CHAPTER 3

RADIATION EFFICIENCY AND IMPEDANCE BANDWIDTH OF BROADSIDE CPW-FED TWIN SLOT ANTENNAS ON CONDUCTOR-BACKED TWO-LAYER SUBSTRATES

3.1 INTRODUCTION

In the previous chapter, it was shown that low radiation efficiency due to parallel-plate mode leakage of matched CPW-fed single slots on conductor-backed two-layer high-low permittivity substrates may be notably improved by increasing the height of the bottom substrate layer at the cost of decreasing bandwidth. However, studies of other planar slot antennas have indicated that the radiation efficiency obtainable with a single slot can be greatly improved by placing two broadside slots half a wavelength of the dominant surface wave mode apart, resulting in substantial phase cancellation of that mode. This has for example been shown for elemental twin slots on a dielectric substrate with a thickness of $\lambda_d/4$ (λ_d is the wavelength in the dielectric) [49]; and for elemental twin slots on a 3-layer, high-low-high permittivity stack with each layer $\lambda_d/4$ thick, a configuration which manages to suppress strong coupling to all but the TM_0 mode [53]. With respect to slots on substrates consisting of one dielectric layer only, it was indicated in [49] that a limited improvement in radiation efficiency would result for a slot spacing aimed at canceling a particular surface wave mode when the substrate was high enough to allow propagation of several modes. In [54] it was demonstrated that the use of twin slots on $\lambda_d/4$ substrates, and twin slots on thin substrates, in both cases with a back reflector positioned $\lambda_0/4$ (a quarter free-space wavelength) away from the back (conductor) side of the antenna, also result in a vast improvement in radiation efficiency. In the case of $\lambda_d/4$ substrates, the use of twin slots achieves partial cancellation of both the parallel-plate TEM mode and the dielectric substrate TM_0 mode. In the thin substrate case, twin slots enhance efficiency predominantly through cancellation of the parallel-plate TEM mode. In [55] it was established that using twin arc-slot radiators of appropriate radius of curvature and arc length could enhance guided leaky-wave cancellation even further. This slot shape ensures that surface wave cancellation is not limited to the slot broadside direction only. (Radiation efficiency of linear slot arrays of more than two elements was addressed in [34, 48].)

In this chapter, the focus is on radiation efficiency of CPW-fed twin (linear) slots on a conductor-backed two-layer substrate with high-low dielectric permittivities, the high permittivity layer being adjacent to the slots.[1] Fig. 3.1 shows the orientation of broadside twin slot dipoles, and explains notation with respect to geometrical parameters and material constants as applied in this chapter. Essentially two investigative goals were identified. The first was to explore the effect of inter-slot distance d on radiation efficiency while also establishing the concomitant effect on impedance bandwidth, relatively wide bandwidth being an appealing feature of CPW-fed slots. The second was to establish the effect of bottom substrate layer height h_2 on the radiation efficiency of optimally spaced twin slots, as it has been shown that radiation efficiency can be increased for single slots by increasing the bottom layer height (*cf.* Chapter 2); again, efficiency was to be considered in conjunction with bandwidth. Throughout, the interest lay in antennas that might be of practical use; hence each antenna configuration reported here involved matched single or twin slots.

It was noted earlier that high radiation efficiencies (*i.e.*, in the order of 90%) can be achieved by using appropriately spaced twin slots on either a $\lambda_d/4$ substrate with a back reflector positioned $\lambda_0/4$ away; or a thin ($\lambda_d/100$) substrate with a back reflector positioned $\lambda_0/4$ away [54]. The total height of these antennas may however become prohibitive for certain applications at microwave frequencies. It is shown below that comparable radiation efficiency may be attained using the structure of Fig. 3.1 – two dielectric layers sandwiched between two conducting plates – with a notably reduced profile compared to the structures of [54].

3.2 NUMERICAL METHOD

Numerical investigations were performed using the moment method-based electromagnetic simulator IE3D [46], assuming laterally infinite top and bottom conducting planes. Details regarding prior verification of the program's performance with respect to radiation efficiency and impedance bandwidth of CPW-fed single slot antennas were given in Chapter 1. In order to evaluate the program's performance with respect to structures containing more than one slot, and given the emphasis on impedance bandwidth in the present study, return loss as a function of frequency was computed for a test case involving matched CPW-fed twin slots on a conductor-backed two-layer

[1] Results described in this chapter were published in [42].

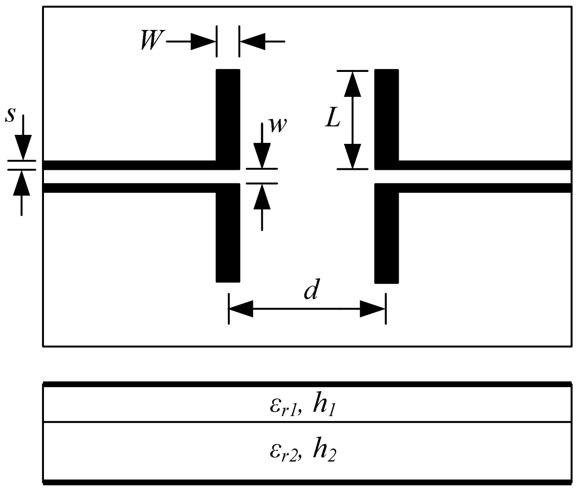


FIGURE 3.1: Top and side views of broadside CPW-fed twin slot antennas on conductor-backed two-layer substrate. L $\equiv$ half-length and W $\equiv$ width of radiating slots; d $\equiv$ distance between radiating slots; $s \equiv$ slot width and $w \equiv$ centre strip width of feed lines; h_1 and $h_2 \equiv$ dielectric layer heights; ϵ_{r1} and $\epsilon_{r2} \equiv$ relative dielectric constants.

substrate designed to operate at 8 GHz (*cf.* Fig. 3.1). The slots were spaced half a wavelength of the two-layer parallel-plate TM_0 mode apart [56]. Fig. 3.2 shows computed and measured results for return loss magnitude against frequency (the measurement was performed using a HP 8510C network analyzer). Good agreement between computation and measurement was obtained. The measured resonant frequency deviated by about 3% from the predicted value. Predicted and measured impedance bandwidth values also agreed well: 20.3% (VSWR $<$ 2) and 11.5% (VSWR $<$ 1.5) in the computed case, and 18.9% (VSWR $<$ 2) and 10.9% (VSWR $<$ 1.5) according to the measured return loss curve.

In simulations directed at investigating radiation efficiency and bandwidth in the manner described above, relative dielectric constant values ϵ_{r1} and ϵ_{r2} were fixed throughout at 2.2 and 1 respectively, while the top substrate layer was held constant at 0.787 mm (this is less than one hundredth of a dielectric wavelength at 2.4 GHz, the frequency at which simulations were carried out). A higher dielectric constant has to be chosen for the top substrate layer than for the bottom layer ($\epsilon_{r1} > \epsilon_{r2}$) in order to achieve a non-leaky transmission line [12]. The choice of a thin top layer in conjunction with a relatively low value of ϵ_{r1} was aimed at maximizing radiation efficiency as explained in Chapter 1. The centre strip width w and slot widths s of the feed lines were adjusted to yield a characteristic impedance of 50 Ω. These dimensions were kept constant when other dimensions of the antenna configuration were varied. Feed line characteristic impedances deviated negligibly from 50 Ω when the height of the bottom substrate layer h_2 was varied in the manner described below.

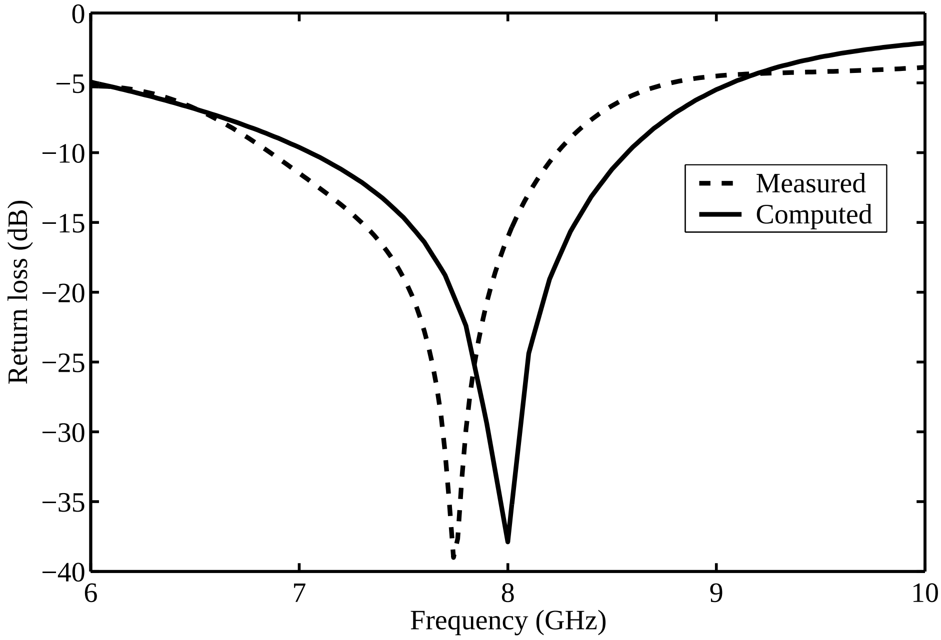


FIGURE 3.2: Return loss against frequency for broadside twin slots matched at 8 GHz. $L = 13.7$ mm; $W = 2.55$ mm; $d = 18.2$ mm; $w = 3.8$ mm; $s = 0.2$ mm; $h_1 = 0.813$ mm; $h_2 = 10$ mm; $\epsilon_{r1} = 3.38$; $\epsilon_{r2} = 1$.

3.3 INFLUENCE OF INTER-SLOT DISTANCE

The effect of inter-slot distance d on radiation efficiency was explored by varying d using increments of arbitrary value. Fig. 3.3 shows radiation efficiency at 2.4 GHz for twin slots as a function of normalized distance d/λ_0 (λ_0 is the free-space wavelength at 2.4 GHz). For each distance value corresponding to markers in the graph, the slots were matched at 2.4 GHz within the twin slot configuration using identical half-lengths L and widths W for each slot (feed lines were also identical). Slots were fed 180° out of phase at the feed line ports to achieve in-phase aperture field distributions. The bottom substrate layer height h_2 was fixed at $0.12\lambda_0$. This particular choice of h_2 (i.e., $h_2 = 15$ mm) was well below an upper limit of 40 mm motivated by an interest in antennas sufficiently thin to allow for use on airframes (*cf.* Chapter 2); it also precluded propagation of two-layer parallel-plate modes other than the TM_0 mode [56]. The radiation efficiency value at $d/\lambda_0 = 0$ shown in the graph of Fig. 3.3 pertains to a single slot matched at 2.4 GHz.

Fig. 3.3 reveals that radiation efficiency at 2.4 GHz for the matched twin slots increased monotonically as distance d was increased to $0.45\lambda_0$ and then decreased as d was further increased to $0.94\lambda_0$. Maximum radiation efficiency occurred for the case $d = 0.45\lambda_0$: 90% as opposed to 39% for the single slot. This value of d is close to half the wavelength of the two-layer parallel-plate TM_0 mode (λ_{TM_0}) at 2.4 GHz. Radiation efficiency at 2.4 GHz was the smallest for the case $d = 0.94\lambda_0$: 28% as opposed to 39% for the single slot case. This distance is close to λ_{TM_0},

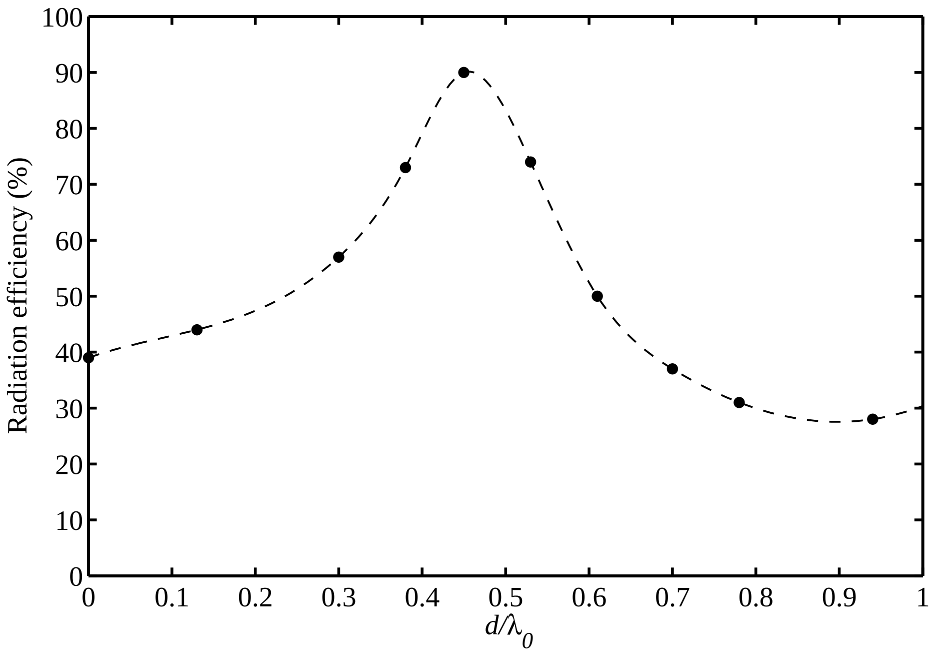
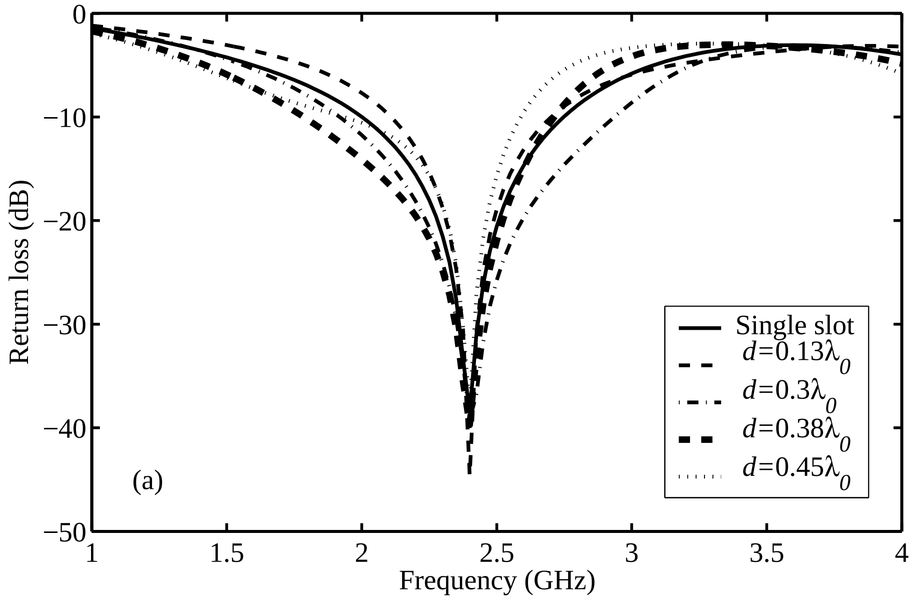


FIGURE 3.3: Radiation efficiency as a function of normalized distance d/λ_0 between slots matched at 2.4 GHz (λ_0 is the free-space wavelength at 2.4 GHz). $w = 10$ mm; $s = 0.25$ mm; $h_1 = 0.787$ mm; $h_2 = 0.12\lambda_0$ (15 mm); $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$. Radiation efficiency at $d/\lambda_0 = 0$ is that for a single slot matched at 2.4 GHz.

resulting in enhancement of the TM_0 fields in the slot broadside directions (an effect which is of course contrary to the desired phase cancellation).

Curves of return loss against frequency for the same twin slot configurations are presented in Fig. 3.4, while Table 3.1 lists twin slot impedance bandwidths at each value of d/λ_0 corresponding to the criteria VSWR < 2 and VSWR < 1.5 (radiating slot dimensions are also provided). The latter bandwidth values are graphed against normalized distance d/λ_0 in Fig. 3.5 (bandwidth values at $d/\lambda_0 = 0$ pertain to a single slot matched at 2.4 GHz). The impedance bandwidth for the highest radiation efficiency case ($d = 0.45\lambda_0$) was 13% (VSWR < 1.5), which is about two-thirds of the bandwidth of an matched single slot antenna on the same substrate. Notably, the case $d = 0.38\lambda_0$ had double the bandwidth (26.1%, VSWR < 1.5) of the best radiation efficiency case while its radiation efficiency at 73% was about four-fifths of the radiation efficiency in the best case, suggesting a reasonable compromise for situations where relatively large bandwidth is a priority.

Fig. 3.6 shows E-plane co-polarization patterns for a single slot matched at 2.4 GHz, and twin slots matched at the same frequency spaced $0.45\lambda_0$ apart (the optimum efficiency case of Fig. 3.3 and Table 3.1). In both cases cross-polarization levels were negligible. The twin slots' co-polarization pattern displays the narrower beamwidth and greater directivity expected for a small



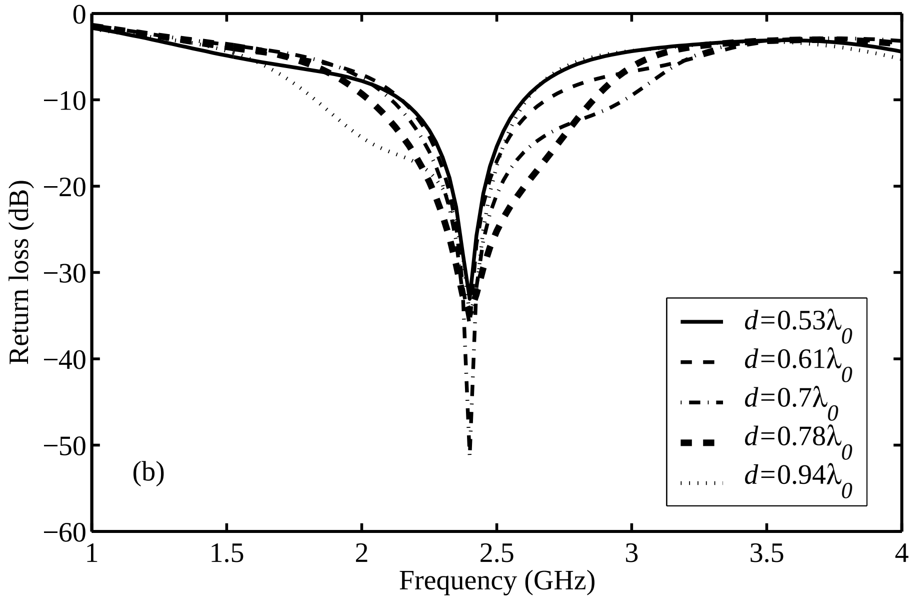


FIGURE 3.4: Return loss against frequency for (a) single slot matched at 2.4 GHz, and broadside twin slots matched at 2.4 GHz with spacings $d = 0.13\lambda_0$, $0.3\lambda_0$, $0.38\lambda_0$, $0.45\lambda_0$; and (b) matched twin slots with spacings $d = 0.53\lambda_0$, $0.61\lambda_0$, $0.7\lambda_0$, $0.78\lambda_0$, $0.94\lambda_0$ (λ_0 is the free-space wavelength at 2.4 GHz). $w = 10$ mm; $s = 0.25$ mm; $h_1 = 0.787$ mm; $h_2 = 0.12\lambda_0$ (15 mm); $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$.

(i.e., 2-element) array. In Fig. 3.7 the corresponding H-plane patterns are shown, in particular co- and cross-polarization patterns for the single slot, and the co-polarization pattern for the twin slots (cross-polarization is negligible in the latter case).

TABLE 3.1: Impedance bandwidth against normalized distance between slots d/λ_0, and corresponding radiating slot dimensions for twin slots matched at 2.4 GHz (λ_0 is the free-space wavelength at 2.4 GHz). $w = 10$ mm; $s = 0.25$ mm; $h_1 = 0.787$ mm; $h_2 = 0.12\lambda_0$ (15 mm); $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$. Bandwidth for matched single slot ($L = 53.8$ mm; $W = 3$ mm): 31.6% (VSWR < 2) and 18.4% (VSWR < 1.5).

	Impedance bandwidth		Radiating slot dimensions (mm)	
d/λ_0	VSWR < 2	VSWR < 1.5	L	W
0.13	26.3%	14.8%	49	3.8
0.3	44.3%	28.6%	51.7	2.0
0.38	40.3%	26.1%	55.5	2.3
0.45	30.3%	13.0%	57	3.5
0.53	20.5%	10.8%	54	4
0.61	24.1%	12.8%	51.7	3.7
0.7	37.8%	19.8%	50.7	3
0.78	36.1%	25.3%	51.7	2.3
0.94	33.8%	23.3%	55.5	3

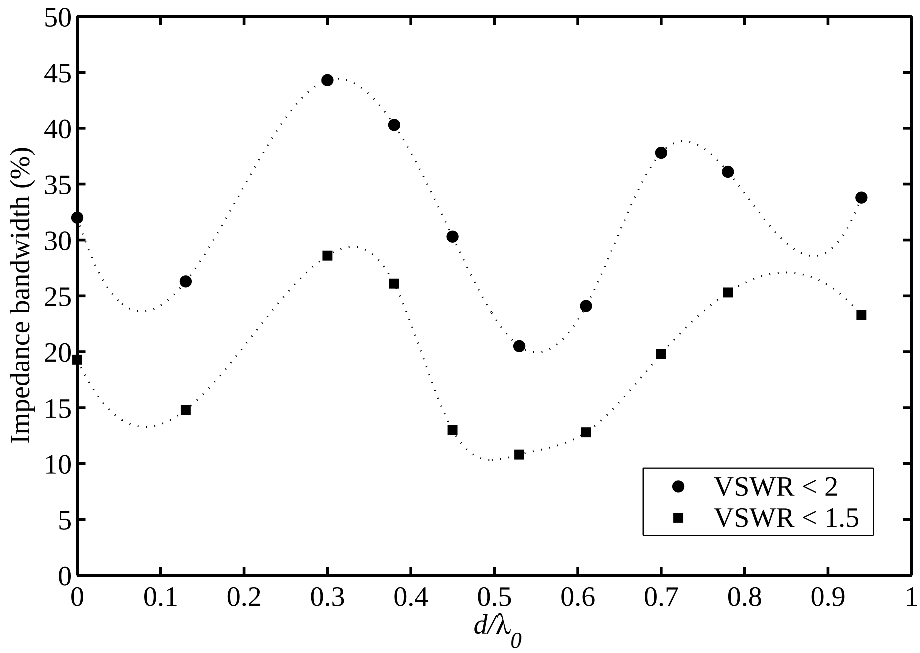


FIGURE 3.5: Impedance bandwidth as a function of normalized distance d/λ_0 between twin slots matched at 2.4 GHz (λ_0 is the free-space wavelength at 2.4 GHz). $w = 10$ mm; $s = 0.25$ mm; $h_1 = 0.787$ mm; $h_2 = 0.12\lambda_0$ (15 mm); $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$. Bandwidth values at $d/\lambda_0 = 0$ pertain to a single slot matched at 2.4 GHz.

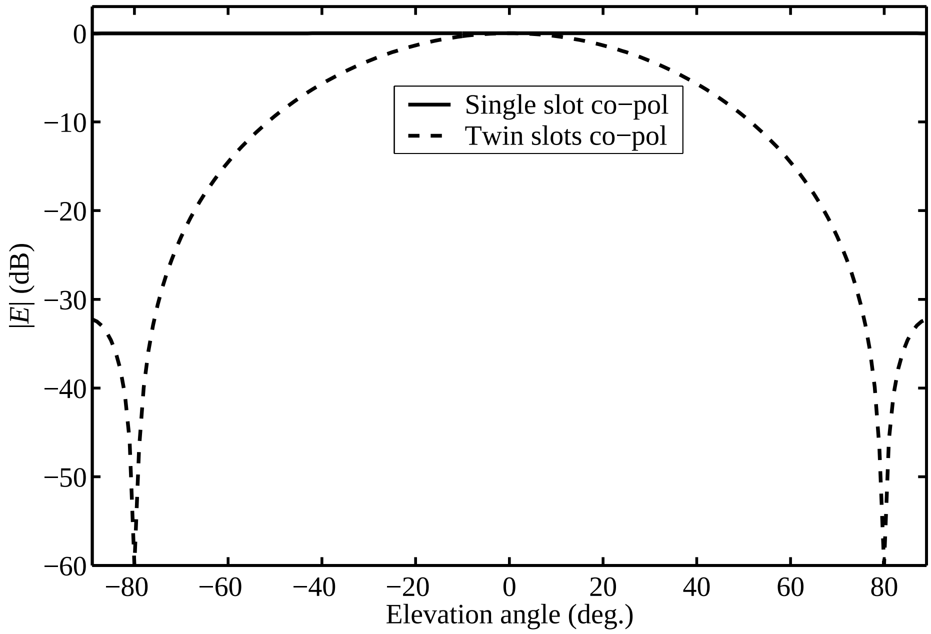


FIGURE 3.6: E-plane co-polarization patterns for a single slot matched at 2.4 GHz, and twin slots matched at 2.4 GHz spaced $0.45\lambda_0$ apart. $w = 10$ mm; $s = 0.25$ mm; $h_1 = 0.787$ mm; $h_2 = 15$ mm; $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$. Single slot: $L = 53.8$ mm; $W = 3$ mm. Twin slots: $L = 57$ mm; $W = 3.5$ mm.

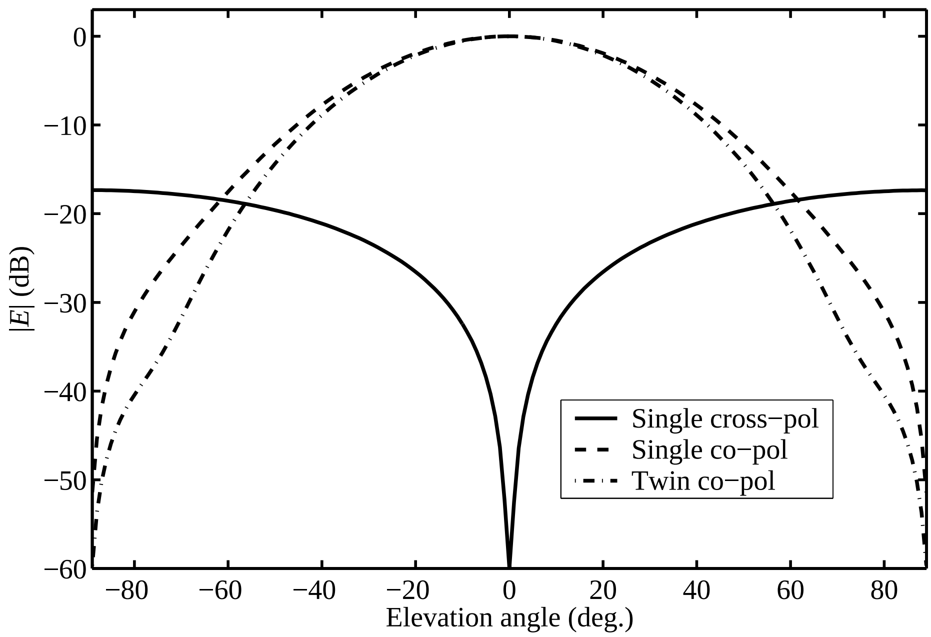


FIGURE 3.7: H-plane co-polarization and cross-polarization patterns for a single slot matched at 2.4 GHz, and H-plane co-polarization pattern for twin slots matched at 2.4 GHz spaced $0.45\lambda_0$ apart. $w = 10$ mm; $s = 0.25$ mm; $h_1 = 0.787$ mm; $h_2 = 15$ mm; $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$. Single slot: $L = 53.8$ mm; $W = 3$ mm. Twin slots: $L = 57$ mm; $W = 3.5$ mm.

3.4 INFLUENCE OF BOTTOM SUBSTRATE LAYER HEIGHT

Subsequently radiation efficiency and impedance bandwidth of $\lambda_{TM_0}/2$-spaced matched twin slots as a function of bottom substrate height h_2 was explored. This step was motivated by the finding in

Chapter 2 that radiation efficiency of CPW-fed single slots on conductor-backed two-layer high-low permittivity substrates may be notably improved by increasing the height of the bottom substrate layer, albeit at the cost of decreasing bandwidth. Also of interest was the effect of h_2 on directivity and gain.

The graph of Fig. 3.8 presents radiation efficiency against frequency for twin slots matched at 2.4 GHz spaced $\lambda_{TM_0}/2$ apart for different bottom layer heights h_2. Radiation efficiency at the operating frequency increased modestly with increasing h_2, which is not surprising given the already high efficiency associated with the lowest bottom substrate layer ($h_2 = 0.04\lambda_0 = 5$ mm). Thus a 3-fold increase in h_2 from $0.08\lambda_0$ to $0.24\lambda_0$ resulted in an increase in radiation efficiency of about 9%. Figs. 3.9 and 3.10 show the corresponding graphs of directivity and gain against frequency. It can be seen that neither gain nor directivity at 2.4 GHz is significantly affected as h_2 is varied. Fig. 3.11 shows return loss against frequency for different values of h_2, while Table 3.2 lists twin slot impedance bandwidths at each value of h_2 for VSWR < 2 and VSWR < 1.5, and the corresponding radiating slot dimensions. For both VSWR criteria, bandwidth decreased monotonically as h_2 was increased starting from $0.08\lambda_0$ (the lowest height case, $h_2 = 0.04\lambda_0$, did not conform to the decreasing trend and rather seemed to display a dual-band characteristic for VSWR < 2). The decrease was modest for the VSWR < 1.5 case: a 3-fold increase in h_2 from $0.08\lambda_0$ to $0.24\lambda_0$ resulted in a decrease in bandwidth of 5.5% from 21.5% to 16%. This decrease is less marked than that observed for a single slot subjected to similar increments in h_2 (*cf.* Chapter 2). In summary, given the already high radiation efficiency for the case $h_2 = 0.08\lambda_0$, a relatively large increase in height is necessary to effect a notable change in radiation efficiency; the same applies to bandwidth.

3.5 CONCLUSIONS

Radiation efficiency and impedance bandwidth of matched broadside CPW-fed twin slot dipoles on conductor-backed two-layer substrates were investigated as a function of distance between the slots, and height of the bottom substrate layer h_2. Radiation patterns were shown for optimally spaced twin slots, and the influence of h_2 on directivity and gain assessed. Twin slots on a relatively low substrate having $h_2 = 0.12\lambda_0$ were shown to yield more than double the radiation efficiency of a single slot on the same substrate (*i.e.*, 90% vs. 39%) 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%, VSWR < 1.5) was about a third less than that of the matched single slot (*i.e.*, 18%). However, an inter-slot distance could be found that resulted in double the bandwidth of the maximally efficient case at the cost of a reasonable comprise with respect to radiation efficiency (73% vs. 90%). It was furthermore observed that the radiation efficiency of matched twin slots spaced $\lambda_{TM_0}/2$ apart could be further improved

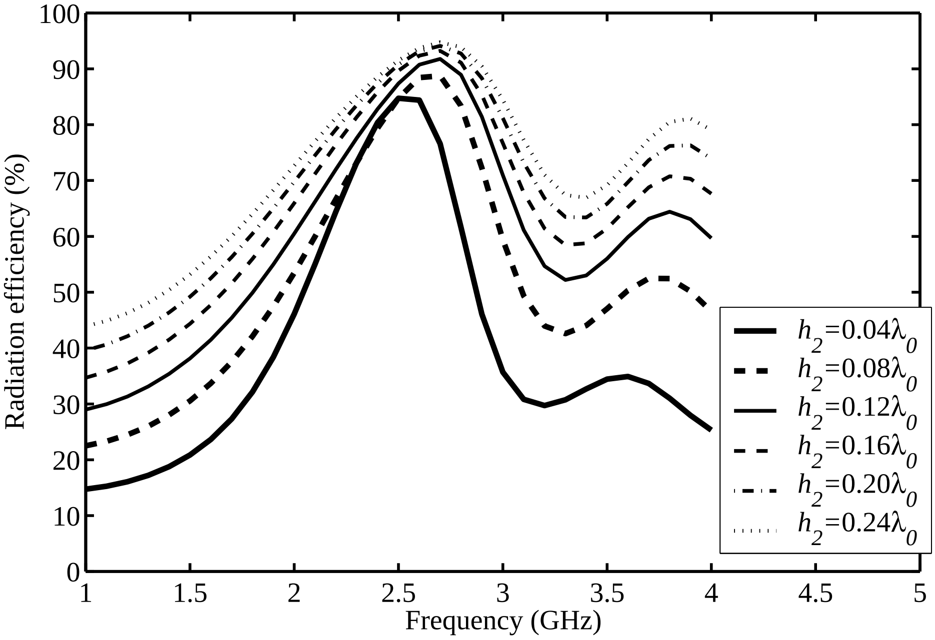


FIGURE 3.8: Influence of bottom substrate layer height h_2 on radiation efficiency for broadside twin slots spaced λ_{TM_0}/2 apart. The twin slots are matched at 2.4 GHz for each instance of h_2 (see Table 3.2 for slot dimensions). $w = 10$ mm; $s = 0.25$ mm; $h_1 = 0.787$ mm; $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$.

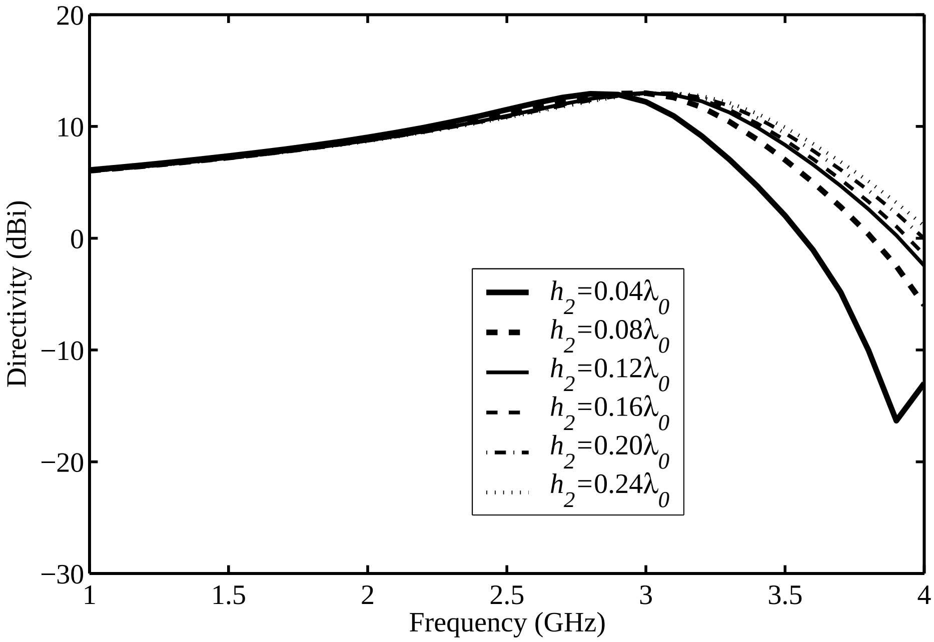


FIGURE 3.9: Influence of bottom substrate layer height h_2 on directivity for broadside twin slots spaced λ_{TM_0}/2 apart. The twin slots are matched at 2.4 GHz for each instance of h_2 (see Table 3.2 for slot dimensions). $w = 10$ mm; $s = 0.25$ mm; $h_1 = 0.787$ mm; $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$.

by increasing bottom substrate layer height h_2 (when $h_2 = 0.08\lambda_0$); bandwidth however decreased, albeit less markedly than in the case of a single slot. It was observed that radiation efficiency attainable with twin slots on two dielectric layers and a back conductor is comparable to that of twin

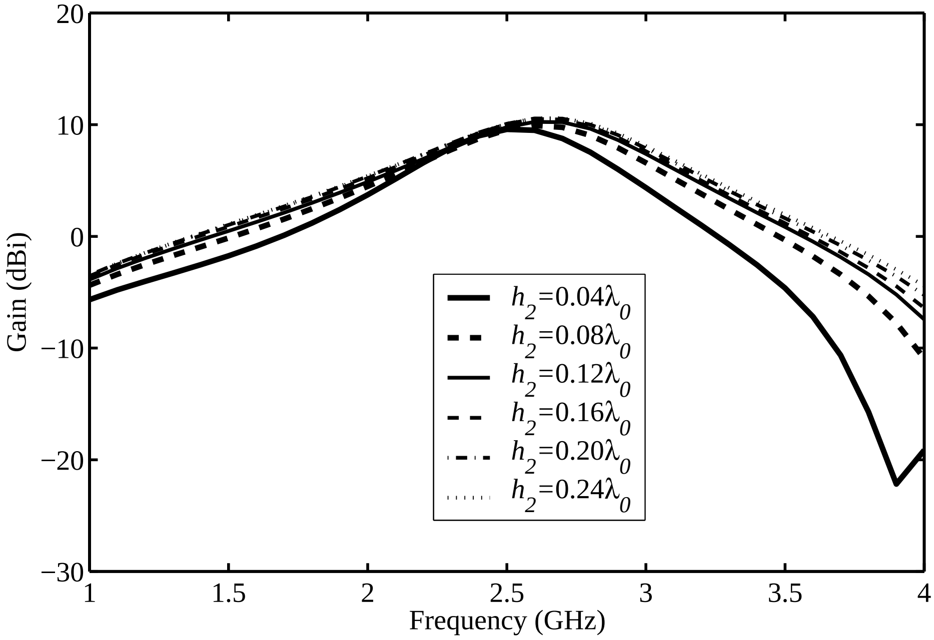


FIGURE 3.10: Influence of bottom substrate layer height h_2 on gain for broadside twin slots spaced $\lambda_{TM_0}/2$ apart. The twin slots are matched at 2.4 GHz for each instance of h_2 (see Table 3.2 for slot dimensions). $w = 10$ mm; $s = 0.25$ mm; $h_1 = 0.787$ mm; $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$.

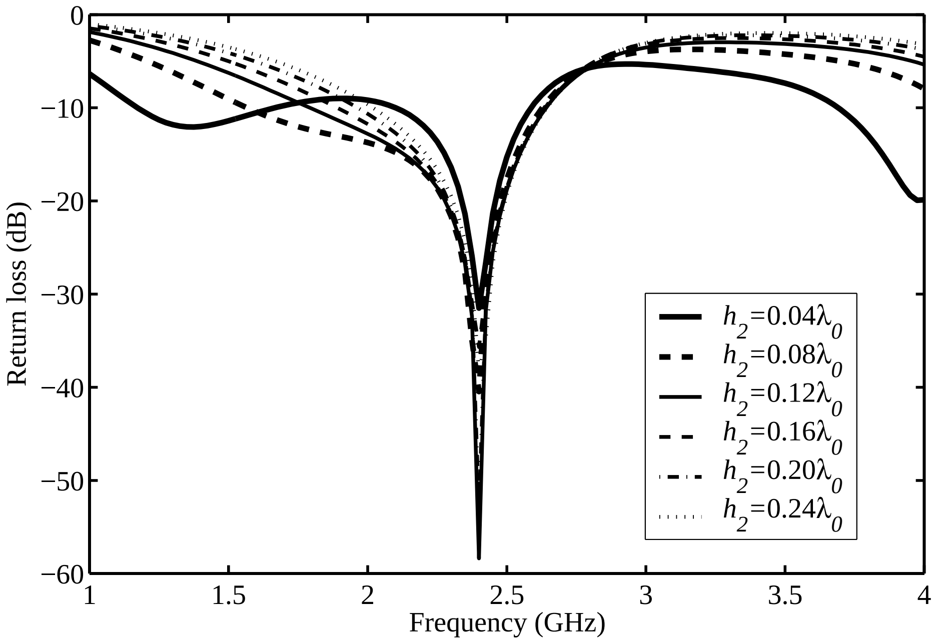


FIGURE 3.11: Influence of bottom substrate layer height h_2 on return loss for broadside twin slots spaced $\lambda_{TM_0}/2$ apart. The twin slots are matched at 2.4 GHz for each instance of h_2 (see Table 3.2 for slot dimensions). $w = 10$ mm; $s = 0.25$ mm; $h_1 = 0.787$ mm; $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$.

slots on $\lambda_d/4$ substrates (or thin substrates) with a back reflector positioned $\lambda_0/4$ away [54]. The lesser height of the two-layer parallel-plate structure would however be an advantage at microwave frequencies.

TABLE 3.2: Bandwidth against normalized bottom substrate layer height h_2/λ_0, and corresponding radiating slot dimensions for identical twin slots matched at 2.4 GHz. Slots were spaced $\lambda_{TM_0}/2$ apart; $h_1 = 0.787$ mm; $\epsilon_{r1} = 2.2$; $\epsilon_{r2} = 1$. In the case $h_2/\lambda_0 = 0.04$, the bandwidth given for VSWR < 2 corresponds to the second minimum (at 2.4 GHz) of the return loss curve in Fig. 3.11.

	Impedance bandwidth		Radiating slot dimensions (mm)	
d/λ_0	VSWR < 2	VSWR < 1.5	L	W
0.04	22.6%	10.8%	63	1.5
0.08	46.1%	21.5%	58	2
0.12	37.3%	20%	56.5	2.7
0.16	32.8%	18.3%	56	3.5
0.2	29.8%	17%	55	4
0.24	27.6%	16%	54	4.5