Chapter 1

Introduction: Basic Concepts and Early Developments
1.1 Motivation

The resonance cavity antenna (RCA) is a class of high gain antenna working based on the principle of Fabry-Perot cavity [1]. A superstrate layer is commonly placed on top of a printed or planar antenna maintaining a separation of $\lambda/2$ to form the cavity resonator and this has been an active area of research for the last two decades due to its high gain characteristics. Several investigations have reported the phenomenon of gain enhancement of different kinds of primary radiator such as Hertzian dipole [2]–[5], metallic slot [6], [7], microstrip patch [8]–[15] or dielectric resonator antenna (DRA) [16], [17]. The superstrate layers were made of engineered metal structure, dielectric or metal-dielectric composite structures.

A wide variety of superstrate geometries have been explored so far and they include dielectric material [1]–[15], [17]–[21], electromagnetic bandgap material (EBG) [22], [23], artificial magnetic conductor (AMC) or double negative metamaterial [24]–[27], frequency selective surface (FSS) [28]–[31], and metal grids [16], [29]. In place of a top-layer superstrate, top-open shaped cavity has also been explored recently [32], [33] as a Fabry-Perot cavity antenna.

The Fabry-Perot cavity is commonly used in the optical domain. A pair of semi-transparent reflecting surfaces are used to impose a condition in favor of enhancing the optical gain. Fabry-Perot laser source is an example of such cavity resonator. In an optical fiber communication system, both temporal and spatial coherence is essentially required from a laser source. The spectral width of a laser source is determined by the temporal coherence. The technique of stimulated emission assures temporal coherence to achieve narrow spectral width, but not the spatial coherence. This is essentially required to produce a highly directive laser source for coupling the power to an optical fiber core for the improvement of coupling efficiency. The Fabry-Perot cavity is the only solution to ensure the spatial coherence and hence to enhance the directivity of a laser source. In an RCA, the same principle is followed and a primary radiator is placed in between a pair of reflecting or partially reflecting surfaces as shown in Fig. 1.1.
**Fig. 1.1.** Schematic diagram of a resonance cavity antenna (RCA).

**Fig. 1.2.** Waveguide-fed RCAs proposed for the first time [34]: (a) cylindrical cavity with metal-strip superstrate; (b) rectangular cavity with wire-grid superstrate; (c) rectangular cavity loaded by an array of circular patches supported by a polystyrene plate.

In here, microstrip patch is working source or radiator. The ground plane (GP) at the bottom serves as a reflecting surface and the other surface is realized by deploying a superstrate above the primary radiator. A separation of $\lambda/2$ ($\lambda$ being the resonant wavelength of the primary radiator) is also marked in Fig. 1.1.

### 1.2 Loading of Primary Antenna by Superstrate(s) or Alike Structure: A Chronological Review

#### 1.2.1 The First Investigation

The survey of the literature indicates an investigation made by Trentini [34] as the first RCA where he termed his device a ‘reflex cavity antenna’. His geometries are shown in Fig. 1.2 where an open-ended waveguide fitted with a circular/rectangular ground plane
has been used as the primary source. In Fig. 1.2 (a), the superstrate is a metal strip grid structure (∼ 2λ× 2λ). A variant of the same is shown in Fig. 1.2 (b), but the superstrate used in Fig. 1.2 (c) is composed of an array of circular patches (∼ 3λ× 2.6λ). Formation of a uniform phase front was successful, resulting in a very high directional radiation. Those antennas produced 14 dB gain with up to 34° half power beam width.

1.2.2 Dielectric Covered Printed Antennas
It took nearly three decades to adopt low profile antennas as a primary radiator. The fundamental effects of protecting dielectric cover or superstrate layer, over printed antennas were studied for the first time by Alexopoulos in their pioneering work [2]. It is very much essential to protect a printed antenna from various environmental hazards and weather conditions due to rain, snow, and fog. The ‘resonance’ condition of the substrate-superstrate combination was established analytically for optimum ‘gain’ of an infinitesimal dipole or Hertzian dipole. The substrate-superstrate with Hertzian dipole as the source is schematically shown in Fig. 1.3 (a). The ‘resonance’ condition [2] required to achieve high ‘gain’ has been referred to as ‘resonance gain’ method by the same authors in [3]. They had derived asymptotic formulas to determine the resonance gain, bandwidth, and beamwidth. Apart from the commonly used broadside radiations, this method has also been applied to any other scan angle of the antenna. A large antenna gain has been predicted [2], [3] in terms of large permittivity (ε) and/or permeability (μ) values of the superstrate.

Achieving very high gain is impractical due to unavailability of low loss substrate/superstrate material with very high ε value. A more realistic design was prescribed in [4] using multilayer superstrate as shown in Fig. 1.3 (b). Due to this inhomogeneous configuration, the radiation properties of the antenna have been presented using reciprocity and transmission line model.

1.2.3 The Leaky-waves Approach
The ‘resonance gain’ mechanism of [3] was explained in terms of ‘leaky-waves’ in [5] using a single layer superstrate and in [35] for a multilayer configurations. The leaky-
wave properties and radiation behavior were presented using simple asymptotic formulas as a function of frequency, scan angle, and \( \varepsilon \) of the superstrate.

1.2.4 Dielectric Covered Patch

The effect of dielectric superstrate of a rectangular microstrip patch (Fig. 1.4(a)) was experimentally investigated by Bhattacharyya [8]. A significant decrease in resonant frequency was observed without much change in matching bandwidth. These changes could be estimated by simple empirical relations as a function of superstrate thickness.
Like [8], several studies and advancements of superstrate loaded patches were made by Luk [9] for a circular microstrip patch antenna (Fig. 1.4(b)). Spectral domain technique, based on Hankel transform was used in [36].

The cavity model was employed in [36] when they used a thin superstrate layer. But, for larger superstrate thickness the cavity model was found to fail as reported in
Fig. 1.5. Aperture-fed microstrip patch antenna covered by a dielectric superstrate [6], [7]; (a) side view; (b) top view.

[37]. Better accuracy was obtained from the mode matching technique [38] based on impedance wall boundary conditions. Later on, the cavity model was more efficiently used in superstrate loaded patch by Bernhard [39] and Guha [40].

It is interesting to note that the radiation efficiency of such a superstrate covered patch can be optimized by varying the substrate/superstrate permittivity [10], [11]. Optimized superstrate thickness is also important to minimize the side lobe levels.
Fig. 1.6. Formation of Fabry-Perot cavity using dielectric slab(s) as superstrate, (a) dielectric plate loaded microstrip patch [18], (b) dipole antenna loaded by dielectric slabs [1].

A slot-coupled microstrip patch with dielectric cover (Fig. 1.5) was studied by Huang [6] and Lo [7]. The slot fields and patch currents were numerically evaluated in [6] with the help of reciprocity theorem and the moment method solution for obtaining the Green’s function of the dielectric superstrate. The antenna characteristics such as
1.2.5 Dielectric Layer to Form Fabry-Perot Cavity

A thin dielectric layer was introduced by Shen [18] for the first time to form a Fabry-Perot cavity (Fig. 1.6(a)) and this was demonstrated to increase the gain of a patch antenna. The resonance condition by multiple reflections between the superstrate and the
A subsequent work [1] tried to find out the reason behind the high gain phenomenon and applied Brag-mirror principle of resonant photonic crystals. They theoretically explained the high gain as a focusing effect caused by the angular selection rules occurring in a Bragg-type mirror. That’s why they used a multi-layer dielectric stack as shown in Fig. 1.6 (b) with a simple dipole symmetrically placed in the middle. This is not really a practically realizable configuration.
1.2.6 EBG as superstrate

The engineered dielectric sheet was used as the superstrate [41] and then it was designated as photonic bandgap or PBG. Indeed, such structures, later on, are called as electromagnetic bandgap or simple EBG. A periodic arrangement of rectangular cavities created in a dielectric sheet forms the EBG layer as shown in Fig. 1.7 where the arrow represents a Hertzian dipole working as the primary radiating element. Strong leaky-wave excitation was conjectured as the cause of achieving high gain as a function of radiation angle. The scattering problem in the EBG was solved using three-dimensional integral-equation and the reciprocity theorem. Periodic dielectric rods with different permittivity were used to compose an EBG superstrate [22] and few variants are shown in Fig. 1.8. Fig. 1.9 shows a multi-layer dielectric superstrate as was examined in [4], [35], [42]. This was treated as a one-dimensional EBG structure for the enhancement of gain and bandwidth of a single patch or slot radiator [42]. The air gap between the ground plane and the first dielectric slab (Fig. 1.9) behaves as the defect in EBG. In [43], the dielectric property of the EBG material decides the gain and radiation bandwidth. Theoretically, the directivity of the antenna increases with the increase in the number of layers or their relative permittivity, but the radiation bandwidth decreases gradually. This gain versus bandwidth issue was trying to be resolved in [42] by illuminating the EBG layers with an
array of primary radiators. Subsequently, a two-layer dielectric superstrate was investigated by Kaymaram [19] as a high-gain and large-bandwidth antenna using a probe-fed microstrip patch as a primary radiator.
A metallic EBG was proposed by Menudier [23] to design a reflector feed. The geometry is shown in Fig. 1.10 (a) bearing a microstrip patch as the radiating element and it was aimed for multibeam coverage in satellite applications. The performance of the antenna was improved by Chantalat [44] by replacing microstrip patch by a horn as shown in Fig. 1.10(b).
1.2.7 Resonant Cavity type Superstrate

This is completely a different type of use of superstrate cavity explored by Sauleau [45] for a horn antenna. The cavity configuration is shown in Fig. 1.11 (a) which is composed of two metal grid mirrors, one being planoconvex type at the top and the other one being flat at the bottom. The cavity was directly fitted to the aperture of a V-band horn and it was aimed to realize a Gaussian Beam Antenna [46]. The function of the cavity is controlled by these two mirrors, their intermediate spacing, and finally the curvature of the top mirror. About 12 dBi peak gain with -25 dB side lobe level was demonstrated at 60 GHz.

This two-mirror cavity approach was extended to microstrip patch by the same group [47] converting the concave mirror to planner configuration using non-uniform mesh as shown in Fig. 1.11(b). This indeed alleviates the possibility of profile errors caused by manufacturing defects.

1.2.8 Metal Superstrate to form a Fabry-Perot cavity

A single layer of metallic mesh was introduced as a superstrate on top of a microstrip patch [31] to form a Fabry–Perot antenna. The geometry is shown in Fig. 1.12.
Fig. 1.13. Resonance cavity antenna using frequency selective surface (FSS) superstrate: (a) Schematic diagram of the RCA using PRS superstrate; (b) RCA configuration using FSS superstrate [48].

where the metallic grid acts as a partially reflecting mirror and the metal ground plane as a perfect mirror. They also reported high gain.

1.2.9 Frequency Selective Surface (FSS) to form RCA

The partially reflecting surface (PRS) was replaced by Frequency Selective Surface (FSS) in [48]. That work [48] demonstrated an increase in gain of an open-ended waveguide as shown in Fig. 1.13(b). Simple ray theory, commonly used for the optical
Fig. 1.14. Schematic diagram of resonance cavity formed by (a) perfect electric conductor (PEC) as ground plane and frequency selective surface (FSS) as the PRS superstrate; (b) perfect magnetic conductor (PMC) as AMC ground plane and FSS as the PRS superstrate (compact design).

cavity [49], was employed to derive some analytical formulations. They considered both ground plane and the superstrate layer to be of infinite size with reflection coefficients $1, e^{-j\pi}$ (magnitude=1) and $R(\theta)e^{j\phi(\theta)}$, respectively. In here, $\phi(\theta)$ represents the phase and $\theta$ is the angle of incidence as depicted in Fig. 1.13(a).

A similar FSS superstrate was examined by Lee [50] employing microstrip patch as the primary radiator instead of using waveguide feed. A more complex and dual layer FSS was reported by Lee again in [28]. They also examined three other FSS configurations. Subsequently, different research groups had addressed resonance gain antenna using various types of FSS superstrates [24], [25], [30], [51], [52]-[62].

**FSS with Artificial Magnetic Conductor (AMC) ground plane**

Artificial magnetic conductor (AMC) was used as the ground plane to reduce the physical height [51]. AMC is actually an engineered printed substrate which supports no
Fig. 1.15. Compact resonant cavity antenna design using high impedance AMC ground plane: (a) RCA using PRS substrate and AMC superstrate made of square patch array [24]; (b) RCA using double-ring type FSS superstrate and single-ring type AMC ground plane [25].
Fig. 1.16. Realization of FSS superstrate using metal strip grating (MSG): (a) schematic diagram of the RCA using MSG superstrate; (b) thick MSG superstrate [29]; (c) thin MSG superstrate [29].

Thus a wave suffers zero phase shift during any reflection from the AMC and provides a boundary condition in support of reducing the cavity height from half-wavelength to quarter-wavelength. This is schematically shown in Figs. 1.14 (a) and (b). Two different sets of ‘element geometries’ were explored for realizing both FSS and AMC surfaces by two different groups [24], [25] as depicted in Figs. 1.15 (a) and (b). Metallic patch arrays


**Fig. 1.17.** Conformal resonance cavity antenna using cylindrical superstrate and substrate configurations made of patch array type EBG and HIS structures respectively [66].

(without vias in AMC) were used in [24] and rectangular ring type geometries were implemented in [25].

*The Metal Strip Grating as FSS superstrate*

Lovat and Burghignoli [63], [64] reconfigured linear metal grating [34], [65] in planer form and realized a periodic metal strip grating (MSG) which looks like Fig.1.16(a). The arrow in Fig. 1.16(a) represents horizontal electric dipole considered as the primary radiator. Foroozesh [29] examined simple MSG with different periodicities (Figs. 1.16(b) and (c)) for a practical antenna using microstrip patch as a primary radiator.

1.2.10 Conformal Resonance Cavity Antenna

High gain base station antennas were realized by Palikaras [66]–[68] using conformal shaped resonance cavity antenna as shown in Fig. 1.17. Both ground plane and superstrate are of a cylindrical shape which makes the overall configuration compact. The E-plane directivity of a dipole was enhanced by this method [66]. The cylindrical ground plane has also been realized as an AMC.
1.2.11 Metamaterial superstrate for RCA design

Few researchers also tried with planer metamaterial type geometries as the superstrate in realizing high gain [26], [69]–[72]. Enoch et al. [69] first showed that the emission from a microwave source embedded in a multi-layered metamaterial structure could be made directive under specific conditions. The optical principle of focusing was adopted in the form of graded indexed metamaterial structures. An example is shown in Fig. 1.18 (a) from [70] where a gradient index function [71] was realized using a tapered distribution of the square ring array elements. Another geometry, shown in Fig. 1.18 (b), uses engineered printed units in three different layers [72] and analyzed in [26].

1.3 Dielectric Resonator Antenna (DRA) as A Primary Radiator

Dielectric resonator antenna (DRA) was used as a primary radiator for the first time by Wu, Kishk, and Glisson in [73]. Their configuration looks like Fig. 1.19 (a) where a probe-fed cylindrical DRA was employed and its far-field radiation pattern was theoretically estimated [73]. Other feeds such as aperture-coupling [16], [17], [74] and CPW coupling [75] were also examined for a series of V-band (57-65 GHz) designs by a group. In those designs using DRA, the superstrates were chosen as dielectric slab [17],
Fig. 1.19. RCA using dielectric resonator antenna (DRA) as primary radiator: (a) probe-fed cylindrical DRA loaded by double layer dielectric superstrate [73]; (b) aperture-fed DRA with dielectric superstrate loading [17]; (c) aperture-fed DRA with MSG superstrate loading [16].
Circularly polarized RCA designs using CP primary radiators loaded by superstrate: (a) dielectric superstrate for CP-RCA [76]; (b) FSS superstrate for CP-RCA with HIS surface as a substrate [79].

[75], metal strip grating [16], or square-ring array [74]. Two superstrate variants are shown in Figs. 1.19 (b) and (c).

1.4 CIRCULARLY POLARIZED (CP) RESONANCE CAVITY

Fabry-Perot principle is also applicable when the primary radiator is circularly polarized (CP). Therefore, high gain CP radiations were achieved by the principle of resonance
Fig. 1.21. Realization of CP-RCA using a linearly polarized (LP) primary source loaded by a superstrate to transform the polarization from LP to CP [81], (a) dipole antenna loaded by FSS superstrate, (b) microstrip patch loaded by two layer FSS superstrate [82].
cavity in several investigations [76]–[80]. Later on, a different approach was successfully examined using a linearly polarized (LP) radiator with specially designed superstrate to transform the polarization from LP to CP along with high gain [81]–[83].

A simple example of the first kind is shown in Fig. 1.20(a) which was theoretically studied for the first time in [76]. The air gap was maintained at the half-wavelength or its multiple. An FSS superstrate with the high-impedance ground plane was explored [79] to realize a high gain CP antenna. The geometry is shown in Fig. 1.20(b) where a corner-fed rectangular patch was used as the primary source. Two examples of the second kind are shown in Fig. 1.21 where a linear half-wavelength dipole [81] and linearly polarized patch [82] were used to produce CP with high gain.

1.5 The Objective of the Dissertation

The superstrate loaded resonance cavity antennas, discussed above, were investigated with an understanding that after multiple reflections in a Fabry-Perot cavity, the electromagnetic energy would leak through its top layer resulting in high gain. The superstrates, therefore, were conceived as semitransparent layers made of pure dielectric or grating type planar or 3D structures [83]–[103].

We, from the very beginning, viewed the problem from a different angle of understanding and hence attacked it by replacing the concept of ‘semitransparent superstrate’ by a nontransparent fully reflecting surface (FRS). We simply used a thin solid metal sheet. Also, we observed that previously reported superstrates were considerably large if compared to an array.

Therefore, the main objectives of this study were: (i) to use a nontransparent solid metal sheet as a superstrate and understand the actual physics behind the high gain radiation from an RCA; (ii) to develop appropriate theory to explain the RCA behaviors; (iii) to investigate the aperture-synthesis concept and study the feasibility of using the same for modifying or generating any desired radiation pattern; (iv) also to reduce the superstrate size to make new generation RCAs handy, lightweight, and practically useful.
1.6 Major Studies and Contributions

The technical investigations made in this dissertation and their novelties are briefly discussed as follows:

1.6.1 New Concept - Nontransparent Superstrate

A nontransparent superstrate in the form of a thin metallic sheet has been proposed and explored as an alternative to the known semi-transparent type superstrate layers. Such a configuration has been physically realized for the first time. The new concept has removed some earlier notions about the requirement of engineered grid type or fully dielectric type superstrates for high gain RCA. Compared to earlier ones, this new superstrate appears much advantageous as it (i) needs no specific design or pattern, (ii) is simple and inexpensive, (iii) bears maintenance free feature, (iv) is highly compact in size, (v) provides wide matching bandwidth along with high gain.

1.6.2 Theory - Cavity Design for Dual Resonances

A theory to determine the optimum height of a Fabry-Perot type resonance cavity has been developed and examined for a setup using DRA as the primary radiator. Two effective cavities based on partial filling by dielectric materials, caused by the DRA itself, have been modeled using Harrington’s formula for two consecutive resonances.

1.6.3 Introduction of a New Concept - Aperture Field Synthesis

The aperture fields over the superstrate surface have been demonstrated as the key to achieve the radiation from an RCA. This concept is fully different from the earlier understanding and helps us in synthesizing ‘desired aperture field’ based on our requirement of the gain pattern. This aperture synthesis concept has been extensively studied and verified through a series of investigations.

1.6.4 New Theory for Resonance Cavity Antenna

A theory based on the spectral technique has been developed and analyzed to demonstrate how the superstrate parameters can control its aperture field distribution and hence the far field parameters. This has been tested and validated in this dissertation for a
set of realistic aperture distributions. This approach has been employed in predicting few modifications in the superstrate field in view of achieving improved radiation properties.

1.6.5 High Gain-Bandwidth Characteristics

We have demonstrated the possibility of achieving up to 15.2 dBi gain with more than 22% impedance bandwidth employing highly compact superstrate ($\sim \lambda \times 0.5\lambda$, much-reduced size compared to all the earlier designs). Attractive flat gain characteristics over the operating band have been obtained from the realized prototype indicating a wide gain-bandwidth performance. The proposed theory and design have helped in obtaining as low as -27 dB of SLL with an acceptable value of cross-polarized radiations.

1.7 THESIS ORGANIZATION

The dissertation embodies six chapters, the contents of which are briefly described below. Chapter 1 contains the detailed general introduction of the RCA and its working principle. This covers the concept, evolution, and application of RCA employing various primary radiators and PRS superstrate geometries in recent years. A brief review of the literature is also presented chronologically.

In Chapter 2, a nontransparent metal sheet superstrate has been proposed for the first time for a high gain RCA design. A probe-fed cylindrical DRA has been used as the primary radiator. The resonance and wide bandwidth characteristics of the antenna have been estimated theoretically. Proposed antenna promises to enhance the antenna gain from 6 to 12 dBi with considerable radiation symmetry in both the principal planes and predicts wide band operation maintaining high gain patterns. These have been verified experimentally. Considerably high radiation efficiency has also been experimentally demonstrated. The physical insight into the high-gain pattern of the proposed RCA has been examined based on its aperture field distribution.

In chapter 3, modification and improvement in the radiation characteristics of an RCA have been addressed from a new approach to aperture field synthesis over the superstrate. This concept has been established through a series of systematic studies and the desired aperture field has been realized using single slit (SS) superstrate geometry. About 22% matching bandwidth with a peak gain of 15.2 dBi has been experimentally
achieved indicating very close agreement with the simulated data. Measured SLL is found to appear about 2 dB higher than the predicted values indicating -11 dB in E-plane and -14 dB in H-plane with 33 dB polarization purity.

In chapter 4, a new theory of aperture field for improved RCA design has been proposed. The theory has been developed to facilitate the design of a superstrate which plays a key role in realizing very high gain. This leads to an analysis establishing relations between the superstrate field and far field parameters, which has been tested using a set of realistic aperture fields comprising of three triangular pulses. Amplitude \((E_0, E_1)\), width \((\delta_0, \delta_1)\), and relative position \((x_1)\) of the triangular pulses play significant role in controlling the far field patterns which provides some useful design insight listed as: (i) increase in \(E_0, E_1, \delta_0, \text{and } \delta_1\) enhances the gain, (ii) \(E_0/E_1\) determines the existence as well as magnitude of the SLL, (iii) smaller value of \(x_1\) pushes the side lobes away from the main beam and makes them insignificant. This would help a designer in standardizing required field specifications across a superstrate. This theoretical knowledge has been validated and employed to achieve compactness in superstrate geometry \((1.1\lambda \times 0.55\lambda)\). The side lobe level has been improved (about 17 dB) by reshaping the rectangular superstrate to ellipse in H-plane along with significant increase in gain. Two different variants of elliptic superstrate have been fabricated and verified experimentally with their simulated predictions.

In chapter 5, a compact superstrate geometry as a circular polarizer filter has been proposed to design a CP-RCA using a dual-fed cylindrical DRA as a primary radiator. A cross-slit metal film superstrate has been conceived and applied as a circular polarizer/superstrate for higher CP gain. Very high gain and axial ratio bandwidth have been achieved simultaneously. This promises to produce 15 dBi gain, which is indeed an improvement by 10.3 dB compared to the standalone DRA configuration without superstrate. The prototype of the proposed design has been fabricated and experimentally tested.

Finally, in chapter 6, the entire work performed in this dissertation is summarized. There should be plenty of scopes for further developments and improvisation employing different type of primary radiators, which may include microstrip patches or slots of varying geometries and polarizations. Such a compact high
gain and light weight antenna should find potential applications as feed or portable wireless base stations for point to point links. The major shortcoming using metal sheet superstrate will be addressed and improved by the reshaping of the superstrate. Full wave analysis may also be taken up to develop clearer theoretical insight. Proposed theory should find the potential scope of applications in conceiving newer engineered superstrate for more efficient RCA designs in the future.

Because of strong near feed characteristics, an RCA may be used as a feed element with some superior characteristics compared to the conventional feeds. There is a potential scope of feed design using RCA in various applications like radar, mobile base station, and satellite applications. There is a potential scope of near field applications where strong near field is highly desirable. This may help in designing, developing, and implementing a wearable sensor required for body area networks. Apart from this, RCA can be applied to various medical applications like cancer detection, microwave imaging etc.

REFERENCES


[76] W. Chen, K. Wong, and J. Row, “Superstrate loading effects on the circular polarization and crosspolarization characteristics of a rectangular microstrip patch


