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Analysis and Design of a Perpendicular-Corporate Feed in Multi-Layer Parallel-Plate Slot Array Antennas

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Contents

Chapter 1

Introduction

1.1 Literature Review

1.1.1 Planar Waveguide Slot Array Antennas

The remarkable demand for high throughput transmission in wireless applications makes the millimeter-wave band a trend in recent years. The wide available spectrum in the millimeter-wave band enables multi-gigabit connection in fixed point-to-point or point-to-multi-points links. However, the vital oxygen or water vapor attenuation in the wave propagation at this frequency hinders long-distance communication. According to the radio link budget analysis in [1], to cover 100-meter line-of-sight access with 2 Gbps data rate by QPSK modulation at 60 GHz-band, the combined gain of the transmitting and receiving antennas should be more than 53 dBi. For the above reasons, a wideband antenna with high gain and high efficiency is essential.

Parabolic antennas are typical high gain candidates but have the drawback of enormous volume, making it unsuitable for many scenarios. The planar slot antenna is a powerful alternative in this circumstance. With advantages of high efficiency, compact geometry, easy-to-control aperture distribution and simple installation, they have been widely used in applications, such as radars [2], [3], fixed wireless access (FWA) communication [4], and wireless power transmission systems [5], [6].

In [4], a 26 GHz band FWA system featuring a planar waveduide slot array antenna with IC modules integrated on its back is designed. Figure 1.1 shows the configuration of the FWA system.

Taking advantage of the low profile of the antenna, the wireless terminal (WT) shows benefits of compact size and low weight. The structure of the WT is shown in Fig. 1.2. The antenna has a high gain of 31.5 dB with 65% aperture efficiency, can be accessed to an access point (AP) of 700 m away. Each AP can link to about 240 WTs at most, so the mass production requires the antenna to be low-cost and easy to fabricate. In this design,

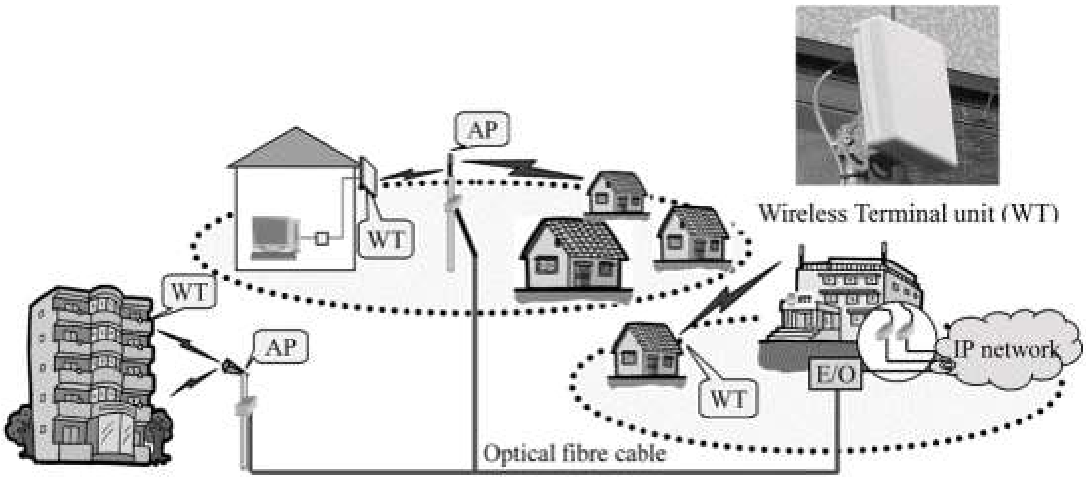


Figure 1.1: A fixed wireless access (FWA) system [4].

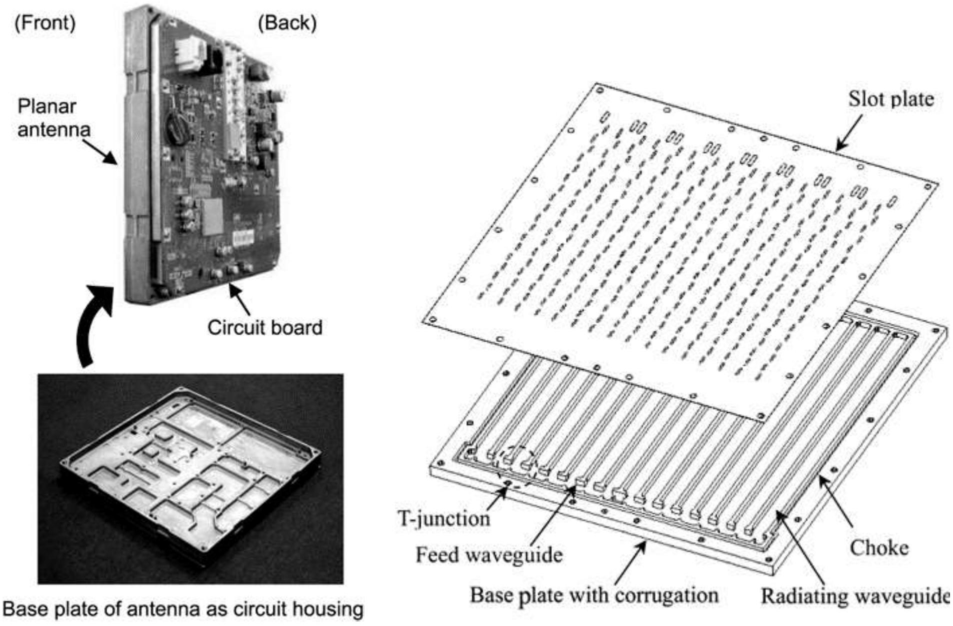
using an alternating-phase fed waveguide slot antenna with a choke at the margin, the top slot plate and base plate are simply stacked. No rigid electrical contact between the plates is necessary because the electrical currents on the narrow walls are cancelled out.

For typical co-phase fed waveguide slot arrays, electrical contact between the top and bottom plates is crucial in fabrication. In [7], the deterioration of performance of the array fabricated by the laser welding technology is displayed in comparison with that fabricated by brazing. In hollow waveguide designs in which the electrical contact between the plates is dispensable, the diffusion bonding technology has been applied in recent researches and demonstrats good performance [8].

Besides the single-mode waveguide slot array antennas, there are also oversized antennas which are excited by multiple modes. The dimensions of the waveguides are much larger than the wavelength. Because the sidewalls between the plates are exempted, the fabrication gets easier. Radial line slot antenna (RLSA) in [9] and parallel-plate slot array antenna in [2] both report efficiency about 50%.

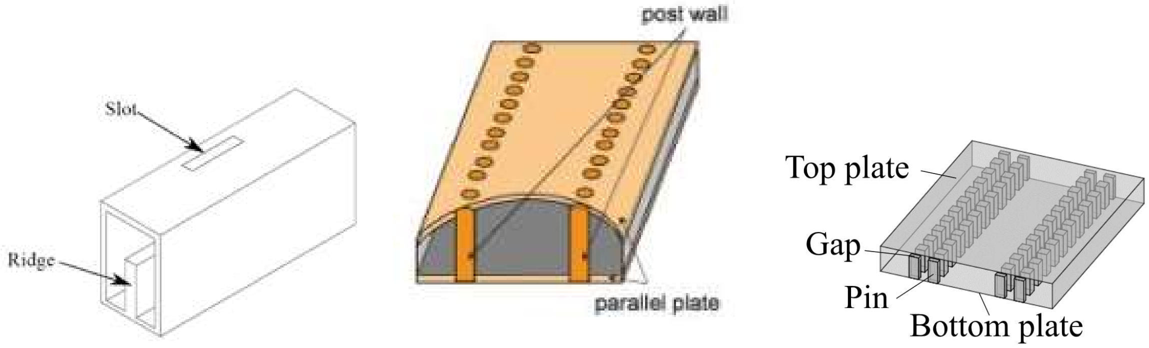
In planar arrays, slots are usually etched serially on the walls of hollow rectangular waveguides (HRW), ridged waveguides, post-wall waveguides (PWW, also known as substrate integrated waveguides namely SIW), gap waveguides (GWG), and parallel-plate waveguides (PPW) [10], [11]. Proper modes should be excited and fed to slotted parts in these waveguides to finally create a radiation into the free space. Three main schemes to feed are series, corporate, and partially corporate [12], depending on whether the slots are excited in serial or in parallel or in a hybrid way. The series feeds feature shorter path leading to less loss. The corporate feeds feature wide bandwidth at the expense of longer path.

Another way to classify the feed topologies relies on the positional relationship between the feeding and radiating parts. If both parts are integrated in the same layer, the array is single-layer [13], otherwise multi-layer [14]. The multi-layer ones usually have more compact apertures without slot-free (aperture blockage) regions contributing little to radiation [15]. The antenna in [14] is center-fed by a feed waveuide at a bottom layer. To realize a single-layer full corporate slot array is difficult [16], [17]. The single-layer coaxial



(a) (b)

Figure 1.2: Planar antenna with circuit board housed at the back in a WT [4].



(a) ridge waveguide (b) post-wall waveguide (c) gap waveguide

Figure 1.3: Varies types of waveguides.

line waveguide fed 16×16-slot array has just a 8.7% impedance bandwidth for VSWR < 2 and antenna efficiency of 76.3% at the design frequency.

1.1.2 Perpendicular-Corporate-Fed 2×2-Element Configuration

To maintain the wideband merit of the corporate feed topology and realize high aperture efficiency simultaneously, perpendicular feed configurations were investigated in the form of multi-layer slot arrays by some researches.

To support a dominant TE_{10} mode in the HRW, the broad-wall width should be larger than a half wavelength. Thus, a challenge is caused for the radiating slots distribution in the corporate feed pattern because a spacing less than one wavelength should also be guaranteed to avoid grating lobes in a two-dimensional planar array. Surely dielectric-filled waveguides such as PWW/SIW can be adopted, but the loss will increase.

An 8×8 triple-layer SIW full corporate-fed cavity arrays featuring vertical power transmission was proposed in [18], realizing a compact aperture. An 8×4-way symmetrical corporate feeding network excites 1×2-element cavities with open apertures uniformly. However, it has only 44.4% antenna efficiency at 60 GHz due to high dielectric loss by LTCC technology, despite of a wide 17.1% impedance bandwidth for VSWR < 2.

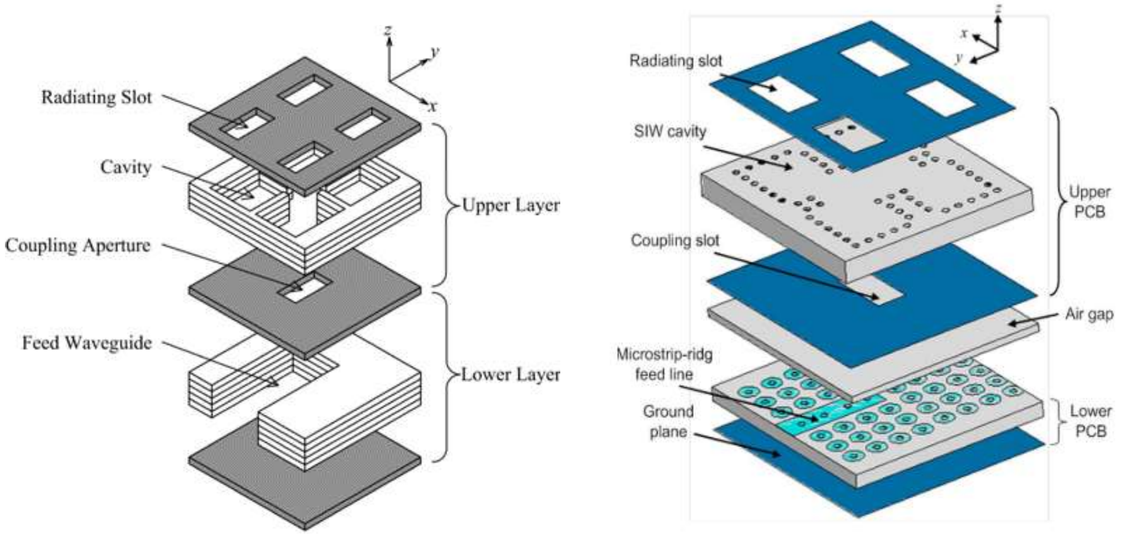
By hollow waveguides, a double-layer array comprising X-shape-cavity-backed 2×2-slot subarrays perpendicularly-fed by a corporate network was proposed in [19] as shown in Fig. 1.4(a). The four slot elements on the cavity top surface are excited perpendicularly by a shared coupling slot beneath in parallel. The vertical transmission gets more efficient than in [18] because the middle layer containing power dividers causing extra insertion loss is removed. The 16×16-slot array shows a measured 12.1% bandwidth for VSWR $<$ 2 and an antenna efficiency high as 83.6% at 61.5 GHz. In [20], the bandwidth of the same structure was further enhanced to 21.5% by superior design methods.

Thereafter, amounts of slot arrays based on the multi-layer perpendicularly-corporate-fed 2×2-element configuration have been designed by the HRWs [24] [25] [26], PWWs/SIWs [21] [27] [28] [29], GWGs [22] [30] [31] [32] [33], PPWs [23] [34] [35] or hybrid of them.

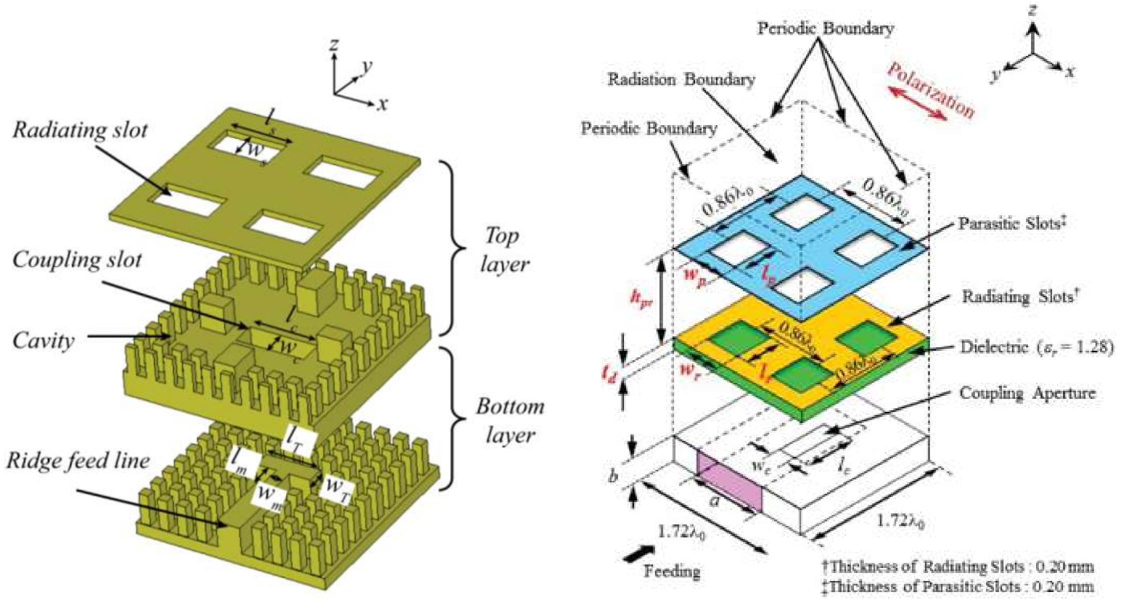
As shown in Fig. 1.4(a), the HRW based cavity-backed design is fabricated by diffusion bonded technology as the electrical contact between plates is important. The design shown in Fig. 1.4(b) has a SIW cavity-backed radiating part and a ridge-type GWG based feed part. The SIW layer utilizes the metal via holes in a PCB (printed circuit board) to realized electrical contacts between the slotted plates. The bottom GWG feed layer is exempted from physical contact due to the air gap of the GWG. In Fig. 1.4(c), the cavity is also formed by the GWG, so the whole subarray requires no physical contact of plates. It can be fabricated by the milling process. The aforementioned three typical designs all require a cavity-backed radiating section. The metal solid walls, via holes, or rows of pins are necessary to build the lateral fences. Furthermore, to get good impedance matching of the subarrays, extra structures such as stubs, posts, and blocks are inserted into the cavity regions, facilitating the X-shape cross-section of the cavities.

In [23], where the concept of perpendicular-corporate feed was firstly proposed, peripheries of the cavities are removed, replaced by a single PTFE substrate sandwiched by parallel plates, as shown in Fig. 1.4(d). The physical metal walls are replaced by virtual periodic boundary walls assumed on two pairs of lateral peripheries, so that the energy of the subarray is still kept in the parallel-plate region. Considering the availability of the PTFE, the single expanded PFFE substrate was further substituted by a stack of one PTFE plate and one air layer [35]. The proposed cavity-free structure significantly decreases the complexity and light of the subarray.

Corresponding to specific geometries, various solutions have been proposed either in the feed layer, or radiating layer, or both of these perpendicular-corporate-fed subarrays to achieve good performance over a wide bandwidth.



(a) HRW X-shape-cavity-backed subarray [19] (b) SIW X-shape-cavity-backed subarray [21]



(c) GWG X-shape-cavity-backed subarray [22] (d) PPW (cavity-free) subarray [23]

Figure 1.4: Varies perpendicular-corporate-fed 2×2-slot subarrays.

In PWW/SIW based designs, besides building tuning stubs as in [19] by via fences [21], introducing patches between stacked cavities [27], [28], removing a little part of the substrate under slot apertures [36] or drilling air holes in stacked substrate cavities of tapered dimensions [37] have also been investigated.

In GWG based designs, pins of electromagnetic band gap (EBG) structures were not only used to construct the cavity walls [22] but also to produce tuning effect. Shorter pins yielding capacitance contribute to significant bandwidth enhancement in power dividing junctions [31] and cavity subarrays [32]. For ridge GWG feeds, more complicated ridge terminal designs engender better matching effect as well [22] [30] [32] [33], as displayed in Fig. 1.4(c).

In [34], although four blocks were used in the cavity subarrays to improve impedance matching and polarization discrimination, the realized bandwidth for VSWR < 2 of the complete array was only about 6% because the subarrays were fed serially through folded PPWs.

In PPW based designs, despite of superimposed third [23] or fourth [35] slotted plates over the basic double-layer arrays, the bandwidth enhancing effects were moderate. The simulated 7.7% bandwidth with VSWR < 1.5 for the triple-layer and the 11.4% for the four-layer subarray are not wide enough compared to the cavity-backed designs. Owing to unexpected detachments between plates in assembly, measured bandwidth and efficiency degraded a lot from the simulated ones.

Even though the parallel-plate perpendicular-corporate-fed subarrays has advantages of simple geometry, light weight, ease of fabrication, the performance of them especially the impedance bandwidth still have a space to be promoted.

1.2 Features and Objectives

1.2.1 Objectives

The objectives of this study are as follows.

1. Rapid analysis and wideband design of perpendicular-corporate-fed multi-layer parallel-plate 2×2-slot subarrays.
2. Realization of wideband and high-gain performance of perpendicular-corporate-fed multi-layer parallel-plate slot array antennas.
3. Realization of low-reflection performance of perpendicular-corporate-fed multi-layer parallel-plate slot array antenna.

1.2.2 Features

Methodology: Hybrid Application of Computational EM Method and Optimization Tool

In a conventional way, at most, four parameters may be disposed simultaneously in the general-purpose EM simulation software ANSYS HFSS due to limited computation capacity and time. When the dimensions to be optimized together are highly correlated and have compound influence on the antenna characteristics, it is usually not easy to get the optimum design, as happened for designs in [23] and [35]. By comparing the results between the design using HFSS [19] and a same structure analyzed and optimized by numerical method of EM computation [20], the latter one got almost double bandwidth.

In this study for the design of the parallel-plate slot array antenna, the method of moments (MoM) based on eigenmode expansion is resorted to analyze the subarray. The analysis of the slot on the plate is treated as a boundary value problem. For the parallel-plate slot array in this study, the MoM is definitely the first option as it only discretizes the surfaces whereas the finite element method (3D-FEM, used in HFSS) gets the entire space discretized. Besides that, it is easier for the MoM to treat open boundaries in problems of antennas [38]. Furthermore, a main target of the study is to realize wide bandwidth of the antennas, compared with time-domain methods such as finite-difference time-domain method (FDTD), the frequency domain method MoM directly providing solutions at all frequency points is more appropriate choice.

Depending on the efficient computation approach, taking advantage of the high-performance computers popular nowadays, the optimization tool will be capable to complete mass computation and acquire the satisfying design results fast. A genetic algorithm (GA) is used for optimization process in the study.

The GA utilization along with the MoM solutions not only leads to better performance of designs but also drastically reduces solution time and storage demand of the optimization process, compared to a conventional way purely depending on the 3D-FEM software simulation. As in [39], a 50% decrease in CPU time was verified for SIW slot arrays. Different from the investigated parallel-plate designs in this study, the SIW-based design requires even more computation for scattering fields from the posts. The hybrid use of the MoM analysis and GA optimization also facilitates an efficient design of a power divider in [40]. Up to 50 parameters can be optimized together, which is much superior to using the general-purpose software HFSS. Usually small number of parameters can be tuned at the same time for the HFSS.

Geometry: Wideband and High-Gain Perpendicular-Corporate-Fed Parallel-Plate Slot Array Antennas

Based on the perpendicular-corporate-fed wall-free (non-cavity) parallel-plate 2 × 2-slot subrrays proposed in [23], MoM analysis and GA optimization are operated to realize wide impedance bandwidth.

Different from the triple-layer subarray of linear polarization in [23] and the four-layer subarray of circular polarization in [35], the first investigated subarray in the study is a double-layer one of linear polarization (same as that in [23]) having a stratified air region with a PTFE plate loaded (same as that in [35]). The replacement of the single expanded PTFE plate used in [23] is due to availability of the material. The evolution of the subarrays investigated conventionally are illustrated in Fig. 1.5.

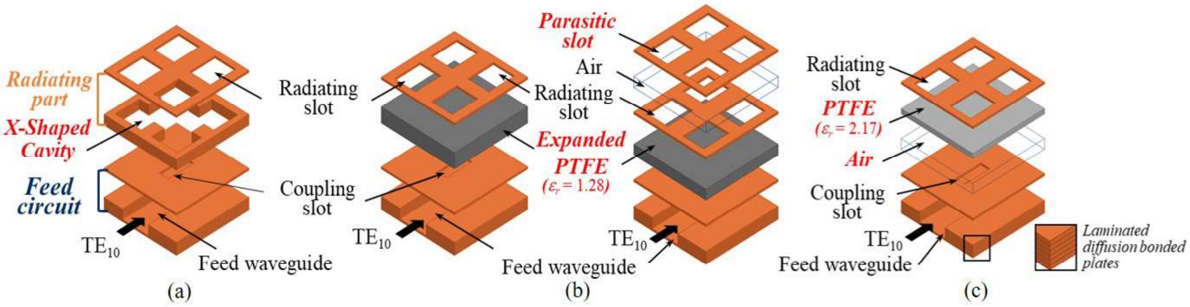


Figure 1.5: Evolution from HRW-fed (a) cavity subarray [19] to (b), (c) parallel-plate subarrays [23][35].

With the benefits of the rapid analysis and optimization, fast wideband designs become feasible for the double-layer and triple-layer PTFE-loaded subarrays.

Then, all-metallic subarrays getting rid of the dielectric influence (loss and field distribution) are analyzed. Auxiliary structures such as gratings and stubs are added into the parallel-plate space to eliminate some high-order mode resonance which have adverse effects on radiation performance.

All the subarrays investigated have a radiating part composed of completely separate metal plates that are simply stacked by screws at array peripheries. They show light-weight, ease-to-fabricate features and competitive wideband, high-gain, or low-refection performance.

1.3 Outline of Chapters

The outline of remaining chapters is shown in Fig. 1.6.

In Chapter 2, the MoM analysis using eigenmode expansion method is applied on the perpendicular-corporate-fed parallel-plate slot subarrays. Several preliminary cases with narrow radiating slots or only one radiating slot are investigated at first. The good agreement between the analysis results and the simulated ones obtained from the HFSS verify the accuracy of the proposed approach. The time efficiency of the analysis is also explicit in the discussion of convergence. The inclusion of the transverse components of the currents into the calculation for wide slots is also a contribution of this chapter.

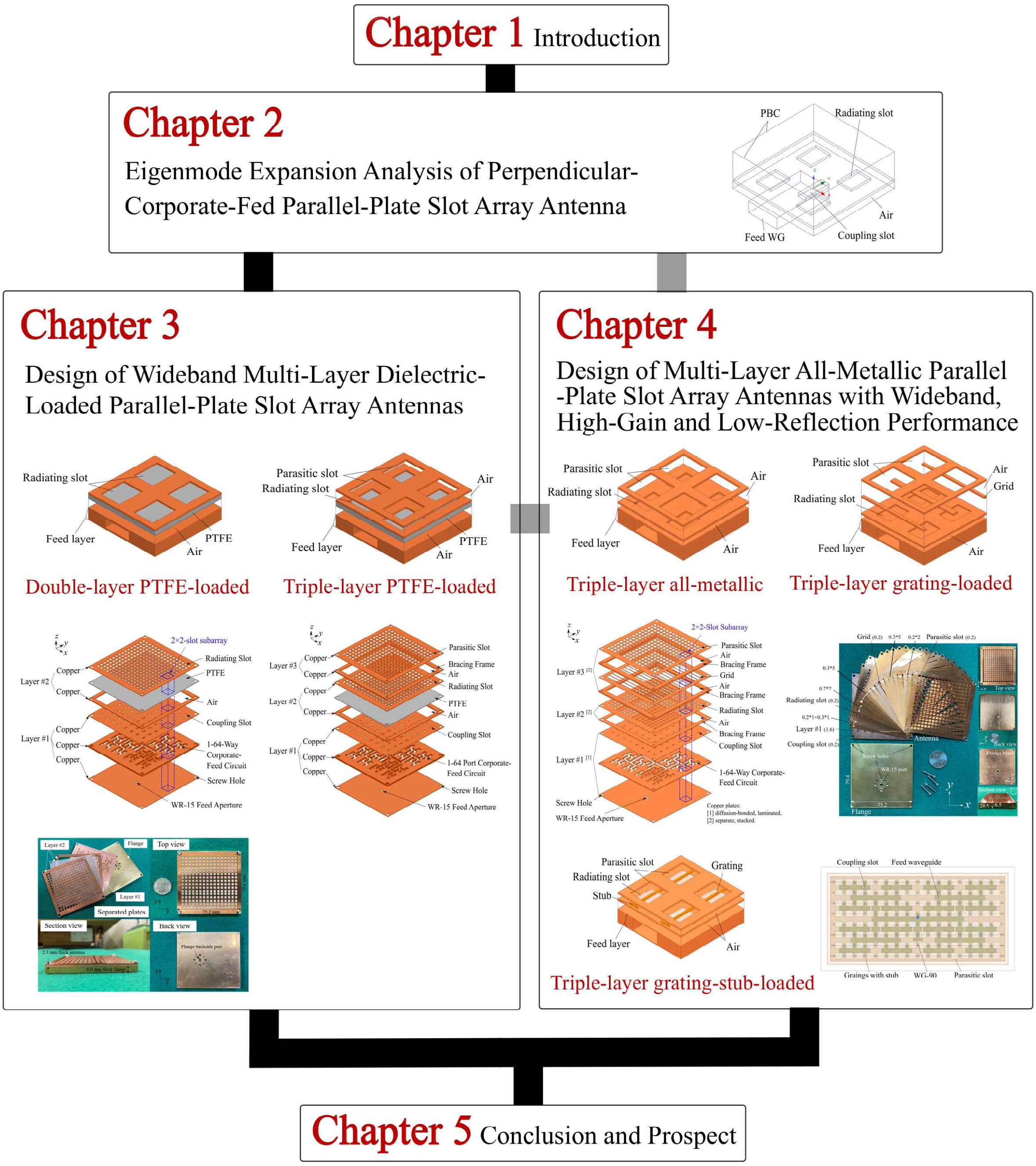


Figure 1.6: Flow chart of the chapters.

In Chapter 3, the MoM is conducted to analyze a double-layer parallel-plate 2×2-slot subarray having a stratified region with an expanded PTFE plate embedded over the air. The derivation of dyadic Green's functions and calculation of reactions in the stratified region are the key parts. Further optimized by a micro genetic algorithm (MGA) about four hours, an optimum bandwidth of the double-layer PTFE-loaded subarray is found to be 13.1%. Fed by a 64-way corporate feed power dividing network, a simulated bandwidth of 14.6% for VSWR < 1.5 is realized for the 16×16-slot array. The measured bandwidth is 13.2% for VSWR < 2.0. The radiation performance is also displayed. Same process was run for a triple-layer PTFE-loaded subarray, which adds one more slot plate atop based the double-layer one. However, the enhancement in bandwidth is not modest.

In Chapter 4, to further improve the performance of the parallel-plate subarray, the MoM analysis and optimization is imposed on a triple-layer all-metallic model firstly. The model is modified from the triple-layer subarray in Chapter 3, with the PTFE plate removed. A high-order mode resonating in the top air region is discovered to have negative effects on radiation. The proposal to solve it is to insert gratings in proper positions into the region. The optimized grating-loaded subarray shows a wide bandwidth up to 18.6% with VSWR<1.5. Combined with a similar modified feed network, the 16×16-slot array shows a simulated 18.2% bandwidth. The measured results validate the wideband, high-gain and high-efficiency characteristics of the array antenna. Next, a 16×8-slot array is designed and simulated in the same way with the target reflection lower than -20 dB in the X-band. The grating-stub-loaded scheme of the subarray facilitates the achievement of the target.

In Chapter 5, this study is summarized and future issues to address are presented.

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