Chapter 1

INTRODUCTION

1.1 The Development of Radio Communications

Since Hertz and Marconi, antennas [1]-[4] have become increasingly important to our society and radio communications have been with us now for the entire twentieth century. They are everywhere: at our homes and workplaces, on our cars and aircraft, while our ships, satellites and spacecraft bristle with them. Even as pedestrians, we carry them.

An antenna is a device that provides a means for radiating or receiving radio waves. In other words, it provides a transition from a guided wave on a transmission line to a "free-space" wave (and vice versa in the receiving case). Thus, information can be transferred between different locations without any intervening structures. Although antennas may seem to have almost infinite variety, they all operate according to the same basic principles of electromagnetics. The theoretical foundations for antennas rest on Maxwell's equations, which James Clerk Maxwell (1831-1879) presented before the Royal Society in 1864, that unify electric and magnetic forces into a single theory of electromagnetism. Maxwell also predicted that light is explained by electromagnetics and that light and electromagnetic disturbances both travel at the same speed.

The fundamental principles of antenna design are based on classical electromagnetic field theory which were established during the second half of the 19th and the beginning of the 20th centuries when the first radio experiments were being performed. Since that time the applications of antenna design have undergone a steady expansion which accelerated during and after the Second World War with the explosive growth in communications, radar, remote sensing and broadcasting. Antenna is a necessary, and often critical, part of any system which employs radio propagation as the means of transmitting information, and this has been recognized in the very considerable effort devoted to the study of their properties and the engineering of practical radiating systems.

With the recent advances of telecommunications, the need for small and low-profile antennas has greatly increased [5]. Especially in mobile communication, the demand for small antennas and low-profile antennas is quite urgent [6]. Electronic equipment has rapidly reduced its physical size due to the development of integrated circuits, but the antennas for communication equipment still remain large compared with the equipment itself.

Low-profile, flat-structured planar antennas are suitable for mounting on portable equipment and have been highlighted recently. For high speed moving objects, such as space shuttles and airplanes, they need to have low-profile antennas that do not protrude from the body.

Among antennas having such a structure, the cavity-type antenna is one of the most promising antennas. Normally, cavity-type antennas are narrow-band antennas with bandwidths ranging from 0.5-2% (high quality-factor antennas) to 10-15% (backfire antennas). For the foregoing frequency and bandwidth, the cavity-type antennas are considerably smaller in size, volume and weight than the better known classical antennas.

Cavity antennas are more like three-dimensional cavity resonators. On one of the metal cavity walls, multitudes of small openings (slots or round holes) are made. Thus, the cavity antenna can also be considered either as an antenna array or, generally speaking, as a semitransparent aperture backed by a closed resonator cavity. Generally, cavity antennas may be considered as cavity resonators, in which the metal wall, or part of it, is semitransparent.

1.2 Progress in Cavity-Backed Slot Antenna Study

The cavity-backed aperture antenna has been the subject of many papers over the past three decades or longer [7]-[10]. In [7] and [8] the backing rectangular cavity was a shorted waveguide whose cross section was the same as that of the aperture. Reference [7] is further restricted to small cavities. In [9]-[10] the thin slot is backed by a rectangular cavity of different cross sections.

A typical cavity antenna with a semitransparent radiating wall was proposed by Jacobsen, Andersen, and Gronlund in 1963 [11]. Its cavity resonator had rectangular shape and dimensions of $10 \times 10 \times 1.5 cm^3$. A basic electromagnetic mode TE_{110} was excited inside the cavity and the antenna had a gain of 20 dB at 9.8 GHz.

The early systematic and analytical contribution to the cavity-backed slot antenna dates back to the beginning of 1960's. In 1962, J. Galejs and T. W. Thompson [12] published the analysis of an annular slot antenna. The antenna was backed by a cylindrical or a coaxial cavity and excited by a current sheet in the slot plane. The integral equation, which relates the radial electric field in the slot plane to the linear source current density, was solved by variational techniques. The numerical calculations emphasized narrow slots and shallow cavities. They found that the slot antennas might resonate with cavity depth $z_o < \lambda/4$. A resonant antenna exhibited nearly the same bandwidth as the slot, which was backed by a $\lambda/4$ deep cavity. Dielectric cavity loading decreased the size of a resonant cavity, but it also decreased the antenna bandwidth.

In 1963, J. Galejs [13] also published the analysis of a cavity-backed rectangular slot antenna that was excited by a current source connected across its center. The longitudinal voltage variation across the slot was obtained from the variational solution of an integral equation. For shallow and narrow cavities the slot appeared inductive and the voltage was rapidly attenuated along the slots. The slot might resonate for deeper and wider cavities, when the voltage along the slot was approximated by a half-cycle of a sine wave. The resonant cavity depth and the antenna bandwidth were examined for various cavity and slot parameters. Dielectric cavity loading was shown to decrease both the resonant cavity depth and the antenna bandwidth.

In 1967, A. T. Adams [14] presented the analysis of the aperture admittance of a rectangular cavity slot antenna, taking into account material loading, an aperture plane iris, and the effect of higher-order modes. The aperture admittance data was then used to derive accurate design techniques for calculating bandwidth, efficiency, resonant frequency, and beam pattern of the antenna.

In 1976, C. R. Cockrell [15] published a paper on the input admittance of the rectangular cavity-backed slot antenna. In the paper the slot was assumed narrow so that the voltage distribution in its aperture was sinusoidal. Equations which represent the input admittance of this slot, backed by a rectangular cavity in which a single propagating wave is assumed to exist, were given. It was found that as the depth of the cavity increased the resonant frequency decreased and the bandwidth became narrower.

In 1980, R. F. Harrington and D. T. Auckland [16] published the general formulas for electromagnetic transmission through an infinitely long slot in a perfectly conducting screen of finite thickness for the case of a narrow slot. The slot might be filled with a homogeneous isotropic material. They also developed a simple equivalent circuit for the narrow slot.

The problem of an electrically small aperture in a conducting screen backed by a conducting body was analyzed by R. F. Harrington [17] In 1982.

It was found that aperture-body resonance could occur for which the power transmitted through the aperture backed by a conducting body was much larger than that when the body was not present. In the loss free case, the transmission cross section of a small-resonated aperture was independent of the size or shape of the aperture. For actual conductors, the transmission cross section would be reduced by conduction loss as the aperture is made smaller.

In 1982, C. H. Liang and D. K. Cheng [18] analyzed the electromagnetic coupling of an incident plane wave through a slot aperture backed by a lossy rectangular cavity by using a generalized network formulation based on an application of the equivalence principle. The conditions for the existence and the characteristics of such double aperture cavity resonance were studied. General expressions for field strength in the aperture field distributions in the cavity, and maximum power penetration were derived. Appropriate expressions for an equivalent magnetic current to replace the aperture were discussed.

In 1989, J. Hirokawa, H. Arai N. and Goto [19] proposed a wide slot antenna to expand the frequency bandwidth of a cavity-backed slot antenna. In the analysis of the antenna the slot width was significant in comparison with the slot length and the feed line was included. The frequency bandwidth (VSWR ≤ 2) of 35% was reached.

In 1991, H. Morishita, K. Hirasawa and K. Fujimoto [20] analyzed the cavity-backed annular slot antenna. In the analysis one short point was introduced to get circular polarization. Resonance frequencies, bandwidths, and radiation patterns were studied with respect to a slot width, a cavity depth, and a slot shorting position. By selecting a slot shorting position, circular polarization and the bandwidth of more than 10%(VSWR ≤ 2) for the input impedance were obtained.

In 1993, S. Hashemi-Yeganeh and C. Birtcher [21] proposed a cavity-backed slot antenna excited internally by a suspended narrow strip. Coupled integral equations were developed to compute the electric field distribution in the slot and the surface current distribution on the strip. The input impedance of the cavity at the feeding point on the strip had been computed theoretically and measured experimentally. The impedance data, being a function of cavity dimension, slot length, strip length, and frequency, could be polyfitted and used to implement a systematic design procedure to construct a planar array of these slots.

In 1994, C. W. Penney and R. J. Luebbers [22] performed a finite-difference time-domain (FDTD) analysis of spiral antennas to calculate input impedance, antenna gain and scattering. A semicircular spiral mounted on a dielectric substrate was simulated for computing the input impedance versus frequency. The gain and scattering computations were performed on a square archimedean spiral mounted in a ground plane with a cavity-backing. Total field FDTD calculations were used to compute the impedance and gain patterns, while a specially modified scattered-field approach for aperture antennas in an infinite ground plane was used for the scattering results. Good results were obtained for impedance, radiation and scattering.

In 1995, J. C. Cheng, N. I. Dib and L. P. Katehi [23] used the hybrid technique that combined the method of moments (MoM) and the finite element method (FEM) to analyze cavity-backed patch antennas. This technique featured the use of FEM in solving the electromagnetic field distribution in the cavity and the use of MOM in solving integral equations outside the cavity. The results of MOM and FEM were combined through the continuity conditions on the boundary of the cavity. Due to the flexibility of FEM, complex cavities filled with inhomogeneous media could be analyzed by this technique.

In 1996, C. J. Reddy, M. D. Deshpande, C. R. Cockrell, and F. B. Beck [24] presented an analysis of the radiation characteristics of cavity fed aperture antennas in a finite ground plane. In the analysis, a hybrid technique using the finite element method (FEM), the method of moments (MoM) and the geometrical theory of diffraction (GTD) was applied. The cavity, which excited the aperture, was assumed to be fed by a cylindrical transmission line. In the analysis, the input admittance of open ended circular, rectangular, and coaxial line radiating into free space through an infinite ground plane were computed and compared with earlier published results. Radiation characteristics of a coaxial cavity-fed circular aperture in a finite rectangular ground plane were verified with experimental results.

1.3 Rectangular-Cavity-Backed Slot Antenna

There has been, recently, a reawakening of interest in cavity-backed slot antennas to produce circularly polarized waves. For the application of antennas to high speed moving objects such as satellite [25]-[27], aircraft [28] and vehicles, low profile and circularly polarized antennas are the most eligible choice. A slot antenna is one of major interests because of its flush mounting and simple structure. Besides meeting the requirements of weight and size for aircraft and spacecraft applications, it can be flush mounted to the surface of vehicles. Usually, a slot antenna can radiate into one side only or have a unidirectional beam by using a cavity. In addition, the use of dielectric or ferrite loading in the cavity permits the reduction of cavity volume and aperture size at the expense of bandwidth and efficiency.

Before such antennas can be of any practical use, their radiation and impedance characteristics must be understood. The input admittance of a narrow slot in a perfectly conducting sheet, for instance, can be determined by the Booker's relation [29] so long as the slot is free to radiate on both sides of the infinite sheet. This relationship, which can be found in many books [30]-[33], is given by $Y_s = 4Z_d/Z_0^2$, where Z_d is the impedance of the complementary dipole (planar dipole) and Z_0 is the characteristic impedance of the surrounding medium. In practical applications, however, the slot must be backed by some sort of cavity or conducting plate reflector, thus destroying the symmetry upon which the Booker's relation depends on.

Among the available researches on antennas, there was no reasonably comprehensive coverage of the cavity-backed slot antennas. Although the straight slot antennas have been extensively studied experimentally and theoretically, no theoretical work has been conducted for cavity-backed rectangularly bent slot antennas. In addition, the mutual coupling calculation between the rectangularly bent slots is more complex than that of the straight slot. Until now, cavity-backed slot antennas are not as well studied, especially for the circular polarization characteristics of these kinds of antennas.

This dissertation is the first attempt to summarize the rectangular cavity-backed rectangularly bent slot antenna configurations of one class of miniature endoresonant antennas, referred to as **the rectangular-cavity-backed slot antenna.** This dissertation will carry out, in somewhat more complete detail, the analysis of the rectangular-cavity-backed slot antennas. The purpose of this dissertation is to investigate the circular polarization characteristics of this kind of antennas, the effect of mutual coupling between the rectangularly bent slots and the effect of the backing cavity on the antenna characteristics.

In this dissertation, the generalized network formulation based on the equivalence principle [34] is used to numerically analyze the characteristics of rectangular-cavity-backed slot antennas. The problem is formulated in terms of a moment method solution of the operator equation. Although the analysis method is straightforward, characteristics of various kinds of rectangularly bent slot antennas can be calculated. By means of the equivalence principle, the problem can be separated into two parts, namely, the half-space region above the ground plane and the interior of the cavity. Two equivalent surface magnetic currents are placed just above or under the aperture region respectively with the aperture shorted by an electric conductor. The enforcement of the boundary conditions results in an integral equation for the magnetic current. The effect of the backing rectangular cavity on the distribution of the magnetic current is considered by applying the Green's function in the cavity. The only coupling is through the aperture, whose characteristics can be expressed by aperture admittance matrices, one for each region.

These admittance matrices depend only on the region being considered, being independent of the other region. The aperture coupling is then expressed as the sum of the two independent aperture admittance matrices. This result can be interpreted in terms of generalized networks as two n-port networks connected in parallel with current sources. Further, the resultant solution is equivalent to an n-term variational solution.

Based on the formulation stated above, computer programs are developed for treating the rectangular-cavity-backed slot antennas. And then, the magnetic current, input impedance, VSWR, radiation pattern and axial ratio are investigated numerically and experimentally.

1.4 Composition of the Dissertation

This dissertation consists of six chapters.

Chapter 1 provides an overall view of the dissertation via a qualitative description of the type of cavity-backed antenna that will be discussed. In this chapter, the background and originality of the study are stated. General description of the rectangular-cavity-backed slot antennas is also given in this chapter.

Chapter 2 is devoted to comprehensive theoretical treatment of the rectangular-cavity-backed slot antennas. The moment method solution of the analytical model, which is based on the application of the equivalence principle and the use of a generalized network formulation, is given in this chapter. Some approximations to the theoretical model are introduced. By applying the generalized network formulation to the slot aperture, the problem can be separated into two regions, namely, the closed cavity and the outer space [34]. By using the equivalence principle, the slot aperture is replaced by an equivalent magnetic current [31]. The effect of the cavity on the magnetic current distribution is taken into account by introducing the Green's function inside the cavity.

Chapters 3, 4 and 5 deal with the applications of the formulation derived in Chapter 2 for the rectangular-cavity-backed slot antennas.

In Chapter 3, three types of circularly polarized rectangular-cavity-backed antenna are proposed and chosen to show the capability of the computer program. First a rectangular-cavity-backed single square loop slot antenna is presented. Then a rectangular-cavity-backed two-element square loop slot antenna is considered. As a final example a rectangular-cavity-backed two-arm square spiral slot antenna is given. They all radiate circularly polarized waves. The technique of short-circuiting the slot is introduced to get circularly polarized radiation. For these examples, it is clarified that suitable parameters for the short-circuiting position, the cavity size and the slot configuration exist to radiate circularly polarized waves. Measured input impedance, axial ratio and radiation patterns for the rectangular-cavity-backed single and two-element square loop slot antennas are provided to validate the calculated results.

The optimization of the rectangular-cavity-backed slot antenna is conducted in Chapter 4. A rectangular-cavity-backed two-element rectangular loop slot antenna for circular polarization is presented and investigated. Two short-circuiting points are introduced on the slots to get circular polarization and symmetrical radiation pattern. The parameters are optimized that the AR minimum and the VSWR minimum are at the same frequency, and the axial ratio bandwidth ($\leq$3dB) with VSWR ($\leq$2) reaches 7.6%.

Besides the circular polarization characteristics, dual-band and wide-band operations are also interesting topics of the rectangular-cavity-backed slot antennas.

In Chapter 5, a rectangular-cavity-backed single arm square spiral slot antenna is introduced. The feed point is set at the outer turn of the single arm square spiral slot to get a dual-band operation. The VSWR bandwidths

(≤ 2) of 5.0% and 5.8% are obtained for the low and high-band resonances, respectively. By decreasing the width of the cavity, the wide band operation with the VSWR bandwidth of 11.4% is obtained.

Chapter 6 is for the conclusions. The summations based on the studies of the rectangular-cavity-backed slot antennas are made in this chapter. The topics for the future research on the rectangular-cavity-backed slot antennas are also considered.