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# Closely spaced array of cavity backed slot antennas with pin curtains walls

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**Abstract:** An array of two cavity backed slot antennas with pin curtain walls is described. The use of pin curtains is shown to result in greatly reduced fabrication errors and improved repeatability. The effects of the pin curtain parameters on coupling between the array elements are investigated in order to establish design guidelines for achieving a mutual coupling performance which is as good as when using solid copper walls. It is found that these are not as strict as the general guidelines for pin curtains found in the literature. By means of extensive Finite Difference Time Domain simulations and measurements, the antenna performance characterised by impedance matching, radiation patterns and efficiency is shown to be unaffected when these pin curtains are used in place of solid copper walls. From this, a practical design has been arrived at.

## 1 Introduction

With the trend towards ever smaller wireless terminal equipment, such as mobile phones, personal digital assistants (PDAs) and the like, the design of antenna elements which are both sufficiently small and efficient is presenting an increasing challenge. Moreover, there are proven advantages to having more than one antenna element on the terminal equipment to allow for interference rejection, increased channel capacity or reliability. In this case, not only does each element have to be as small as practicable, but in order to reduce losses, the mutual coupling between elements should be minimised.

Slot antennas are used for many different applications, due to their simple structure, conformability, low cost and small size. One of the drawbacks of the slot antenna, however, is its bidirectional radiation. It is usually desirable to confine the radiation from the slot to one direction and this is often done by placing a cavity behind the slot [1]. The cavity backed slot (CBS) antenna has been well covered in the literature both analytically and experimentally [1–7]. Many of the CBS designs use deep cavities which are not suitable for our application and there has been much less work on shallow cavities. The latter, however, have been proven to be as efficient as monopole antennas [8] and, in addition, arrays of CBS antenna elements have been shown to have low mutual coupling [4], which make them a good choice for antenna array systems. Moreover they offer good multiple input multiple output (MIMO) capacities compared to competing designs such as the planar inverted-F and the dielectric resonator antenna because of their high efficiency [8, 9].

In order to get rid of the metallic cavities used in the conventional CBS antennas, low-profile CBS antennas which are manufactured on printed circuit boards have been proposed [10]. This type of antenna can be further improved by the use of pin curtains instead of solid copper walls since manufacturing then becomes much easier and more repeatable and integration with other circuitry is also facilitated. As early as 1974, in [11–13], pin curtains were proposed in order to form transverse walls in slot array antennas and boxed stripline feeds. In these papers, however, the parameters of the pin curtains do not receive much attention and are either said to be ascertained by measurement [13] or simply stated to suppress all internal mutual couplings [11].

More recently, the substrate integrated waveguide (SIW) technique, which was first presented in [14], has been shown not only to reduce the size, weight and cost but also to greatly enhance the repeatability and reliability of manufacture [15, 16]. Since then, the technique has been applied to many microwave devices including waveguide slot antennas [17–20] and slot antennas based on SIW cavities [21–23]. Up to now, however, these structures have only been characterised in terms of waveguide modes, usually just the dominant mode and the mode attenuation due to leakage. Guidelines for choosing the radius and spacing of the pins making up the SIW have been based only on this. For a CBS antenna, however, the field distribution within the cavity is very different from that of an individual mode and, in addition, it is the mutual coupling between antenna elements, rather than mode attenuation, which is of primary interest. While these two properties are related, they have quite different behaviour. In this contribution, it is shown that pin curtains can readily be realised, which do not cause any increase in the coupling between the antennas over and above that observed using solid copper walls. Moreover, this can be achieved by means of rows of shorting pins whose diameter and spacing are much less restrictive than the range normally recommended, for example, in [23, 24]. This is shown not to adversely affect the performance of the antennas, while preserving the advantages of SIW technique. The intention is to find the best pin parameters which would lead to a performance as good as solid metal walls.

In Section 2, a CBS antenna element is introduced which is derived from the one described in [9], but which uses pin curtain walls instead of the solid copper walls. It is demonstrated that substantial improvements in repeatability in manufacture are obtained by the use of pin curtains. In Section 3, a novel two-element CBS antenna array for use on small terminals is described and the effect of the pin curtains on the behaviour of this array is analysed. To minimise the area required by the array, the elements are very closely spaced, just 11 mm, or λ/6, between the slots. The effect of the pin curtain parameters on the coupling between the array elements is investigated and it is shown that the previous analyses in the literature, based on waveguide theory, are not applicable for this case. In Section 4, the mechanisms of mutual coupling between the elements are explained. Coupling into an adjacent cavity is investigated in Section 5 for the case of integration of the antenna with other SIW circuits. Finally, experimental results are presented and the best choice of parameters for a practical array is discussed in Section 6.

## 2 CBS antenna element design

In order to investigate the properties of a CBS antenna with pin curtains, and to establish design guidelines, a closely spaced, two-element CBS antenna array designed to operate at 5.2 GHz was considered. As a step towards this, a single element is designed and the effects of using pin curtains in place of a copper wall on manufacturing repeatability and on antenna performance are investigated. The slot is excited with a stripline located in the vertical midplane of the antenna. The position of the feed has a horizontal offset for matching purposes as shown in Fig. 1. The cavity is filled with a substrate having a dielectric constant of 2.2. The dimensions of the antennas are shown in Figs. 1*a* and *b* and the range of spacing and diameter which were used for the shorting pins are shown in Fig. 1*c*. The slot is considered to be thin since its length is much greater than its width. Its lowest slot resonance will therefore be primarily defined by the slot length rather than the slot width. This first-order slot mode $TE_{10}$ theoretically resonates at 5.08 GHz when the effective dielectric constant is taken as $\epsilon_0$ of the air. The cavity mode with the lowest resonant frequency is $TE_{101}$ provided $b < a < d$ where $b$ is the cavity height, $a$ is the cavity width and $d$ is the cavity length. Assuming that the backing cavity is fully enclosed, $TE_{101}$ mode resonant frequency is calculated to appear at 9.535 GHz using (1). Since this is a much higher frequency than the dominant slot mode, the structure can be analysed independently of

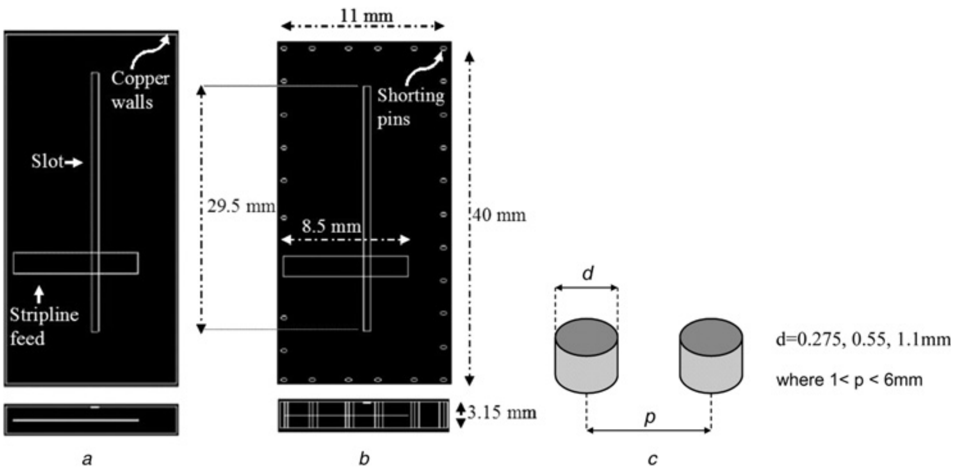


**Figure 1** *Geometry of the CBS antenna*

*a* CBS antenna with copper walls
*b* CBS antenna with pin curtains
*c* Shorting pins

the cavity modes. That is why the operating frequency of this antenna is primarily affected by the size of the slot although the cavity dimensions do have a small effect on the frequency response

$$f_{\mathrm{nml}} = \frac{c}{\sqrt{\epsilon_r}} \sqrt{\left(\frac{l}{2d}\right)^2 + \left(\frac{m}{2b}\right)^2 + \left(\frac{n}{2a}\right)^2} \qquad (1)$$

The repeatability problem of ordinary CBS antennas has been observed previously during prototyping and design [8]. To confirm this, four nominally identical CBS antennas using conventional solid copper cavities of which layout is given in Fig. 1*a* were manufactured. The same mask consisting of two layers of Duroid RT/Rogers 5880 with thickness of 1.575 mm was used and then the reflection coefficient of each of these manufactured antennas was measured over the frequency range of interest. It can be seen in Fig. 2*a* that, despite much care being given to the fabrication process, the measurements show considerable discrepancy. This was found to be due to misalignment between the two layers, resulting in the feed line being inaccurately positioned.

The use of pin curtains, consisting of a number of metal shorting pins instead of solid copper walls, for the cavity was expected to greatly improve the repeatability in prototype manufacturing. This is because the shorting pins act as alignment points so that the relative positions of the different layers are well defined. To verify this, four samples of the new design were manufactured and measured, as before. The parameters were chosen to be $p = 4$ mm and $d = 0.55$ mm. Fig. 2*b* shows that the agreement between the results is very much improved, thus confirming the effectiveness of the new design. The good matching of the antennas confirms that the feed line is accurately positioned. Another advantage of this technique is that it simplifies the integration of the antenna with the other components on the same substrate. Although the manufacturing is more complicated because of the necessity of including many pins, the advantages are considered to far outweigh this disadvantage. It is noted that, although in the test structures, the pins need to be laboriously soldered in place during prototyping of the device, in a production context this would not present a difficulty.

## 3 Effect of pin curtain parameters on array performance

In order to investigate the effect of pin curtain parameters on the performance of an array of CBS antenna elements, the two-element array shown in Fig. 3 was considered. Characterisation of SIWs, as has been done previously for antenna or circuit applications, has been based on treating them as equivalent rectangular waveguides. Empirical equations for the equivalent width of such waveguides are provided in [19, 25], as are guidelines for choosing the diameter and spacing of the shorting pins. Also, in [23] it is specified that the ratio of diameter to spacing must be greater than 0.5 and the diameter must be less than $\lambda_0/10$ which is 0.577 cm at operating frequency of 5.2 GHz. This is intended to ensure that leakage between the shorting pins can be neglected and that the attenuation constant is acceptably small. However, for the present application different criteria prevail. For instance, near field penetration is more important than power leakage and, even then, some leakage can be tolerated provided that this does not cause the mutual coupling between the antenna elements to significantly increase. It will be shown that the conditions on shorting pin size and spacing are not as restrictive as previously considered necessary in the literature. Previously mentioned diameter to spacing ratio will be chosen in the order of 0.1 for the normal operation of the array.

In this application, mutual coupling between the elements is the main parameter of interest. This is a consequence of

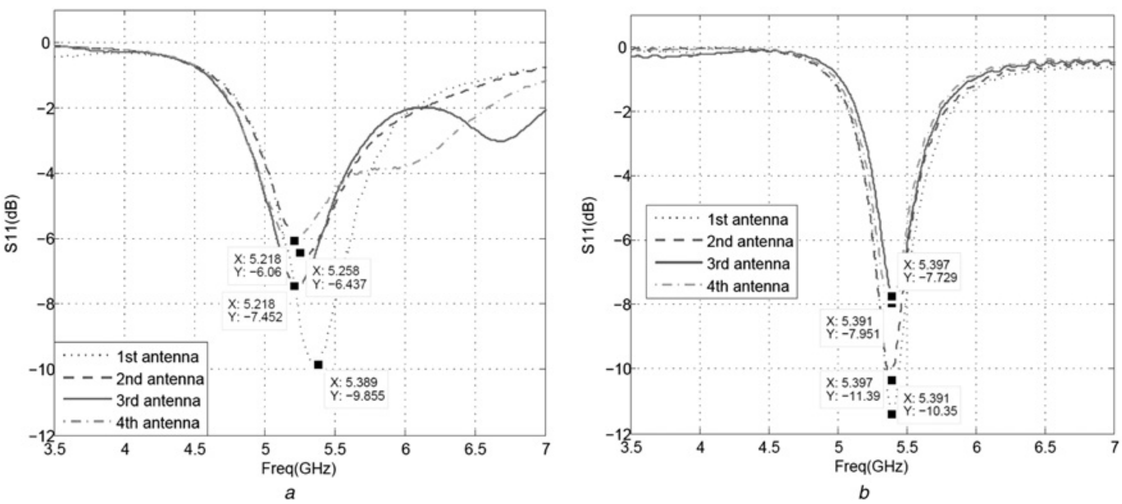


**Figure 2** *Comparison of measured frequency responses of CBS antennas*

*a* CBS antennas with copper walls
*b* CBS antennas with pin curtains



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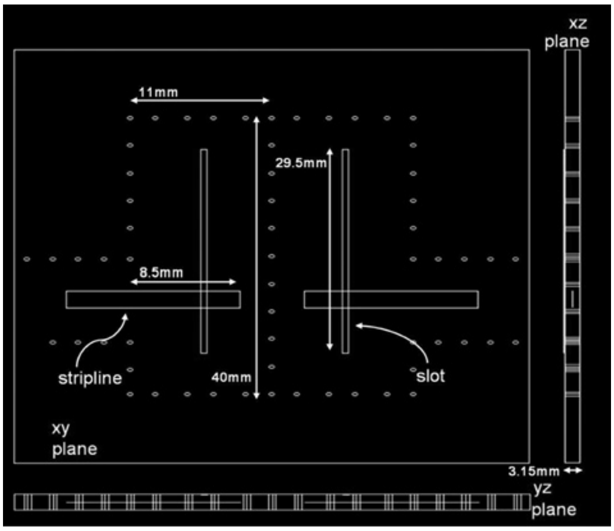


**Figure 3** *Array of CBS antennas with pin curtains*

both the penetration of fields through the pin curtains and the direct coupling between the slots. The number and radius of the shorting pins can be decreased as long as the contribution of the penetration through walls is not significant compared to the direct coupling. Simulations were done, using the finite difference time domain (FDTD) method, with pin curtains made up of shorting pins having different diameters and spacing. Since it was found that the pin curtain which separated the two elements had by far the greatest effect on the change of mutual coupling, the parameters of the outer walls were fixed whereas those of the separation wall were varied. Pin diameters of 0.275 mm ($0.005\lambda_0$), 0.55 mm ($0.01\lambda_0$) and 1.1 mm ($0.019\lambda_0$) and spacing between 1 mm ($0.017\lambda_0$) and 6 mm ($0.104\lambda_0$) were modelled. In addition, the effect of using two rows of shorting pins in between the antennas instead of one was investigated. For these tests the shorting pins in the outer $x$-directed walls had a spacing of 2 mm, and the $y$-directed walls had a spacing of 4 mm. Fig. 4 shows the maximum mutual coupling between the elements at the frequency band of interest around 5.2 GHz against a pin spacing of between 1 and 6 mm for both one row of shorting pins and two rows of shorting pins. To confirm the insensitivity of mutual coupling on the parameters of the outer pin curtains, coupling is plotted against spacing for three different configurations of the outer walls where the pin diameter is 0.55 mm. Fig. 5 shows that the results from all three configurations show no significant difference. From the results shown in Fig. 4 it is possible to choose a suitable diameter and spacing which will not cause the mutual coupling to increase significantly while avoiding the use of an unnecessarily large number of pins.

In Fig. 6, the coupling between the two elements is shown as a function of frequency for various choices of pin spacing. It can be seen that as the spacing between the shorting pins is increased, the coupling increases and the frequency at which maximum coupling is observed decreases. It has been found that the frequency of maximum coupling coincides with that of maximum return loss and therefore with the frequency at which the antenna would be used. The influence of pin spacing on centre frequency is believed to be mainly due to the change in equivalent width of the cavity [25] and is not a problem as it can be readily compensated for by a small change in slot length.

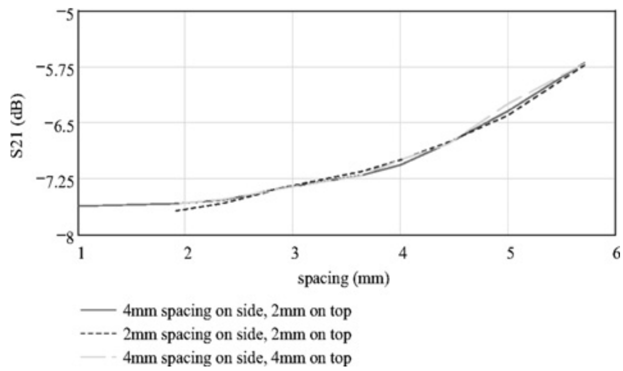


**Figure 5** *Effect of shorting pin spacing around the antennas*

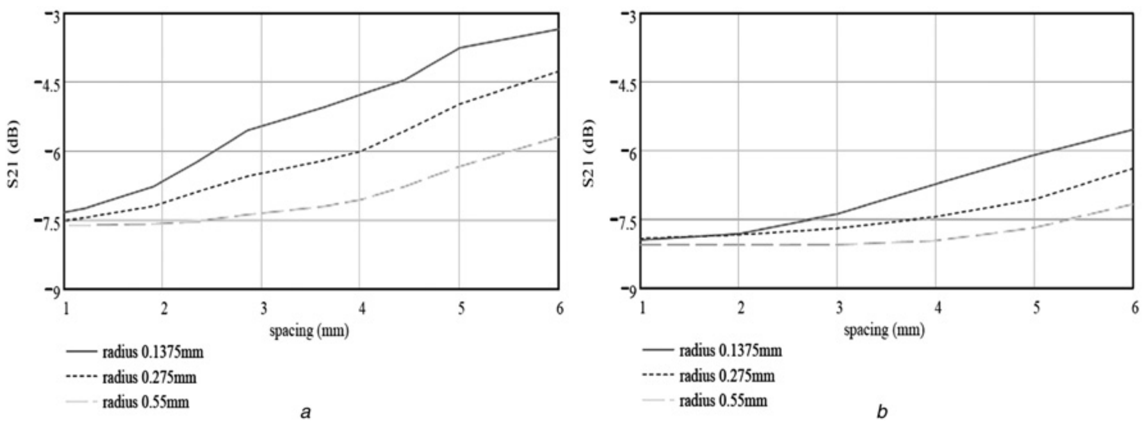


**Figure 4** *Coupling between the slots against pin spacing for different shorting pin radii*

*a* One row of shorting pins
*b* Two rows of shorting pins

 

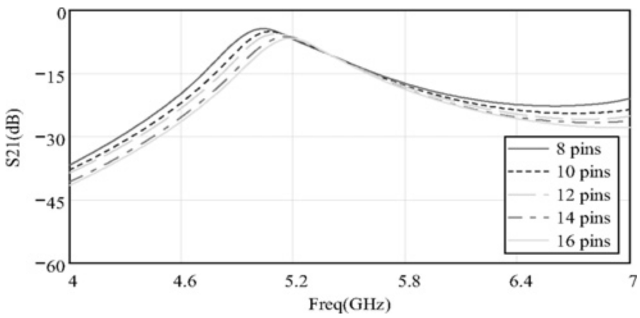


**Figure 6** *Coupling against frequency for different shorting pin spacing*

## 4 Mechanisms of mutual coupling

Mutual coupling between the elements can be caused by several different mechanisms, namely coupling between the two feed lines via the pin curtain, coupling from the slot of one element to the feed line of the other via the pin curtain and direct coupling between the slots outside the cavity. In order to establish the relative importance of these mechanisms, further tests were performed. First, a structure having the same dimensions as the array but with the slots absent, as shown in Fig. 7, was modelled. The only coupling now is directly between the two feed lines. This coupling is plotted against the spacing between shorting pins for different shorting pin radii in Fig. 7*b*. The highest coupling for this test is −60 dB which is far below the direct coupling and therefore not significant.

Next, the coupling from the excited slot into the adjacent cavity, through the pin curtain, was modelled by placing a metal screen outside the box. The screen is in *xz* plane, half way between the slots, so that direct coupling between slots is removed but the slots can still radiate into the opposite cavity via the pin curtain. This coupling is plotted in Fig. 8. For the highest separation and the lowest radius when the $d/p$ ratio is around 0.046 the coupling is −11.52 dB, which is high enough to worsen the overall mutual coupling between the elements.

Finally shorting pins are positioned right next to each other forming a solid wall so that coupling via the pin curtain is completely blocked. In this case, direct coupling between the slots shows almost no variation with pin dimension, as maximum values of −7.441, −7.549 and −7.608 dB were obtained for shorting pin radii of 0.1375, 0.275 and 0.55 mm, respectively, at the operating frequency of 5.2 GHz. The amplitudes of all three sources of couplings are added together and the sums are plotted in Fig. 9. Since these three contributions all originate from the same signal source, it is appropriate to add their amplitudes rather than their powers. Although there will be some phase difference between the contributions, this difference is expected to be low because the path lengths are similar. It can be seen that the result agrees with the results plotted in Fig. 4*a*, which confirms that the mutual coupling mechanisms are decomposed correctly and that the phase difference between the contributions is small as expected.

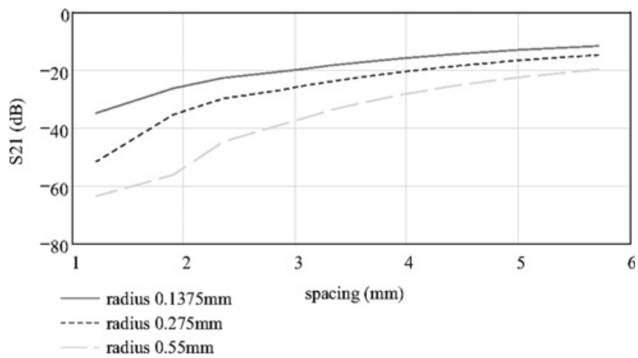


**Figure 8** *Coupling against pin spacing when the slots are shielded*

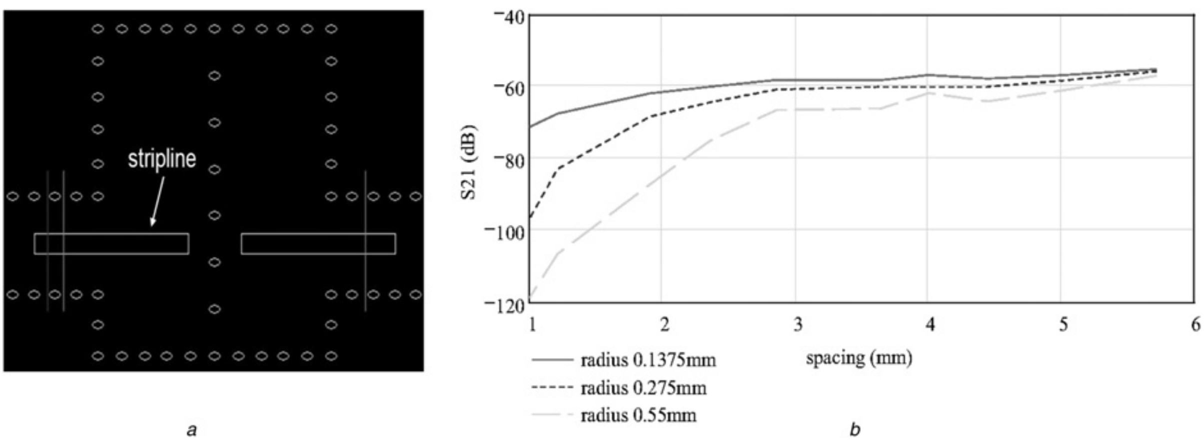


**Figure 7** *Slots are removed from the cavities*

*a* Geometry of the structure
*b* Coupling between the striplines against pin spacing



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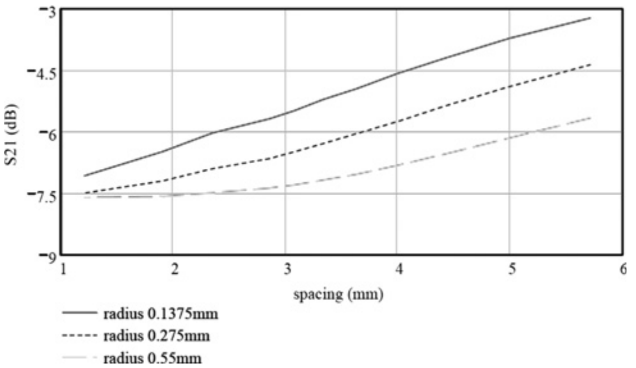


**Figure 9** *Expected maximum coupling combining all sources of coupling against pin spacing*

# 5 Coupling into an adjacent cavity

One of the strong advantages of using pin curtains for the antenna is the ease of integration with SIW circuits. For this reason, it is important that the pin curtains do not increase mutual coupling between the antenna elements but also that coupling to adjacent circuits is minimised regardless of the size of the cavity in which they are contained. In order to investigate this, the structures shown in Fig. 10 were modelled. Here, an antenna element is enclosed in a larger cavity which has a resonant $TE_{201}$ mode close to its operating frequency. This was considered to be a severe test since the coupling would be strongest under these conditions. Based on the results described above, four examples of pin diameter and separation were chosen for closer study. Fig. 10 shows the electromagnetic (EM) field penetrating the gaps between the shorting pins for these cases. These near field snapshots demonstrate the effect of each pin curtain parameter visually. Fig. 10*a* shows the first case of $d = 0.55$ mm and $p = 4$ mm. In Figs. 10*b* and *c* the number of shorting pins and their radii are doubled, respectively. Finally, in Fig. 10*d* two layers of shorting pins are used with the same number of shorting pins as the second model in Fig. 10. The pins were aligned as shown, rather than being staggered, in order to preserve symmetry. It was found that staggering the pins did not make a significant difference to the coupling. In the waveguide analysis the ratio $d/p$ is often used as a design parameter [22]. This demonstration shows that this analysis is not suitable for this case since halving $p$ is more effective than doubling $d$ even though the ratio is kept constant. The maximum electric field values detected outside the cavity, normalised to the excitation, in Figs. 10*a*, *b*, *c* and *d* are 0.98, 0.096, 0.022 and 0.019 $(V/m)/(V/m)$ respectively.

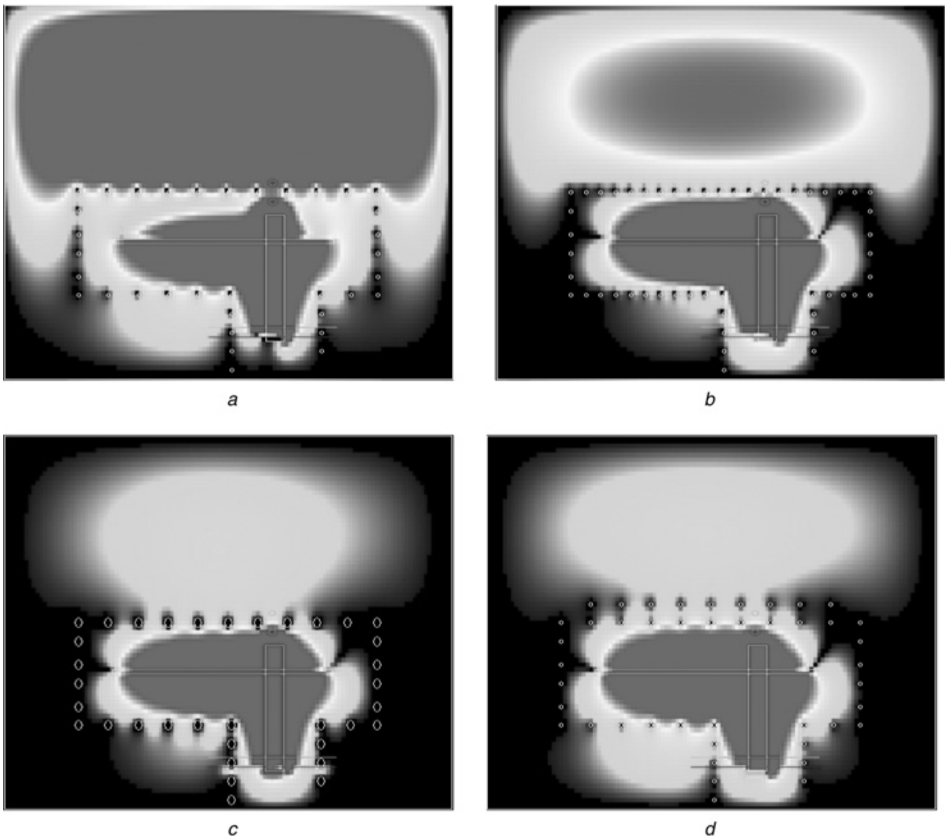


**Figure 10** *Near field snapshots*

*a* EM field distribution, $p = 4$ mm, $d = 0.55$ mm
*b* EM field distribution, $p = 2$ mm, $d = 0.55$ mm
*c* EM field distribution, $p = 4$ mm, $d = 1.1$ mm
*d* EM field distribution, two layers of shorting pins with $p = 4$ mm, $d = 0.55$ mm


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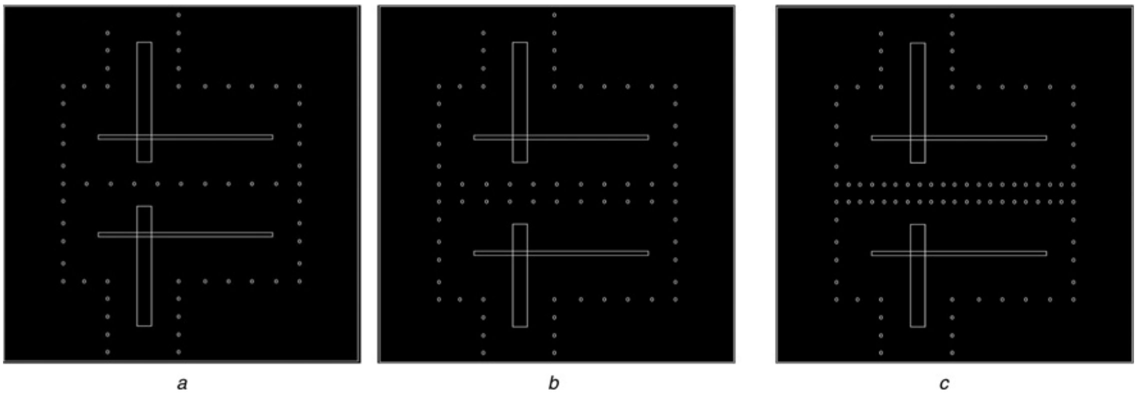


**Figure 11** *Geometries of the modelled arrays*

*a* Pin curtain between the antennas: $p = 4$ mm, $d = 0.55$ mm (model 1)
*b* Pin curtain between the antennas: two rows of shorting pins with $p = 4$ mm, $d = 0.55$ mm (model 2)
*c* Pin curtain between the antennas: two rows of shorting pins with $p = 2$ mm, $d = 0.55$ mm (model 3)

It can be seen that, for the first case, the coupling is severe whereas for the last two situations, the coupling is quite low.

## 6 Experimental results

In the light of Sections 3–5, three arrays were manufactured where the pin curtain parameters were chosen as a compromise between minimising the increase in mutual coupling and minimising the number of pins. The first array has 0.55 mm diameter shorting pins located 4 mm apart from each other as seen in Figs. 11*a* and 12. In the second array, twice as many shorting pins are used and these are arranged in two rows, since it has been found that this arrangement is more effective than one row of twice the density. Finally the spacing between the shorting pins is decreased to 2 mm in the third model.

The measured *S*-parameters of all three arrays are shown to be consistent with simulations. Table 1 shows the coupling between the antennas in models 1, 2 and 3, which depends on both the SIW parameters and the distance between the slots. The first model in Fig. 11*a* shows a significant rise in coupling of about 1 dB compared to the coupling when the shorting pins are located right next to each other; model 2 in Fig. 11*b* shows a small, but tolerable, increase of about 0.5 dB and model 3 in Fig. 11*c* shows no significant difference. Thus model 2 is chosen as the best compromise between reducing coupling as much as possible and the number of pins needed. Measured and simulated *S*-parameters of this model are shown in Fig. 13 and a good agreement is observed.

**Table 1** Comparison of simulated and measured S21 values

| | First model | Second Model | Third model |
|---|---|---|---|
| simulation | −6.01 | −7.46 | −7.91 |
| measurement | −6.34 | −8.5 | −9.05 |

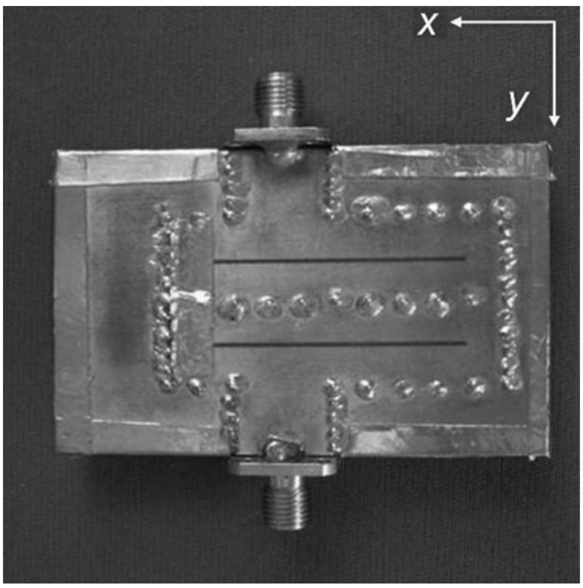


**Figure 12** *One of the manufactured arrays, model 1*

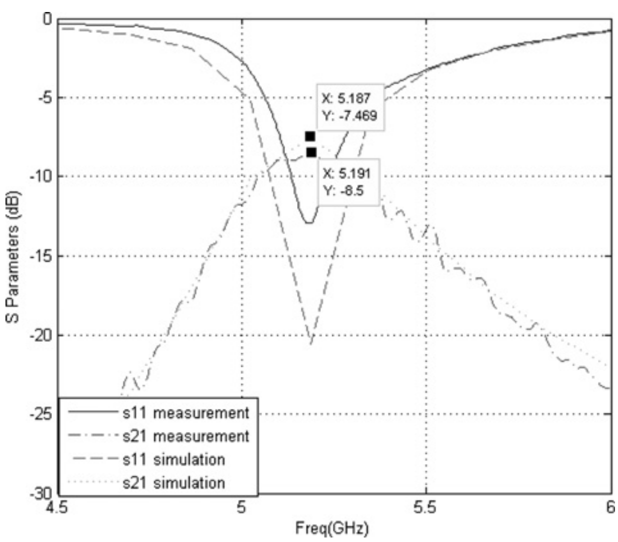


**Figure 13** *Comparison of measured and simulated S-parameters of the array in Fig. 11b, model 2*



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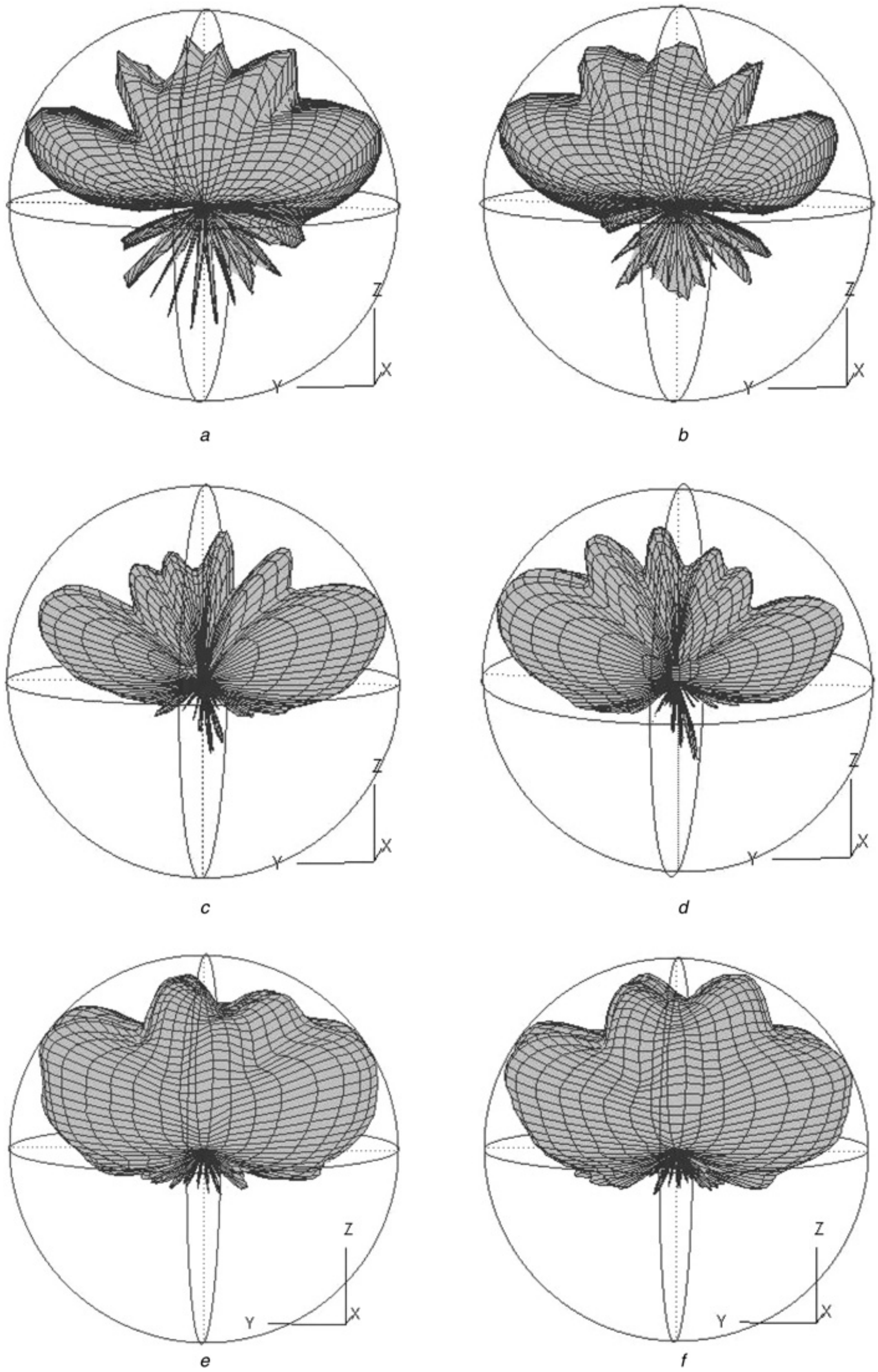


**Figure 14** *Simulated and measured radiation patterns of the array shown in Fig. 11b and single CBS antennas with copper walls and pin curtains on a circular ground plane with 30 cm radius*

*a* Simulated radiation pattern of the first antenna with the second antenna terminated in matched load
*b* Simulated radiation pattern of the second antenna with the first antenna terminated in matched load
*c* Measured radiation pattern of the first antenna with the second antenna terminated in matched load
*d* Measured radiation pattern of the second antenna with the first antenna terminated in matched load
*e* Measured radiation pattern of a single CBS antenna with copper walls
*f* Measured radiation pattern of a single CBS antenna with pin curtains

The radiation pattern of the each element of the chosen design was measured with the other element terminated in a matched load in an 8 m long anechoic chamber at 5.2 GHz. The array was mounted on a ground plane of 300 mm radius (considering the difficulty in measuring electrically small antennas). The 18 planes of the co-polarised components of the data are displayed in Fig. 14 where the level at the centre of the plot is −20 dB relative to that at the outside. It can be seen that the beam is squinted at an angle of $\theta = \pm 60$. This squint, which is

 

**Table 2** Directivity, polarisation purity and the relative efficiency of the antennas

| | Directivity, dBi | Co-polar power, % | $\eta_{\Omega_{AUT}}/\eta_{\Omega_{REF}}$, % |
|---|---|---|---|
| CBS with copper walls | 7 | 98 | 97 |
| CBC with pin curtains | 7.1 | 98 | 93 |
| CBS array, model 2 | 9.2 | 96 | 93 |

due to the mutual coupling, is generally advantageous for MIMO applications as pattern diversity leads to a reduced correlation between the antenna elements. Clearly the ground plane would be expected to affect the patterns and this can be seen in Fig. 14 that show complicated patterns caused by diffraction effects at the edge of the plane. The simulations which included a ground plane of the same size as the one used in the anechoic chamber are shown in Figs. 14*a* and *b* and the measurements in Fig. 14*c* and *d*. It can be seen that the results are in good agreement. In addition, comparison of measured patterns for an individual CBS with copper walls (Fig. 14*e*) and one with pin curtains (Fig. 14*f*) shows that there is no significant distortion in the radiation patterns because of shorting pins.

The radiation pattern of a monopole antenna operating at 5.2 GHz in addition to these measured radiation patterns are processed to get the directivity, polarisation purity and the relative antenna efficiency. These performance measures of CBS antenna with copper walls, with pin curtains and the chosen design of the array (model 2) are given in Table 2. In order to calculate the efficiency, a technique described in [8] is followed. The total power radiated by each antenna is calculated and used to compare the efficiency of the antenna under test and the reference antenna, which is a quarter-wavelength monopole in this case. The comparison is represented by (2) where $E$ is the electric field level, $\eta_m$ is the mismatch efficiency and $\eta_\Omega$ stands for the conductor and dielectric losses. Note that this technique has approximately $\pm 5\%$ measurement uncertainty. According to the data given in Table 2 in which $\eta_m$ is eliminated, a 4% decrease in efficiency is observed because of the pin curtains. However it is clear that the final model is still very highly efficient structure while being far easier to fabricate

$$\frac{\oiint_S |E_{AUT}|^2 dS}{\oiint_S |E_{REF}|^2 dS} = \frac{\eta_{m_{AUT}}\ \eta_{\Omega_{AUT}}}{\eta_{m_{REF}}\ \eta_{\Omega_{REF}}} \tag{2}$$

## 7 Conclusion

A novel closely spaced array of CBS antennas using the pin curtain technique has been designed. It has been shown theoretically and experimentally that the use of a pin curtain leads to an improvement in manufacturing repeatability and construction reliability. The effects of pin curtain parameters such as shorting pin radius and spacing have been investigated by means of extensive FDTD simulations and practical measurements, leading to a choice giving a good balance between the need for isolation and the desirability to use as few pins as possible. For this type of structure $0.07\lambda_0$ separation and $4.77 \times 10^{-3}\lambda_0$ radius are chosen as the guidelines to maintain this balance. In particular, it has been shown that the commonly used analysis of SIW walls, based on rectangular waveguide modes, is too restrictive for this case. Namely, $d/p > 0.5$ is one of the design guidelines given in the literature [23, 26], whereas this ratio is less than 0.2 in this kind of structure. Finally some efficient arrays were manufactured and measured to show the practicality of this approach, which has the advantages of small size, better mechanical performance, convenient fabrication by normal printed circuit board process and seamless integration with other SIW structures. The achieved coupling coefficient of −8 dB is considered adequate for use as a terminal array under the constraints of close spacing. If a higher performance is required then this could be achieved by increasing the spacing between the slots.

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