CHAPTER 1
INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

Slot antennas fed by coplanar waveguide (CPW) exhibit various attractive qualities including significantly wider impedance bandwidth than microstrip patch antennas. Fig. 1.1 shows a CPW-fed rectangular slot dipole on a single-layer substrate, which is the simplest kind of practical CPW-fed slot with a standing-wave-type field distribution. The basic operation of such a slot is roughly as follows: the resonant frequency can be adjusted by adjusting the slot half-length L, while input impedance and bandwidth can be varied through adjustment of the slot width W (of course, fine-tuning could entail joint adjustments of these dimensions). Narrower slots yield wider E-plane radiation beamwidths [1]; the E-plane coincides with the plane $\phi = 90°$ in Fig. 1.1. The fractional bandwidth (VSWR < 1.5) of such an antenna on an electrically thin substrate may exceed 10% [2], which is substantially greater than that of a rectangular microstrip patch on an electrically thin substrate. Recent years have seen a spate of articles introducing modified geometries aimed at enhancing the bandwidth even further, *e.g.*, [2–5], or achieve dual-band operation [6, 7]. A recently introduced broadband CPW-fed circular slot antenna was reported to have a fractional bandwidth of 143% [8]. In the sub-millimeter and millimeter-wave ranges, CPW-fed slots have been used as feeds in dielectric lens antennas for single-pixel atmospherical and astronomical applications [9]; arrays of CPW-fed slots are anticipated to be used in space missions [10].

There are also advantages implicit in the use of CPW as feed transmission line: CPW offers easy integration of lumped circuit elements which takes place entirely in the plane of the transmission line, and exhibits less dispersion than microstrip at millimeter-wave and submillimeter-wave frequencies.

For applications that call for unidirectional radiation such as antennas mounted on airframes, a conducting plane is needed to back the antenna structure. The transmission line is then referred to as

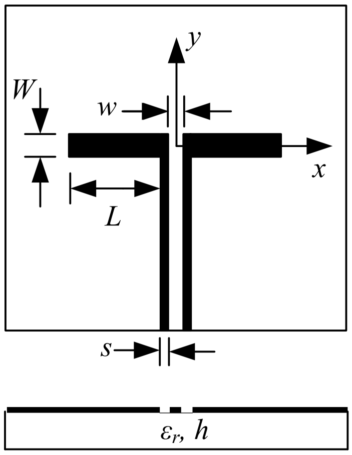

FIGURE 1.1: Top view, and side view looking into feed line of CPW-fed rectangular slot antenna on single-layer substrate. L ≡ half-length and W ≡ width of radiating slot dipole; s ≡ slot width and w ≡ centre strip width of feed line; h ≡ height of dielectric layer; ϵ_r ≡ relative dielectric constant. The z axis points out of the page.

conductor-backed coplanar waveguide (CBCPW). A fundamental drawback of a simple single-layer CBCPW that is not laterally confined is power leakage into parallel-plate mode waves; a zero cutoff TEM mode is always present [11]. A CPW on a conductor-backed two-layer dielectric substrate may be designed to eliminate leakage into the substrate through appropriate choices of dielectric constants, layer heights and CPW dimensions [12, 13]. However, once the CPW is used as feed line to a radiating slot as shown in Fig. 1.2, power leakage into the TM_0 substrate mode (and potentially higher-order modes as well depending on the substrate height) caused by the discontinuity posed by the transition from the CPW into the radiating slot, and by the radiating slot itself, may still degrade radiation efficiency to such an extent that the antenna becomes unusable.

This thesis has two main objectives.

The *first* is to address a paucity of work on CPW-fed slot antennas on two-layer parallel-plate substrates[1]: while many studies have appeared on CPW-fed slots on single-layer substrates without conductor backing, only a handful are available addressing slots on the above two-layer substrate, *e.g.*, [14–16]. This objective is carried out in terms of both a fuller exploration of single-slot behaviour on two-layer parallel-plate substrates, and the investigation of a practically feasible minimum antenna configuration, namely a twin slot configuration, that is not debilitated by the problem of parallel-plate mode leakage. Emphasis is placed on the trade-off between radiation efficiency and impedance bandwidth as a function of substrate geometry, which has not been done

[1] The designations conductor-backed two-layer substrate and two-layer parallel-plate substrate will be used interchangeably in this thesis.

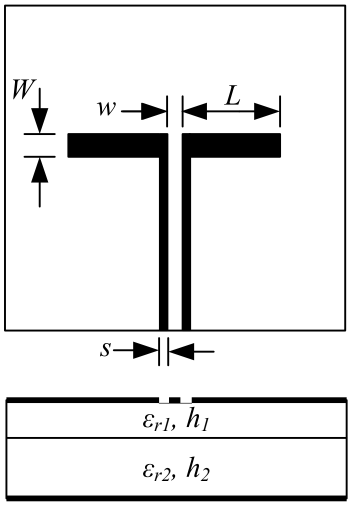

FIGURE 1.2: Top view, and side view looking into feed line of CPW-fed slot antenna on conductor-backed two-layer substrate. $s \equiv$ slot width and $w \equiv$ centre strip width of feed line; $L \equiv$ half-length and $W \equiv$ width of radiating slot dipole; h_1 and $h_2 \equiv$ heights of top and bottom dielectric layers; ϵ_{r1} and $\epsilon_{r2} \equiv$ relative dielectric constants of top and bottom layers.

previously.

The *second* main objective is to develop a technique, built on a standard reciprocity-based expression for centre-fed slots, to find the mutual admittance between two broadside CPW-fed slots on a two-layer parallel-plate substrate. It is instructive to formulate this objective in the context of antenna array design theory.

The design of high-performance arrays of longitudinal slots in rectangular waveguide has been well understood since the late 1970s/early 1980s, when a series of seminal papers by R. S. Elliott and co-workers, e.g., [17–20] made available a general iterative design procedure which notably accounted for mutual coupling in an accurate fashion. This made it possible to design non-uniform linear and planar arrays subject to stringent sidelobe level requirements. Other types of slot arrays that were reported in the wake of this work included arrays of transverse and longitudinal slots fed by boxed stripline [21–23], and slot arrays in the ground plane of microstrip line [24, 25].

In recent years, a variety of CPW-fed slot arrays on single-layer dielectric substrates have been reported. These include a wideband linear CPW-fed log-periodic dumb-bell slot array [26], amplifier arrays using CPW-fed folded slot antennas (*e.g.*, [27, 28]), a leaky-wave CPW-based slot antenna array for millimeter-wave applications [29], and CPW-fed two-dimensional slot arrays in multichip module-deposition (MCM-D) technology [30, 31] using metallic bridges realized on top of a thin film deposited over the CPW feed lines to cancel excitation of the undesired slotline mode at discontinuities. None of these studies however addressed mutual coupling in a rigorous manner.

Of special interest to the present research are CPW-fed, *i.e.*, series-fed, linear slot arrays. Two kinds have been reported in the literature, namely *uniform* arrays, aimed at realizing an aperture distribution consisting of equal-amplitude and equal-phase element excitations [32–34], and *non-uniform* arrays, aimed at realizing an aperture distribution consisting of non-uniform amplitude, equal-phase excitations [35].[2]

More specifically, *uniform* CPW-fed arrays on single-layer dielectric substrates have been considered in [32–34]. In [32, 34], arrays on single-layer substrates that radiate in the presence of a back reflector positioned $\lambda_0/4$ away from the back (copper side) of the antenna are also described. Information given in [32, 33] regarding design procedures is very sparse; it was however possible in the course of the research undertaken for this thesis to successfully extend the iterative procedure of [34] to the design of an 8-element CPW-fed uniform array on a conductor-backed two-layer substrate as reported in [36]. The procedure relies on a full-wave electromagnetic simulator to compute the input impedance of individual slots as well as the input impedance of the array as a whole, and is notable for not requiring explicit mutual admittance or impedance calculations, yet indirectly does approximately account for the effects of mutual coupling via the above full-wave calculations.

As to *non-uniform* CPW-fed slot arrays, a design procedure is available for arrays on substrates consisting of a single thin dielectric layer [35]. The design of non-uniform arrays subject to rigorous sidelobe-level specifications generally requires explicit, accurate calculations of mutual coupling.[3] In [35], the problem of finding the mutual admittance between any two slots in the array is reduced, via a series of assumptions and approximations, to an equivalent problem that involves finding the mutual impedance between two wire dipoles in a homogeneous medium; a well-known reciprocity-based expression can be used for this purpose [18].[4] Since the authors apply their procedure to the design of a small uniform array only, the validity of the above approximations remains to be tested via the design of a non-uniform array subject to a low sidelobe level requirement.

Insight can be gained into how mutual coupling influences array functioning by briefly reviewing the network model underlying the design of linear broadside CPW-fed (*i.e.*, series-fed) slot arrays

[2] Both kinds have main beams at broadside.
[3] Trial-and-error approaches quickly become unfeasible as array size increases.
[4] This approach, which does not use the Green's function of the substrate, will be discussed in greater detail in Section 5.1.

[35]. Consider the generic array shown in Fig. 1.3. The substrate (not shown) could simply consist of a single dielectric layer as in [35], or be multi-layered, as in the case of the two-layer parallel-plate substrate implemented in [36]. There are N slots in the array that are spaced λ_{CPW} apart; this spacing ensures that slots are fed in phase. The half-length and width of each slot are denoted by L_m and W_m respectively, where $m = 1, 2, \ldots N$.

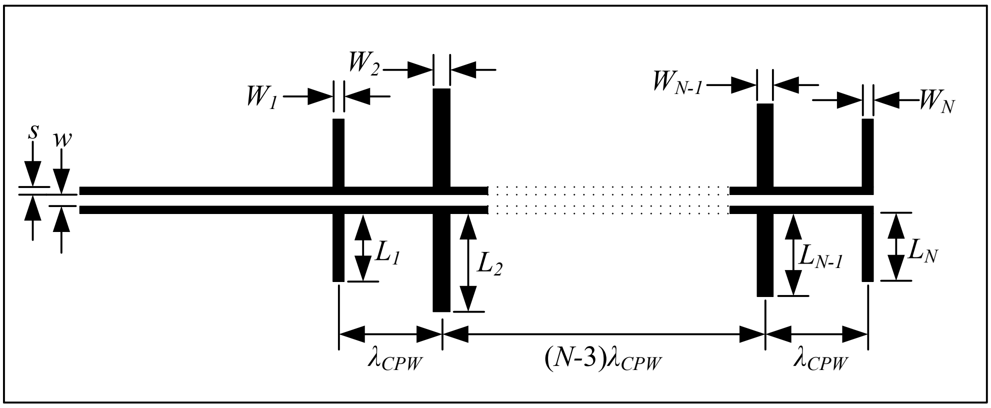

FIGURE 1.3: CPW-fed linear slot array ($N \geq 4$).

The above CPW-fed slot array can be represented as an equivalent transmission line circuit with the slots denoted by series impedances in the circuit [34, 35], as shown in Fig. 1.4. In terms of the usual multiport circuit formulation, with (V_m, I_m) the voltage and current pair at the terminals of slot m,

$$I_m = \sum_{n=1}^{N} Y_{mn} V_n \tag{1.1}$$

where $m = 1, 2, \ldots N$. In the above,

$$Y_{mn} = \frac{I_m}{V_n} \tag{1.2}$$

with $V_k = 0$ for $k \neq n$.

In the equivalent circuit of Fig. 1.4, each slot m is represented by its *active* (input) impedance Z_m^a, which includes the effects of mutual coupling with other slots in the array, or alternatively its active admittance $Y_m^a = 1/Z_m^a$. The active admittances Y_m^a can be obtained by dividing Eq. (1.1) by V_m:

$$Y_m^a = \frac{I_m}{V_m} = \sum_{n=1}^{N} Y_{mn} \frac{V_n}{V_m} \tag{1.3}$$

The input impedance of the array, Z_{in} can be expressed in terms of the active admittances Y_m^a as

$$Z_{in} = \sum_{m=1}^{N} \frac{1}{Y_m^a} \tag{1.4}$$

The above expression reflects the fact that the array of Fig. 1.4 is terminated in a short circuit; termination in other load impedances, *e.g.*, corresponding to tuning stubs, is also possible.

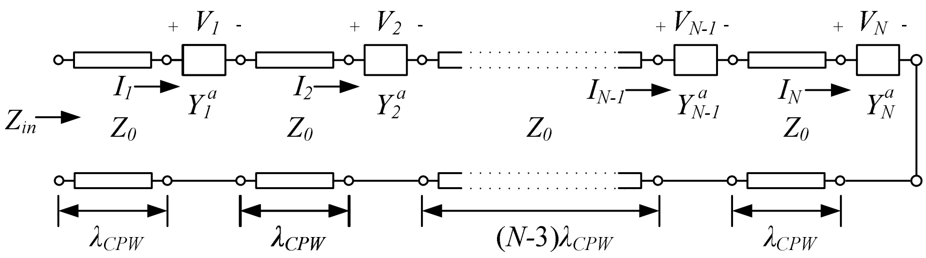

FIGURE 1.4: Transmission-line model for CPW-fed linear slot array.

In practice, it is normally assumed that the N-port self-admittances Y_{mm} are the same as the corresponding isolated slot self-admittances [35]. Also, it is strictly speaking necessary to calculate mutual admittances Y_{mn} in the context of the array, *i.e.*, with all the other slots present and short-circuited. However, the mutual admittance between a specific pair of slots is normally taken to be the mutual admittance between that pair of slots removed from the array in order to simplify calculations. Hence what may be termed a first-order interaction approach is adopted, neglecting the contribution of the rest of the short-circuited array [37].

In the open literature, mutual coupling between pairs of CPW-fed slots on multi-layered substrates has been calculated using a full method of moments (MoM) analysis approach [38] (the reciprocity-expression approach of [35] described earlier can only be applied to electrically thin, single-layer substrates and appears to require further investigation as noted). Hence, the second objective of the thesis, expressed more specifically, is to develop an alternative approach for finding (the first-order interaction approximation to) Y_{mn} of Eq. (1.2) using a simpler technique that would be more readily applicable in an array design procedure than a technique requiring a full MoM analysis, yet with comparable accuracy. An approach based on a standard reciprocity-based expression[5] will be formulated and implemented in conjunction with the appropriate substrate Green's function. In [10], it has been postulated (though not extensively motivated) that an accurate account of the CPW-to-radiating-slot transition in input impedance computations invariably requires a finely-discretized MoM analysis. Hence a question to be addressed is to what extent the accuracy of a simpler formulation would be affected by simplifying this particular aspect of a rigorous analysis, *i.e.*, circumventing a MoM analysis of the whole structure consisting of two radiating slots and their feed lines.

[5] It also has been the method of choice in earlier array designs such as the series-fed strip dipole array described in [18].

Both of the main objectives outlined above represent original contributions, some of which have been published [39–45]. An aspect of the second objective is the derivation of the required component of the spatial-domain Green's function for the magnetic field inside a conductor-backed two-layer substrate due to a horizontal magnetic dipole on the conducting plane adjacent to the higher-permittivity dielectric layer. The main objectives, subsidiary objectives, and their scope are specified in greater detail in the chapter-by-chapter overview of the thesis presented in Section 1.2.

1.2 OVERVIEW OF THESIS

The remaining chapters of the thesis are organized as follows.

In Chapter 2, radiation efficiency and impedance bandwidth of single matched CPW-fed slot dipoles on conductor-backed two-layer substrates are systematically investigated as a function of bottom substrate layer height.[6] Curves for radiating efficiency and return loss are provided that could be used to determine the bottom layer height that would yield the optimum efficiency/bandwidth combination for a particular application.

Chapter 3 investigates radiation efficiency and impedance bandwidth of matched broadside twin slot dipoles fed by CPW on a conductor-backed two-layer substrate as a function of distance between the slots, and height of the bottom substrate layer.[7] Previous reports dealing with slots on other layered media configurations indicated that radiation efficiency can be improved by using, instead of a single slot, two broadside slots spaced half a wavelength of the dominant surface-wave mode apart. The effect of bottom substrate height on gain and directivity is also investigated. The radiation efficiency of twin slots on a conductor-backed two-layer substrate is compared to that of previously reported twin slot antennas on a single dielectric substrate and a back plane placed $\lambda_0/4$ away from the etched side (λ_0 is the free-space wavelength). Measured scattering parameter results are presented to validate bandwidth computations.

In Chapter 4, general aspects of the mutual admittance between twin CPW-fed slots on a conductor-backed two-layer substrate with an air bottom layer are investigated using the full-wave moment-method-based simulator IE3D [46]. Two separate issues are addressed. First, a more comprehensive characterization of the mutual admittance between CPW-fed slots on a conductor-backed two-layer substrate than is currently available, is presented. Curves for the mutual admittance between first-resonance twin slots and second-resonance twin slots as a function of separation distance along standard paths are presented and compared to well-known curves for the

[6] Results presented in this chapter were published in [40].
[7] Results described in Chapter 3 were published in [42].

mutual admittance between two identical narrow center-fed slots on an infinite ground plane in free space. Second, the effect of an added conducting back plane on the mutual coupling between twin CPW-fed slots on a single-layer substrate is investigated as a function of back plane distance.[8]

Chapter 5 forms the bulk of the thesis. Here, a computational strategy, based on a well-known reciprocity-based expression, is developed for finding the mutual admittance between CPW-fed slots on a two-layer parallel-plate substrate (the context has been explained in Section 1.1). The mutual admittance Y_{12} between the slots can be viewed as the sum of external and internal mutual admittances: the external mutual admittance is due to coupling that takes place in the half-space adjacent to the slots, while the internal mutual admittance is due to coupling inside the substrate. In order to compute the internal mutual impedance, the appropriate component of the spatial-domain Green's function for the magnetic field inside a conductor-backed two-layer substrate due to a horizontal planar magnetic current density on the conducting plane adjacent to the higher-permittivity dielectric layer is required. A derivation is presented here which, to the knowledge of the author, has not been published elsewhere. Several results are presented for the mutual admittance between CPW-fed slots as a function of broadside inter-slot distance on a variety of two-layer parallel-plate substrates, and compared to results from the moment-method-based simulator IE3D. The effect of a shift in reference planes (situated along the CPW feed lines) on the two-port Y parameters is investigated and its implications for the reciprocity-expression approach considered. The relative contribution of external and internal mutual admittances to the total mutual admittance is discussed. Mutual admittance for twin slots with a fixed inter-slot distance is also computed as a function of frequency and compared to a measurement. Conclusions are drawn regarding the suitability of the reciprocity-based approach for accurate mutual admittance calculations as an alternative to moment-method-based calculations.

Finally, Chapter 6 presents general conclusions and suggestions for future work.

Throughout the thesis, all electromagnetic quantities are assumed to be sinusoidally time-varying according to an $e^{j\omega t}$ time dependence, which is suppressed. Vectors are denoted in boldface (*e.g.*, $\mathbf{E}$) and scalar quantities including vector components in italics (*e.g.*, E_x), while their spectral concomitants are indicated by means of adding a tilde to the original symbols (*e.g.*, $\tilde{\mathbf{E}}$ and $\tilde{E}_x$).

[8] This portion of the work served as basis for [43].

CHAPTER 2

RADIATION EFFICIENCY AND IMPEDANCE BANDWIDTH OF SINGLE CPW-FED SLOT ANTENNA ON CONDUCTOR-BACKED TWO-LAYER SUBSTRATE

2.1 INTRODUCTION

The objective of this chapter is to provide a systematic theoretical investigation of radiation efficiency and impedance bandwidth of a CPW-fed slot dipole on a conductor-backed two-layer substrate as a function of selected antenna dimensions, notably height of the bottom substrate layer.[1] Slot dipoles are attractive candidates for use in arrays due to their geometrical simplicity [34, 35]. Although a limited number of case studies of two-layer CBCPW-fed slot dipole antennas are available [14–16], systematic examinations of neither radiation efficiency, nor radiation efficiency in conjunction with impedance bandwidth, have been presented. For antennas on laterally infinite conductor-backed layered media, radiation efficiency can be defined as the ratio $\frac{P_{rad}}{P_{rad}+P_{sub}}$, where P_{rad} is radiated power, and P_{sub} is power associated with substrate modes [47, 48]; in the former definition, ohmic losses (conductor and dielectric) are considered negligible.

Previous studies of printed (non-CPW-fed) slot antennas have indicated a dependency between antenna height and radiation efficiency, for instance in the case of slots on thick substrates without conductor backing [49], and infinitesimal slots and rectangular slot dipoles on single-layer and two-layer parallel-plate substrates with conductor backing [47]. In [14, 16] a dependency between antenna height and radiation efficiency is suggested for CPW-fed slots on conductor-backed two-layer substrates but not fully investigated. This chapter examines radiation efficiency of matched (to 50 Ω) CPW-fed slots on a conductor-backed two-layer substrate as a function of height of the bottom

[1] Results presented in this chapter were published in [40].

substrate layer (the operating frequency is 2.4 GHz). The bottom substrate layer has the lower dielectric constant of the two layers. Increasing its height lowers the effective permittivity of the combined layers, improving radiation efficiency (a high effective permittivity would tend to confine electromagnetic fields to the inside of the antenna). As the interest lies in practically useful antennas, the concomitant impedance bandwidth is also considered. Furthermore, the influence of slot width on input impedance and radiation efficiency when substrate layer heights are fixed, is addressed.

2.2 NUMERICAL METHOD AND RESULTS

Numerical investigations were carried out using the moment method-based electromagnetic simulator IE3D [46], which uses a mixed-potential integral equation formulation [50] and assumes laterally infinite layered substrates.[2] In order to assess the program's performance with respect to planar slot antennas, the return loss, gain and directivity as a function of frequency, and principal radiation patterns were computed for two CPW-fed antennas reported in the literature: a CPW-fed slot dipole on a conductor-backed two-layer substrate [16] and a broadband slot antenna (consisting of a slot dipole capacitively coupled with another slot) on a single-layer substrate without conductor backing [51]. (Radiation efficiency can be calculated directly as gain divided by directivity [52].) In both cases good agreement with published results were obtained.[3]

The geometry of a CPW-fed slot dipole on a conductor-backed two-layer substrate is shown in Fig. 2.1.[4] In order to ensure a non-leaky transmission line, it is necessary (but not sufficient) for the top substrate layer to have a higher relative dielectric constant than the bottom substrate layer ($\epsilon_{r1} > \epsilon_{r2}$) [12, 13]. In simulations, dielectric constant values ϵ_{r1} and ϵ_{r2} were fixed throughout at respectively 2.2 and 1. For any slot dipole antenna used as a point of departure, the centre strip width w and slot widths s of the feed line were adjusted to yield a characteristic impedance of 50 Ω. These dimensions were kept constant when the effect of other dimensions of the structure, such as the height of the bottom substrate layer h_2, was investigated. Notably, feed line characteristic impedances deviated negligibly from 50 Ω when h_2 was varied as described below.

Fig. 2.2 graphs the input impedance against frequency of a slot dipole (referred to the edge of the slot) with half-length L = 53.8 mm, width W= 3 mm, top substrate layer height h_1 = 0.787 mm $\approx 0.01\lambda_d$, and bottom layer height $h_2 = 15$ mm $= 0.12\lambda_0$ (λ_d and λ_0 are the wavelengths in the dielectric and free space at 2.4 GHz). The curves corresponding to the real and imaginary

[2] A good overview of general characteristics of laterally open MoM formulations can be found in [50].
[3] In Sections 3.2, 4.3.3, and 5.4.2.5, measured results involving CPW-fed twin slots are presented and compared to IE3D calculations.
[4] For the purposes of this chapter and the next, the slot half-length L is defined to include the CPW slot width s. In Chapters 4 and 5, s is not considered part of L, which conforms to the definition of slot half-length in the CPW-fed array literature.

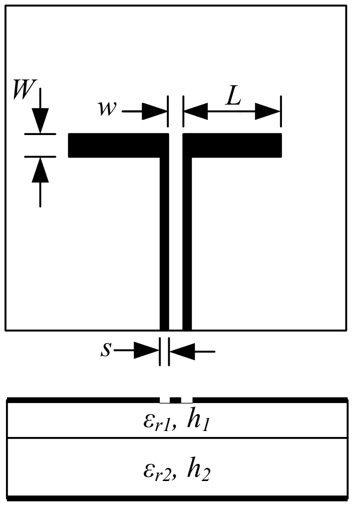

FIGURE 2.1: Top view, and side view looking into feed line of CPW-fed slot antenna on conductor-backed two-layer substrate. $L \equiv$ half-length and W= width of radiating slot dipole; $s \equiv$ slot width and $w \equiv$ centre strip width of feed line; h_1 and $h_2 \equiv$ heights of top and bottom dielectric layers; ϵ_{r1} and $\epsilon_{r2} \equiv$ relative dielectric constants of top and bottom layers.

components suggest the alternation of "steep" resonance regions with "flat" resonance regions; these curves are typical for the slots considered in this thesis (*cf.* [15]). Furthermore, antennas discussed in this chapter are designed to operate within the first "flat" resonance region because of the better matching possibilities compared to the "steep" regions (*cf.* [15]); the antenna of Fig. 2.2 thus would have an operating frequency corresponding to its second resonant frequency of 2.4 GHz. The form of the electric field in the radiating slot wil be considered at length in Chapter 4; it also has been treated elsewhere [14–16].

Since matched antennas are of interest and because it is known that input impedance can be adjusted by varying radiating slot width W [16], this dependency was investigated first for fixed half-length and substrate layer heights (L = 53.8 mm; h_1 = 0.787 mm; h_2 = 15 mm). The real and imaginary parts of the input impedance as a function of frequency are shown in Figs. 2.3 and 2.4 respectively for different slot widths. Inspection reveals a match to 50 Ω at 2.4 GHz for the case W/L = 0.056 (this antenna is the same as the $h_2 = 0.12\lambda_0$ case of Figs. 2.5 and 2.6 below). As W increased from L/40 to L/4, there was approximately a seven-fold increase in the value of the second-resonant input resistance (*i.e.*, the input impedance at the frequency where its imaginary component was zero). Radiation efficiency against frequency was also computed for each slot width. On the whole, and in particular in the vicinity of 2.4 GHz, radiation efficiency changed negligibly as W was varied in the manner described above. This appears to be consistent with the observation in [47] that, for rectangular slot dipoles on either single-layer or conductor-backed two-layer substrates, neither slot

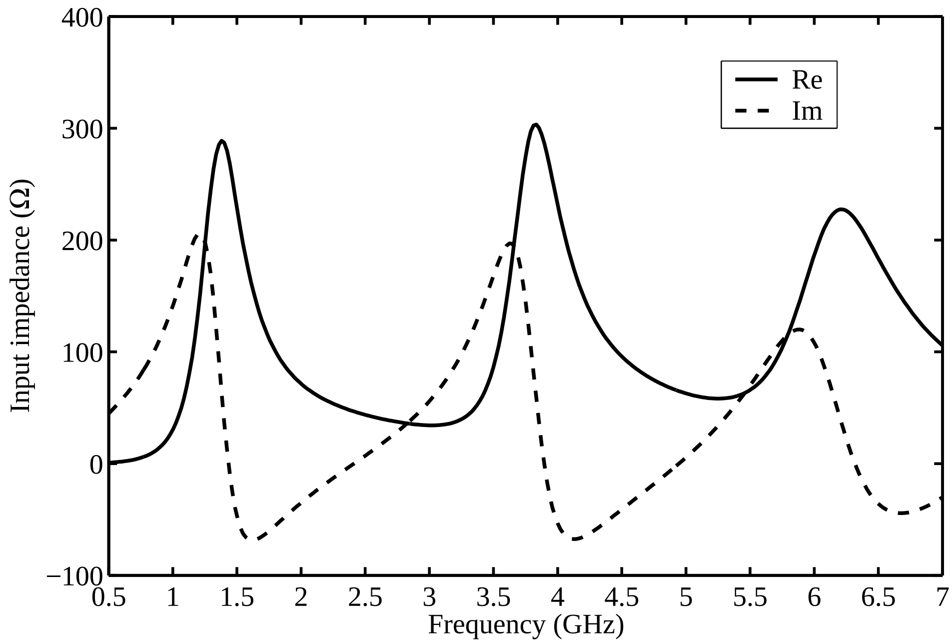

FIGURE 2.2: Input impedance of CPW-fed slot on two-layer parallel-plate substrate referred to edge of radiating slot. L = 53.8 mm; W= 3 mm; w = 10 mm; s = 0.25 mm; h_1 = 0.787 mm; h_2 = 15 mm; ϵ_{r1} = 2.2; ϵ_{r2} = 1.

length nor width has a significant effect on radiation efficiency.

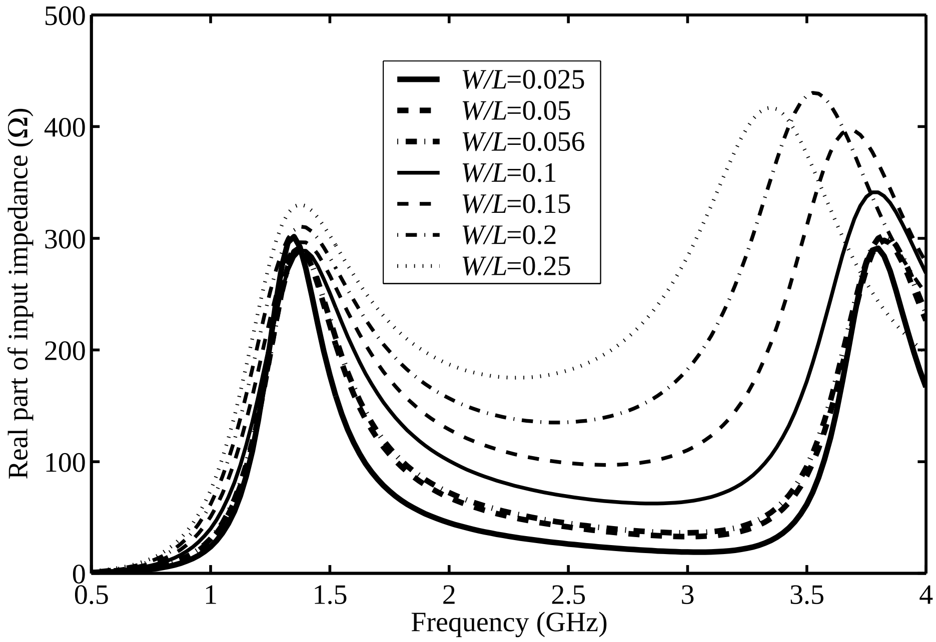

FIGURE 2.3: Influence of radiating slot width W on real part of input impedance. L = 53.8 mm; w = 10 mm; s = 0.25 mm; h_1 = 0.787 mm; h_2 = 15 mm; ϵ_{r1} = 2.2; ϵ_{r2} = 1.

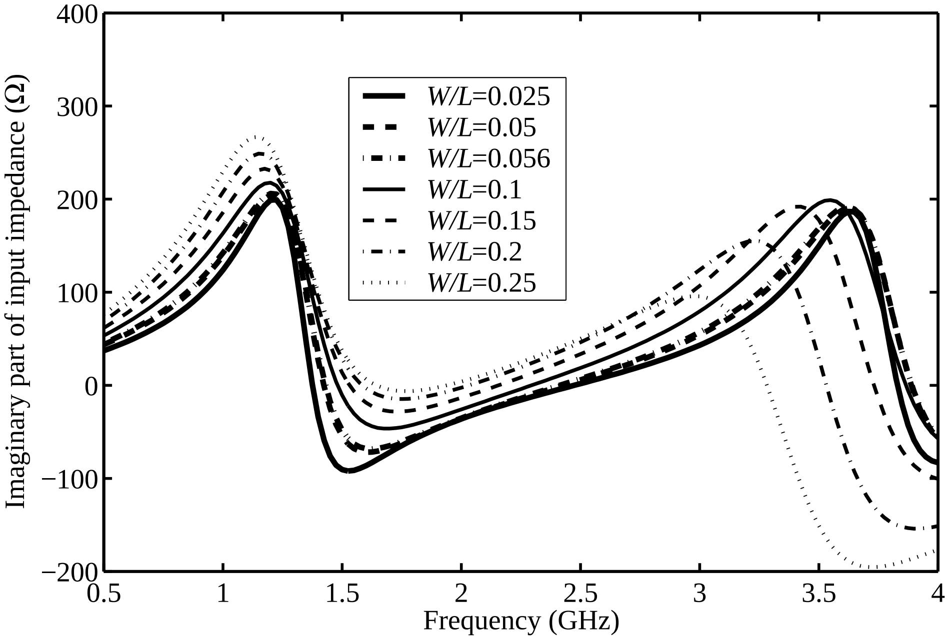

FIGURE 2.4: Influence of radiating slot width W on imaginary part of input impedance. L = 53.8 mm; w = 10 mm; s = 0.25 mm; h_1 = 0.787 mm; h_2 = 15 mm; ϵ_{r1} = 2.2; ϵ_{r2} = 1.

Next the effect was considered of bottom substrate layer height h_2 on radiation efficiency and impedance bandwidth of matched slot dipole antennas designed to operate at 2.4 GHz (in other words, slot dimensions were adjusted for each instance of h_2 to achieve an input match to 50 Ω at 2.4 GHz).

Fig. 2.5 shows return loss against frequency for different values of h_2. The interest was in slot dipoles that might potentially be used on airframes; hence the maximum value of h_2 was limited to less than 40 mm (40 mm = 0.32λ_0 at 2.4 GHz; as before, λ_0 is the free-space wavelength at the operating frequency). Table 2.1 lists the impedance bandwidths at each value of h_2 corresponding to VSWR < 2 and VSWR < 1.5, as well as radiating slot dimensions. For both instances of VSWR, bandwidth decreased monotonically with increasing values of h_2. Fig. 2.6 shows the corresponding graph of radiation efficiency against frequency. Radiation efficiency increased markedly with increased height. However, as h_2 became larger, increases in radiation efficiency in response to the same incremental increases in height became less pronounced.

2.3 CONCLUSIONS

The behaviour of matched CPW-fed slots on conductor-backed two-layer substrates was systematically explored as a function of height of the bottom substrate layer. It was found for slots with a common operating frequency that radiation efficiency increased and bandwidth decreased as

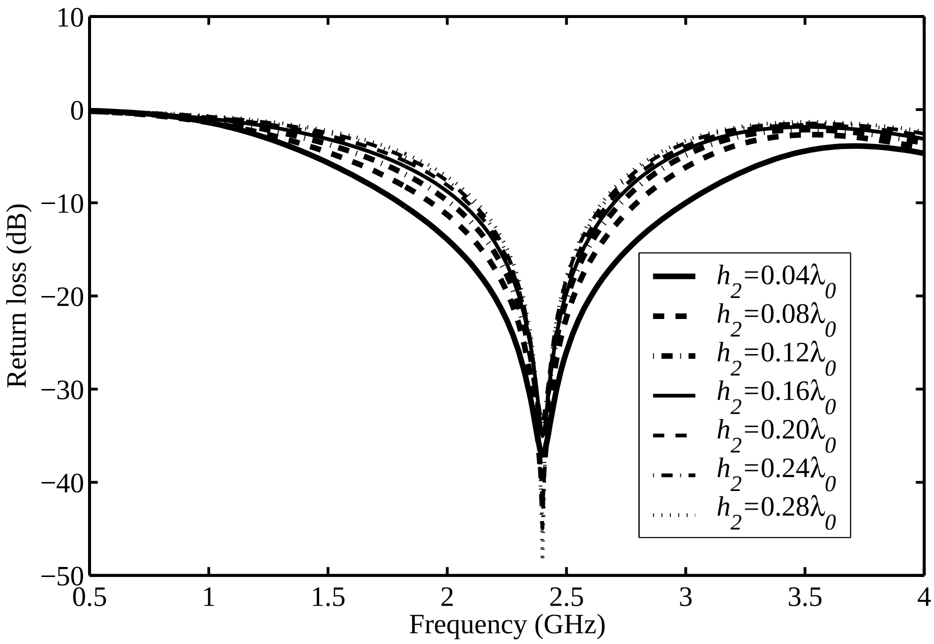

FIGURE 2.5: Influence of bottom substrate layer height h_2 on return loss for slots matched at 2.4 GHz. w = 10 mm; s = 0.25 mm; h_1 = 0.787 mm; ϵ_{r1} = 2.2; ϵ_{r2} = 1 (see Table 1 for radiating slot dimensions).

TABLE 2.1: Bandwidth against bottom substrate layer height h_2 for slots matched at 2.4 GHz. $w =$ 10 mm; $s =$ 0.25 mm; $h_1 =$ 0.787 mm; $\epsilon_{r2} =$ 2.2; $\epsilon_{r2} =$ 1.

	Impedance bandwidth		Radiating slot dimensions (mm)	
h_2	VSWR $<$ 2	VSWR $<$ 1.5	L	W
0.04	52.3%	33%	49.9	1.1
0.08	38%	22.8%	53.3	2.2
0.12	31.6%	18.4%	53.8	3
0.16	28%	16.7%	53.6	3.8
0.2	26%	15.5%	53.3	4.6
0.24	24.3%	14.3%	52.9	5.4
0.28	23.1%	13.4%	52.3	6

height of the bottom substrate was increased. The most efficient antenna had a bottom dielectric layer height of $0.28\lambda_0$ (λ_0 is the free-space wavelength at the 2.4 GHz operating frequency) and a bandwidth of 13% (VSWR $<$ 1.5); in this band, radiation efficiency varied between 56% and 59%. Curves for radiating efficiency and return loss for matched slots with different bottom substrate layer heights of the sort provided here could be used, in conjunction with expressed constraints

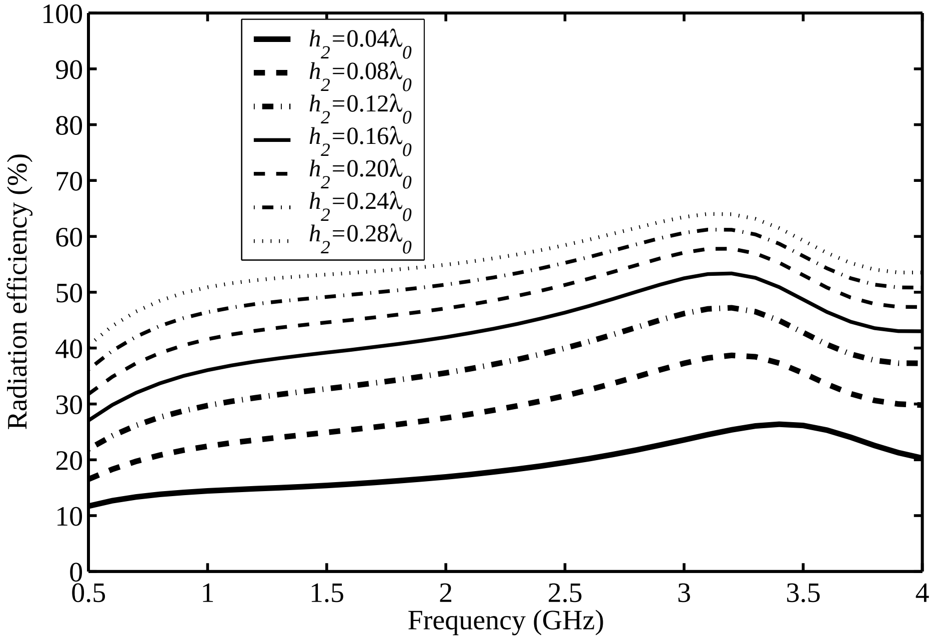

FIGURE 2.6: Influence of bottom substrate layer height h_2 on radiation efficiency for slots matched at 2.4 GHz. w = 10 mm; s = 0.25 mm; h_1 = 0.787 mm; ϵ_{r1} = 2.2; ϵ_{r2} = 1 (see Table 1 for radiating slot dimensions).

on antenna physical height, to determine the bottom layer height that would yield the optimum efficiency/bandwidth combination for a particular application.