et al. (2016); Gangwar et al. (2016); Das et al. (2017); Singh et al. (2016); Kumari and Gangwar (2016)]. Guha and his group have done work on different DRAs [Guha et al. (2015a, 2015b)]. Three different types of feeds—coaxial probe, microstrip line, and aperture coupling—are common for both microstrip patch antenna and dielectric resonator antenna. However, the feed selection depends on the placement of the antenna and its associated circuitry. For instance, the coaxial probe would be the proper choice for the antenna that is placed separately from it’s transmitting or receiving unit. If the antenna element is kept along with the associated circuitry as an integrated unit (on same circuit board), a microstrip-line feed or aperture-coupled configuration appears to be convenient.

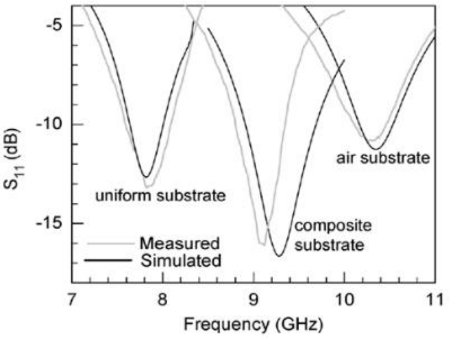
Zou et al. (2017) reported a review article on dielectric resonator nano-antennas. Scaling DRAs toward optical frequencies i.e. optical dielectric resonator antennas for high efficiency beam control and reconfigurability is demonstrated with some theoretical backgrounds. It is still challenging to develop dielectric materials, structure topologies and fabrication technologies for optical DRAs with efficient and delicate control of nano-scale light matter interactions for advanced photonic applications.

Guha et al. (2016) compared the performance of cylindrical microstrip patch antennas (MPAs) and cylindrical dielectric resonator antennas which are fed using different feeding techniques keeping the processing parameters and the material unchanged. The result of this study shows that the DRA is well ahead of MPA in terms of bandwidth and efficiency but compromising the gain value by approximately 1 dB. It should be noted that both the antenna characteristics are dependent on their respective dielectric properties. Integrated DRAs or MPAs require microstrip-line feed or aperture feeds, which are superior in terms of cross-polarization performance. However, if efficiency is the concern, the coaxial probe feed is preferred.

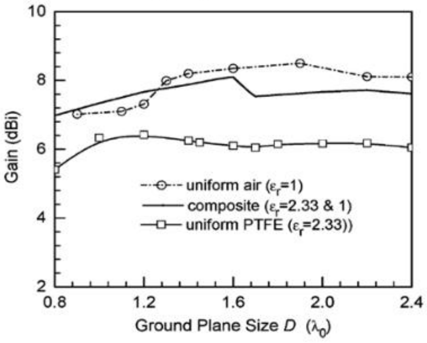
Chattopadhyay et al. (2009) theoretically and experimentally investigated a rectangular microstrip patch on a composite dielectric substrate (Figure 1.3). Considerably wide radiation beam-width along with high gain was experimentally demonstrated. Compared to a conventional microstrip patch, the proposed configuration shows as much as 75% increment in beam-width in its H-plane and nearly 10% in E-plane, indicating the peak gain of the order of 8 dBi. This concept of composite substrate has been utilized for the design of dual segment-rectangular DRA (Chapter 9) and its effect on gain and beam-width has been compared.



Schematic diagram of a rectangular microstrip patch with composite substrate (a) Top view (b) Cross-sectional view



Measured and simulated return loss characteristics of a rectangular microstrip patch using different substrates



Simulated peak gain of a rectangular microstrip patch using different substrates for varying ground plane size.

Figure 1.3 Results of rectangular microstrip patch antenna using composite substrate configuration [Chattopadhyay et al. (2009)].

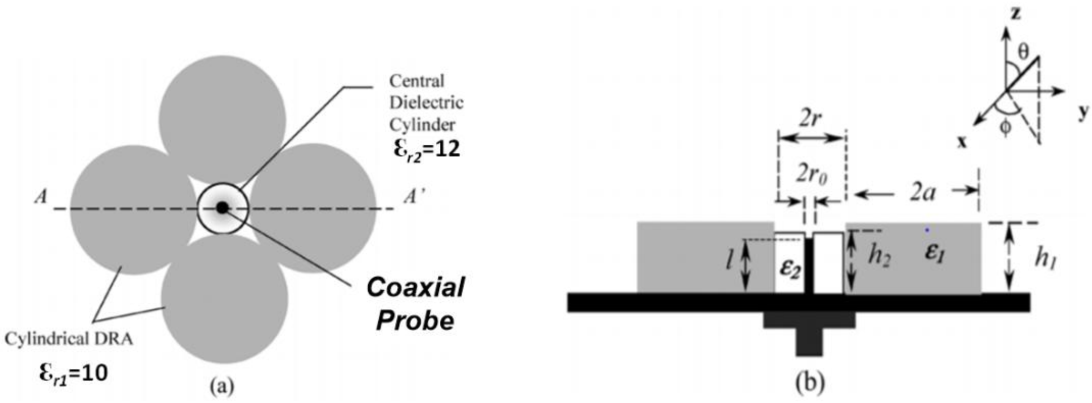
Among the different shapes of DRA, cylindrical DRA (CDRA) is widely investigated due to its simple design and ease of fabrication. Sharma et al. (2016b) reported triple band hybrid MIMO CDRA with dual polarization. The proposed CDRA is applicable for different applications such as LTE2500 (2.5-2.57 GHz for uplink, 2.62-2.69 GHz for downlink), WLAN (5.15-5.35/ 5.725-5.825 GHz) and WiMAX (5.250-5.850 GHz). Sharma et al. (2017b) investigated the tri band composite CDRA having hybrid mode excitation with the help of modified annular ring printed line and cross polarization suppression. Both the hybrid modes i.e. $HEM_{11\delta}$ and $HEM_{12\delta}$ are excited and support broadside radiation characteristics. Guha et al. (2015b) worked on the CDRA for the suppression of cross-polarized radiation by identifying its source. After cylindrical geometry, rectangular and triangular geometry have also been widely investigated. Maity and Gupta (2017) did theoretical investigations on equilateral triangular dielectric resonator antenna (ETDRA) for TM^z mode. ETDRA is excited by different feeding mechanisms such as coaxial feed, microstrip line, aperture etc. using HFSS software. The practical excitation of an odd mode is not observed. Some of the experimental investigations have been reported for fundamental TM^z_{101} mode for ETDRA [Lo et al. (1999, 2001a, 2001b); Kishk (2001); Maity and Gupta (2017)].

(a) Multi-elements DRAs: Several investigations on multi-element DRAs have been done to obtain the wideband monopole like radiation patterns.

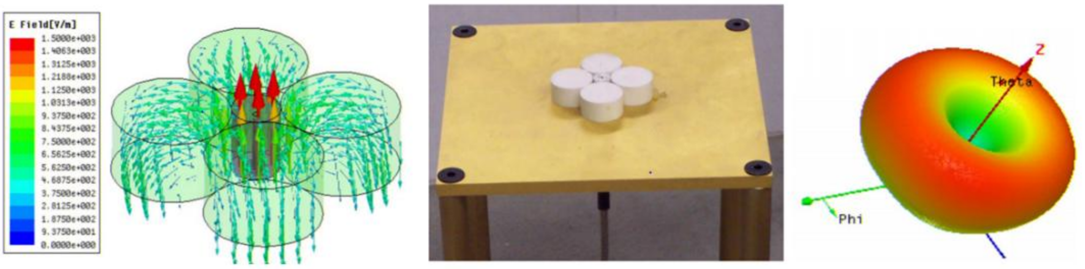
Gupta et al. (2013) did investigation on a wideband dual segment three element TDRA. The simulated -10 dB reflection coefficient bandwidth of the proposed antenna (~23%) was found to be maximum when compared to the single element, three element and single element dual segment TDRAs. The proposed antenna provides omnidirectional radiation pattern with wide angle coverage considering 10 dB angular width with no broadside radiation.

Guha et al. (2006) proposed a four element cylindrical dielectric resonator antenna for wideband monopole like radiation (Figure 1.4). HEM_{11} mode is excited in each DRA element and the composite field patterns result in a uniform monopole like radiation pattern over wide bandwidth, 29% matching bandwidth ($S_{11} < -10$dB) with 4 dB peak gain. The elements of the composite structure are packed together in a compact way on a metallic ground plane. The array is centrally excited by a coaxial probe which itself is surrounded by a small dielectric rod. It actually touches the surfaces of all four CDRAs. The small dielectric rod in association with the probe acts as a modified probe touching each CDR, and helps in launching fields from probe to CDRAs. Chaudhary et al. (2012) proposed a three–element multilayer multi-permittivity (MLMP) CDRA for wideband applications (Figure 1.5). This MLMP CDRA is excited with central MLMP CDR using coaxial probe excitation above the finite ground plane. The central MLMP CDR is located at the centre of three–element MLMP CDRA arrangement. The $TM_{01\delta}$ mode is excited in central MLMP CDR using coaxial probe and hence $HE_{11\delta}$ mode would be excited in each MLMP CDRA element. The measured impedance bandwidth is 52.9 % from 3.88 to 6.22 GHz for reflection coefficient less than -10 dB with omnidirectional radiation pattern and low cross-polarization. The average gain of proposed antenna is 5.70 dB in the frequency range of 3.88 – 6.22 GHz. Gangwar et al. (2017) designed and fabricated a wideband four element triangular dielectric resonator antenna (TDRA). Nearly 37% bandwidth at a resonant frequency of 5.45 GHz with 4.76 dB peak gain is obtained (Figure 1.6). Consistently symmetric monopole type radiation pattern with low cross polarization for WLAN (IEEE 802.16) and WiMAX applications has been reported. The TDRA is taking very less radiation area for giving better performance than other DRA shapes.

Among these multi element DRAs, the fabrication is complex in case of composite feed proposed by Guha et al. (2006) and is very complex fabrication in case of multi-layer multi-permittivity composite feed structure proposed by Chaudhary et al. (2012). In the present work, emphasis has been given on the development of wideband monopole like radiation pattern keeping in view the ease of fabrication.

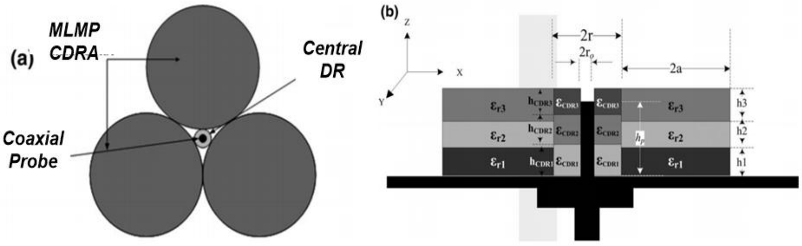


Four-element cylindrical DRA fed by a central coaxial probe.
(a) Top view, (b) cross-sectional view at AA' plane.

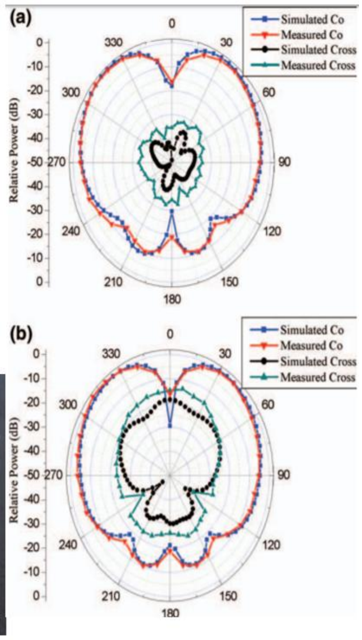


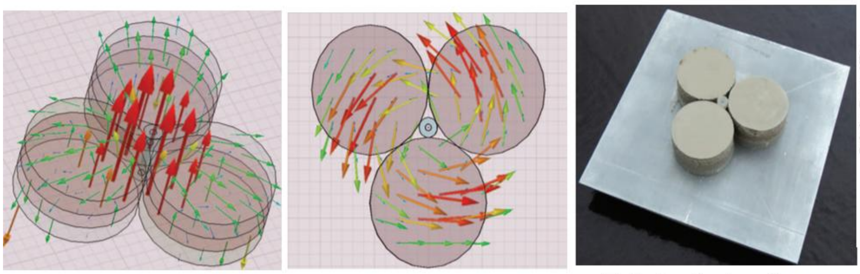
E-field Distribution ***Fabricated antenna Prototype*** ***3D Gain***

Figure 1.4 Four element CDRA for monopole like radiation [Guha et al. (2006)].



(a) Three-element MLMP CDRA with MLMP central CDR fed by coaxial probe: Top View. (b) Three-element MLMP CDRA with MLMP central CDR fed by coaxial probe: cross-sectional view





E-field Distribution ***H-field Distribution*** ***Fabricated antenna Prototype*** ***Radiation Pattern***

Figure 1.5 Multi-layer multi-permittivity CDRA for monopole like radiation [Chaudhary et al. (2012)].

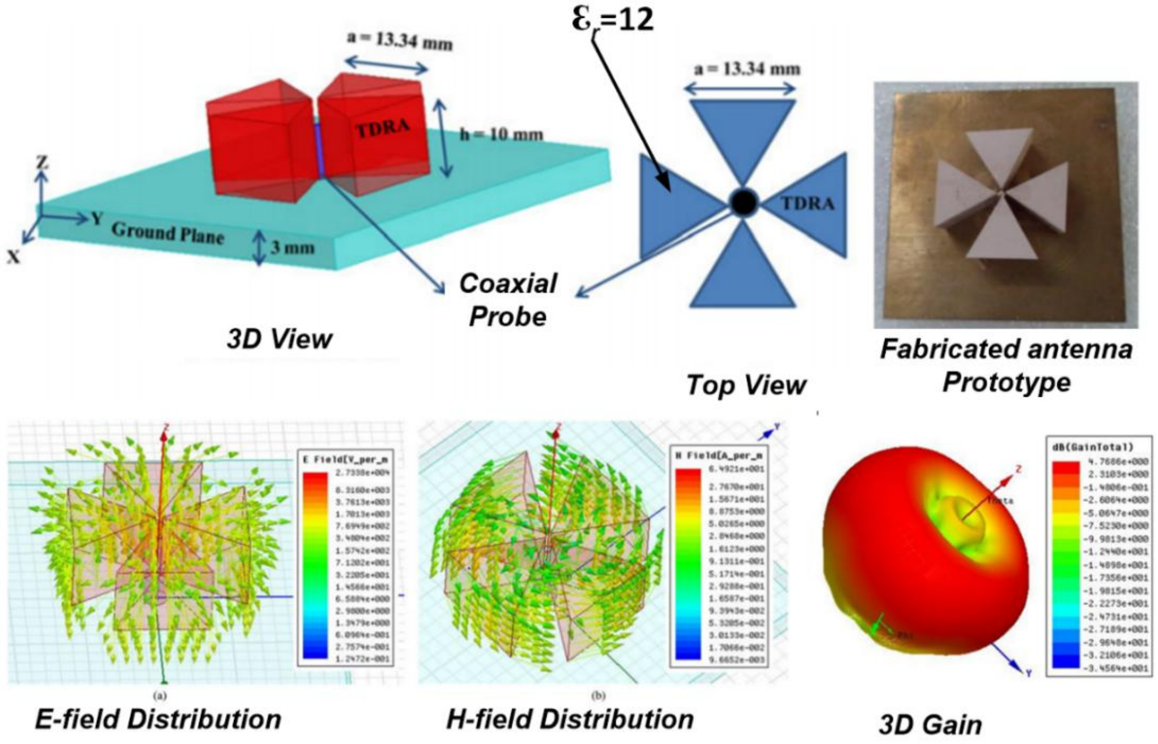


Figure 1.6 Four-element TDRA for monopole like radiation **[Gangwar et al. (2017)].**

(b) DRAs designed using Alumina Ceramic: In most of the designed DRAs, alumina ceramic has been widely used for the investigation [Sharma et al. (2015, 2016a, 2016b, 2016d, 2017a); Gupta and Gangwar (2016, 2017); Sahu et al. (2017); Gangwar et al. (2016); Das et al. (2017); Gupta et al. (2013); Rajan et al. (2015)]. Since this ceramic material is easily available commercially, many antenna engineers used this material for investigation on DRAs which increased the complexity of their design to get better performance out of easily available materials at reasonable prices. Due to non-availability of laboratory materials, they opted commercially available materials, which are only a few in number.

On the other hand, wide range of microwave dielectric materials are available and can be prepared in a laboratory. Sebastian et al. (2008a, 2008b, 2015) investigated and reported thousands of ceramic dielectric materials with their microwave dielectric properties.

Many material researchers have worked and still working on the development of different types of dielectric materials but most of these have not yet been utilised practically at the specific application level. Thus, it is the need of the hour to bridge the gap between the material advancement and the antenna technology so as to obtain high performance antenna or any other electronic component. Antenna designers are no longer bound to design antennas as per the available conventional materials. Rather they are free to design antennas as per their requirements and correspondingly the material is prepared (by varying the compositions to tailor their dielectric properties i.e. dielectric constant and dielectric loss) to meet the desired antenna properties. Emphasis should be placed on cost effective approach and simple design (fabrication ease). Therefore, in the present investigation, the prepared dielectric materials are characterized and then experimentally investigated by designing microwave antennas.

The present-day technology demands continuing growth in electronic systems operating in the RF and microwave spectrum. These systems are designed to provide high efficiency, wide bandwidth and reduced equipment size. The material selection plays a key role for the design of any microwave module or device. The low loss dielectric materials with preferably low dielectric constant are required for the substrate applications for the design of high efficiency DRAs. Also, a wide range of low loss (tan delta $< 10^{-2}$) dielectric materials with low to medium permittivities ($\varepsilon_r = 5 – 50$) can be used as resonators for DRA applications.

1.2 Numerical simulation software

For wireless communications, radar and navigation many antennas are having irregular metal patches, finite dielectric substrate thicknesses and complex structures. Their characteristics can also be affected by the materials used for their fabrication. Their performance characteristics cannot be evaluated by simple analytical means. Instead, numerical modelling techniques, such as integral equation techniques, method of moments and finite-difference–time-domain methods must be employed [Gibson (2008); Harrington (1968); Taflove (1995, 2nd ed. 2000, 3rd ed. 2005)]. Efficient optimization techniques such as finite element method may be employed to generate accurate design solutions. Books on finite element numerical method has been written by Volakis et al. (1998) and Jin and Riley (2008). Many design and simulation tools are now commercially available to simplify the lives of practicing antenna engineers. With the emergence of new numerical simulation software i.e. High Frequency Structure Simulator (HFSS) based on finite element method, the design and simulation analysis of various new models have become easier. Ansoft HFSS employs the Finite Element Method (FEM), adaptive meshing and brilliant graphics which provide unparalleled performance and insight to all of the 3D electromagnetic problems. Many new researchers were attracted towards it because they could determine the electromagnetic characteristics of the structures including antenna structures and get deeper understanding of the subject. Different theory and concepts of the structure can be visualized if implemented in the design process following certain boundary conditions. In case of antenna, the far field and near field distributions, the reflection coefficient, 3D gain at different frequencies, current density, etc. can be easily determined. The finite element analysis involves four steps:

1. Discretizing the solution domain into a number of sub-regions or elements, typically a triangle in 2D and tetrahedron in 3D problems (Figure 1.7)
2. Obtaining field equations in and on the surface of each element in terms of unknown coefficients defined on the nodes, along the edges, or on the faces of the element using simple linear or higher order functions
3. Assembling all the elements in the solution domain into a matrix of equations
4. Solving the system of equations thus obtained.

HFSS provides certain advantages such as it takes less time when compared to Finite Difference Time Domain (FDTD), high modelling capability for general electromagnetic structures, provides a very wideband frequency response. The disadvantage of HFSS is that it requires more memory space.

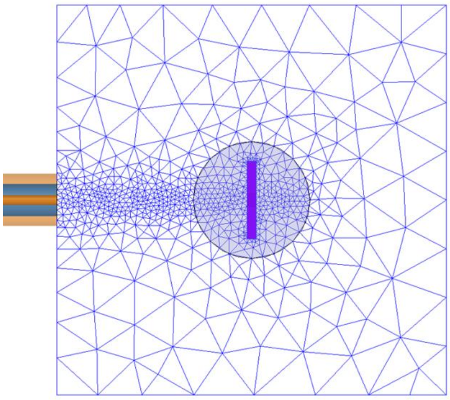


Figure 1.7 Meshes on the ground plane of aperture couple CDRA in HFSS.

Antenna research is entering another phase of significant development of modern wireless communication as well as radar and navigation technologies which are required to cover wide frequency bandwidth. More emphasis is given for the design of planar or low profile antennas for aforesaid applications.

1.3 Low Temperature Co-fired Ceramic (LTCC) technology

In LTCC technology, several thin layers of low dielectric constant ceramic substrates along with the conductors and passive components, are combined together to form a multilayer 3D LTCC module. It is a packaging technology for RF/microwave, high density and fast digital applications requiring hermetical packaging and good thermal management. The LTCC technology has certain remarkable features including miniaturisation, light weight, design flexibility, 3D design, reliability, high circuit density. It has certain applications in microwave range, such as use in handsets, optical transceivers, sensors, satellite communication, radar and radio navigation. Since last two decades, numerous investigations have been carried out for the development of new LTCCs for the microwave applications. More than 1000 papers and ~ 500 patents have been reported for the LTCC and other related technologies.

Three different types of LTCC materials have been developed so far:

1.3.1 Glass-ceramic

Glass-ceramics are polycrystalline materials which are initially a glassy system. Then this devitrifies almost completely during the sintering process. The end-properties of the glass-ceramic system depend on the degree of crystallisation which can be controlled by the addition of a small amount of suitable nucleating agent.

1.3.2 Glass + ceramic

In the glass + ceramic approach, a low softening point glass and a crystalline ceramic are initially mixed. The densification is achieved through liquid phase sintering. The liquid glass penetrates the 3D mesh structure of the ceramic and wets the ceramic particles to affect the densification of the ceramic body. In general, the commercially available LTCC systems are either glass-ceramic or glass + ceramic.

1.3.3 Ceramic materials

Out of these ceramic compositions, phosphate ceramics have attracted much attention as promising LTCC materials. Metal phosphates are multifunctional materials as these are suitable for several different applications, such as corrosion resistant coatings, biomedical cements, high quality fertilizers, chelating agents, and microwave dielectric materials. Various pyrophosphates $A_2P_2O_7$ (A = Ca, Sr, Ba, Mg, Zn, Mn) have been reported to possess good microwave dielectric properties as well as relatively low sintering temperatures. But, pyrophosphates have one drawback that these react with silver. Another lithium transition metal phosphates $LiMPO_4$ (M = Fe, Mg, Mn, Co and Ni) have attracted much attention as promising LTCC materials.

1.4 Material requirements

1.4.1 Sintering temperature

Recently extensive research has been carried out to find materials which are co-fireable with silver electrodes for miniaturisation of microwave devices or antennas. Reduction of sintering temperature of the ceramic material to a level such that it can be co-fired with silver is essential. Glass-ceramics and glass + ceramic routes are commonly used to develop glass based LTCC materials. Also, glass free ceramic systems have been developed with low sintering temperatures for LTCC applications. The sintering temperature of the LTCC material must be lower than the electrode melting point. In addition, the material should be chemically compatible with the electrode. Then by co-firing the LTCC material with an inner electrode structure, a 3D LTCC module is formed. The melting point of the silver electrode is 961 ^{o}C. Therefore, sintering temperature should be ~900 ^{o}C. For other electrode materials like copper, gold or gold-palladium having melting point ~1080 ^{o}C, the sintering temperature should be ~1000 ^{o}C. In the glass+ceramic composite, the sintering temperature reduces depending on the amount and type of the initial glass composition. Sintering occurs through the viscous flow mechanism of the glass. In these composites, the main crystalline phase makes a significant contribution to the dielectric properties while the glass phase lowers the relative permittivity and increases the dielectric loss.

Another point which needs to be noted is that lowering the sintering temperature below 800 ^{o}C is undesirable. It can stop the evaporation of binder, solvent in conductive paste, plasticisers etc. which further results in traces of residual carbon in the microstructure. The residual carbon content should be < 300 ppm to obtain the desirable dielectric properties [Sebastian and Jantunen (2008b)]. The removal of carbon from the green sheet is observed up to 800 ^{o}C. Thus, the densification or crystallisation of the ceramic material should start above 800 ^{o}C. The material selection and identification of a suitable composition is therefore, very challenging.

1.4.2 Dielectric constant

Low dielectric constant ranging from 4 – 12 is required for LTCC substrate application while dielectric constant ranging from 5 – 50 is required for dielectric resonator in the design of antenna. The functionality of a LTCC substrate material is related to its dielectric properties. In electronic packaging, one of the most important factors is signal propagation, which is a direct function of relative permittivity.

In the ceramic packages, the signal propagation delay (t_d) is given as:

$$t_d = l(\varepsilon_r)^{1/2}/c \qquad (1)$$

where l is the line length, ε_r is the relative permittivity of the substrate and c is the speed of light. Thus, a substrate with low ε_r is required to increase the speed of the signal. Alumina as well as FR–4 fall into this range of ε_r. However, one advantage is that the relative permittivity of all commercial LTCCs is very stable and batch to batch variations are generally less than 2%.

1.4.3 Tan delta

In case of LTCC components, the main loss in the microwave frequency range is conductor loss. The dielectric loss value of common LTCC materials is generally expressed with Qxf value i.e. (1/tanδ) multiplied by the measurement frequency in GHz. Low tanδ value is required for the material to be used as substrate as well as for the dielectric resonator for antenna. Very low loss ceramic is required for its application as LTCC substrate (tanδ $<10^{-3}$).

1.4.4 Temperature coefficient of resonant frequency (τ_f)

This is an important parameter when the material is going to be used as an antenna resonating element. Due to temperature variation, resonant frequency of the material may shift to a certain degree. The relation between τ_f , temperature coefficient of dielectric constant (τ_ε) and coefficient of thermal expansion (α) is expressed as [Sebatian et al. (2017)]:

$$\tau_f = -\alpha - \tau_\varepsilon/2 \quad \text{..(2)}$$

However, it should be noted that τ_f value of the most novel LTCCs is much better than that for FR–4 (+80 ppmK^{-1}).

1.4.5 Temperature coefficient of dielectric constant (τ_ε)

The sample will resonate only if the loss tangent is very low (less than 0.001). For most of the glass-ceramic samples, generally the loss tangent value is higher than this and therefore, for these types of materials monitoring of TE_{011} mode is not possible. If the TE_{011} mode is not clearly detected, the measurement of τ_f becomes very difficult. So, in this case, the temperature coefficient of dielectric constant as a function of temperature is reported. This is also an important parameter for substrate applications. Glasses in general have negative τ_f or positive τ_ε. TiO_2 has positive τ_f (+400) or negative τ_ε (–800). Addition of TiO_2 will stabilize the τ_f and τ_ε values for glasses having negative τ_f and positive τ_ε.

1.4.6 Chemical compatibility with electrode material

Different electrode materials such as aluminium (Al), copper (Cu), silver (Ag), gold (Au), palladium (Pd) and platinum (Pt) are available. Out of these, copper and aluminium are cheaper but react with the environment. Silver, gold and palladium are stable in the atmosphere. Silver has the greater electrical conductivity than many other metal and it is also less costly as compared with other stable electrodes i.e. gold or palladium or platinum. Thus, silver is widely used as the electrode material in electronic industry. To use silver as an electrode material on the LTCC substrate, it must not react with the ceramic substrate to form any additional phases which can degrade the performance of the microwave modules. The conductive patterns are printed on the LTCC using pastes instead of pure metals. Thus, one has to consider reaction of the ceramic not only with the electrode material but also with other additives of the conductor paste.

1.4.7 Coefficient of thermal expansion (CTE)

The CTE values for the commercial LTCCs lie in the range 4.5 – 7.5 $ppmK^{-1}$ [Sebastian and Jantunen (2008b)]. If the system integrated with silicon chips is mounted on a LTCC substrate, any mismatch of their thermal expansion would result in system failure by hampering the solder connections between the chip and the substrate. This affects the system reliability. The CTE of LTCC should matches with that of the mounting board and chip. Thus, for the LTCC module which is getting mounted on silicon, its CTE should lie in the range ~7–9 $ppmK^{-1}$ while for mounting on PCB, it should lie in the range ~12–20 $ppmK^{-1}$.

1.4.8 Thermal conductivity

It is one of the important aspects which needs to be considered for the heat sensitivity of LTCC module, such as high power devices. If any component in the assembled LTCC module is heat sensitive, then removal of heat generated by the device is necessary for reliable functioning of the package. It is desired to maintain the device temperature below 100 ^oC. Most of the developed LTCC materials have the disadvantage of low thermal conductivity in the range ~2–5 $Wm^{-1}K^{-1}$. It is 10 times higher when compared with the organic laminates. A most common technique to improve thermal dissipation in high power devices is the use of heat spreader but another alternative provided by the LTCC technology is employing metallic via arrays beneath the high power components.

1.5 Recent advancements in LTCC materials

The LTCC technology shows some advantageous features but development of LTCC materials is still in the early stages. The main difficulties in developing new LTCC materials are not only related to their microwave dielectric properties but also to their densification behaviour, chemical compatibility, production cost and thermo-mechanical properties. Many investigations have been carried out to decrease sintering temperature of ceramic material by addition of different glasses for LTCC applications [Jei et al. (2005); Lim et al. (2003); Seo et al. (2006); Chen et al. (2006); Chakraborty et al. (1984); Jo et al. (2008); Fang et al. (2006); Dai et al. (2002)].

1.5.1 Ceramic systems: Several microwave dielectric ceramics with low sintering temperatures have been reported such as tellurium and bismuth rich compounds (Sintering temperature < 850 ^oC) show good microwave dielectric properties [Li et al. (2009); Kwon et al. (2005, 2007); Subodh and Sebastian (2007); Honkamo et al. (2009);

Udovic et al. (2001, 2004); Valant and Suvorov (2001, 2004); Zhou et al. (2009)]. But Te based ceramic has one drawback that it reacts with silver. Tummula (1991) has reported that for the ceramic sintered below 800 ^{o}C, the complete evaporation of organics and solvents used during the LTCC processing may not occur and hence, it degrades the dielectric properties of the ceramic.

Some vanadate systems like $Mg_3(VO_4)_2$, $Ba_3(VO_4)_2$, $M_{3-x}Co_x(VO_4)_2$ (M=Mg, Ba) etc. have also been reported with good dielectric properties [Umemura et al. (2005, 2006)]. $Ba_3(VO_4)_2$ sintered at 1600 ^{o}C/5h has $\varepsilon_r = 11$, $Q\times f = 62350$ GHz and $\tau_f = 28.8$ ppm/^{o}C. Addition of B_2O_3 (0.5 wt %) lowered the sintering temperature to 950 ^{o}C/5h with $\varepsilon_r = 12.5$, and $\tau_f = 38.8$ ppm/^{o}C.

Yano et al. (1993) reported that TiO_2 can be added to tailor the microwave dielectric properties, particularly τ_f of the glass-ceramic systems. Many authors have investigated ZnO-TiO_2 systems for LTCC application [Kim et al. (1999a); Zhang et al. (2005); Chai et al. (2008); Chaouchi et al. (2007)]. Zinc magnesium titanate (ZMT) solid solution is also reported for LTCC application [Kim et al. (1999b); Lee et al. (2004, 2005); Gangwar et al. (2010)]. This material has also been used for the design of dielectric resonator antenna [Gangwar et al. (2011)].

$MgTiO_3$-$CaTiO_3$ (MCT) ceramics have also been investigated for microwave applications. Effect of different RBS glass addition (where R= MgO, CaO, BaO, SrO; B = B_2O_3; S = SiO_2) in MCT ceramics on the densification and microwave dielectric properties have been studied [Chen et al. (2003, 2004); Zhang et al. (2006); Shin et al. (2006); Jantunen et al. (2000a, 2000b, 2002) and Hu et al. (2005)].

Tripathi et al. (2015) have reported the characterisation of liquid phase sintered cobalt doped magnesium titanate and used this ceramic for the fabrication of wideband stacked rectangular dielectric resonator antenna whose operating frequency range lies between 6.5 and 9.5 GHz with good gain of ~6 dB. Glass added barium strontium titanate is also widely used for the design of different dielectric resonator antennas due to its medium dielectric constant in the range 15 – 27 [Tripathi et al. (2018)].

Several niobates MNb_2O_6 (where M= Ca, Zn, Co, Ni, Mn) show medium ε_r (22-25) [Maeda et al. (1987); Lee et al. (1997)]. $Ba_5Nb_4O_{15}$ was found to have good microwave dielectric properties but it has drawback of high sintering temperature of 1400 ^oC and high positive τ_f [Sreemoolanathan et al. (1995); Ratheesh et al. (2000)]. B_2O_3 addition has lowered its sintering temperature to 925 ^oC [Kim et al. (2002)]. $Ba_5Nb_4O_{15}$ with 3 wt% of B_2O_3 shows $\varepsilon_r = 39$, Q×f = 18,700 GHz with zero temperature coefficient of resonant frequency. Zhou et al. (2008) reported that Li_3NbO_4 ceramic possesses good microwave dielectric properties with $\varepsilon_r = 15.8$, Q×f = 55,009 GHz and $\tau_f = -49$ ppm/^oC. These materials are chemically compatible with silver.

Several phosphate systems have also been reported by different authors and found to have good microwave dielectric properties. Arun et al. (2014) reported that mixed rare earth orthophosphate ceramic sintered at 1250^oC showed ε_r of 9.6 (at 13.5 GHz), high Qxf of 45,200 GHz and τ_f of -35 ppm/^oC. Its room temperature thermal conductivity is 3.25 $Wm^{-1}K^{-1}$ while CTE is 7.3 ppm/^oC. Guo et al. (2012) synthesized $A_3(PO_4)_2$ compounds by solid-state reaction method when the A-site atoms were Sr or Ba. The ε_r of the α-$Sr_3(PO_4)_2$ is higher than that of $Ba_3(PO_4)_2$, but $Ba_3(PO_4)_2$ has a higher Qxf value than that of β-$Ca_3(PO_4)_2$ and α-$Sr_3(PO_4)_2$, which could be interpreted by the differences in ionic polarizability and bond strength. τ_f have positive values, between +11 and +66 ppm$\circ C^{-1}$.

Bian et al. (2005) reported the phase evolution, sintering behavior and microwave dielectric properties of mixed pyrophosphates $(Ca_{1-x}Zn_x)_2P_2O_7$ (x=0.1 – 0.9) were investigated in this paper. A single-phase composition of $CaZnP_2O_7$ has formed at low sintering temperature (≤ 900 ^oC) having low ε_r (< 9), high Qxf value 63,130 GHz and negative τ_f (-82 ppm/^{o}C). One of its major drawbacks is that it reacts with the common electrode material silver. Thomas et al. (2010) reported a low temperature sinterable $LiMgPO_4$ (LMP) ceramic for the first time. The ceramic sintered at 950 ^{o}C showed ε_r of 6.6, high Qxf of 79,100 GHz with τ_f of -55 ppm/^{o}C. The composite with 0.12 volume fraction of TiO_2 showed good microwave dielectric properties: ε_r = 10, Qxf = 26,900 GHz and τ_f = +1.2 ppm/^{o}C. LMP has low bulk density (<3 g/cm^3), so it is suitable for fabrication of light weight devices. Thomas et al. (2012) prepared $LiMg_{(1-x)}Zn_xPO_4$ ceramic by solid state route. It is orthorhombic up to x = 0.2 and compositions with 0.3 ≤ x ≤ 0.8 exist as a mixture of orthorhombic and monoclinic phases. $LiMg_{0.9}Zn_{0.1}PO_4$ (x = 0.1) sintered at 925 ^{o}C exhibits ε_r = 6.7, Qxf = 99,700 GHz and τ_f = -62 ppm/^{o}C. $LiMg_{0.9}Zn_{0.1}PO_4$ –TiO_2 composite sintered at 950 ^{o}C has ε_r = 10.1, Qxf = 52,900 GHz and τ_f = -5 ppm/ ^{o}C. Dong et al. (2014b) prepared $LiMg_{(1-x)}Ni_xPO_4$ ceramic by solid state route. Single phase $LiMg_{(1-x)}Ni_xPO_4$ (x = 0 - 0.1) solid solution formed. $LiMg_{0.95}Ni_{0.05}PO_4$ (x = 0.1) ceramic sintered at 875 ^{o}C exhibits ε_r = 6.91, Qxf = 98,600 GHz and τ_f = -55.3 ppm/^{o}C. $LiMg_{0.95}Ni_{0.05}PO_4$ –TiO_2 composite (11 vol% TiO_2) sintered at 875 ^{o}C for 2h shows ε_r = 9.88, Qxf = 50,800 GHz and τ_f = -1.4 ppm/ ^{o}C. Dong et al. (2014a) studied $Li(Mg_{1-x}Co_x)PO_4$ (x = 0 – 0.09) ceramics prepared by solid-state route. Single-phase $Li(Mg_{1-x}Co_x)PO_4$ solid solution formed. Substitution of Co^{2+} for Mg^{2+} can lower the sintering temperature and enhance the value of $LiMgPO_4$ ceramics. The microwave dielectric properties of $LiMg_{0.95}Co_{0.05}PO_4$ ceramic shows ε_r = 6.97, Qxf = 111,200 GHz and τ_f = -53.8 ppm/ ^{o}C.

1.5.2 Glass + Ceramic systems

Several methods have been developed to decrease the densification temperature of LTCCs. For the first time, Takada et al. (1994) reported the effect of glass addition on the sintering temperature and microwave dielectric properties of ceramics. Since then different sintering aids and low melting glasses have been added to the ceramic systems to obtain low sintering temperatures. Varghese et al. (2013) have reported the effect of glass fillers on sintering temperature and microwave dielectric properties of $Cu_2ZnNb_2O_8$ (CZN) ceramics. CZN sintered at 975 ^oC for 4 h has ε_r =15.2, tanδ = 0.0007 (at 5.1GHz) and τ_f of -98 ppm $^oC^{-1}$ and CTE =1.9 ppm $^oC^{-1}$ (temperature range 30 – 100 ^oC). Addition of lithium borosilicate (LBS) and lithium magnesium zinc borosilicate (LMZBS) glasses reduces the sintering temperature below the melting point of silver. With 1 wt.% LBS addition in CZN ceramic, sintering temperature reduces to 935 ^oC giving ε_r = 14.7, tanδ = 0.001 (at 5.1GHz) and τ_f = -19 ppm $^oC^{-1}$ and CTE = -0.5 ppm $^oC^{-1}$. On addition of 0.7wt% of LMZBS glass to CZN sintered at 935 ^oC has ε_r =14.8, tanδ = 0.002 (at 5.1GHz) and τ_f = -39 ppm $^oC^{-1}$ and CTE = -0.9 ppm $^oC^{-1}$. Manu et al. (2011) reported the microwave dielectric properties of the $SrCuSi_4O_{10}$ (SCS) ceramic and its low temperature sintering. SCS sintered at 1100 ^oC shows ε_r =4 and tanδ = 0.0011 (at 5 GHz). SCS ceramic with 5 wt% lithium magnesium zinc borosilicate (LMZBS) glass sintered at 900 ^oC has ε_r = 5.0 and tanδ = 0.0019 (at 5 GHz) and also shows no reactivity with silver. Sasikala et al. (2008) reported the effect of glass addition on the densification, sintering temperature and dielectric properties of forsterite (Mg_2SiO_4) ceramics. 15 wt% of LBS glass is added to forsterite ceramic and this reduces the sintering temperature from 1500 ^oC to 950 ^oC without significantly affecting its dielectric properties. Borosilicate glass (BSG) has also been widely used to reduce the densification temperature of crystalline ceramics. These include BSG+cordeirite, BSG+alumina, BSG+TiO_2 [Jean and Gupta (1992a, 1992b); Noro and Tozaki (1986); Imanaka et al. (1987)].

1.5.3 Glass-ceramic systems: In another method, glass-ceramics are developed in which fully glassy system vitrifies during the heat treatment. Glass ceramics are an important class of materials which have been commercially quite successful. These are polycrystalline materials produced by the controlled crystallisation of glass and are composed of randomly oriented crystals with some residual glass, typically between 2 and 5 percent, with no voids or porosity [Barsoum (1997)]. The unique combination of properties can be achieved for glass ceramics. This opens up entirely new fields where no alternative material can satisfy the technical requirements. These are truly engineered materials, capable of a wide range of microstructure and properties [Harper and McMillan (1972); Lewis et al. (1979); Strnad (1986)]. These combine the ease of fabrication of a glass with the generic properties e.g. high strength and stiffness of a ceramic. Physical properties of the resulting glass-ceramic compositions are controlled by degree of crystallisation which can be enhanced by the small addition of crystalline phase which acts as a nucleating agent [Sebastian (2008a)]. Preparation of glass-ceramic involves several stages. First, a glass is melted and formed into an appropriate shape. The glass sample is then given heat treatment to nucleate and grow crystals in its volume until a material with the desired amount of crystallite size is produced. The discovery of the role of nucleating agents in initiating glass crystallisation from a multitude of centres was the major factor allowing the introduction of glass ceramic [Stookey (1959)]. The presence of these agents in the parent glass is essential to promote the development of high density of nucleation sites [Hanson and Fernie (1993)]. It is necessary to obtain a fine-grained microstructure. The addition of constituents known as nucleating agents to the glass to promote the development of high density of internal nucleation sites is the key to the achievement of controlled crystallization. The crystalline phases and the remaining glass phase would be responsible for dielectric characteristics and densification, respectively. Glass ceramics have a number of diverse applications for electronic devices and circuits. These include microelectronic substrates and packaging, disc, multilayer and barrier layer capacitors, cryogenic sensors, electro-optic, piezoelectric and pyroelectric devices [Herczog (1973); Partridge (1994)]. Hybrid microwave integrated circuits are used in bulk for present day radar, communication and electronic warfare systems. These commonly take the form of a thin film open micro-stripline circuit populated with discrete passive and active devices. For frequencies up to 26 GHz, 99.5% alumina with a dielectric constant of 10, low loss characteristics and excellent mechanical properties is well suited to the job. At higher frequencies, the wavelength and hence, the circuits become smaller and so it becomes necessary to offset this by using substrate materials with low value of dielectric constant resulting in an increase in the effective wavelength.

Commercially available Ferro A6-M contains $CaO–SiO_2–B_2O_3$ glass which forms wollastonite ($CaSiO_3$) crystals on sintering with some residual borosilicate glass. This dielectric tape is viable for aerospace and military applications (20 – 30 GHz). Among dielectric glass-ceramic systems, $MgO–B_2O_3–SiO_2$ (MBS) glass-ceramics have been reported by Dosler et al. (2012) as a suitable LTCC candidate. Keshavarz et al. (2017) investigated the sintering and crystallization of forsterite/MBS glass-ceramic composites along with their thermal and microwave dielectric properties. MBS glass-ceramics show appropriate microwave dielectric properties with $Mg_2B_2O_5$ (suanite) and $MgSiO_3$ (enstatite) as crystalline phases at low sintering temperatures.

Considerable attention is required in selecting the LTCC material to meet the demands of application specific requirements. So, in the present study the material is selected as per the requirement of dielectric resonator antenna components including both the radiating antenna element and substrate material. The two compositions i.e. Li_2O–(2-3x)MgO–(x)Al_2O_3–P_2O_5 based ceramic and MBS based glass-ceramic system are investigated in the present study.