Chapter 1

Introduction

In the early days, Dielectric Resonator (DR) was merely used in the design of active and passive microwave components, such as oscillators and filters. In a shielded environment, the resonators build with DRs can reach the unloaded Q factor of 20,000 at frequencies between 2 and 20 GHz. When a dielectric resonator is not entirely enclosed by a conductive boundary, it can radiate, and so it becomes an antenna.

The potential for dielectric resonator as an effective radiating source was proposed by Long *et al.* in [1]. As a result of subsequent research, the dielectric resonator antenna (DRA) has emerged as a low-loss, low-profile and broadband radiating element. In addition, the DRA is easy to fabricate and can be effectively excited by a variety of feed topologies which are easy to design. The low-loss nature of the DRA is primarily due to the absence of metallization, which also makes it particularly suited to millimeter-wave applications. This can be compared to the microstrip patch, where the conductor loss limits the efficiency of the antenna in the millimeter-wave range [2]-[4].

Telecommunication and radar systems are increasingly being used in the millimeter-wave band for the larger bandwidth available. The potential of DRA for radar applications was investigated in [5]. In radar application number of DRs can be used to construct linear or planner phased arrays [5], [6]. Printed or patch antennas have been designed to operate in the millimeter-wave range. However, conductor and dielectric losses could be significant at these millimeter-wave frequencies, which degrade the efficiency and adversely affect the performance of the system. On the other hand, the dielectric resonator antenna shows great potential for these applications. For applications requiring high gain antennas, dielectric resonator antenna arrays may be a good choice [2], [5]-[12].

Miniaturized antennas are becoming increasingly important especially in wireless and low frequency applications. The demand for wireless technology has increased dramatically in the past decade. The DRA may be good candidate for many of the existing and emerging communication applications such as Wireless LAN, UWB Wireless Communication Systems, local multi-point communications, indoor wireless, EHF portable satellite communications, RFID applications, WiMAX applications, mobile and personal communication system (PCS) [6], [7], [13]-[22]. Antenna which is small, efficient and integrable into mobile devices must be developed [20]-[22]. Alternatively, as the frequency of operation is lowered, miniaturization techniques must be employed to keep antenna size practical. There are two primary techniques to achieve antenna miniaturization. The first is using a novel topology to reduce the overall area consumed by the radiating structure, the second is using materials with permittivity, permeability, or both greater than one; since wavelengths inside such materials are reduced, the characteristic size of the antenna decreases. This increases the effective permittivity seen by the slot or probe and lowers its resonant frequency.

The dielectric resonator antenna (DRA) can be fed with different feed topologies. The impedance bandwidth of the DRA mainly depends on the type of feed used and DR properties such as shape and dielectric constant. The impedance bandwidth of the single-layer DRA ranges from 5% to 15% depending on DR properties and type of feed used. If the DRA is used in the high power applications in the millimeter-wave range such as radar, then wave-guide is an attractive feed for the DRA. However, the impedance bandwidth obtained with wave guide feed is moderate ranging from 3% to 5% in the X-band. For the frequencies below X-band, the coaxial probe or microstrip slots are important feeds for the DRA due to their smaller size as compared to waveguide feed.

The hemispherical DRA (HDRA) excited in the TE_{111} mode produces broad side radiation pattern similar to the slot antenna. On the other hand the HDRA excited in the TM_{101} mode produces monopole like radiation pattern. However, the larger 10 dB impedance bandwidth with good radiation efficiency can be obtained with DRA excited by slot or probe.

1.1 Survey of Literature

The dielectric resonator (DR) was traditionally used for designs of filters and oscillators [7] because of its inherent merit of low dielectric loss. The dielectric resonator antenna originally proposed by Long *et al*. [1] as a radiating element is characterized by low loss due to the absence of conductor loss. In addition, the DRA can be easily excited by a variety of feed mechanisms. In the microwave filter or oscillator designs DR with relative permittivities in the range of $(\varepsilon_r \cong 20-100)$ are used. However, for using DR as antenna, lower relative permittivity materials $(\varepsilon_r \leq 16)$ are used to have lower Q factors. With the use of DRs, small size, low cost, light weight, and high radiation efficiency DRAs can be fabricated.

Since the first use of DR as an antenna, the researchers have demonstrated that different shape of DRAs, such as cylindrical [1], hexagonal [15], rectangular [23], hemispherical [24], triangular [25], [26], conical [27], elliptical [28], cross [29], [30] can be designed to radiate efficiently through proper choices of feed position and feed dimensions. Cylindrical DRs are easy to fabricate, but they have edge shaped boundaries which make the analytical solution difficult to obtain. The perfect magnetic wall approximation used by Long [23], however causes unsatisfactory discrepancies of about 20% between simulated and measured results. Other theoretical models such as the surface integral equation technique [31]-[34] and the finite-difference time-domain (FDTD) [35], [36] are fairly accurate but require extensive computational time. Rectangular DRs are also easy to fabricate but they have more edge shaped boundaries, which makes the analytical solution even more difficult. The FDTD method can be used for the analysis of rectangular DR [35], [36] but it relies heavily on the intensive numerical calculations. The conical DR is difficult to fabricate as well as difficult to analyze analytically. For triangular and other types of DR only experimental studies have been carried out so far [7].

Hemispherical DRs are however easy to study analytically because of its simple interface with free space [37]. Hence hemispherical DRs are used in this dissertation. The hemispherical DR sitting on the infinite ground plane can be viewed as a spherical DR by using image theory. In the spherical coordinate system, the variables of the wave functions are separable, which greatly simplifies the analysis. For the spherical geometry, exact closed form expressions for the Green's functions of point currents in the dielectric body can be derived using the modal expansion technique. The unknown feed current, and hence the input impedance and return loss, can then be found by the method of moments (MoM) [38].

The DRA can be easily excited by a variety of feed mechanisms, including the coax-probe feed [39], [40], the microstrip slot-coupled feed to the DRA [41]-[49], the coplanar waveguide feed to the DRA [50]-[53], the direct microstrip line coupled to DRA [54]-[56], the strip-line feed to the DRA [57], the conformal strip excitation to the DRA [58]-[60] and the rectangular waveguide feed to the DRA [61]-[66].

One of the limiting factors of DR antenna is less impedance bandwidth. The typical 10 dB impedance bandwidth of the single layer DRA lies in the range of 5% to 15%. To enhance the bandwidth of DRAs, researchers have developed various techniques. In [67]-[71] stacked DRA configuration was employed to achieve broadband behaviour. An embedded topology was used in [72], [73] where broadband configurations were realized using a DRA with two different dielectric materials. Wideband DRA designs were also reported using a parasitic patch on the DRA surface [74], [75] or a parasitic slot in the ground plane [76]. In [77], an ultra-wideband antenna configuration has been presented using the mutual coupling between a monopole and an annular DRA. Bandwidth enhancement in [78] was achieved by loading DRA by a low-profile dielectric disk of very high permittivity. The split cylindrical DRA was employed to achieve broadband behaviour in [79]. In [80] an investigation is conducted on increasing the bandwidth of dielectric resonator antennas by changing the radius-to height and length-to-height ratios for cylindrical and rectangular geometries, respectively. A wide band vertical strip fed cylindrical DRA was studied experimentally in [81] where conical shaped radiation pattern was generated with 35% impedance bandwidth. The wide band antenna was designed by exciting the two modes of the simple cylindrical DRA [82]. This was done by suitably choosing the radius to height ratio of the cylindrical DRA. A wide-band compact antenna combining a rectangular DRA with a grounded and inverted L-plate was investigated in [83]. Two rectangular DRAs displaced near two edges of a single slot in the ground plane of a microstrip line were employed in [84] to increase the impedance bandwidth. Other broadbanding techniques include use of shaped DRAs [85]-[87], disc-ring DRAs [88], [89], DRA fed by L-shaped probe [90], surface mounted horn integrated with the DRA [91], multi-segment DRA [92]-[94].

One of the techniques to extend the bandwidth of a single DRA element has been the multilayer DRA configuration. A broadband hemispherical DRA excited by a coax probe was presented in [95] where an air-gap of hemispherical shape between the ground plane and the DRA was used to enhance the bandwidth. A broadband coax-fed [96] and microstrip slot-coupled [97] two-layer DRA topology was proposed with the inner dielectric resonator surrounded by a dielectric shell. With the two-layer DRA topology in [95]-[97] a maximum impedance bandwidth of about 24% was reported. In [95]-[97] the multilayer DRA structures have been described in terms of the mode of the innermost resonator, which does not take into account the outer layers, and thus do not correspond to the actual modes of the antenna structure. In addition Green's functions with single mode approximation were used to analyze two-layer HDRA in these cases.

The dual band or multifrequency antenna design has been another popular research topic for DRA [48], [98]-[100]. In [48] Hybrid DRA excited by circular slot and eccentric ring slot is studied experimentally for dual band operation. In this dual resonance was resulted from the DRA resonance and the slot resonance. In addition the different schemes for the frequency tuning of the DRA were demonstrated in [101]-[103] with stable radiation patterns in the pass band of the antenna.

Many efficient feed mechanisms have been proposed for the DRA [39]-[60]. All these feeds types are suitable for the applications below X-band. This is because, a major disadvantage of these feed types is their considerable loss at millimeter-wave frequencies. On the other hand, the rectangular waveguide, proposed in [61]-[66] is an attractive feed alternative to the DRA at high frequencies. This is due to the fact that the rectangular waveguide is surrounded by metallic walls, and as such radiation loss and interference effects are not present. Thus, realization of a proper waveguide based feed is very significant for fully realizing the advantages of the DRA in the millimeter-wave frequency range. However it was found that good coupling to the rectangular waveguide could only be achieved with a DRA of high-permittivity [61]. The coupling could be improved only with the use of a second DRA element inside the waveguide [62], [63] or by a coax probe fed DRA coupled to the waveguide through an aperture in the waveguide broad-wall [64], [66].

In [61], an equilateral-triangular shaped DRA of dielectric constant 82.0 was used to excite the DRA through the rectangular waveguide. The high permittivity of the DRA was needed to enhance the coupling between the waveguide and the antenna. A cylindrical DRA coupled to the broad-wall of a rectangular waveguide was presented in [65], using a lower permittivity DRA of dielectric constant 10.5. However, insufficient coupling was observed between the waveguide and the DRA. Coax-fed DRA and stacked DRA configurations resting on the waveguide broad wall with the coax probe coupled to the waveguide through an aperture were discussed in [64]. The return loss performance, particularly for the stacked DRA, was seen to be improved in this case. A coax-probe excited embedded DRA array topology coupled to rectangular waveguide, E/H plane horns and pyramidal horns with hard walls presented in [66] for spatial power combining applications also demonstrated good coupling to the waveguide / horns. A cylindrical DRA slot-coupled to the shorted end of a rectangular waveguide was reported in [62], [63]. In this case, the coupling between the DRA, of permittivity 16.0, and the waveguide was improved using a second DRA inside the waveguide to focus the incident waveguide field on the slot. However, this necessitates the use of another DRA element in addition to the radiating DRA to improve the return loss performance. In addition, the antenna is narrowband. The bandwidth was improved by replacing the rectangular slot by an I-slot, however the impedance bandwidth still remains at 5.38%.

Second limiting factor in the DR antenna analysis is the large amount of computation time required to obtain the input impedance. This is because the most of the research work so far on the different feeds to the hemispherical DRA (HDRA) is based on the Green's function and MoM [38] approach. The DRA Green's function is an integrand in the integrations of MoM. The order of integrations in the MoM may be either two fold or four fold. The amount of computation time needed to evaluate four-fold integration involving DRA Green's function is usually very large as compared to two fold integrations. The integration of DRA Green's function has been performed analytically by virtue of novel recurrence formulas in [58], [59], [74]. The analytic integration requires much less computation time compared to the numerical integration of the Green's function. Analytic integration in [58], [59], [74] is possible because both the DRA Green's function and integration are in the same spherical coordinates. Though this technique is quite fast, it cannot be used for the analysis of the structures in [24], [39]-

[42], [44]-[49], [53], [76], [95]-[97]. This is due to the fact that the Green's functions in these cases are in the spherical coordinates but integrations are either in the rectangular or in the cylindrical coordinates. This necessitates time consuming four fold numerical integration of DRA Green's function in MoM.

The design and analysis of the multilayer HDRA based on the Green's function and MoM with slot or probe feed is very much time consuming. This is due to the fact that multilayer HDRA involves large number of design parameters such as layer permittivities and layer thicknesses. The optimization of multilayer DRA involving large number of design parameters needs to perform more number of simulations to arrive at the optimized antenna dimensions.

The two most popular commercially available simulation softwares used for the antenna design are Ansoft's High Frequency Structure Simulator (HFSS) [104] and CST Microwave studio [105]. The HFSS is based on the Finite Element Method (FEM), whereas CST Microwave studio is based on Finite Integration Technique (FIT). Both softwares are fairly accurate for different types of antenna simulations. The performance of these softwares mainly depends on the processor speed and amount of RAM in the computer. Both softwares offer different accuracy levels for antenna simulations. The simulation time and memory resources required by HFSS or CST however increase with increasing accuracy levels. For the DRAs constructed with different permittivities simulation time varies in between few hours to 50 hours on the good computing machine. It can be noted that the computation time and memory resources required by HFSS or CST increases exponentially with increase in the number of layers in the DRA. As an example, the simulation of a four-layer DRA using HFSS with a lambda refinement of 0.15 and $\Delta s = 0.01$ is beyond the capability of computer having Pentium-4 processor and 2 GB RAM. Another problem in the design of multilayer DR antenna using HFSS or CST is that, the physical insight into the modes of the multilayer DRA is not possible. Without identification of the resonant frequencies of the multilayer DRA the optimization of the antenna is difficult and time consuming.

The design of an antenna having dual band or multifrequency operation has been a popular topic for DRA. Dual or multifrequency operation of antenna is highly desirable in modern wireless communication systems. If a single dielectric resonator antenna (DRA) can support multifrequencies, then the need for multi single frequency antenna is not necessary. Applications requiring different frequency bands can be operated simultaneously with one radiating element. This reduces the circuit size and leads to compact systems. In addition, when multi frequencies are located closer to each other, the antenna may have a broad operating bandwidth.

1.2 Areas to be Investigated

From the survey of the literature, it is clear that very little data or studies have been reported for the efficient computation of the input impedance of DRA. It is also seen that bandwidth enhancement has been a popular research topic for DRA. However, nevertheless an impedance bandwidth greater than 24% was reported in the past research on the multilayer HDRA. In addition the two-layer DRA structures have been described in terms of the mode of the innermost resonator [95]-[97], which does not take into account the outer layers, and thus do not correspond to the actual modes of the antenna structure. A proper identification and understanding of the antenna modes is extremely essential in the investigation of coupling and the radiation mechanism of the antenna structure. Also, without the knowledge of modes, no physical insights can be obtained in the antenna operation which is essential to the practical realization of the antenna structure. In addition there was insufficient research work on the rigorous analysis of the multilayer DRA for wide band antenna design. As such the previous investigation on the multilayer HDRA remained incomplete.

The research work presented in this thesis aims at four different objectives. First objective of the research work is the reduction of the computation time required to obtain the input impedance of the antenna based on the Green's function and Method of Moments (MoM) approach. Second objective is the further improvement of the impedance bandwidth of the HDRA for different feeds such as microstrip slot feed, probe feed, waveguide slot feed and the conformal strip feed. Third objective is the investigation and identification of the modes of multilayer HDRA. Final objective is the rigorous analysis of the mode excitation of multilayer HDRA to obtain new insights for the coupling mechanism of the antenna structure. The particular significance of this work arises from the fact that any serious investigation in the design of multilayer DRA structures has to be based on the excitation of modes in the multilayer DRA. In addition, the mode excitation analysis presented in this work is used to further reduce the computation time required to obtain the input impedance of the antenna. This thesis has made an all out effort to fill in these gaps in the existing state of knowledge.

The exact Green's function of *N*-layer HDRA has been derived first time in this dissertation work. In addition, the modes of the *N*-layer DRA has been first identified in this research work using a matrix formulation for the Green's function analysis of a DRA. In the previous work on the two-layer DRA [95]-[97] the unknown constant evaluation in the Green's function was not based on the matrix equation. This makes the derivation of the unknown constants in the *N*-layer HDRA Green's function extremely complicated and lengthy. A three-layer HDRA configuration is chosen as the optimization of the structure. For the microstrip slot feed and conformal strip feed to three-layer HDRA the unity permittivity is chosen for the second layer. This eases fabrication of the structure and also results in wide bandwidth due to the reduced Q factor. The multilayer DRA structure acts as an impedance transformer between the free space and the DRA feed. As a result, very good broadband coupling is achieved. The configuration also affords flexibility in frequency tuning by varying the design parameters. The return loss, radiation characteristics and the effect of tuning on the radiation performance of the antenna is investigated.

In the proposed work, the Green's function approach is presented to analyze a hemispherical DRA with arbitrary number of layers. All higher order modes have been taken into consideration. The analysis of the *N*-layer DRA structure is accomplished by separation of the source terms from the field-matching equations at the dielectric interfaces and incorporating them in the Green's function. The resultant matrix equation can be easily solved. It is seen that the approach also needs significantly less computational time and memory compared to FEM based electromagnetic softwares like HFSS [104] or FIT based software like CST [105], particularly when the number of dielectric layers increase. This is particularly useful for the design of broadband antennas based on the multilayer DRA topology. The simulation time and memory requirements are almost independent of the number of layers, which is one of the main advantages of this approach over other simulation softwares. A novel efficient computation technique named as "Product of Two Double Integrations" (PTDI) is first time presented in this thesis for the evaluation of the input impedance of the DRA. The use of PTDI technique results in the reduction of overall computation time by a factor of 37 and 100 for microstrip slot feed and probe feed respectively as compared to previous techniques. In addition for centred probe fed multilayer HDRA a novel efficient computation technique "Product of Two Single Integrations" (PTSI) is proposed. With the use PTSI technique for the centred probe fed HDRA the overall computation timed has been reduced by a factor of about 319. The theoretical results show good agreement with the results obtained from the HFSS or CST simulations and the experiments. In addition, the impedance bandwidth of the hemispherical DRA is improved by adding hemispherical shells of optimized permittivity and thicknesses. An impedance bandwidth of $\sim 63\%$ is achieved in case of centred probe fed three-layer HDRA. In case of previous studies on Wideband antenna, the primary attention was usually paid on the impedance bandwidth $(\mathrm{VSWR} \leq 2)$. However, the radiation pattern may deteriorate significantly even within the impedance pass band. In his work it has been found that multilayer HDRA excited by either centred slot or probe produces stable radiation pattern over much wider 10 dB impedance bandwidth.

Dual or multifrequency operation of the antenna is highly desirable in modern wireless communication systems. This is because a single physical antenna behaves electrically as multiple separate antennas. If a single dielectric resonator antenna DRA can support multifrequencies, then the need for multi single frequency antenna is not necessary. Applications requiring different frequency bands can be operated simultaneously with one radiating element. This reduces the circuit size and leads to compact systems. In this dissertation work, it has been shown that with optimized feed dimension and the optimized three-layer HDRA parameters it is possible to achieve dual band or multifrequency operation of the antenna very easily. In addition frequency tuning of the proposed antenna can be done very easily without degrading the radiation properties of the antenna in the pass band.

1.3 Organization of the Thesis

The thesis describes a rigorous modal analysis and characterization of multilayer HDRA excited by different feeds such as microstrip slot, waveguide slot, co-axial probe and conformal strip. In the proposed work, the Green's function and MoM approach is presented to analyze an HDRA with arbitrary number of layers. All higher order modes have been taken into consideration. In addition, the Green's function of *N*-layer HDRA is derived in the double summation form in which source and field terms are in the absolute product form. This facilitated the numerical evaluation of the time consuming four fold integration to be performed as a Product of Two Double Integrations, that result in the drastic reduction of the computation time. Reasonable agreements between computed data and experimental observations have been obtained. The input impedance versus frequency, return loss versus frequency, resonant frequency, and the radiation patterns of the HDRA has been investigated.

- **Chapter 2**

In this chapter, the exact Green's function of *N*-layer HDRA sitting on the infinite ground plane due to unit magnetic and unit electric currents are derived. The *N*-layer HDRA residing above the ground plane can be viewed as *N*-layer spherical DRA by using image theory. For the spherical geometry, exact closed form expressions for the Green's functions of point current in the dielectric body are derived using the modal expansion technique. The unknown constant evaluation in the *N*-layer HDRA Green's function is based on the matrix equation and is different from the previous work on the DRA. The *N*-layer HDRA Green's functions derived in this chapter are referred repeatedly in the rest of the thesis. In the last section the spectral domain Green's function of grounded dielectric slab due to unity magnetic current and unity electric current are derived. These spectral domain Green's functions of grounded dielectric slab are referred in chapter 3 and chapter 4 for the analysis of microstrip slot coupled DRA.

- **Chapter 3**

In this chapter, a novel efficient technique for the computation of input impedance of single-layer HDRA excited by microstrip slot and co-axial probe is presented. This is accomplished by manipulating the DRA Green's function in double summation form rather than single summation form. In the double summation form of DRA Green's function the source and field terms are in the absolute product form. The absolute product form of source and field terms facilitate the four fold integration in the MoM to be performed as a Product of Two Double Integrations (PTDI). This result in the drastic reduction of computation time needed to obtain the input impedance of the antenna. With the proposed efficient technique it has been shown that the overall computation time needed to obtain the input impedance of the microstrip slot coupled HDRA can be reduced by a factor 37. Similarly the time reduction factor of about 100 is reported for the computation of input impedance of probe coupled HDRA. In addition for the centre probe fed HDRA a time reduction factor of about 319 is achieved with the use of Product of Two Single Integrations (PTSI) technique.

- **Chapter 4**

In this chapter, a novel method is proposed to enhance the coupling of microstrip slot coupled HDRA over wide impedance bandwidth. The wide impedance bandwidth is achieved by using a three-layer HDRA topology with unity permittivity in the second layer. The permittivity of the third layer is taken as approximately half the permittivity of the innermost layer. This selected permittivity combination of the three-layer DRA resulted in lowering the Q factor of the TE_{111} mode thereby increasing the impedance bandwidth. By using the proposed technique the 10 dB impedance bandwidth of ~ 43.4% is obtained. Also, the maximum bandwidth realization of microstrip slot coupled three-layer HDRA is discussed relative to the parametric variation of the second and third layer permittivities.

In addition, the modal analysis of three-layer HDRA excited by unity magnetic source is investigated. It is seen that new insights can be obtained for the coupling mechanism of this antenna topology using the modal decomposition of the three-layer DRA. Particularly, it is seen that the centred slot couples only to a single TE_{11p} mode of the multilayer DRA. It is also seen that the computation time for the evaluation of input impedance for the slot-coupled antenna can be significantly reduced by accounting for only the relevant modes. Measurements were carried out to verify the theory.

- **Chapter 5**

In this chapter, rigorous analysis of rectangular waveguide slot coupled three-layer HDRA is demonstrated theoretically and experimentally for wide band operation. The scattered magnetic field inside the waveguide due to an aperture in the transverse plane is derived in the second section. The ground plane thickness is taken into account in the analysis by modelling the slot thickness as a rectangular cavity. The Green's function of a rectangular cavity due to magnetic point source is derived in the third section. In the MoM analytical integrations are performed inside the rectangular waveguide and the slot cavity, whereas DRA Green's function is integrated numerically using the novel PTDI technique discussed in chapter 3. It is seen that wide bandwidth of the rectangular waveguide slot coupled to three-layer HDRA is obtained when the permittivity of the innermost layer is unity and the dielectric filling the waveguide is air. Thereafter maximum bandwidth realization of the empty rectangular waveguide slot-coupled two-layer and three-layer HDRA is discussed relative to the parametric variation of the layer permittivities. The computed and simulated results of the dielectric filled rectangular waveguide slot coupled multilayer HDRA are also discussed. The 10 dB impedance bandwidth of ~ 12.9% is achieved with an empty rectangular waveguide slot coupled to three-layer HDRA.

- **Chapter 6**

In this chapter, a novel method is proposed to enhance the coupling of co-axial probe coupled HDRA over wide impedance bandwidth. The wideband antenna operation of three-layer HDRA excited in TM_{101} mode is demonstrated. The wide impedance bandwidth is achieved by using a three-layer HDRA topology. It is shown that for the fixed permittivities of the first and third layer of HDRA the optimum non unity permittivity in the second layer must be found to lower the Q factor of a TM_{101} mode. This selected permittivity combination of the three-layer DRA resulted in lowering the Q factor of the TM_{101} mode thereby increasing the impedance bandwidth. By using the proposed technique the 10 dB impedance bandwidth of about ~ 63% is obtained. Also, the maximum bandwidth realization of co-axial probe coupled three-layer HDRA is discussed relative to the parametric variation of the second and third layer permittivities. In addition, the modal analysis of three-layer HDRA excited by unity electric source is investigated. It is seen that the centred probe couples only to a TM_{10p} modes of the multilayer DRA. It is also shown that the computation time for the evaluation of input impedance for the probe-coupled antenna can be significantly reduced by accounting for only the relevant modes. Measurements were carried out to verify the theory.

- **Chapter 7**

The full wave analysis of conformal strip fed three-layer HDRA for wide band operation is demonstrated in this chapter. The exact general Green's function for three conformal strip locations on the three dielectric interfaces in the three-layer DRA is derived. The input impedance is obtained by determining unknown strip current using MoM. Analytic integration involving DRA Green's function is performed in the MoM. The effect of conformal strip location in the three-layer DRA topology on the impedance bandwidth is investigated. The maximum bandwidth realization of the three-layer HDRA excited by conformal strip at the first dielectric interface in TE_{111} mode is discussed relative to the parametric variation of the second and third layer permittivities. Finally the modal analysis of three-layer HDRA excited by unity $\hat{\phi}$-directed electric source is investigated. It has been observed that the convergence of the DRA Green's function is obtained with large number of modal terms $\left(\text{about } n = 60\right)$. This is because of the matching of conformal strip geometry with the DRA geometry.

- **Chapter 8**

The final chapter 8 of this thesis sums up the achievements reported in this work, based on the analysis and results presented. In addition, a comparative study of different feeds to the multilayer DRA is discussed. It also critically examines the areas which are not studied in the present work, and outlines the areas where efforts need to be put in to further the state of knowledge in this area.