CHAPTER 1
INTRODUCTION

An antenna may be looked upon as an element that accepts power from a preceding circuit, usually through a suitable transmission line, and subsequently radiates it into free space. Conceptually, an antenna is perceived as a transmission line that has been “opened out” in order to extend the linking field lines into free space. As an example, a dipole antenna may be considered as a natural extension of the twin-wire transmission line. The monopole is similarly derived from a coaxial line by extending a quarter-wavelength long stub of the centre conductor and spreading the shield in the form of a ground plane. Accordingly, a horn antenna derives from a waveguide by flaring the walls – pyramidal horns from rectangular waveguide and conical from circular waveguide. This reasoning may be reworded by saying that a radiating element is made structurally compatible with the feeding transmission line.

Microstrip and stripline have gained immense popularity for use as microwave transmission lines as they are of planar configuration, may be adapted readily for photolithography techniques and can be integrated easily to microelectronic IC type of applications – MIC or MMIC. Traditionally, antennas used at microwave frequency ranges were either dipoles or horns. To feed these types of radiators with microstrip one needs to devise complex transitions to waveguide or to use baluns. This aggravates the problem of impedance matching to the succeeding circuit element. So it was found expedient to devise antennas that are structurally compatible to microstrips (or in some cases to striplines.)

Owing to such requirements, the first microstrip antenna was proposed by Deschamps in 1953 [1]. It was fairly well-known that radiation loss occurs from microstrips - in
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fact specific care is taken in the design of microstrip trays to minimize such losses. On the other hand, a microstrip antenna actually exploits this property to enhance radiation (loss) and thus obtains an efficient radiating structure. After that initial proposal, the concept was not practically utilized till the 1970’s. This was in part due to the photo-etching techniques being still in their infancy. Further, it was in those years only a need for flush-mounted, low-profile antennas was felt for use in missiles and other aerial / spaceborne platforms. Howell [2] reported the first working prototypes in 1972 operating in both linear- and circular-polarizations at L-Band specifically highlighting their flush property and minimal obtrusion to the rear side. He explained resonance conditions and the cavity approximation; outlining design steps and proposing dual-polarized microstrip antennas. Probably for the first time also, the CP-variant actually used a coplanar quadrature hybrid to excite a square patch. In 1974, Munson [3] proposed two types of conformal antennas that could be fabricated on a thin “deformable” substrate and be wrapped around a cylindrical body such as a missile. Corporate feed networks, also deposited conformally, were used in conjunction with long microstrip radiators or an array of microstrip patches to achieve nearly omnidirectional coverage from on-board the missile platform. When placed in a flat configuration, such antenna elements were shown to provide fan beams that could be made steerable by using pin-diodes for digital phase-shifting. The transmission-line analogy was introduced by them for the analysis of the microstrip radiator. Even after these developments, it took almost another decade before commercial manufacture of microstrip antennas could begin. Carver & Mink who reviewed the state of the microstrip antenna technology in 1981 [4] pointed out the criticality of tolerances on the dielectric constant, thickness and coefficient of thermal expansion of the substrates employed for microstrip antenna fabrication. In terms of
fractional change in predicted resonant frequency of the radiator, the manufacturer’s tolerances on the substrate parameters were compared in some available commercial products especially in regard to anisotropy and uncertainty in measurement methods for $\varepsilon_r$ and $\tan \delta$. Evidently, only from this decade onwards substrate products were available with the requisite tight tolerance bands for microwave antenna realization which paved the way for commercial manufacture.

Microstrip antennas had been originally proposed to be employed with a microstrip-type feed. However, several other feeding arrangements give different benefits like bandwidth enhancement, simpler transitions and greater packing efficiency when used in an array environment. The feeding methods are classified into three types based on the exact mechanism by which the feed line transfers energy to the radiator. These are direct-contact, proximity-coupled and aperture-coupled feeding methods. These feeding techniques, along with their variants will now be briefly described.

**Direct-contact Feeds**

In the case of the first of these types, the direct-contact feeds, the feeding transmission-line is directly connected to the microstrip antenna. This is the most straightforward and relatively simple feeding technique. These were among the first feeding methods to be proposed. Two basic types of feeds fall under this category – the microstripline (or edge-coupled feed) and the coaxial feed. These two types of feeding methods will be briefly described in the following.

**Microstripline (or Edge-coupled) Feed**

A microstrip line of the appropriate impedance, generally 50 $\Omega$ to suit the preceding circuitry, also etched on the same substrate is connected to the patch. The contact
point may lie either at the radiating edge of the patch or the non-radiating edge – this leads to the term ‘edge-coupled’. Since the patch edge is associated with high impedance levels due to the standing-wave nature of the surface currents, some sort of impedance matching arrangement becomes necessary. The traditional method, also suggested by Howell [2], is to incorporate a quarter-wave transformer on the same substrate as shown in Fig. 1.1(a.) Alternatively, the feed line may be inset by breaking the patch margin and locating the feed point at the correct impedance location (see Fig. 1.1(b)) [4].

**Fig. 1.1: Direct-Contact Feeds – Microstripline (or Edge-Coupled) Feed**

(a) with quarter-wave transformer (b) with inset feed
The key advantage of this feed is its simplicity as it can be fabricated along with the antenna e.g. in an array, a single photo-etch sequence is enough to realize the antenna. The disadvantages are that the antenna pattern exhibits asymmetry since the feeding is impressed from one side. Direct radiation from the microstrip also degrades the antenna radiation pattern. Being coplanar, the feeding line, impedance matching network and power division circuit, if employed, all encroach on the antenna real estate. With the inset feed as in Fig. 1.1(b), a part of the patch needs to be broken, affecting the radiation pattern symmetry further.

This simple feeding method is still very much in use as shown by literature. A more sophisticated impedance matching network than the one in Fig. 1.1(a) has been employed by van Wyk and Palmer in 2001 [5]. They compare the benefits of this method with a relatively wideband matching network using two pairs of half-wavelength open-circuited stubs in shunt with the main feed line. In 2009, Zaker et. al. have proposed edge-coupling for a parasitically-loaded microstrip antenna for ultra-wideband (UWB) applications [6]. The patch is loaded with a pair of L-shaped slots and U- or M-shaped patches to achieve the broadbanding. Again in 2009, Thomas and Sreenivasan have used edge-coupling for an indented patch [7]. The ground plane is also etched out with indentations together with the patch achieving UWB properties. Interestingly, a via-coupled patch is realized in series with the main edge-coupled feed line, within the radiator geometry, to ‘notch out’ the WiFi band around 5 GHz to minimize interference from the proposed antenna.

Coaxial (or Probe-coupled Feed)

This is the second type of direct-contact feed and avoids radiation losses conserving the top-level space needed for an impedance-matching transformer [4]. The feed
configuration is achieved by extending the inner conductor of the coaxial line in the form of a probe that enters through a ground-plane hole under the patch and contacts its under-surface through the dielectric. The outer conductor of the original coaxial line is connected to the ground plane (see Fig. 1.2(a, b.))

![Diagram of Direct-Contact Feeds – Coaxial (or Probe-Coupled) Feed](image)

**Fig. 1.2: Direct-Contact Feeds – Coaxial (or Probe-Coupled) Feed**

(a) for rectangular patch (b) for circular patch
In his 1982 paper, Lier [8] has presented improved formulas for the input impedance of the coaxial feed. These are suitable for both rectangular as well as circular patch geometries (see Fig. 1.2(b.)) The author accounts for fringing fields and also the dielectric surface roughness. Palit & Hamadi [9] also stressed the importance of the feed-point location to obtain a good match and an increased impedance bandwidth for a patch radiator proposed in 1999. A notch is placed in the patch metallization, opposite the coax-feed and is found to compensate the probe inductance to provide a better matching. The arrangement also allows wideband or dual-band operation. The asymmetrical nature of the feed is associated with the excitation of higher-order modes causing greater cross-polarization levels in the radiation pattern. In 2007, Guha et. al. have extended Harrington’s formula to determine the feed reactance of probe-fed antennas [10] attesting to the popularity of the coaxial feed even today.

The chief benefit of the coaxial feed is that the feed point can be precisely located underneath the patch – for instance to match the exact impedance of the coax as determined by the standing-wave distribution across the patch surface. Different modes may also be excited e.g. by diagonal placement of the probe, two degenerate orthogonal modes can be excited to obtain circular polarization. The coaxial feed closely approximates an ideal point feed. This feeding technique has certain demerits also. There are three fabrication steps involved – etching a ground plane aperture equivalent to the coax outer conductor size, drilling of the substrate and soldering. For antennas requiring environmental qualification, special care may be needed to ensure the integrity of the joint under vibration loads, for instance, in spaceborne systems. Further, the unbalanced probe for the extent of the substrate height represents a large parasitic inductance especially in thick substrate / air-suspended patches. This alters
the resonant frequency of the antenna and also needs compensation to achieve a broadband match. Particularly at millimeter or higher bands, the probe inductance increases to an extent that renders the coaxial feed practically unusable.

The next category of feeds viz. proximity-coupled feeds is now described.

**Proximity-coupled (or Electromagnetically-coupled) Feeds**

This is the second major category of feeds for microstrip antennas [11, 12]. As opposed to the previous category of feeds, in proximity-coupled feeds, the need for a direct contact between the feed line and the antenna is eliminated. The feed line is run close to the patch (‘proximity’) and linking fields are allowed to span across the gap to electromagnetically couple energy from the line to the patch. The simplest configuration is where the feed line is etched normal to the edge of the patch in a sort of end-gap arrangement (see Fig. 1.3(a.)) To increase the amount of energy coupling to the patch, the feed line may be run parallel to the edge rather than across it. On this theme, van Wyk & Palmer have proposed in 2001, a coupled-line structure [5] to achieve a compact, broadband feed for a microstrip patch (shown in Fig. 1.3(b.)) Even though slight pattern asymmetry is found in the H-plane, the cross-polar behavior is very good. An interesting variation of this kind of coplanar proximity feed proposed by Lin & Chung in 2009 which is an inset-coupled line resulting in a notched or U-shaped microstrip antenna [13]. Investigation of the RLC equivalent circuit reveals a filter-like response of the feeding structure. Coplanar proximity feeds have looser coupling to the antenna as they couple energy from one side only. For tighter couplings, the microstrip line can be made to overlap the layout of the patch by embedding the feeder between it and the ground plane by employing two dielectric layers (as illustrated in Fig. 1.3(c.))
Fig. 1.3: Proximity-coupled (or Electromagnetically-Coupled) Feeds
(a) with end-gap (b) with coupled line (c) with embedded feed
In a 1981 paper, Oltman & Huebner have investigated a variety of such feeds in conjunction with the microstrip dipole radiator [11]. The feeding microstripline is etched on a thinner substrate with a ground plane towards its lower face. The microstrip patch is etched on another substrate placed above the first substrate with the cladding from the other side completely etched out. In this manner, the feed line gets sandwiched between the patch and ground metallizations. As an example, the EMC patch reported by Rowe & Waterhouse in 2003 [14] shows the standard configuration of such a feed (as in Fig. 1.3(c.)) The authors have further developed this to a stacked patch configuration for enhanced bandwidth. The feeding line is terminated in an open-circuited stub to match the input impedance. Another example is a circular patch with an embedded crossed slot reported by Chan et al. in 1997 [15]. The benefits of this feeding method are: a) improved bandwidth and efficiency as the radiator is spaced higher from the ground plane; b) increased radiation conductance as fringe-fields are more loosely coupled; and c) radiation from boundaries, junctions and similar discontinuities is reduced as the feeder substrate is much thinner. In this configuration, proximity-coupled feeds are very useful especially for arrays of microstrip patches. The feed and power division circuitry is embedded in the intermediate layer and the top-level area is freed-up for radiators. Bandwidth extension techniques may also be employed by using parasitically-coupled elements [12]. This is described further in the next paragraph. A possible disadvantage is increase in fabrication complexity as two substrates need to be realized and aligned.
**Gap-coupled Feed (with parasitic elements)**

As a spin-off of the proximity-coupling method, parasitic elements may be excited using this approach even though direct-coupling may be used for the fed element. The edge-coupled element of Nirate *et. al.* reported in 2008 [16] uses the non-radiating edges of the central driven patch to excite a pair of parasitic patches placed adjacent to it. Additional resonances of these elements are used to stagger-tune the resonant frequencies to extend the bandwidth in excess of 50%. Also in 2008, Ansari *et. al.* have reported a stacked-patch using gap-coupling with dual-resonance behavior [17]. The driven patch is encircled by two U-shaped patches and an upper patch is stacked over the group. A distinct dual-resonance response is obtained.

Although the feed layer is embedded between two dielectric substrates and the thinner substrate minimizes fringing, it still remains exposed on the upper side for spurious radiation. The next category of feeds overcomes this limitation and these are described in the following.

**Aperture-coupled Feeds**

This category of feeds encompasses feeds that couple energy to the microstrip patch through an aperture in the ground plane. Pozar proposed the aperture coupled feed in 1986 [18, 19]. The configuration uses a microstripline that feeds the patch antenna through a ground plane aperture. This feed is described in more detail in the following:

**Aperture-coupled Feed (using microstrip line)**

Pozar’s earliest proposal [18] uses a circular aperture etched into a common ground plane with two dielectric substrates to either side of it (see Fig. 1.4 (a.)) The upper
substrate carries the patch overlaid over the ground-plane slot and the lower substrate carries the feeding line. In this manner, the coupling aperture is sandwiched between the two substrates and the energy crosses to the other side of the ground plane through it to excite the microstrip patch.

Fig. 1.4: Aperture-coupled Feed using Microstrip Line
(a) feed configuration (b) exploded view
Fig. 1.4(b) shows an exploded view of an aperture-coupled feed with a rectangular slot and it is evident that proximity coupling is used to excite the radiator. Pozar has also proposed an edge-connected feed line in which its substrate is assembled perpendicular to the patch substrate with aperture coupling between the two – this approach is suitable for brick-type array configurations. In his follow-up paper [19], Pozar uses the reciprocity method for computing the radiation pattern of a slot-coupled microstrip antenna. An elementary dipole assumed to be placed at the surface of an infinite half-sphere is used to deduce the antenna pattern. Also in 1986, Sullivan & Schaubert have reported the analysis of an aperture-coupled microstrip antenna using a rectangular coupling slot [20]. The method-of-moments using the equivalence principle and piecewise sinusoidal functions is used for the analysis. Subsequently in 1991, Croq & Pozar have presented parametric studies and design guidelines for aperture-coupled single- and stacked-patch microstrip antennas [21]. The dimensions of the two patches, tuning stub length and the aperture size are related to the resonant frequency and other operating parameters. In the same year, Navarro et. al. have reported an aperture-coupled antenna at 29.3 GHz [22].

The advantages of the aperture-coupled feed are manifold. Substrate area at the top layer is freed for the radiators without the need for a thicker substrate as in the case of the buried proximity feed described earlier. Two different dielectric constants may be chosen – feeding circuitry needs a higher dielectric constant in order to prevent losses and for compact dimensions while the patch operates better with a low \( \varepsilon_r \) for optimum radiation efficiency. Further advantages are absence of soldering / drilling that results in an accurate and reproducible feeding structure, particularly at millimeter frequencies and also is easily integrable to planar micro-electronic circuits.
This feeding method had gained immense popularity and a few examples are referred to reinforce this fact. In 1997, Lindmark has used a cross-shaped aperture to excite a patch and used this for dual-polarized operation [23]. Good isolation is reported between the two orthogonally-polarized ports. Also in 1997, Hammad et. al. have used a rectangular aperture to feed a patch that has a pair of spur-lines embedded within its layout [24]. The authors have reported good cross-polarization response from the structure. Even higher frequency operation is reported by Gauthier et. al. in 1999. The micromachining process is employed to implement an air-gap below the radiator to obtain an effective feed at 94 GHz [25]. Of late the thrust has been towards developing techniques similar to chip fabrication methods. Due to its excellent repeatability, the aperture-coupling method is found to be ideal for this purpose. Pavaluri et. al. have presented a micromachined slot-coupled antenna in 2008 which finally achieves a suspended patch supported by a thin polyimide membrane [26]. The typical Si substrate is placed below this for the preceding circuitry and the air gap below the patch is created by a using polymer posts. As a final example, Wang et. al. have proposed a $K_b$-band aperture-coupled antenna based on the LTCC process [27]. An H-shaped slot is used for the coupling energy to the overlying patch. A series of vias around the patch perimeter are provided as also are a pair of via ‘fences’ around the feed line to inhibit surface waves.

Microstriplines become prohibitively lossy as the operating frequency is increased. The optimum solution to prevent undue losses within the transmission medium as well as through radiation is to use waveguides. This type of feed is next described.
Aperture-coupled Feed (using waveguide)

The coupling aperture described above may be conveniently used in conjunction with a waveguide to feed a microstrip patch antenna. In 1983, Kanda et. al. have proposed an aperture-coupled patch that is fed through an end-wall iris by a waveguide [28]. The antenna operates satisfactorily at 63.2 GHz which underscores the benefits of this method of feeding at millimeter-wave bands. This configuration has also been investigated using M-o-M by Harish [29] (see Fig. 1.5.) A configuration similar to this but using a circular patch radiator is reported by Ho & Hsu in 2007 [30]. The antenna is further developed for dual-band operation. An advantage highlighted by them is that the waveguide might function as heat sink also. There are some difficulties with the impedance matching of this antenna because a large shorting plate (or iris) is placed across the waveguide section. This antenna requires individual feeding waveguides for each element when employed in array configurations.

![Diagram of Aperture-coupled Feed using Waveguide End-Wall Iris](image)

**Fig. 1.5: Aperture-coupled Feed using Waveguide End-Wall Iris**
Choi & Lee have attempted to excite an array of two elements using a waveguide end-wall aperture as reported in 2005 [31]. A dumb-bell shaped resonant iris is used to couple to a central, undersized patch that subsequently excites two adjacent coplanar patches using edge-coupling. Later in 2009, they have extended the concept to a $2 \times 2$ array also [32] noting that bandwidth limitations are encountered. However, theoretically, an $n \times n$ array seems to be feasible. In 2008, Yu et. al. have used a waveguide end-wall feed to excite a planar array of corner-fed patches [33, 34]. Although the coupling takes place to a relatively short rectangular element, it is not a patch feed and the waveguide acts instead as the input section of a 1:2 power divider.

These difficulties may be circumvented by using instead, a waveguide top- or side-wall slot. With such a feeding arrangement, a linear array can be realized by feeding through a sequence of coupling slots. Chang & Schaubert have investigated a linear array of microstrip patches fed by inclined slots in the side-wall of a waveguide in a 1998 paper [35]. Also known as a “stick array”, this module may be used to build a planar array by stacking a number of them edge-to-edge.

Longitudinal slots have also been utilized by Wu et. al. [36] reported in 2007; but again as a central feed line rather than as a stick module. Each slot excites a central non-radiating patch designed for impedance matching and this patch edge-couples energy to either side to a pair of mirror-image series-fed linear arrays. Central feeding ensures no frequency-scanning of the array across the waveguide axis. Finally, an antenna reported in 2009 by Borji et. al. is referred in the manner of a milestone since the technique represents an important trend in the context. The authors have used a substrate-integrated waveguide realized using multiple substrates, bounding ground metallizations and via-fences [37]. In the actual paper, the waveguide is the front
section of a microstrip T-junction that subsequently excites an array of notched patches. This technique may be developed in the future for realizing high-frequency substrate-integrated, waveguide-fed microstrip antenna elements or arrays.

Longitudinal slots for exciting a microstrip antenna have been studied by Sood [38] in 1992 in his postgraduate work under Dr. S. N. Sinha. By employing longitudinal slots, change of offset also provides a convenient way of controlling the exact fraction of power coupled to any individual patch. The waveguide would also provide structural rigidity especially at millimeter-wave frequencies where the structural dimensions are relatively small and the substrates forced to be thin as with a micro-machined or membrane-type arrangement.

1.1 Statement of the Problem

This thesis embodies the investigation of a rectangular microstrip patch antenna excited by a waveguide top-wall longitudinal slot. Subsequently, the study is extended to the investigation of a linear array comprising this proposed element as the unit cell. The investigation has four parts:

a) An analysis of the proposed antenna configuration is carried out using the Method of Moments to predict both the input and radiation characteristics. A problem-specific formulation is developed using entire-domain sinusoidal basis functions across the coupling slot as well as the radiating patch. Since the formulation is dedicated (and optimized) for the analysis of the specific problem geometry, it may be implemented with minimum usage of computing resources as long as the radiator configuration remains unchanged. The M-o-M method and analysis is, in general, applicable to this class of problems but
would require a fresh derivation of the M-o-M expressions if a different waveguide, slot or patch shape needs to be addressed.

b) Validation of the derived M-o-M analysis is carried out using a commercial FEM-based solver. The problem geometry is simulated in Ansoft® HFFS® modelling the waveguide, coupling slot, substrate and radiating patch to obtain the input and far-field characteristics. Since it is impractical to analyze an infinite ground plane (as assumed in the M-o-M formulation) in FEM, a finite problem size is used in conjunction with radiation boundaries with an aim to obtain adequate convergence. The results are compared to the M-o-M analysis for validation.

The FEM investigation is extended to two cases: (i) a finite ground-plane of different sizes; and (ii) inclusion of fold-over currents from the ground-plane edges to its rear surface. The former will establish an appropriate size to be employed to restrict the problem / matrix size when using FEM. Since the surface wave launched into the substrate attenuates away from the patch, it is important to determine up to what size the surface-wave amplitude continues to be significant. The latter case estimates a second-order effect that results from the currents that fold towards the rear of the ground-plane. Though the effect is relatively negligible on the forward half-plane radiation, the backlobe is significantly altered.

c) The proposed radiating element is used as a unit cell to build Linear Arrays of proposed Waveguide-Fed Microstrip Elements using a common waveguide as a serial feed. A generalized formula is employed to compute the array factor for this linear array. This is used in conjunction with the computed element pattern from M-o-M to obtain the net radiation pattern of the linear array as
per the principle of pattern multiplication. Two sample amplitude distributions are analyzed: (i) uniformly-excited; & (ii) tapered Dolph-Chebyshev excitations for equalized reduced sidelobes. However, the efficacy of the proposed element is established for linear arrays with desired arbitrary amplitude excitations. Analysis validation of both types of sample linear arrays is subsequently carried out using the FEM-based Ansoft® HFFS® software.

d) Prototype fabrication of the proposed Waveguide-fed Microstrip Antenna is carried out in order to validate the M-o-M analysis and to demonstrate a working hardware. Experimental investigation of this prototype is performed for impedance & radiation characteristics. The obtained results are compared to the M-o-M and HFSS® results.

1.2 Scope and Significance of the Work

This section briefly addresses some key aspects regarding the quantum of work reported in this thesis, the significance of the research work, what it establishes, some of its limitations, some important design guidelines it generates for future workers, and how future research efforts may be continued on this antenna configuration.

The M-o-M formulation employed for the analysis of the proposed geometry actually commences from a general problem configuration. A waveguide of arbitrary cross-section is perforated along its curved surface by the coupling slot which is also of an arbitrary shape. The slot couples into a ground-plane that is assumed as infinite in both transverse dimensions and is also covered along its entire upper surface with the dielectric slab (or substrate). The radiating patch is placed on the top surface of the
substrate directly over the exciting slot. To this point, the problem formulation is completely general. The waveguide may be rectangular, circular, elliptical or any uniform section. Similarly the slot or patch may be rectangular, circular or of an arbitrary shape. From this point, for the purpose of this thesis, the formulation is continued for the specific case of a rectangular patch fed by a rectangular waveguide through a rectangular coupling slot. However, work is possible by future researchers on modified variants of the problem as enumerated above.

The specific problem geometry is formulated using entire-domain sinusoidal basis functions. This choice of basis functions makes the formulation and resulting analysis problem-specific. The coordinate systems as well as the basis functions are chosen optimally suited to the structure being analyzed. Such a choice can only be made when some *a priori* information about the current distributions across the source region is available. If on the other hand, such data is not known, and the problem is a new or arbitrary structure, sub-domain basis functions are preferable as they assure convergence. There are several commercial e.m. simulation softwares available currently based on M-o-M, FEM and other analysis methods. Since these are optimized for analyzing any arbitrary structure specified by the user, they segment the source / problem region to elementary sub-domains like triangles or tetrahedra. This increases the matrix and storage size requirements manifold as compared to the case when entire-domain basis functions are used. Thus, the present analysis is particularly optimized for the specific problem geometry and is expected to yield a converged solution with a very few expansion terms. The matrix size and memory storage requirements will also be very modest. This aspect will be especially useful when the formulation is extended to rigorously analyze a linear array (or a full-fledged planar
array). Though this has not been attempted presently, such an extension will account for mutual-coupling between the various array elements through a perturbation of the cross-coupling terms between the expansion functions. With a sub-domain approach, this problem may become too large by comparison. Finally, unlike with sub-domain functions, the field prediction within the problem geometry will not be granular. Although this may not be significant for the prediction of network parameters or radiation pattern, it may be important if peak power or hot-spot identification is required in a problem geometry, for instance in breakdown threshold estimation.

A possible limitation of the present analysis approach is that it cannot be directly adapted for a case where one of waveguide, slot or patch shapes (or a combination thereof) is altered. This is not a limitation of the M-o-M method as such, but only because we selected a specific basis function suited for our particular geometry. However, a similar formulation may be equally well carried out for other problem variants. Within the rectangular / square patch, there is an avenue to extend the analysis to include current variations along both edges of the patch. This will account for higher-order modes being excited in the patch. In case these modes are evanescent, they may only disturb the quality of the impedance match. Also their contribution to cross-polarization may be estimated. The formulation may be extended to the case of a nearly square patch radiating circularly-polarized waves. Analysis of a circular patch may employ Bessel’s function expansion while the existing functions may be retained across slot if still rectangular. An elliptical slot may be analyzed using suitable elliptical coordinate systems / Mathieu functions, etc. Thus, a good scope exists for further investigating this configuration with rectangular / square patch or with altered element shapes for future workers.
The M-o-M analysis developed herein has been employed to carry out a series of parametric studies with an aim to devise design guidelines. Since the rectangular patch antenna and the aperture-coupled feeds for them are not new, design guidelines / parametric studies for the design variables are published by earlier workers. Chiefly, design guidelines for the determination of patch dimensions and patch aspect ratio are already available. Guidelines for slot length and width are available in open literature for coupling from other transmission media like microstrip feeding though not for waveguide feeding. Parametric study and recommendations for optimum dimensions for slot are obtained using the M-o-M analysis developed in this thesis. No studies are also previously reported on the transverse offset of a (non-resonant) longitudinal slot as loaded by a microstrip patch. This is a valuable set of data obtained in this thesis. Subsequently, when building an array of prescribed amplitudes, this data set is used to obtain the tapered distribution required for sidelobe equalization. When building linear / planar arrays with prescribed amplitude distributions, this study can be utilized by other workers / design engineers. Thus a designer could use the values recommended herein for these variables and arrive at a nearly optimum design set and can quickly proceed to the analysis of the full array. A parametric study about the sensitivity of centering of the coupling slot to the patch has been reported earlier but for other aperture-coupled feeds. So a study has been carried out for the present configuration to assess the effect of centering tolerances during fabrication. Thus, design guidelines for variables specific to this configuration, and not reported by earlier investigators, are been obtained using the developed M-o-M analysis.

With the MoM analysis of the proposed configuration complete, a prototype design is performed at a suitable frequency. An analysis is carried out using FEM-based
Ansoft® HFFS® software with an aim to validate the results of the MoM analysis developed. As compared to the latter method, FEM segments the entire problem region to solve for the fields – in this case the waveguide, substrate and the forward half-space. The last is appropriately truncated to keep the problem and matrix size finite. This gives us an important factor to estimate. The fields around the radiator geometry fringe to occupy a certain volume around the patch metallization. A large enough volume must be retained for meshing to consider all the significant effects. The dielectric-clad ground plane also supports surface waves that retain significant magnitude till a certain distance away from the patch within the substrate to affect the analysis results. Thus, not only is the HFSS® analysis is carried out with a finite ground plane, the effect of increasing its size on the input parameters and radiation pattern is also assessed. Apart from validating the MoM results, HFSS® is used for this additional study. Residual currents at the edge of the substrate/ground associated to the outward-travelling surface waves not only scatter but also fold-over towards the rear of the ground. These represent second-order disturbances to the radiated field in the forward half-plane but can significantly alter the backlobe. This effect is also analyzed using HFSS® and which could not be done with the present MoM formulation because of the infinite ground assumption in the Green’s function itself.

The proposed WGMPA is very suited to the realization of linear arrays using a common waveguide to feed a set of cascaded elements in a series-fed configuration. The feasibility of this linear array configuration has been investigated in further study upon the proposed feed within this thesis work. At present, a 5-element linear array module is selected to illustrate the proof-of-concept though the efficacy of this technique is not expected to be limited to this number.
Two sample amplitude distributions are studied – uniform excitations and tapered Dolph-Chebyshev distribution for sidelobe levels equalized at -20dB. By extrapolation, the results of these sample array modules will establish the suitability of this feeding technique for any arbitrary amplitude distribution of the linear array. The generalized formula for an array with arbitrary element locations is utilized to compute the array factor for both the above cases. As against the array factor for a linear array, this choice of array factor was felt more appropriate since adjacent elements in the linear array are alternately imparted transverse displacement in opposite directions to compensate for phase reversal. This computed array factor is used along with the MoM-computed element radiation pattern to obtain the net pattern of the array employing the principle of pattern multiplication. Since the expected radiation patterns from these two array distributions are well-known, these analyses serve as benchmarks to illustrate extension to arbitrary amplitude distributions. By utilizing the array factor for the pattern computation, evidently the mutual-coupling between the elements is neglected. Also neglected is the effect that due to coupling at successive elements, the incident wave amplitude attenuates as it propagates down the feeding waveguide. Both these effects may be rigorously accounted for in a possible future extension of this work, wherein the MoM analysis considers the elements of the linear array within the formulation. Presently, subsequent validation of the proposed linear array modules is carried out by analyzing both configurations using HFSS® software. The optimum ground-plane size estimated earlier is used to obtain a converged solution. An adequate match verifies the MoM results.

Finally sample prototype hardware for the proposed single WGMPA is fabricated and characterized to experimentally validate the findings of the MoM analysis (and the
FEM validation). The waveguide portion is a machined metallic structure with the slot & patch realized as a single PCB. Bench measurements are carried out prior to pattern measurements in an anechoic chamber. The obtained experimental results are compared to the analytical results as mentioned above. An adequate match validates the analytical findings experimentally. A limitation encountered during pattern measurements was due to the low coupled power from the slot. This resulted in measurements being close to the noise floor of the anechoic chamber. Owing to this, chiefly, the linear arrays could not be experimentally characterized. A possible solution to this impediment may be the use of a longer linear array, perhaps with 25 or more elements to increase the peak gain. Thus, this may be an avenue for future work to develop this feeding technique further.

1.3 Organization of the Thesis

This thesis is organized into eight chapters. Chapter 1 recounts the development and current status of the microstrip antenna feeding techniques along with associated features and constraints. Chapter 2 briefly reviews the analysis methods in use for microstrip antennas and presents details of the theoretical analysis carried out of the proposed antenna configuration. This analysis commences from a generalized moment method formulation and the expressions for the matrix elements and vectors are derived for the particular case of a rectangular microstrip patch fed by a rectangular longitudinal waveguide slot. Expressions for computing input parameters and radiated fields are presented. Chapter 3 discusses the logic and implementation of the computer program developed from the computed analytical expressions. In Chapter 4, the numerical results of the M-o-M program are presented with parametric studies on a C-Band prototype design. Chapter 5 provides details of the concurrent
analyses carried out on a proven commercially-proven electromagnetic solver – Ansoft® HFFS® for validation. Finite ground-plane size and fold-over current effects to the rear of the ground-plane were investigated. Chapter 6 describes the analysis of linear array modules of longitudinal aperture-coupled microstrip patches. Two cases are analyzed: uniformly-excited; and with Dolph-Chebyshev tapered amplitude distribution to illustrate feasibility of applying desired arbitrary amplitude distributions. The single element pattern obtained from the MoM analysis is used with an array factor formulation to obtain the linear array patterns. These are later validated through a concurrent analysis using HFSS®. Chapter 7 presents details of experimental hardware based on the C-Band prototype for the waveguide-fed microstrip radiator and discusses its measured performance. Measured results obtained are compared to the MoM and HFSS simulations. Chapter 8 provides a set of conclusions arising from the investigations embodied in this thesis. An appraisal of the work done, the key findings thereof as also suggestions for further research are presented.