Chapter 1
Introduction

Abstract This chapter deals with a brief review of fractal electrodynamics including fractal antenna, fractal frequency selective surface and metamaterials. A brief review of different classes' of aperture coupling problems in waveguides, conducting screens and cavities has also being reported here. Based on the review work, several aperture coupling problems involving rectangular waveguides, conducting screens and cavities are identified.

1.1 Introduction

The rapid growth in the wireless systems during the past several years has set new demands on electromagnetic engineers. There is a trend to integrate the entire system, including antennas, on a single chip. This requires the design of miniaturized, power efficient, and low profile antennas. Further, multiband operation of wireless systems has been receiving considerable attention during the last decade. This requirement has initiated research in various directions, especially, in the design of compact multiband antennas and filters. One of the promising area of research for multiband operation is fractal electrodynamics, in which the fractal geometry is combined with electromagnetics for the purpose of investigating a new class of radiation and scattering problems. Fractals are complex shapes which contain an infinite number of scaled copies of the geometry and resonate at different frequencies. This property has been successfully used in the design of multiband antennas, frequency selective surfaces (FSS) and electromagnetic band gap (EBG) structures.

A survey of the large body of literature on fractal electromagnetics shows that no effort has been made so far, to exploit the multiband properties of fractals in aperture problems. Apertures in conducting screens, waveguides, and cavities constitute an important class of boundary value problems and find many applications in electromagnetic systems. The aim of the present study is to initiate research in the investigation of the properties of fractal apertures.

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To lay an understanding on the behavior of fractal geometries in the aperture coupling problems, a brief review of fractal geometries and their applications in the electromagnetic engineering is presented. This is followed by a brief review on the study and analysis of different aperture coupling problems in waveguides, conducting screens and cavities.

1.2 Fractal Electrodynamics

1.2.1 Fractal Geometries

Many patterns in the nature are so irregular and fragmented that they exhibit not only a higher degree, but also a higher level of complexity. The number of distinct scales required to describe the natural phenomenon are infinite. Hence, it was generally believed by scientists and mathematicians that these natural phenomenon were beyond rigorous explanations before Mandelbrot [1] proposed a new geometry and its use in various diverse fields. The geometry describes many of the irregular and fragmented patterns of nature around us. Mandelbrot coined the term 'fractal' from the Latin word '*frangere*' which means to break, to create irregular fragments. He used the term fractal to describe some complex and convoluted objects such as mountains, coastlines and many other natural phenomenon.

An iteration algorithm such as multiple reduction copy machine (MRCM) is applied in order to construct the ideal fractal geometries [2]. Basically, the process consists of an initiator and a generator. Based upon the nature of the iteration process, there may be deterministic and random fractals. Also, depending upon the mass ratio, the fractals may be homogeneous or heterogeneous [3]. Some of the most commonly used fractal geometries, such as Sierpinski gasket, Sierpinski carpet, Hilbert curve, Koch curve are shown in Fig. 1.1. The generation procedure of all the geometries follows the same rule and starts with an initiator and a generator. For example, as shown in Fig. 1.2, an equilateral triangle is taken as the initial geometry for the generation of Sierpinski gasket fractal. The mid points of each sides are connected and the initial triangle is subdivided into four triangles. The center triangle is removed and this gives the generator of the Sierpinski gasket fractal. In the next iteration, the same process is repeated on the remaining three triangles and if this iteration process is continued for an infinite number of times, then one can obtain an ideal Sierpinski gasket geometry.

The important properties of the fractal geometries are self-similarity, space-filling ability, and lacunarity. When an object is composed of smaller copies of the original geometry, it is said to be self-similar. A self-similar object can be described as a cluster, which is again made up of smaller clusters that are identical to the entire geometry. Thus, within the whole geometry, an infinite number of similar copies can be found. Hence, fractal geometries are said to have no characteristic size. The scaling factors in two orthogonal directions can be same or different. The former gives a

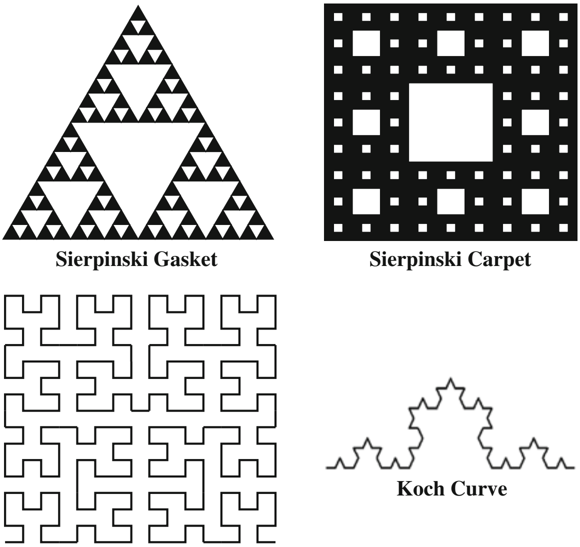

Fig. 1.1 Some of the most commonly used fractal geometries. *Credit note* First published at [2]

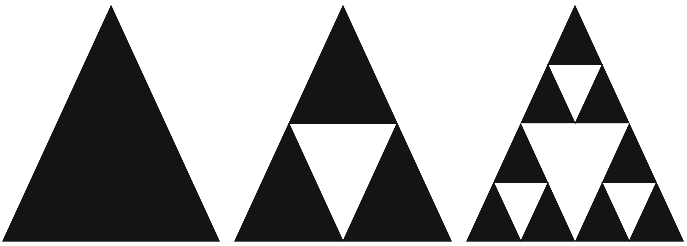

Fig. 1.2 Generation steps of Sierpinski gasket fractal. *Credit note* First published at [2]

self-similar geometry and the later produces a self-affine geometry. Geometries like Hilbert curve or Peano curve, when iterated for large number of times, fill a two dimensional area with the curve length tending to infinity which describes the space-filling property of the fractal geometries. Lacunarity is a term which describes the hollow space in a fractal geometry [1].

Another unique feature of the fractal geometries is the fractional dimension. There are different notations of the dimension of fractal geometries, such as topological dimension, *Hausdorf dimension*, Box counting dimension, and self-similarity dimension [2]. Among these, the self-similarity dimension is one of the most important parameters for the characterization of the fractal geometries. The self-similarity dimension of the fractal geometry is defined as

Table 1.1 Self-similarity dimension of typical fractal geometries

Fractal geometry	Scale factor (s)	No. of self-similar copies	Dimension D_s
Sierpinski gasket	$\frac{1}{2}$	3	1.5850
Sierpinski carpet	$\frac{1}{3}$	8	1.8927
Koch curve	$\frac{1}{3}$	4	1.2619
Hilbert curve	$\frac{1}{2}$	4	2

$$D_s = \frac{\log(N)}{\log \frac{1}{s}} \tag{1.1}$$

where N is the number of self-similar copies and s is the scale factor. The dimensions of some typical fractals are tabulated in Table 1.1. It should be noted here self-similarity dimension of the fractal does not uniquely describe the fractal geometry [4].

Iterative function system (IFS)is an extremely versatile tool for convenient generation of fractal geometries. The iterative function system is a collection of self-affine transformations [2] given by,

$$w\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix} x' \\ y' \end{pmatrix} + \begin{pmatrix} e \\ f \end{pmatrix} \tag{1.2}$$

where the parameters $a,\ b,\ c$ and d are defined by scaling and rotation of initial geometry and e and f denote the translation.

Let $\{w_n,\ n = 1, 2, 3, ..., N\}$ be a set of affine transformations defined in (1.2) and let A denotes the initial image. The application of this set of transformations on the initial image produces a set of self-affine copies $\{w_n(A),\ n = 1, 2, 3, ..., N\}$. Finally, a new image is obtained by collecting all these images as

$$W(A) = w_1(A) \cup w_2(A) \cup ... \cup w_N(A) \tag{1.3}$$

where W is called the Hutchinson operator. By repeated application of W to the previous geometry, an ideal fractal geometry can be obtained. That is,

$$A_1 = W(A_0),\quad A_2 = W(A_1), ..., A_k = W(A_{k-1}) \tag{1.4}$$

The IFS has proved to be a very powerful design tool for fractals because this provides a general framework for the description, classification and manipulation of the fractal geometries.

In the following sections, a brief review is provided on the applications of fractals in electromagnetics.

1.2.2 Fractal Antenna Elements

The scattering and reflection from fractal screens have been studied extensively and a good review on the radiation and scattering from fractal surfaces can be found in [4]. It has been shown that the diffracted field in Franhauffer zone is self-similar. The interesting feature of fractal screens is that the scattered patterns from these fractal geometries contain the fractal pattern imprinted on these. Several self-similar geometries are used in the design of multiband antennas like Sierpinski gasket, Koch curve, Hilbert curve etc. A comprehensive review on the fractal antenna and frequency selective surface elements can be found in [5]. Sierpinski gasket is the most popular in fractal antenna engineering. The behavior of Sierpinski gasket monopole and dipole antennas have been investigated in [6, 7]. It has been found that the antenna exhibits a log periodic behavior with a periodicity of 2. A downward shift of resonant frequencies has been observed as the order of iteration increases. Also, the radiation patterns at different resonant frequencies of the antenna show a large degree of similarity, although some side lobes are generated at higher resonant frequencies. The behavior of the Sierpinski gasket antenna was explained in terms of an iterative network model in [8, 9], where the scattering matrices for the initiator and generator were used to predict the behavior of fractal antenna by cascading the scattering matrices. It was demonstrated in [10] that the location of different resonant frequencies of the antenna can be controlled by changing the scale factor of the fractal geometry. The flare angle of the initial triangle affects the antenna input characteristics [11]. The resonant frequencies shift downward as the flare angle of the initial triangle is increased. Also, too small a flare angle causes the multiband fractal antenna to operate as a simple monopole antenna. Several modifications of the Sierpinski gasket antenna and its effects on the radiation pattern of the antenna have been investigated [12–14]. Design equations for determining the resonant frequencies of Sierpinski modes and for the side length of the Sierpinski gasket antenna is proposed in [15].

An important property of fractal curves is that the length of the curve tends to infinity, although the overall height of the curve remains same. Hence, fractal curves are very useful in reducing the resonant frequencies of the wire antenna. One of the widely used fractal geometry in the design of wire antennas is the Koch curve. The behavior of Koch curve fractal antenna has been presented in [16, 17] where, a fifth iteration Koch monopole antenna has been investigated and it has been found that the Koch curve effectively reduces the resonant frequency of the wire antenna. Additionally, the resonant frequencies are more closely spaced for higher order iterations of the fractal. A rigorous comparison of Koch curve fractal antenna and their Euclidean counterpart has been reported in [18, 19]. The effect of indentation angle on the performance of the monopole and dipole antenna has been investigated in [20]. It was found that the indentation angle plays an important role in locating the resonant frequency of the antenna. Also, the resonant frequencies decrease with the increase in the indentation angle and this decrement is much more dominant in higher order resonant frequencies than at the primary resonance.

Hilbert curve is widely used in the miniaturization of antenna element because of its space-filling property. The advantage of Hilbert curve antenna is that it offers a higher frequency compression factor as compared to the Koch curve fractal antenna, since the length of the Hilbert curve is much larger than that of the Koch curve for a given 2D area [21, 22]. Hilbert curve fractal is also widely used in the design of reconfigurable antennas [23].

Due to the low input resistance of the small loop antenna, fractal loops have proved to be very efficient in increasing the input resistance of the antenna. A fractal loop antenna based on the Koch snow flake geometry is reported in [24, 25]. The input resistance of the antenna was found to increase with increase in the order of iteration. However, the fractal loop antenna exhibits a multilobe pattern due to the increased length of the antenna. Another kind of fractal loop antenna based upon the Minkowski fractal has been investigated in [18, 26, 27]. Also, the performance of Minkowski fractal antenna has been compared with another fractal curve known as 3/2 curve fractal antenna in [26]. A fractal loop antenna based on modified Minkowski fractal geometry has been investigated in [28] which has a better space-filling characteristics as compared to the conventional Minkowski fractal geometry. Several combinations of regular and fractal elements are reported in [29–31] which exhibit a considerable degree of improvement in the antenna performance. A small size patch antenna combining the Koch and Sierpinski carpet fractals is analyzed in [32].

Fractal antennas are not limited to monopole and dipole antennas; they can also be implemented in the design of microstrip patch antennas. Several fractal geometries are used to obtain multiband fractal patch antennas and a stacked arrangement has been shown to have a broadband response [33, 34]. Microstrip antennas having fractal boundaries and mass distribution are illustrated as antennas supporting localized modes. These localized modes are very useful to obtain a broadside and very directive pattern [35, 36]. Recently, a reactively loaded stacked patch antenna with fractal radiating edge has been investigated in [37] which gives a considerable amount of bandwidth enhancement. Comprehensive analysis on the resonance and radiation behavior of the conformal antenna based on the Sierpinski gasket is reported in [38, 39]. A printed log-periodic Koch dipole antenna is investigated in [40] which offers 12 % reduction of the antenna size with a minimal degradation in impedance and bandwidth. The characteristics of a CPW-fed planar antenna based on the Koch fractal loop are presented in [41, 42]. A radial stub has been used in [41], whereas a stub embedded with U-slot has been used in [42] to obtain the impedance match. Two other fractal antenna based on circular fractal and Sierpinski carpet are also reported in [43, 44]. Several compact and multiband fractal patch antenna based on Sierpinski gasket, Sierpinski carpet, Koch curve, Hilbert curve, Minkowski curve are reported in [45–56]. Some arbitrary shaped fractal geometries are also reported in the design of patch antennas such as Spidron fractal [57], octagonal fractal patch antenna [58], and circular [59]. Hybrid or combination of two or more fractal geometries can also be very efficient in the design of miniaturized multiband antennas [60, 61]. Nowadays the fractal antennas are optimized using genetic algorithm and particle swarm optimization techniques. One such optimized antenna using particle swarm optimization is reported in [62]. The radiation from photoconductive fractal antenna on a simi-insulating gallium arsenide substrate is reported in [63]. Recently, a fractal photoconductive antenna based on Sierpinski fractal has been reported for terahertz radiation in [64]. A CPW fed slotted koch snowflake monopole antenna is presented in [56]. The proposed antenna operates at WLAN/WiMAX frequency band and in combination with a U slot, the proposed geometry was shown to be very compact in size.

Recently, fractal geometries are efficiently used in the design of implanted and wearable antenna for medical applications. An antenna based on Hilbert curve geometry for dental applications is reported in [65]. It was shown that a high compression factor and gain can be achieved using a combination archimedean spiral and Hilbert curve geometry. Another novel antenna based on the Koch curve has been fabricated on a jeans substrate [66] which was shown to be very efficient in realizing a miniaturized antenna.

1.2.3 Fractal Frequency Selective Surfaces and Filters

Space-filling and multiband properties of fractal geometries are also used in the design of size miniaturized and multiband FSS. A dual-band fractal FSS based upon the Sierpinski gasket geometry has been reported in [67–69]. It was shown that the fractal FSS offers two stopbands with an attenuation level of 30 dB. A tri-band FSS designed with cross bar fractal tree has been reported in [70, 71]. The characteristics of the FSS were shown to remain unchanged for both TE and TM polarizations. Also, it was shown that the ratio between the successive resonant frequencies of the FSS can be changed by changing the scale factor of the geometry. Several fractal frequency selective surfaces based upon Sierpinski carpet, Minkowski island and inset crossed dipole elements are reported in [72], which present dual-band and dual-polarized characteristics. A novel fractal frequency selective surface based on the Sierpinski tripole elements is presented in [73]. The fractal geometry is optimized in order to obtain a dual-polarized and dual-band frequency selective surface.

Recently, several fractal geometries are used in the design of microstrip filters. A dual mode bandpass filter based on the Sierpinski carpet fractal geometry with a perturbation at the corner of fractal element is reported in [74]. In [75], a wideband microstrip bandpass filter using a triangular patch element is analyzed. It is shown that introducing fractal defection in the patch, a wider bandwidth can be achieved. A low pass filter using Koch fractal geometry is reported in [76].

1.2.4 Fractal Electromagnetic Band Gap Structures and High Impedance Surfaces

Electromagnetic bandgap structures and high impedance surfaces have attracted considerable amount of attention due to the growing interest in improving the antenna gain, reducing the mutual coupling and restricting the propagation of higher order modes. Three different fractal geometries have been investigated in [77] which are capable of producing a wider stopband along with additional new stopband. A circularly polarized compact and dual band GPS patch antenna has been investigated in [78] which is placed over a fractal EBG surface. The antenna exhibits wider axial ratio bandwidth. A high impedance metamaterial surface based on the Hilbert curve and Peano curve inclusions has been shown to offer a reflection coefficient $\Gamma \simeq +1$, when illuminated by a plane wave [79, 80]. Kern et al. [81] proposed several design methodologies for multiband artificial magnetic conductors using Minkowski fractal geometry. An electromagnetic bandgap structure based on a novel fractal similar to that of a crown square fractal has been analyzed in [82]. Several other fractal geometries are employed in the design of frequency selective surfaces and electromagnetic bandgap structures like Durer pentagon prefractal [83], Gosper fractal [84], Minkowski fractal [85], Vicsek fractal [86], T-shaped fractal [87], Sierpinski carpet [88, 89], H-fractal [90], Sierpinski gasket [91]. In [92], a defected ground structure employing fractal has been reported.

Recently, extensive research is directed to the miniaturization and implementation of the complete microwave circuit in a single chip and substrate integrated waveguide (SIW) is a major step forward in this direction. Fractal geometries especially Hilbert curve fractals are employed in the SIW structure for extremely smaller antenna and filter circuits which operated below the cut off frequency of the waveguide [93, 94].

1.3 Aperture Problems in Electromagnetics

Coupling through apertures is a classical problem in electromagnetic field theory and finds wide applications in microwave technology ranging from waveguide passive components, slotted waveguide antenna arrays, slotted conducting screens, frequency selective surfacesfrequency selective surfaces (FSS) to cavity-backed slot antennas. Aperture coupling problems have been exhaustively investigated during the past 50 years and a large amount of literature exists on their analysis and applications. In the following sections, we present a brief review of the various types of aperture coupling problems.

1.3.1 Apertures in Waveguide Transverse Cross-Section

Aperture in the transverse cross-section is one of the most common type of discontinuity in waveguides. When waveguides are used in practice, it is necessary to introduce some discontinuities to produce waveguide filters, matching networks, and power dividers. The presence of discontinuities basically modifies the propagation characteristics of the waveguide but the end result depends upon the type and dimension of discontinuity. Various types of discontinuities are incorporated into the waveguide, among which aperture type discontinuities in the transverse plane of the rectangular waveguide is an important problem. Inductive or capacitive discontinuities in the transverse cross-section of the waveguide are widely used in the design of matching networks due to the weak dependence of their parameters on frequency. Traditional waveguide filters use inductive or capacitive elements or a combination of these in order to produce the desired filter response [95]. Largely, these filter elements consist of aperture irises of rectangular or circular shapes [96–99] and are located in the transverse cross-section of the waveguide. The filter response improves with the increase in number of waveguide sections which makes the waveguide filter very large and bulky. Instead of using a non-resonant aperture, a resonant aperture can be used as a classical element. A waveguide filter with such resonant elements has been shown to have better out-of-band characteristics in [100, 101]. The filter response can be further improved by using multi-slot iris due to the formation of rejection resonance. The formation of such rejection frequency was first mentioned in [102] with a five aperture iris. Later in [103], the existence of total rejection frequency using two slots was explained by simultaneous excitation of two natural oscillations of the iris. It was shown in [104], along with [103], that to form a rejection resonance, it is necessary to have at least a pair of natural oscillations with close real parts of eigen frequencies and essentially different Q factors, determined by the imaginary parts and the number of zeros and poles in the frequency response depend upon the number of slots with different electromagnetic properties. Also, the number of sections needed to obtain the desired out-of-band rejection decreases with multi-aperture iris as compared to the single aperture iris [105]. Recently, frequency selective surfaces have been used to realize elliptical function filter with multiple attenuation poles in the stop band [106]. A much compact and light weight waveguide filter using two closely spaced array of rectangular resonant apertures is reported in [107].

Several numerical and analytical methods are used to analyze the transverse discontinuity in a waveguide. Among all these methods, the most popular and powerful technique is the formulation of the problem in terms of an integral equation which is then solved using MoM. In 1972, VuKhac [108] described the waveguide coupling problems by an integral equation. He solved this integral equation by expanding the field in terms of pulse functions and using point matching technique. Auda and Harrington [97] presented a solution for multiple inductive posts and diaphragms of arbitrary shape in a rectangular waveguide using moment method. The obstacles were approximated by a finite number of constant current strips or filaments. Electric dyadic Green's function was used to represent the field. Point matching technique was used in this analysis. In 1983, Auda and Harrington [109] used the equivalence principle to solve the waveguide junction problems. The fields were expressed using waveguide modes and a generalized network representation of the problem was obtained by using moment method. Sinha [110], in 1986, adopted the same procedure to analyze the discontinuities formed by multiple strips and apertures. A MoM analysis of two thick apertures in rectangular waveguide has been reported in [111]. In [112], a nonconventional T junction with thick apertures has been investigated using MoM. Later, in 1993, Yang and Omar [105] used a TE^{x}_{mn} modal expansion approach along with MoM to solve the scattering from multiple rectangular apertures. Recently, multilayered planar structures in the transverse cross-section of waveguide have been analyzed using generalized scattering matrix (GSM) in conjunction with MoM [113, 114].

It has been observed that MoM and mode matching methods exhibit an inherent phenomenon known as 'relative convergence', when used to solve waveguide discontinuity problems. Lee et al. [115], Mittra et al. [116] and Aksun and Mittra [117] have reported a detailed study of the phenomenon and have proposed some useful guidance to solve this problem.

1.3.2 Coupling Through Apertures in an Infinite Conducting Screen

A thin conducting screen perforated with multiple apertures has a bandpass characteristic when illuminated by a plane wave of varying frequency and makes it a useful candidate for the design of frequency selective surfaces, electromagnetic band gap structures, bandpass radoms, artificial dielectric and antenna reflector or ground planes [118]. In some applications, apertures may cause undesirable coupling such as a crack or slit in the door of microwave oven or any RF transmitting equipment leading to the problems of electromagnetic compatibility and electromagnetic interference. A rejection band in the frequency response can also be realized using multiple apertures of different electromagnetic properties [119].

Photonic band gap structures are capable of reflecting the electromagnetic waves at a selected frequency and are conveniently constructed by using a periodic arrangement of dielectric materials. The dimension of the photonic band gap structures has to be a few times the wavelength of the point of total reflection which makes it very large for larger wavelength applications. Frequency selective surfaces are also capable of totally reflecting the incident electromagnetic wave. However, the frequency of total reflection is determined by the lateral dimension of unit cell and hence, it requires a larger surface area. It was shown in [120, 121] that the planar metallic fractal based upon H shape fractal geometry can reflect electromagnetic wave at a wavelength much larger than the dimension of sample size. The fractal pattern shows a quasi log periodic behavior for lower order iterations of fractal geometry, and the response becomes log periodic for large number of iterations. It was pointed out in [122] that the increase in number of iterations downshifts the passbands, as well as, the stop bands. A fractal slit based on the same fractal geometry was analyzed in [123], where, it was pointed out that the fractal slit supports the subwavelength transmission of electromagnetic waves.

The general and rigorous formulation of coupling through apertures in conducting screen was made through the use of equivalence principle and equivalent magnetic currents [124]. The coupling through rectangular apertures in infinite screen was reported in [125]. An integral equation was obtained by using equivalence principle and image theory. The equation obtained in terms of the equivalent magnetic surface currents was solved using MoM. The aperture characteristics were presented in terms of transmission coefficient and transmission cross-section. Harrington and

Aukland [126] analyzed the electromagnetic transmission through an aperture in a thick conducting screen using equivalence principle and MoM. The problem was decoupled into three independent problems consisting two half space regions and a closed cavity region. It was found that the apertures offer an exceptionally large transmission of electromagnetic energy at the resonant condition. Later, in 1982, Chih-Lin and Harrington [127] analyzed the problem of electromagnetic transmission through an arbitrary shaped aperture in a thin conducting screen using the RWG functions [128]. The problem was solved using MoM and transmission through various arbitrarily shaped apertures were investigated.

Several other methods have also been investigated to analyze these problems. Lin et al. [129] used Babinet's principle in order to find the electric field distribution on the surface of aperture, as well as, in the far field region. Gluckstern et al. [130] obtained the potential distribution on the surface of aperture using variational technique, where the effect of aperture in conducting screen was expressed in terms of electric polarizability and magnetic susceptibility, using small aperture approximations. An approximate expression for the field distribution on the surface of a circular aperture was obtained in terms of circular aperture dimensions in [131]. Savov [132] analyzed the coupling between two circular apertures in an infinite screen using Fourier transform method and the reaction theorem. The effect of different polarizations on the coupling was also investigated. In 1994, Hajj and Kabalan [133] presented a characteristic mode solution of coupling through a rectangular aperture in an infinite conducting screen. The solution was obtained in terms of eigenvalues and eigenvectors using MoM. Kim and Eom [134] used the Fourier transform method in conjunction with mode matching technique to obtain the field distribution on the aperture surface. A rigorous analysis of coupling through apertures in conducting screen was analyzed using finite difference time domain (FDTD) method in [135].

The reflection and transmission coefficient characteristics of an infinite conducting screen perforated with multiple apertures have been investigated by many authors in the past. Chen [118] used MoM in conjunction with the Floquet space harmonics in order to solve the integral equation. The treatment of finite structure is also of practical interest. Early in 1984, Sarkar et al. [136] analyzed the problem of electromagnetic transmission through wire mesh covered aperture arrays by using MoM. Truncated periodic structures have been analyzed in [137, 138]. Recursive schemes have been successfully applied to analyze finite and non-periodic structures [139, 140]. In 1999, Park and Eom [141] presented a Fourier transform and mode matching method to analyze the electromagnetic scattering from multiple apertures of rectangular shapes. The numerical results were obtained for different number of apertures and angles of incidence. A similar analysis for multiple circular apertures were investigated in [142] using integral transform and superposition principle. Anderson [143] carried out a method of moment formulation of electromagnetic transmission through multiple apertures using singular basis functions which greatly improved the convergence rate of the solution.

1.3.3 Rectangular Waveguide-Fed Aperture Antennas

Waveguide-fed aperture antennas are widely used in radars, satellites, and phased arrays and as primary feed to parabolic reflectors. For an open-ended waveguide, the input matching is very poor. The input matching can be improved by either using a dielectric plug at the open end of the waveguide [144] or by using a resonant aperture [145]. Here, also multiple apertures of different dimension can be used to realize multiband waveguide radiators.

Several methods are used for the analysis of the rectangular waveguide fed aperture antennas. In [146], variational principle was used to analyze the radiation from aperture fed by a rectangular waveguide. The method proposed in this article was complicated even with the assumption of a single TE_{10} mode field distribution and numerical results were given only for guide wavelength up to $1\lambda_0$. Das [147] computed the admittance of an open-ended rectangular waveguide without flange. Jamieson and Rozzi [148] have given an nth order Rayleigh-Ritz variational solution to the flanged waveguide problem using longitudinal modes, LSE^y and LSE^x. MacPhie and Zaghloul [149] investigated the radiation from a rectangular waveguide terminated by an infinite flange and radiating into half space. The correlation functions of the TE and TM mode electric fields on the aperture and the conservation of complex power were used to obtain a correlation matrix from which the scattering matrix of the problem was derived. Baudrand et al. [150] presented a method based on the transverse operator. The boundary condition in spectral domain was used to relate the electric and magnetic fields and the expansion of fields in TE and TM modes were used to obtain the admittance matrix. Mongiardo and Rozzi [151] analyzed the problem of radiation from flanged waveguide using singular integral approach. They used a basis function which satisfies the edge condition and therefore, improves the convergence of solution. Shen and MacPhie [152] presented a simple and effective method based on the extrapolation method. The half-space was approximated by a large waveguide with homogeneous filling with lossy dielectric and convergence data was obtained for different loss tangents. Based on the data, an extrapolation method was used to calculate the solution of original problem.

Many authors have used the integral equation approach with MoM or mode matching method to solve the aperture radiation from a flanged rectangular waveguide. The generalized network formulation for the aperture problem [124] based upon the equivalence principle and MoM was applied to waveguide with a thin window [153], finite phased arrays [154, 155], and reactively loaded waveguide arrays [156, 157]. Formulation in [153, 157] used rooftop basis function, whereas the piecewise sinusoidal basis functions were used in [155]. In [154, 156] waveguide modes with sinusoidal aperture function were used.

1.3.4 Cavity-Backed Aperture Antenna

In satellite communication, the antennas are generally designed to have the radiation pattern directed towards the eostationary satellite. The antennas must be suitable for installation on mobile, as well as, stationary stations. Therefore, the antenna should be flat and flush mounted. A typical antenna is a planar microstrip antenna which suffers from feeder loss [158]. Slot antennas are used for their high efficiency and flush mounting nature. However, the slot antennas suffer from their inherent bidirectional radiation pattern. In many applications, the antenna needs to be located in close proximity to earth, or conductive bodies, or to be integrated with the rest of the transceiver in a multilayered structure. In order to alleviate the adverse effects of the interaction between a slot antenna and the structure behind it, traditionally, a shallow cavity is used due to the unidirectional nature of the cavity-backed aperture antennas. When cavity-backed slot antenna is used as an array element, it produces small mutual effects between the elements and this makes it a suitable element in the design of large antenna array system, such as phased antenna array [159]. Also, the metallic cavity can serve as a heat sink to improve the heat dissipation. Generally, due to the resonance of the cavity, the cavity-backed aperture antenna suffers from low bandwidth. In [160], it has been shown that using two arallel parasitic slots, the bandwidth of the antenna can be increased. Several modifications have incorporated in the slot geometry in order to widen the bandwidth, such as, an S-type slot [161], meandered slot [162], rectangularly bent slots [163], and cross-loop slot [164]. Also, it has been found that the miniaturized slot antennas have higher bandwidth and efficiency compared to the electrically small wire antennas [165]. So, by using a cavity backing, efficient slot antennas can be designed [166]. A dual band antenna with three slots backed by a cavity has been proposed in [167] which uses a single feed.

In the earlier works presented in [168–170], the input characteristics of the antenna were calculated assuming a sinusoidal variation of voltage across the slot and the cavity was assumed as a short circuited section of rectangular waveguide. In 1989, Hadidi and Hamid [159] first presented a full wave analysis of cavity-backed slot antenna using MoM with the aid of dyadic Green's function in spatial domain to obtain the electric field on the aperture. In [171], the electric field and the current distribution on a wide slot antenna backed by a cavity were analyzed using MoM.

The antenna fed by a coaxial probe is of practical interest and a detailed study of a probe-fed cavity-backed aperture antenna has been presented in [172, 173]. The effects of various parameters, such as, slot length and width, offset, probe locations on the input characteristics of the antenna were also investigated. In [174], the radiation pattern of a finite plane cavity-backed slot antenna was computed using MoM in conjunction with uniform geometrical theory of diffraction. A comprehensive comparison between the radiation pattern of cavity-backed antenna with infinite and finite planes was presented.

Lee et al. [175] presented a MoM formulation of a cavity-backed aperture antenna with dielectric overlay using the spectral domain Green's function. The integral equation was solved using both the entire domain and subdomain basis functions. Later in [176], a similar analysis was presented for the case of a cavity-backed aperture antenna with dielectric and magnetic overlays. The problem was formulated using modified magnetic field integral equation. A dyadic Green's function in space domain was used for the cavity region, whereas, the Green's function for overlayed medium was obtained in spectral domain. An MoM approach based on generalized network formulation and equivalence principle for the analysis of single as well as multiple apertures backed by cavity was proposed in [177].

In 1995, Despande and Reddy [178] analyzed the electromagnetic scattering by cylindrical cavity recessed in 3D metallic object. The equivalence principle was applied to decouple the problem and the field outside the cavity was expressed in terms of free space Green's function and equivalent surface magnetic currents. The fields inside the cavity were expressed using waveguide modal expansion function. MoM is used to solve the coupled integral equation.

An FDTD approach for the analysis of cavity-backed aperture antenna was presented in [179]. The paper also deals with the problems encountered in the formulation and design of antennas using the FDTD method. The spectral leakage was decreased by means of time windows. However, it does not reduce the computation time and number of steps required for an estimation of input characteristics. The problem was analyzed with accurate estimation of input characteristics in [180].

In 1998, Rao et al. [181] presented a finite integral technique for the analysis of scattering from cavity-backed antennas. The cavity was subdivided into a number of triangular cylinders and constitutive material property was assigned to each cylinder. Unknown electric and magnetic fields were approximated by a specially designed basis function.

Nowadays, hybrid techniques are widely used in the analysis of complex electromagnetic problems. FDTD methods are used to model complex cavity-backed aperture geometries and the field radiated at a distance of few wavelengths is calculated using near-to-near field transformation. This requires a large amount of storage and computation time. So, this method is only applicable to relatively smaller geometries. On the other hand, finite element method (FEM) is simple and is very popular in the analysis of complex penetrable structures. This method results in a sparse matrix that can be stored efficiently and solved. However, it does not incorporate the Sommerfeld radiation condition and hence requires discretization outside the source region, which limits the application of FEM in large structures. As compared to this, MoM incorporates the Sommerfeld radiation condition through the use of appropriate Green's function and as a result, domain discretization can be kept minimum. However, this method is too complicated for penetrable structures. Also, the MoM produces a dense matrix which requires a large storage for large complex structures. The unique feature of MoM is the knowledge of Green's function which limits its application to some regular shaped geometries whose Green's function is known. Additionally, the computation of admittance matrix involves slowly converging mode sum, which reduces the efficiency and increases the computation time. So, in order to take the advantage of individual methods, hybrid techniques have become very popular for the analysis of cavity-backed antennas. A hybrid FDTD-MoM method of analysis electromagnetic radiation from cavity-backed aperture antenna was proposed in [182]. The external and internal region of the cavity was modeled using MoM and FDTD, respectively, and the external radiation was computed using the reaction theory. In [183], a combined FEM-FDTD method was used to analyze the coupling of cavity-backed slot antennas.

The hybrid FEM-MoM [184–187] is a very useful method for the analysis of cavity backed antennas. The problem is decoupled into two equivalent problems and the field inside the cavity is formulated using the finite element method and the field outside the cavity is calculated using the boundary integral approach. A detailed formulation of feeding structures is presented in [188, 189]. These papers also deal with the effect of finite ground plane on the antenna characteristics using geometrical theory of diffraction.

Chang et al. [190] analyzed a coaxial fed cavity-backed slot antenna. The equivalence principle was applied to find out the scattered field inside and outside of the cavity. The half space Green's function was used to calculate the field outside and Green's function inside the cavity was calculated using a parameter like extrapolation method. Complex Poynting theorem was used to calculate the input impedance.

A circuital approach to predict the behavior of electromagnetic field backed by a cavity has been proposed in [191]. The aperture is modeled as a stripline ended by a short and the metallic cavity is modeled as short circuited waveguide. The voltage on the apertures was calculated using Thevenen's equivalent circuit approach.

1.4 Motivation for Present Research

From the discussion presented in the previous section, it is evident that aperture coupling problem is an extremely important class of boundary value problem with wide ranging applications in antennas, waveguide filters and power dividers, frequency selective surfaces, and metamaterials. Apertures of both regular and irregular shapes, resonant and non-resonant, narrow and wide have been investigated.

In the past decade, application of fractal geometries has been proposed in the design of antenna elements, frequency selective surfaces and metamaterials, and the special characteristics offered by the fractals are widely acclaimed. Antennas using some of these fractal geometries are already available commercially. It is found that the use of fractal geometries leads to miniaturized, low profile antennas with moderate gain as compared to their Euclidean counterparts and the self-similarity property results in multiband antennas and FSS elements. What is missing, however, is the study of fractal geometries in aperture coupling problems. The present research work is primarily intended to initiate a study of the characteristics of fractal apertures in waveguides, conducting screens, and cavities.

During the course of this research work, several questions about the properties of fractal geometries are addressed and an effort has been made to answer these questions by comparing the conventional fractal antennas and FSS elements with the present observations. A number of fractal geometries have been investigated in order establish the universal nature of the properties of fractal apertures. The investigations have been further extended to correlate the response of fractal apertures with different geometrical parameters and modifications. Some observations have also been made from an application point of view to show the effectiveness of the fractal apertures as compared to the existing multi aperture geometries.

1.5 Research Problems

The aim of the present research work is to investigate the properties of fractal apertures in different types of aperture coupling problems. Based on the aforementioned discussion on the requirement of multiband and reduced sized waveguide components and aperture antennas, and the efficiency of fractal geometries in the design of low profile, multiband and miniaturized antennas and FSS, the following problems have been taken up in this research work:

- Analysis of fractal apertures in the transverse cross-section of rectangular waveguide
- Electromagnetic transmission through fractal apertures in an infinite conducting screen.
- Radiation from fractal apertures in an infinite screen fed by a rectangular waveguide.
- Analysis of cavity-backed fractal aperture antennas.

A major part of the analysis of above problems is the formulation using a suitable numerical procedure. The first three problems have been formulated using MoM and a hybrid FEM/MoM method has been used to analyze the problem of cavity-backed aperture antenna. Based on the formulation, MATLAB codes have been developed to find out different near-field and far-field parameters. The final task is to validate the numerical results which has been done by simulation on HFSS [192].

1.6 Organization of the Book

The work embodied in this book has been arranged as follows:

Chapter 2 presents the general MoM formulation of coupling between two arbitrary regions via multiple apertures of arbitrary shape and size. The formulation of matrix equation, geometric discretization, and the types of basis functions used are described. A detailed derivation of various matrix elements for different regions such as rectangular waveguide and free space regions, are presented. The last section of the chapter deals with computation of different measurement parameters.

In Chap. 3, properties of fractal apertures in the transverse cross-section of a rectangular waveguide have been presented. Some self-affine fractal structures based on the Sierpinski gasket and plus shape fractals are proposed and the effect of scale factor on the response is investigated. Self-similar structures like Hilbert curve, Koch curve and Minkowski fractals are shown to be efficient in reducing the resonant frequency of the aperture.

Chapter 4 investigates the electromagnetic transmission through fractal apertures in a thin infinite conducting screen. A number of fractal apertures, like Sierpinski gasket, Koch curve, Hilbert curve, Sierpinski carpet and Minkowski fractal have been investigated. Numerical results are presented in terms of transmission coefficient and transmission cross-section for both parallel and perpendicular polarizations of incident wave. The effects of variation of angle of incidence on the frequency response of these fractal apertures are also investigated.

Chapter 5 combines the problems of Chaps. 3 and 4 to analyze the problem of radiation from waveguide-fed fractal apertures in an infinite screen. The self-similarity and space-filling properties of fractals have been exploited to achieve multi-band radiation. Some self-affine fractal geometries, suitable for waveguide-fed apertures, have been proposed and investigated. It is shown that the scale factor of the fractal geometry can be used as a design parameter for controlling the resonant frequencies.

Chapter 6 deals with the characteristics of probe-fed cavity-backed fractal aperture antenna. A general formulation of the problem using hybrid FEM/MoM method is presented. The numerical results for input reflection coefficients and the far-field radiation pattern of the antenna are presented.

Chapter 7 summarizes the work with concluding remarks and outlines the possible future research directions inspired by the work presented here.

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