An Introduction To The Phase-Switched Screen

B. Chambers and A. Tennant

Dept. of Electronic & Electrical Engineering, University of Sheffield, U.K.
e-mail: b.chambers@sheffield.ac.uk

Abstract: The Phase-Switched Screen is a novel technique for the dynamic control of radar cross-section. It relies on the modification of the signal scattered from an object in such a way as to place the signal energy outside the bandwidth of a receiving system. The paper includes a theoretical discussion of the new technique and examples of its application in practice.

1. Introduction

Although conventional (i.e. passive) microwave absorbent materials have been widely used for many years to modify the radar cross-section (RCS) of military platforms, such materials may not have adequate performance or flexibility to satisfy future requirements. For example, a passive microwave absorber, once designed and manufactured, has fixed characteristics that are bounded by the electrical thickness at the lowest desired operating wavelength, following the so-called "Rozanov limit" [1]. Hence if the threat for which the absorber was designed changes, then either reduced performance against the new threat must be accepted or the material must be replaced by an improved one. Active materials, however, offer the potential to overcome the Rozanov limit and to enable additional "smart" functionality such as monitoring damage, adaptive control of RCS or target appearance, Identification-Friend-or-Foe (IFF) and Absorb-While-Scan (AWS) [2]. In this paper, we introduce a particular technique for realising an active material for use at microwave frequencies and explore its potential.

As an introduction, consider a semi-infinite half-plane in free-space whose surface is illuminated by a plane electromagnetic wave. Although the structure comprising the half-plane is not yet known, let the surface at any instant be able to present one of two different admittances Y_1 or Y_2 to the incident wave, the instantaneous choice of Y_1 or Y_2 being controlled by the application of a particular electrical or optical stimulus to the surface. In practice, the choice of Y_1 and Y_2 is not arbitrary and for normal incidence they should satisfy the relationship $Y_1Y_2 = Y_0^2$, where Y_0 is the characteristic admittance of free-space. Hence Y_2 may be written in terms of Y_1 as $Y_2 = Y_0^2/Y_1$, which is the equivalent of transforming Y_1 by a length of transmission line of length $\lambda/4$ and characteristic admittance Y_0. For the two admittance states of the surface, the incident wave experiences reflection coefficients of +A and –A (A is generally complex) and if these are each present for half of the time, then the surface exhibits a time-averaged reflection coefficient of zero, i.e. it appears to act as a perfect absorber at the incident frequency corresponding to the wavelength λ. This behaviour is quite different to that of a conventional microwave absorbent material since no apparent loss of energy is involved. The *modus operandi* is clarified, however, if the behaviour of the surface is examined in terms of the spectrum of the incident and reflected waves. It is clear then that by periodically changing the surface admittance, the reflected wave is being binary phase-modulated with the result that all of the energy at the incident wave frequency is redistributed into an infinite number of sidebands. If the frequency of the periodic stimulus signal that alters the surface admittance is high enough, then none of this redistributed energy falls within the pass-band of the receiving system and hence the surface mimics the behaviour of a perfect absorber, as measured by the receiver. We have called this new type of active 'absorber' the "Phase-Switched Screen" (PSS).

2. Transmission-line analysis of the single layer phase-switched screen

The transmission-line analogue of the single active layer PSS consists of a short-circuited length, d, of transmission line with characteristic admittance Y_c and propagation constant β, across whose input terminals is placed an admittance Y(t), defined as

$$Y(t) = Y_1 \qquad 0 < t < \tau$$
$$\quad = Y_2 \qquad \tau < t < T \qquad (1)$$

where τ is the 'on' time and T is the time period for one cycle of the waveform used to control the state of Y(t). Depending on the incident polarisation and angle of incidence, θ, Y_c is given by either $Y_c = Y_0/\cos\theta$ for parallel polarisation, or $Y_c = Y_0\cos\theta$ for perpendicular polarisation. For either polarisation, β is given by $\beta = \beta_0 \cos\theta$. Then the required general relationships between Y_1 and Y_2 are given by [3]

(a) *parallel polarisation*

$$[Y_1 - j\frac{Y_0}{\cos\theta}\cot(\beta_0 d\cos\theta)][Y_2 - j\frac{Y_0}{\cos\theta}\cot(\beta_0 d\cos\theta)] = \frac{Y_0^2}{\cos^2\theta} \qquad (2)$$

(b) *perpendicular polarisation*

$$[Y_1 - jY_0\cos\theta\cot(\beta_0 d\cos\theta)][Y_2 - jY_0\cos\theta\cot(\beta_0 d\cos\theta)] = Y_0^2\cos^2\theta \qquad (3)$$

If $\theta = 0°$ and $Y_1 = G_1$, $Y_2 = G_2$ (active layer has switchable conductance only), then (2) and (3) simplify to $G_1G_2 = Y_0^2$. Typical reflectivity characteristics for the single active layer PSS when $G_1 = 0$ and $G_2 = \infty$ are shown in Figure 1, together with those for the classic Salisbury screen.

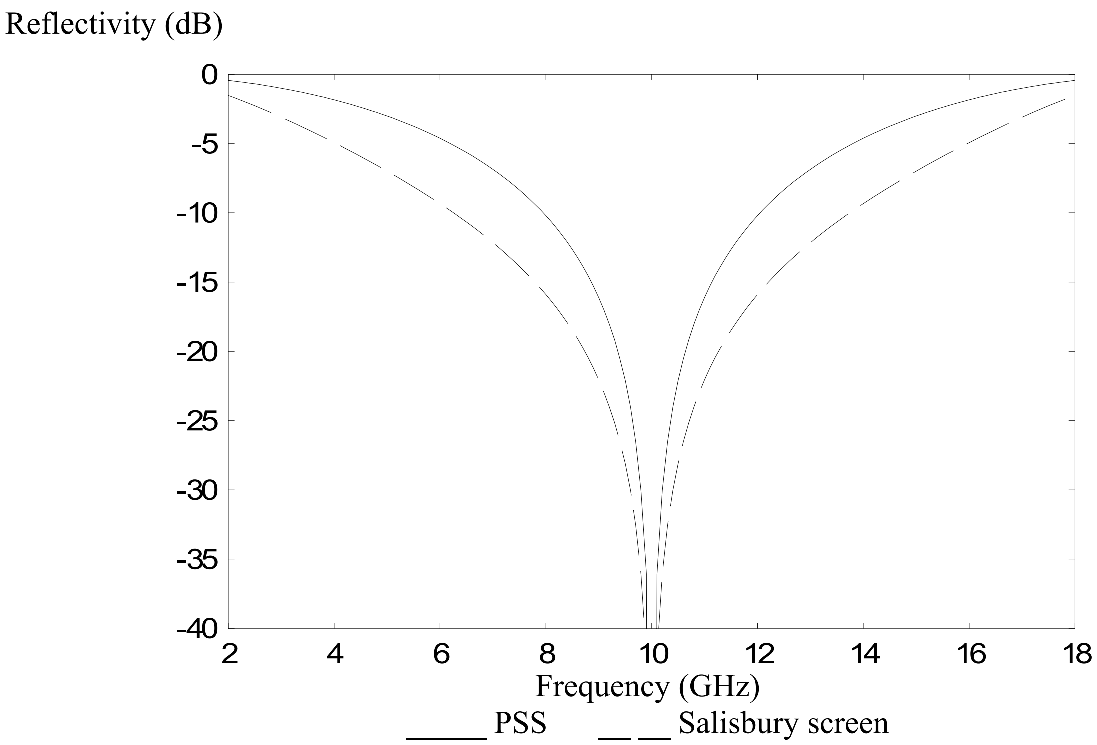


Figure 1 *Frequency responses of switched conductance PSS and Salisbury screen d = 7.5 mm, PSS: $G_1 = 0$, $G_2 = \infty$, Salisbury screen: R = 376.7 Ω/□*

The two curves are different due to a lack of multiple reflection phenomena in the PSS. By adjusting the 'on' time of the active layer (i.e. the ratio τ/T) we can change its effective sheet resistance and so control the depth of the PSS reflectivity null [4], as shown in Figure 2. Hence the PSS can be configured dynamically to act as a good reflector or as a variable absorber. Furthermore, by replacing the PEC backplane of the PSS by a second active layer, the structure may have these properties when viewed from either side. In the bi-directional PSS (BPSS), each active layer is switched so that at successive instants in time, $G_1 = 0$, $G_2 = \infty$; $G_1 = \infty$, $G_2 = 0$; $G_1 = 0$, $G_2 = \infty$, etc.

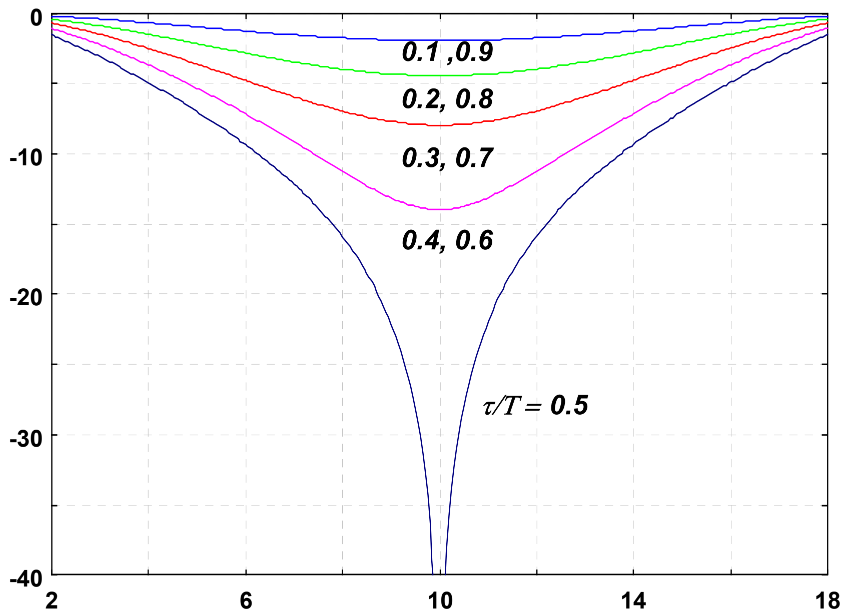
From Figure 1, it can be seen that the switched conductance PSS has a narrow bandwidth, but this can be broadened by making the active layer reactive. For example, if $\theta = 0°$, $Y_1 = jB_1$, $Y_2 = jB_2$, then (2) and (3) give the required relationship between B_1 and B_2 as

$$B_1 B_2 = -Y_0^2 \cos ec^2 \beta_0 d \qquad (4)$$

Hence, if an active layer whose B_1 and B_2 had the form $B_1 \approx -jY_0 \cos ec\beta_0 d$ and $B_2 \approx jY_0 \cos ec\beta_0 d$ could be realised, then the bandwidth of the PSS would approach infinity. In practice, these values of B_1 and B_2 cannot be realised over a very large bandwidth, but a combination of switchable susceptance and conductance in the PSS active layer is still advantageous, as shown by the measured data in Figure 3 [5].

Although the transmission-line analysis given above enables us to examine the frequency characteristics of the PSS, it does not allow us to determine the optimum choice of switching waveform shape and frequency, particularly in the presence of pulsed incident signals; this requires a spectral analysis, which we consider next.

Reflectivity (dB)



Frequency (GHz)

Figure 2 *Variation of null depth with τ/T for switched conductance PSS*

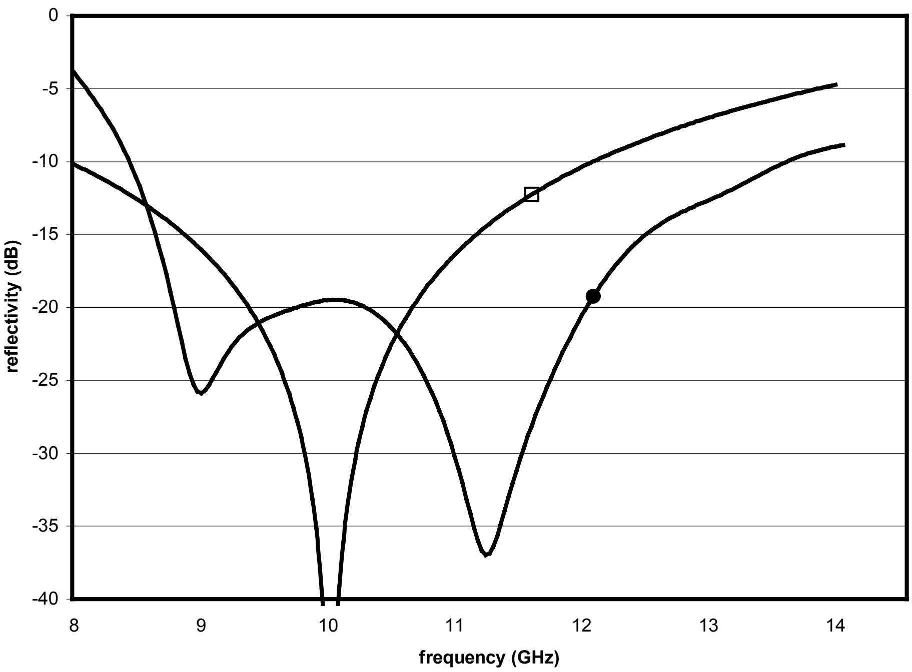


Figure 3 *Reflectivity characteristics of ideal switched conductance PSS* (□) *and experimental single layer PSS* (●).

3. Spectral analysis of the single-layer phase-switched screen

For simplicity, we will consider here only the case of a single active layer PSS operating against a periodic train of rectangular pulses of carrier frequency f_c [6], as shown in Figure 4(a). Each pulse is of length T_p and the pulse repetition period is T. After reflection from the PSS, assume that each incident carrier pulse is replaced by M cycles of a bipolar rectangular waveform, as shown in Figure 4(b). Hence, the period of this modulating waveform, 2τ, is given by

$$2\tau = \frac{T_p}{M} \tag{5}$$

and the switching frequency, f_s, is given by $f_s = \dfrac{M}{T_p}$

Since the incident pulse train is periodic, with period T, its spectrum and that of the signal reflected from the PSS may be determined using Fourier analysis. Hence, the incident and reflected signals may be written in the form

$$v(t) = \sum_{n=-\infty}^{n=+\infty} c_n e^{jn\omega_0 t} \tag{6}$$

where $\omega_0 = 2\pi/T$

The complex Fourier coefficients, c_n, are then given by

$$c_n = \frac{1}{T}\int_0^T v(t) e^{-jn\omega_0 t} dt \tag{7}$$

For the incident periodic pulse train, c_n are given by

$$c_n = \frac{-j}{2n\pi}\left(1 - e^{-j2n\pi\frac{T_p}{T}}\right) \tag{8}$$

For the PSS-modulated wave and M integer, c_n may be written in the form

$$c_n = \frac{j}{2n\pi}\zeta\chi\sum_{m=1}^{M} e^{-2\gamma(m-1)} \tag{9}$$

where

$$\gamma = jn\omega_0\tau\,, \quad \zeta = 1 - e^{-\gamma}\,, \quad \chi = \left(e^{j2\beta d} + e^{-\gamma}\right) \quad \text{and} \quad \beta = \frac{2\pi}{\lambda} \tag{10}$$

The more general equations for the case of non-integer M are given in [6]. The apparent PSS reflectivity at frequency f_c, for any switching frequency f_s, may now be found by comparing how much energy would enter the receiver pass-band in the absence of PSS modulation and when PSS modulation has taken place. For simplicity, it is assumed that for a pulse-width T_p, the receiver has a total bandwidth of $2/T_p$, since this is consistent with the generally accepted rule of thumb that the receiver bandwidth at the 3dB points is given approximately by $B = 1/T_p$.

Figure 5 shows the apparent reflectivity of a resonant (i.e. $d = \lambda/4$) PSS when the incident signal is a periodic train of 1μsec rectangular pulses of sinusoidal carrier with f_c = 10 GHz and a pulse duty cycle of 1%. When the PSS is in a non-resonant condition ($d \neq \lambda/4$), then it presents periodic reflection coefficients of –1 (active layer on, $G(t) = \infty$) and $-e^{j2\beta d}$ (active layer off, $G(t) = 0$) to the incident signal. The other two curves in Figure 5 show the PSS reflectivity performance for incident signals at frequencies of 11 and 15 GHz. These curves are identical to those for incident signals at 9 and 5 GHz, respectively, thus confirming the symmetrical nature of the PSS frequency response. It should also be noted that for high values of switching frequency, the predicted values of PSS reflectivity agree with those calculated from $20\log_{10}(|\cos \beta d|)$.

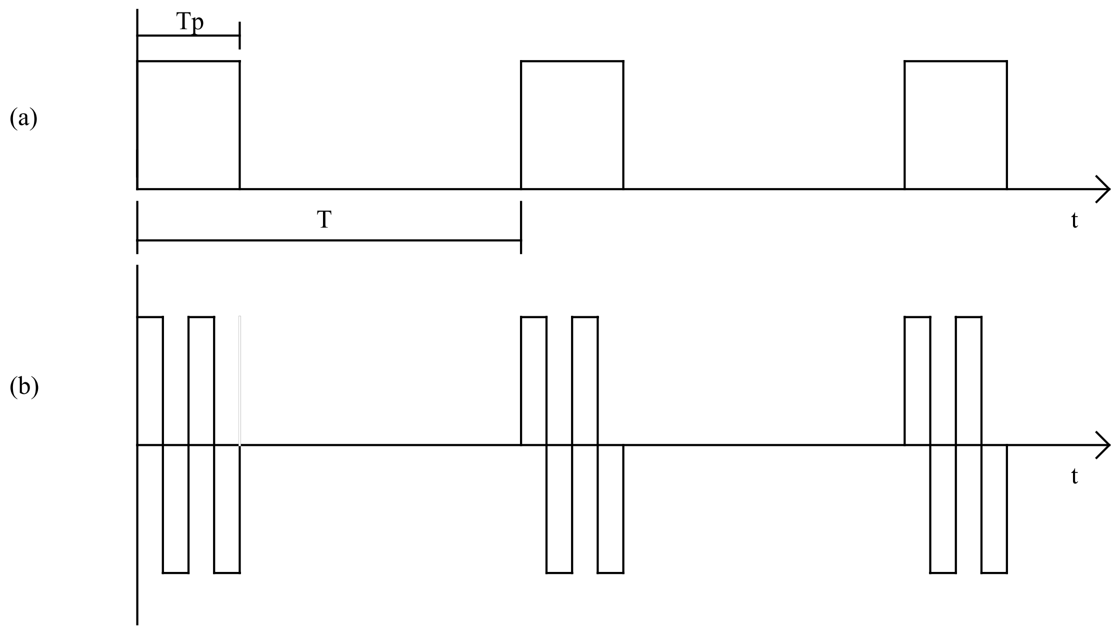


Figure 4 *Operation of the phase switched screen, (a) incident wave, (b) reflected wave (M = 2. For clarity, the sinusoidal carrier frequency signal itself is not shown)*

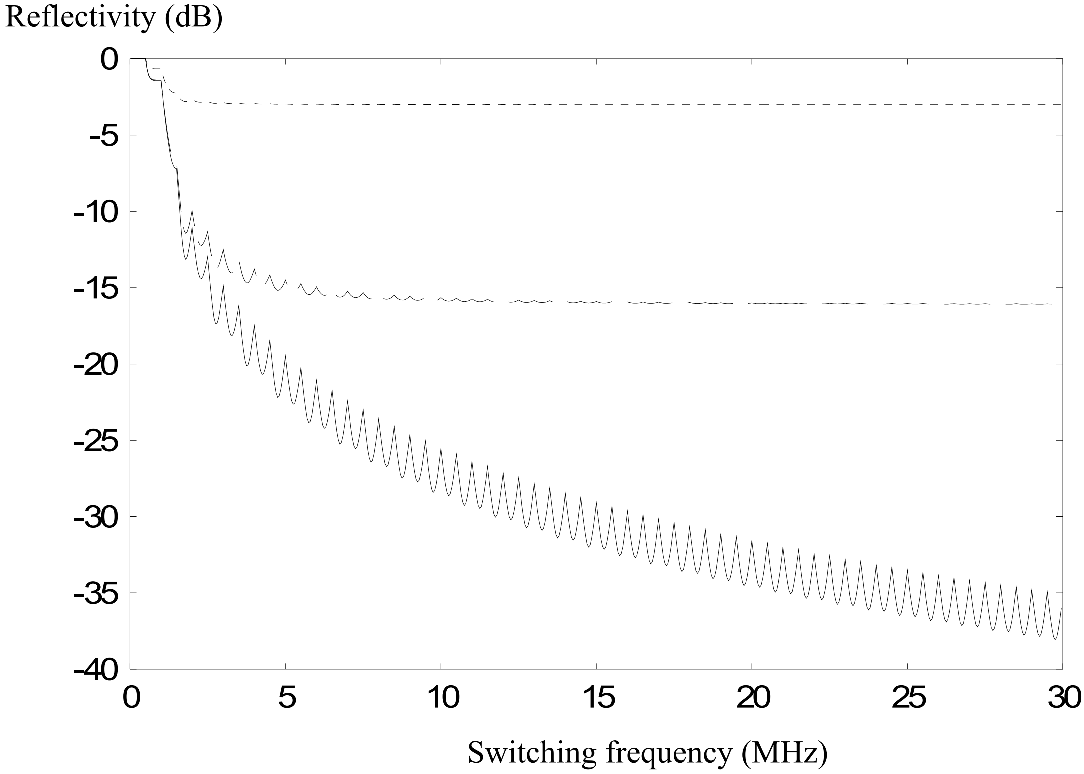


Figure 6 *Reflectivity of planar single layer PSS with 1:1 bipolar square-wave switching (1 μsec pulse length, 1 % duty cycle, 2 MHz receiver bandwidth)*
_____ f_c = 10 GHz, __ __ f_c = 11 GHz, ….. f_c = 15 GHz

4. Practical implementation of a PSS

To realise a practical PSS we need a surface that can be rapidly switched between two or more impedance states. Potentially this could be achieved using some type of functional material such as an active conducting polymer [7]; however, our present active layers consist of a two-dimensional grid of half wavelength dipoles that are loaded at their centres with *pin* diodes, as shown in Figure 7.

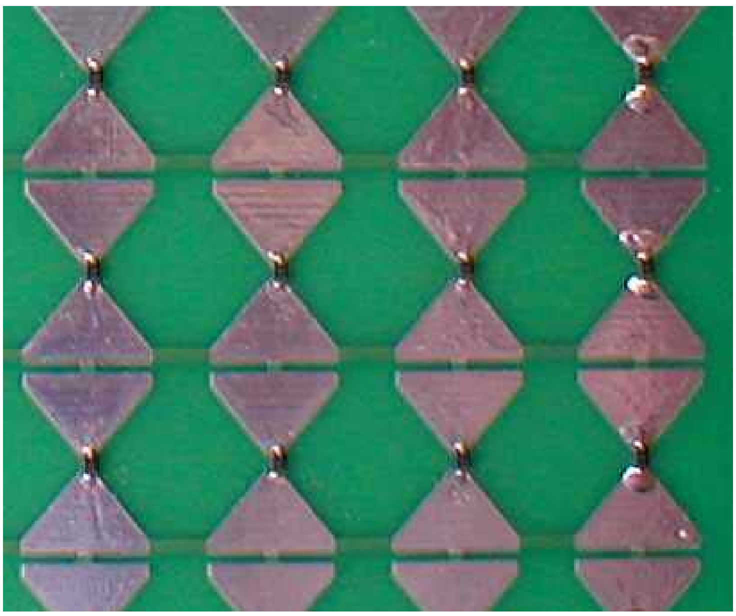


Figure 7 *Layout of PSS active layer showing pin diode-loaded bow-tie elements*

Under no-bias conditions the *pin* diodes present high microwave impedance and the dipoles may be considered open circuit. Hence the grid of dipoles is non-resonant and represents a high impedance equivalent surface. When the diodes are biased 'on', however, their high frequency impedance becomes low and the dipoles are resonant at the half wavelength frequency. Hence the grid of shorted dipoles becomes a strong scatter and represents a low impedance surface.
Because of its topology, the structure shown in Figure 7 will only be effective for one plane of polarisation. By combining two such structures, rotated with respect to each other by 90° however, a dual polarised PSS may be realised. One element from the resulting active layer is shown in Figure 8 and typical measured reflectivity characteristics for two values of 'on' time are shown in Figure 9.

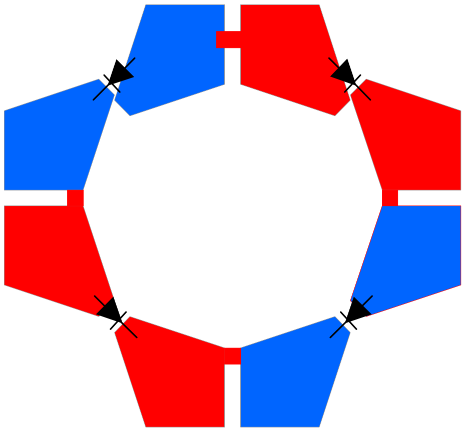


Figure 8 *Active surface element for dual-polarised PSS*

5. Multi-layer PSS

In the same way that multiple layers may be used in passive RAM to increase bandwidth, the use of several active layers in a PSS increases its functionality, with the added advantage of dynamic reconfiguration. At normal incidence, the time-averaged reflection coefficient $\rho(f)$ of an N layer PSS is given by

$$\rho(f) = -(a_0 + a_1 e^{j2\beta_0 d} + a_2 e^{j4\beta_0 d} + \dots a_{N-1} e^{j2(N-1)\beta_0 d}) \qquad (11)$$

This expression is *exact* for the ideal PSS (i.e. active layer conductances switched repetitively between the values of 0 and ∞) since no multiple reflection phenomena occur within the structure. The coefficients a_n are the normalised 'on' times τ_n/T associated with each active layer and these are related by $\sum_{n=0}^{N-1} a_n = 1$. Hence, by choosing appropriate values for a_n, the multi-layer PSS may be configured dynamically to have different reflectivity characteristics. As a simple example, consider a PSS having two active layers and a PEC back-plane; this corresponds to the case for N = 3. Assuming a symmetrical structure, then $a_0 = a_2$ and since $a_0 + a_1 + a_2 = 1$, this means that a_0 and a_1 are related by [26]

$$a_1 = 1 - 2a_0 , \quad 0 \le a_0 \le 0.5 \qquad (12)$$

Figure 10 shows the application of (12) to define the 'on' times for a PSS containing two active layers. When $a_0 = 0.5$, the reflectivity response has a single null at the frequency where $d = \lambda/4$. As the value of a_0 decreases, however, the null bifurcates to give two nulls that move apart as 'mirrorimages'. Thus a reflectivity null may be positioned anywhere within the frequency range $c/8d \leq f \leq 3c/8d$, where $c = 3 \times 10^8$ m/s. If $a_0 = 0$, and $G_1G_2 \neq Y_0$, then the reflectivity characteristic only has a single null which fills in as $a_1 \rightarrow 0$ or 1. This case is analogous to that shown in Figure 2. When the PSS has more active layers, then the use of appropriate 'on' time relationships deduced by induction from (12) result in the formation of multiple 'mirror-image' reflectivity nulls which can also be tuned dynamically over a wide band of frequencies.

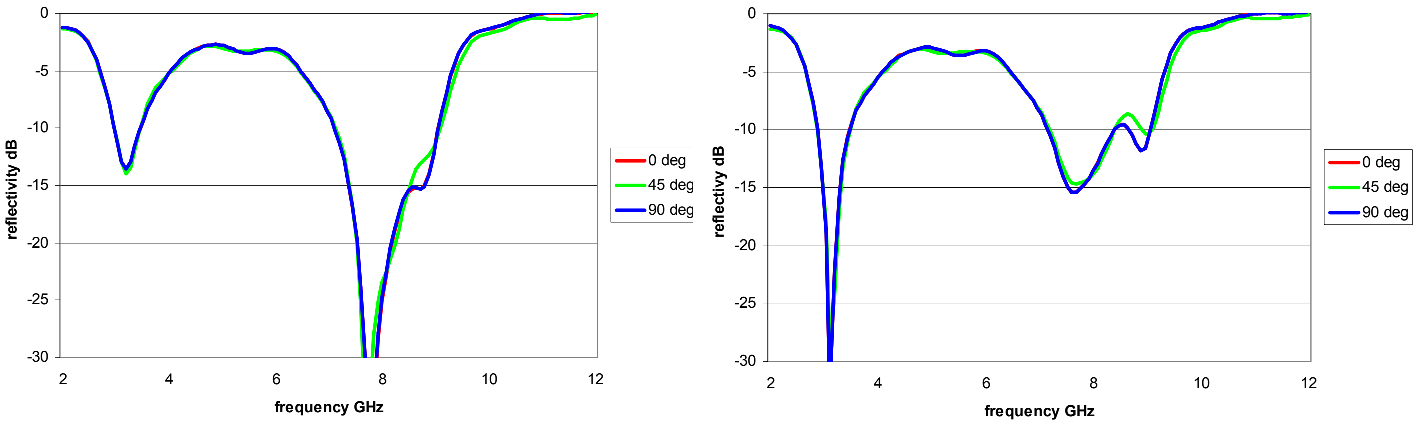


Figure 9 *Measured performance of dual-polarised PSS*

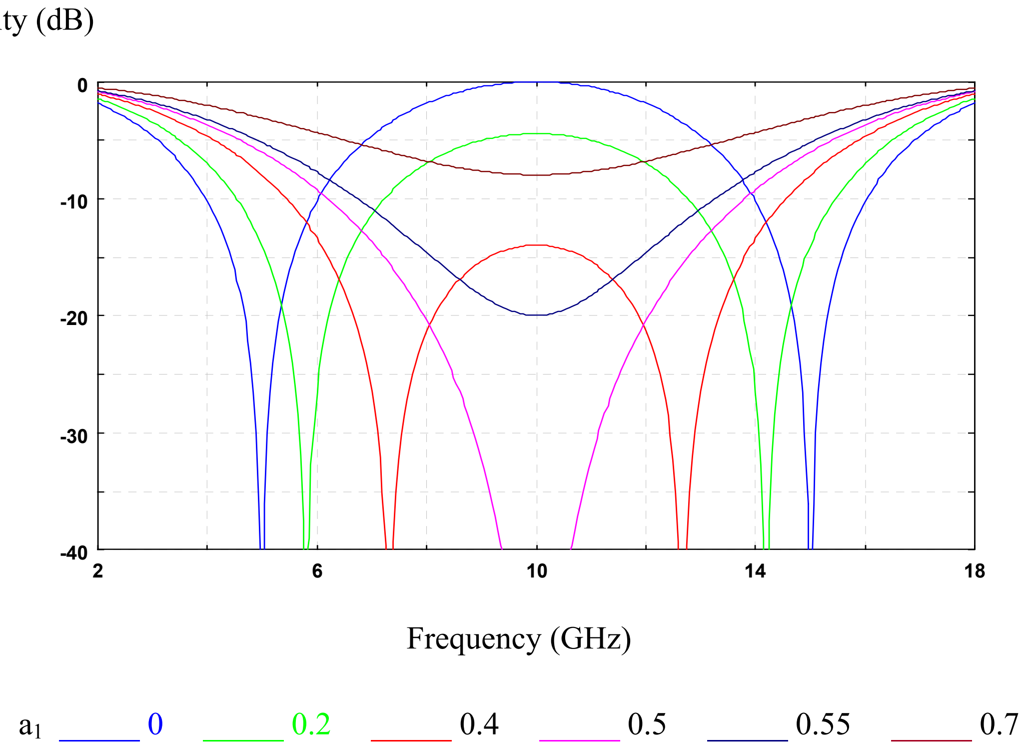


Figure 10 *Control of null position and depth in a two active layer PSS by varying the layer 'on' times*

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