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Adaptive radar absorbing structure with PIN diode controlled active frequency selective surface

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Abstract
A brief description of the theory of passive and active absorbers is presented followed by details of an experimental study of a new design of adaptive absorber. The absorber is a single-layer planar structure based upon the topology of a Salisbury screen, but in which the conventional resistive layer is replaced by an active frequency selective surface (FSS) controlled by PIN diodes. The resulting structure has superior reflectivity–bandwidth characteristics compared to conventional passive absorbers of corresponding thickness. Experimental results are presented and compared to those obtained from a transmission line model, and show that the reflectivity response of the absorber can be dynamically controlled over the frequency band from 9 to 13 GHz.

1. Introduction

The effectiveness with which a radar system can detect a target depends primarily on how much of the electromagnetic energy illuminating the target is reflected back to the radar, and this is described by the radar cross section (RCS) of the target [1]. In military scenarios it is often advantageous to lower the RCS of an object to reduce its probability of detection by radar, a classic example being the B2 stealth aircraft. In other situations, for example air traffic control or maritime tracking radar, steps may be taken to increase the RCS of a platform to aid detection by using devices such as corner reflectors. Although geometrical shaping is the primary mechanism for controlling the RCS of an object, the surface of the object may also be covered with radar absorbing materials (RAMs) to reduce the RCS of features that are not amenable to surface shaping. Whatever method is used to control the RCS of an object its actual radar signature remains fixed and this information can be used by modern radar systems to classify and identify the object. Therefore, in certain situations it may be advantageous to have the capability to modify the radar signature of a target in response to a given operational environment. For example, the RCS of a military vehicle could be changed from a high value during 'peace-time' operations to a low value in combat situations. Furthermore, a platform with active RCS control could, potentially, be adaptively reconfigured and used in a deception role to mimic the radar signature of different targets.

In this paper we review the operation of passive radar absorbers and describe how they can be modified to provide active RCS control. We also describe a new design of adaptive absorber based on an active frequency selective surface (FSS) and present theoretical and experimental results.

2. Theoretical background

We start by examining the basic theory of operation of a passive, single layer resonant absorber, and then explain how this structure can be modified to act as an active absorber. The structure to be considered is depicted in figure 1 and consists of a thin sheet of resistive material spaced in front of a perfectly conducting back-plane by a low-loss dielectric material with a thickness d and relative permittivity ε_r. Assuming plane-wave incidence, the reflectivity characteristics of the structure may be analysed using the transmission line equivalent circuit shown in figure 1. Using this approach, the free-space input impedance of the absorber for normal incidence is given by

$$Z_{in} = \frac{jZ_s Z \tan(\beta d)}{Z_s + jZ \tan(\beta d)} \quad (1)$$

where Z_s is the sheet impedance, Z is the characteristic impedance of the dielectric spacer and $\beta = 2\pi\sqrt{\varepsilon_r}/\lambda$

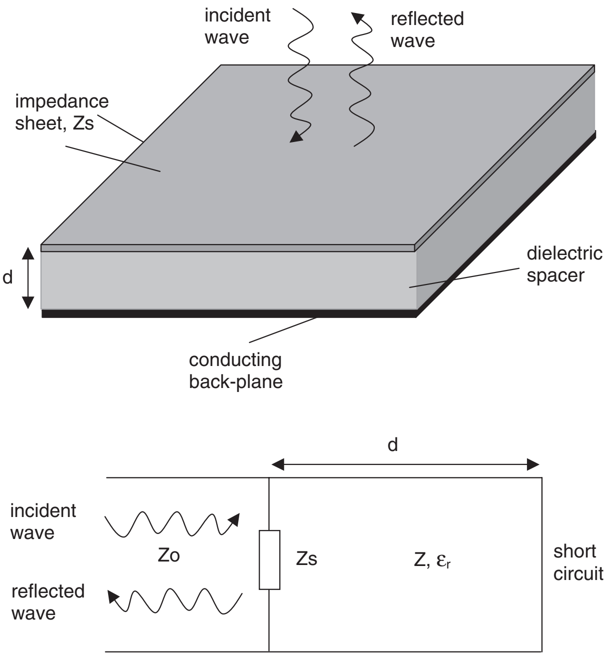

Figure 1. A single-layer planar absorber (top) and transmission line equivalent circuit (bottom).

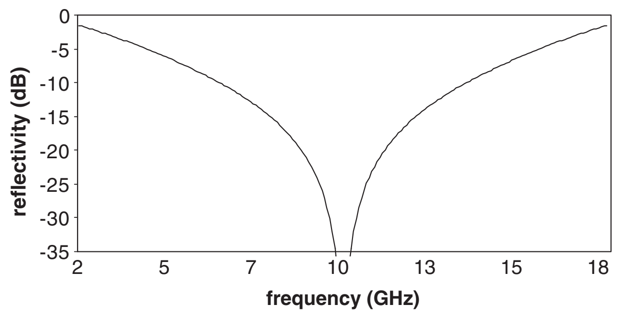

Figure 2. Reflectivity characteristics of a Salisbury screen designed for operation at 10 GHz.

is the propagation constant of the spacer material. The corresponding free-space reflection coefficient of the absorber at normal incidence is given by

$$\rho = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{2}$$

and the reflectivity by

$$\Gamma = 20 \log_{10}(\rho)$$

where Z_0 represents the impedance of free space and is approximately equal to 377 Ω.

If the sheet impedance is purely resistive and equal to Z_0, the absorber shows a reflectivity null when $\beta d = \pi/2$, and this occurs when $d = \lambda/4$ (and at harmonically related distances of $3\lambda/4$, $5\lambda/4$ etc). This is the classic Salisbury screen, and an example of the reflectivity response of this type of absorber designed for operation at 10 GHz is shown in figure 2.

The reflectivity, and hence RCS, of a single-layer absorber can be controlled by changing the value of the screen input impedance, Z_{in}. Examination of equation (2) shows that the parameters that are available to modify Z_{in} are the sheet impedance, the permittivity of the spacer material, and the spacer thickness. In practice we are interested in a parameter that can be rapidly changed in response to an electrical or optical control signal, and this precludes the use of mechanical systems for changing the spacer thickness or permittivity. The easiest parameter to control electrically is the sheet impedance, Z_s, which may be achieved by using functional materials [2] or, as will be described later, by using a two-dimensional grid of semiconductor devices.

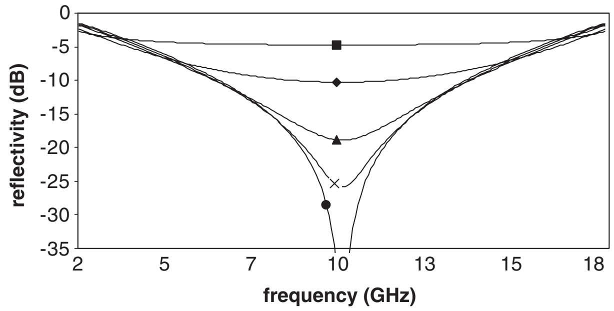

Figure 3. Variation in reflectivity with sheet resistance for a 10 GHz Salisbury screen. Sheet resistance values (Ω/□): ■ = 50 or 2838, ♦ = 100 or 1419, ▲ = 300 or 473, × = 340 or 417, ● = 377. Note that the high and low values of sheet resistance are related by the formula $Z_{high} Z_{low} = Z_0^2$ and therefore give identical reflectivity curves.

Consider first the case when Z_s is purely resistive. Figure 3 shows the reflectivity characteristics of a screen, designed for operation at 10 GHz, for various values of sheet resistance. The effect of changing the sheet resistance is to modify the reflectivity of the structure from that of a strong reflector when $Z_s \gg Z_0$ or $Z_s \ll Z_0$ to that of a good absorber when $Z_s \approx Z_0$. However, although this system does show adaptive characteristics, it is only useful as an absorber over a relatively narrow band of frequencies.

To increase the bandwidth of a single-layer, passive absorber a reactive component can be added to the sheet impedance to produce what is often referred to as a circuit analogue absorber [1, 3–5]. In practice this may be achieved by replacing the purely resistive impedance sheet of a Salisbury screen with an FSS containing loss, or by embedding an FSS within a lossy composite [6].

The impedance of a lossy FSS layer can be described by a series equivalent circuit containing resistance, inductance and capacitance, $Z_s = R_s + j\omega L_s + 1/j\omega C_s$. Previous theoretical work in this area suggests that the optimum tuning performance that can be obtained from a single-layer screen is achieved by varying the capacitive component of the sheet impedance [7]. Here, however, we examine a system in which L_s and C_s are fixed and R_s is a variable, as this describes the basic operation of our experimental system. Although the values of inductance and capacitance used in this model are fixed, they do affect the reflectivity characteristics of the screen and are important parameters in the design process. For example, figure 4 shows the performance of a screen in which the (fixed) values of capacitance and inductance are chosen to provide a wideband adaptive absorber with a reflectivity response that can be resistively tuned to give a reflectivity level of less than −20 dB between 5 and 15 GHz. Other combinations

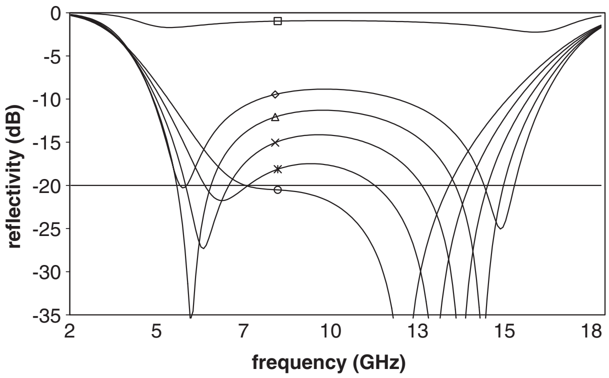

Figure 4. Predicted reflectivity response of a single-layer absorber with a series equivalent impedance described by $Z_s = R_s + j\omega L_s + 1/j\omega C_s$, with $L_s = 3.4$ nH and $C_s = 9.1$ fF and R_s : $\square = 20\ \Omega$, $\Diamond = 180\ \Omega$, $\triangle = 220\ \Omega$, $\times = 260\ \Omega$, $* = 300\ \Omega$, $\circ = 340\ \Omega$.

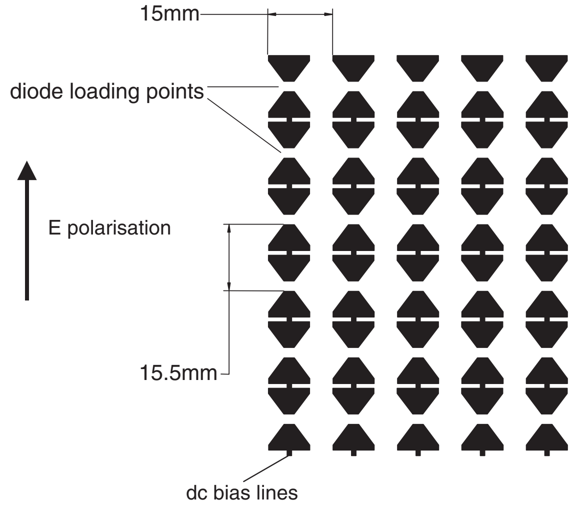

Figure 5. Details of the linearly polarized active FSS topology.

of L_s and C_s may be chosen for larger bandwidths at lower reflectivity levels or, conversely, lower reflectivity levels over smaller bandwidths, but there is always a trade-off between reflectivity performance and bandwidth.

3. An experimental adaptive absorber

To implement the ideas discussed in the previous section we require a material with appropriate impedance tuning characteristics. One approach is to use PIN diodes which act as current controlled resistors at microwave frequencies. Conventionally, PIN diodes are used as discrete, lumped elements in VHF, UHF and microwave circuits and the design techniques for this type of application are well documented [8]. However, the use of PIN diodes to form a 'sheet' material for use in absorber applications is not straightforward, and requires an alternative design strategy. A basic approach to this problem is described by Dittrich and Wulbrand [9], in which a variable resistance layer is formed from parallel strips of series connected PIN diodes. The Dittrich absorber implementation requires *two* such PIN diode layers to provide reflectivity tuning. In this contribution we incorporate PIN diodes into an FSS to form a variable impedance layer that also has a significant reactive component, and use this to construct a broadband adaptive absorber from a *single* active layer. This strategy provides a lower diode density and hence power consumption and, as only a single layer is required, also reduced thickness and weight.

In its basic form an FSS consists of a two-dimensional, planar periodic grid of conducting patches, or elements, supported on a dielectric substrate. An ideal FSS (i.e. one which contains no loss) has a free-space input impedance that is purely reactive, with the values of L_s and C_s determined by the shape of the FSS element. In order to incorporate a resistive component into the FSS impedance, we have designed an element based on a bow-tie dipole which is loaded at its centre with a PIN diode. The PIN diodes act as current controlled variable resistors at microwave frequencies and provide the required impedance tuning function. The design of the active FSS is complicated by the need to incorporate a dc voltage bias line into the structure to provide the necessary control current to the diodes. The FSS design we have used is designed for single, linear polarization and consists of parallel strings of dipole elements arranged on a rectangular lattice, as shown in figure 5. This design was used to construct an FSS from 0.8 mm thick printed circuit board using standard photo-etching techniques. The board measures 185 mm by 235 mm and contains 180 (15 by 12) dipole elements which are loaded with commercially available surface-mount PIN diodes (Phillips BA585) using hand-soldering techniques.

An active absorber was constructed using the assembly details shown in figure 1 by mounting the FSS above a conducting back-plane using a 4.0 mm thick, low-loss, foam dielectric spacer (Rhocell 51, $\varepsilon_r = 1.05, \tan\delta = 0.0017$). The FSS circuit board was arranged 'face downwards' in the assembly so that the surface mount diodes could be embedded into the dielectric foam spacer by the application of moderate pressure, resulting in a rigid structure with an overall thickness of less than 5.0 mm. An additional advantage of this topology is that the outer dielectric layer formed by the circuit board provides increased bandwidth, as well as a protective outer skin [10].

The free-space reflectivity characteristics of the active absorber were measured for linearly polarized illumination over the frequency range of 8–14 GHz in a calibrated NRL arch using an HP 8510C network analyser. Figure 6 shows the measured reflectivity responses obtained for various diode bias current levels in the range 0.0–1.0 mA. For zero applied bias current the structure is strongly reflecting. However, as the bias current is increased the reflectivity level reduces across a band of frequencies from 9 to 13 GHz and shows a double null response. At a diode bias current level of approximately 0.08 mA a reflectivity level of less than −20 dB is achieved from 9.5 to 12.5 GHz. For further increases in bias current, the reflectivity curve shows a single null at around 10.5 GHz and resembles the response of a single-layer Salisbury screen, but with increased bandwidth. Further increases in bias current result in a progressive increase in reflectivity until, in the saturated state (bias current $>$ 1 mA), the structure again becomes strongly reflecting. The bias current levels required by the active absorber are extremely small and the average power consumption is estimated to be less than 25 μW cm^{-2}.

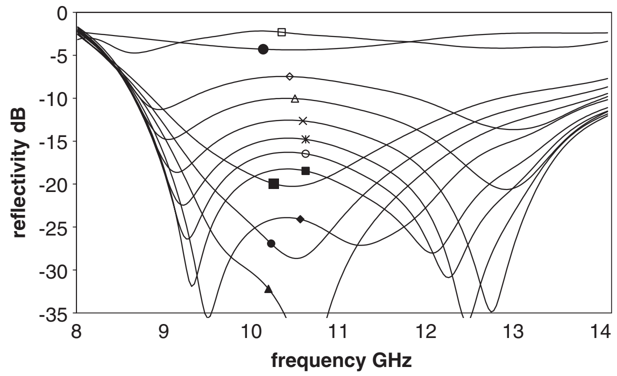

Figure 6. Measured absorber reflectivity as a function of diode bias current. □ = 0.0 mA, ◊ = 0.025 mA, △ = 0.05 mA, × = 0.06 mA, ∗ = 0.07 mA, ○ = 0.075 mA, ■ = 0.085 mA, ▲ = 0.1 mA, ● = 0.11 mA, ■ = 0.13 mA, ● = 1.0 mA.

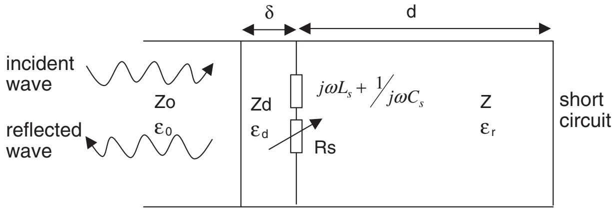

Figure 7. Transmission line equivalent circuit of the experimental active absorber with outer dielectric skin of thickness δ.

4. Theoretical modelling of the absorber

The experimental absorber can be analysed using an approximate model based on the transmission line theory presented earlier in the paper. However, the original model must be extended to include the effect of the finite thickness of the circuit board substrate on which the FSS is fabricated, and this is shown in figure 7. The predicted reflectivity responses obtained from this model are shown in figure 8 and confirm the basic operation of the screen. The values of inductance and capacitance used to describe the reactance of the experimental FSS were derived from a simple optimization procedure designed to give a 'best fit' to the measured data. However, the values of series resistance used to generate figure 8 were chosen to illustrate a similar tuning response to the measured data rather than to match it.

5. Conclusions

In this paper we have described how passive radar absorbing materials can be modified by the inclusion of an active impedance layer to provide a structures with adaptive reflectivity control. The design of experimental adaptive radar absorber which uses a PIN diode loaded FSS to provide a variable impedance layer has been described. Measured results show that the structure can be tuned to provide a continuously variable reflectivity level of less than 25 dB

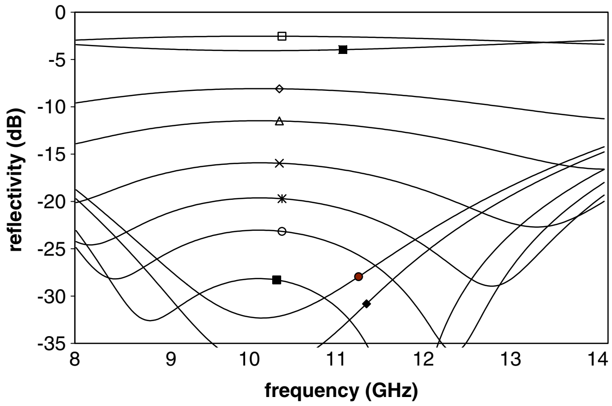

Figure 8. Predicted reflectivity characteristics of the single-layer active absorber using the model in figure 7 with $C = 4.9$ fF, $L = 4.7$ nH, R, □ = 50 Ω, ◊ = 150 Ω, △ = 200 Ω, × = 250 Ω, ∗ = 280 Ω, ○ = 300 Ω, ■ = 320 Ω, ♦ = 350 Ω, ● = 360 Ω, ■ = 1500 Ω.

over a broad frequency range. The reactive impedance of the FSS layer results in an absorber that is considerably thinner than that of a comparable Salisbury screen absorber, and also shows increased bandwidth. The time constant associated with the PIN diodes are of the order of 10 ns and the absorber has been switched at rates in excess of 20 MHz. Work is currently being carried out to investigate the increased reflectivity–bandwidth performance offered by multiple-active-layer absorbers. Research is also being carried out on dual polarized and conformal structures, and the results of these studies will be reported at a later date.

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