CHAPTER 6

CONCLUSIONS AND FUTURE WORK

Main conclusions on the work presented in this thesis are summarized below, and areas for future work are identified.

The thesis had two main objectives.

The first was to alleviate a paucity of work on CPW-fed slot antennas on conductor-backed two-layer substrates by means of a fuller characterization of the behaviour of single CPW-fed slots on such substrates, and by the investigation of a viable minimum antenna configuration, namely a twin slot configuration, that is not disabled by the problem of parallel-plate mode leakage that invariably accompanies single slots.

With respect to single slots it was found that radiation efficiency increased and bandwidth decreased as height h_2 of the bottom substrate layer was increased. Thus it was possible to design a single slot antenna on a substrate with top and bottom dielectric layer heights of about $0.01\lambda_d$ and $0.28\lambda_0$ that had a bandwidth of 13% (VSWR < 1.5) with a radiation efficiency of around 57% in the band, compared to a bandwidth of 18% and a radiation efficiency of around 39% in the band for a slot on a lower-profile substrate (the reference substrate for this investigation) that had top and bottom dielectric layer heights of about $0.01\lambda_d$ and $0.12\lambda_0$. Broadside twin slots on the latter substrate were however shown to yield more than double the radiation efficiency (*i.e.*, about 90%) of the single slot (on the same substrate) when they were spaced close to half a wavelength of the two-layer parallel-plate TM_0 mode apart; the bandwidth of this configuration (13%) was about a third less than that of the single slot. Further investigation showed that radiation efficiency of matched twin slots spaced exactly $\lambda_{TM_0}/2$ apart increased as bottom substrate layer height increased; the improvement was incremental given the already relatively high radiation efficiency (just over 80% at the operating frequency) at the starting $h_2 = 0.08\lambda_0$ value. Bandwidth again decreased with increasing bottom layer height, albeit less markedly than in the case of a single slot. It was found that radiation efficiency attainable with optimally-spaced twin slots on the reference ($h_2 = 0.12\lambda_0$) conductor-backed two-layer substrate is comparable to the high radiation efficiencies attainable with similarly-spaced twin slots on thick λ_d/4 substrates (or thin substrates) with a back reflector positioned λ_0/4 away; at microwave frequencies, the lower profile of the two-layer parallel-plate substrate would likely be an added advantage.

The second main objective of the thesis was to develop an approach for finding the mutual admittance Y_{12} between CPW-fed slots on a conductor-backed two-layer substrate that would be more readily applicable in an iterative array design procedure than a technique based on a full moment-method-based analysis, yet be of comparable accuracy. The approach was to be based on a well-known reciprocity-based expression, and intended to rigorously account for the substrate by use of the appropriate Green's function.

An initial step was an exploratory investigation, using the moment-method-based electromagnetic simulator IE3D, of general aspects of the mutual admittance between identical (twin) CPW-fed slots on a conductor-backed two-layer substrate with an air bottom layer. *First*, curves for mutual admittance Y_{12} between twin CPW-fed slots on such a conductor-backed two-layer substrate as a function of slot separation d along broadside and collinear paths were computed. This was done for slot half-lengths in the vicinities of the first and second resonant half-lengths of the corresponding isolated slots (a characterization of this nature was not yet available in the literature; such data might be used towards a first-order array design). Two-port network parameters were referred to radiating slot centres. Mutual admittance curves for the set of broadside second-resonance twin slots were "irregular" in shape, and shifted with respect to each other, unlike the first-resonance curves that were similar in shape to mutual admittance curves for centre-fed narrow slots in an infinite ground plane; the irregularity was most marked for twin slots with half-length equal to the isolated slot second-resonant half-length. The mutual admittance between broadside second-resonance CPW-fed twin slots referred to the magnitude of the isolated slot self-admittance – a measure of the degree of mutual coupling – was greater than that for first-resonance CPW-fed twin slots, which in turn exceeded that for broadside $0.5\lambda_0$ centre-fed narrow rectangular slots in an infinite ground plane. Compared to the broadside case, mutual coupling between identical collinear slots with half-lengths in the vicinity of the second-resonance half-length was negligible. *Second*, the effect of back plane distance on mutual coupling between CPW-fed twin slots on conductor-backed two-layered substrates was investigated. For the substrate under investigation, a back plane at a distance of λ_0/4 and λ_0/6 yielded normalized mutual admittance curves with substantially higher maxima and minima compared to the case where no back plane was present. Normalized mutual admittance in the

λ_0/6 case was somewhat larger than in the λ_0/4 case, suggesting that the effect of mutual coupling increases as back plane distance decreases.

The predominant contribution however was the above-mentioned development of an approach based on a standard reciprocity-based expression for finding the mutual admittance between two broadside CPW-fed slots on a conductor-backed two-layer substrate. Simplifying assumptions included negligible interaction of radiating slots with CPW feed lines, and radiating slot aperture fields that are directed across the width of the slot, and are constant across the width of the slot. In order to compute curves of Y_{12} between two CPW-fed slots against slot separation d, the reciprocity-expression approach requires the electric field and "terminal" voltage (*i.e.*, the voltage at the end of the CPW feed line) of each slot radiating in isolation; the terminal voltage includes the effect of the CPW-to-radiating-slot transition. Thus computing Y_{12} against d requires only a once-off moment-method analysis of each slot in isolation, and then calculating external and internal reaction integrals at each value of d; this is computationally more economical than the alternative of a full moment-method analysis of the whole twin-slot structure at every value of d.

In order to evaluate the internal mutual admittance, the relevant component of the spatial-domain Green's function for the conductor-backed two-layer substrate was determined in integral form; this was not available in the open literature.

Using the reciprocity-expression approach, mutual admittance Y_{12} against slot separation d was computed for broadside CPW-fed twin slots – and some non-identical slot pairs – on three different conductor-backed two-layer substrates (the range of d was $0.9\lambda_{CPW} \leq d \leq 3\lambda_{CPW}$). The substrates had top layers of contrasting dielectric thickness, and the same air bottom layer. For each substrate, three or four broadside twin slot configurations were considered that had radiating slot half-lengths in the vicinity of the second-resonant half-length of an isolated slot on the substrate. Results were compared to moment-method-based simulations obtained using IE3D. Y_{12} calculations were referred to radiating slot centres by choosing CPW feed lines that were $0.5\lambda_{CPW}$ long. In general, good agreement was observed between the above methods; the greatest discrepancy occurred for twin slots that had the same half-length as an isolated second-resonant slot on the substrate. Here, IE3D curves appeared like "irregular" versions (in the sense of the above initial explorations) of the reciprocity-expression curves, with the deviation the most marked for the substrate with the top layer that had the greatest electrical height. The discrepancy was related to the manner in which slot self-properties are accounted for in the two models: the reciprocity-expression approach assumes unchanging slot self-admittances equal to isolated slot self-admittances, while IE3D in fact predicted two-port self-admittances that were not constant as a function of slot separation, "oscillating" with a decaying envelope about the isolated slot self-admittances.

Completely “regular” IE3D mutual admittance curves – as well as two-port self-admittance curves equal to the isolated self-admittance values – were however obtained for the above second-resonant twin slots when a shift of reference planes was established by reducing feed line lengths to $0.4\lambda_{CPW}$; reciprocity-expression Y_{12} calculations furthermore matched the IE3D results very closely. It was subsequently established that more accurate (*i.e.*, “irregular” in the above sense) Y_{12} curves for resonant-length slots referred to the centres of radiating slots can be obtained using the reciprocity-expression approach as follows. First, identify a set of reference planes (and corresponding feed line lengths) for which Y_{11} against d is essentially constant. Second, since the reciprocity-expression assumption of unchanging self-admittances would be valid, determine Y_{12} using the reciprocity-expression method; this implies a once-off moment-method analysis of the corresponding isolated slots, which for each slot could yield the isolated self-admittance Y_{self} in addition to the terminal voltage and electric field. Finally, construct a Y parameter matrix from Y_{self} and Y_{12} for each value of d, and transform it to the desired $l_f = 0.5\lambda_{CPW}$ reference planes.

Using the reciprocity-expression approach, it was established that, for CPW-fed slots on the above conductor-backed two-layer substrates, the internal contribution to the mutual admittance was more than twice that of the external mutual admittance. The relative contribution of the internal mutual admittance was greater for substrates with electrically thicker top layers. The predominance of the internal mutual admittance is contrary to the case of, for example, longitudinal slots in the broad wall of rectangular waveguide, where in general the external coupling is most pronounced.

It was concluded that the reciprocity-based approach for mutual admittance calculations between CPW-fed slots on a two-layer parallel-plate substrate can be a viable alternative to a moment-method-based approach. The reciprocity-expression approach however would have the advantage of being considerably simpler to implement in an array design procedure. Future work could entail the actual incorporation of the method in an array design procedure, as well as investigating methods to optimize the speed of computing the reaction integrals that are part of the method.