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Switchable Frequency Selective Slot Arrays

B. Sanz-Izquierdo, E. A. Parker, and J. C. Batchelor

***Abstract*—A switchable frequency selective surface (FSS) made of square loop slots and PIN diodes connected to a novel separate biasing circuit is presented. The structure uses a very thin, flexible substrate sandwiched between two physically independent metallic layers to create the active filter. An application is the modification of the EM architecture of buildings, where propagation could be controlled using active FSS. The relatively small number of elements employed creates a compact FSS structure which could fit in an aperture within a wall of a building. The Fabry-Perot approach is used to design a cascaded version for improved filter selectivity.**

***Index Terms*—Electromagnetic wave propagation, EM architecture, frequency selective surfaces (FSS), PIN diodes, switching.**

The electromagnetic architectural configuration of a building determines the electromagnetic wave propagation conditions inside the structure as well as reflection or transmission to the exterior. Most existing buildings have been designed and built with no account of the variety of wireless technologies that nowadays co-exist, and their impact on network efficiency and security. As the structure of buildings cannot generally be easily modified, the installation of frequency selective surfaces (FSS) into buildings could be the answer to some of these issues [1]–[4]. FSS can transmit or reflect electromagnetic waves striking the surface at predetermined operational frequency bands. The surfaces could be applied to a partition wall or sections of buildings, allowing efficient frequency re-use or increasing security. Several projects funded in the U.K. by Ofcom have studied FSS in the built environment, some reported in [1], [2]. Active frequency selective surfaces can add a higher level of control over the electromagnetic wave propagation in buildings. They permit the time dependent modification of the characteristics of the surface by applying an external magnetic [5]–[7] or electric [7]–[20] control. Two related procedures might be considered when applying active devices to frequency selective surfaces: switching [7]–[17] and tuning [5]–[7], [18]–[20]. Switching between transmitting and reflecting states using PIN diodes on metallic dipole patches is well known [7]–[11], and has already been tested in the built environment [12]. The development of switched slot form FSS has been reported more recently, for example [13]–[17]. In that work, band pass active FSS consisted of slots etched on one side of an FR4 substrate, with the biasing circuit on the other side, and metallic vias connected both sides. An equivalent circuit for that configuration was derived in [16], [17]. In this communication, we discuss active square loop slot arrays fabricated on a double sided structure, sandwiching a very thin, flexible dielectric substrate. The thin substrate employed allows placing the biasing circuit with the diodes on the rear side without physical connection to the front surface which contains the slots. These in turn could lay on a second, thick dielectric layer if necessary for support, or for additional bandpass shaping. The studies presented focus on the application of this novel biasing technique to dual-polarized square loop slots. The Fabry-Perot approach [21] is also explored to design a cascaded version for improved filter selectivity.

II. SWITCHABLE SQUARE LOOP SLOT ARRAYS

A. Design and Fabrication

The square loop is a relatively compact geometry commonly employed as FSS elements. The transmission response of a closely packed array of this element is typically characterized by wide bandwidth and relatively good resonance stability with angle of incidence [22], [23]. A double-sided switchable structure using square loop slots on one side and the biasing circuit on the other side is described in this section.

The front and the rear views of the unit cell of the structure are presented in Fig. 1(a) and (b). A side view showing the slots on the front, the biasing circuit with the PIN diodes at the rear and the thin dielectric layer in the middle can be seen in Fig. 1(c). There is no physical connection between the two sides and the PIN diodes capacitively couple to the area surrounding the slots. A flexible polyester substrate 0.05 mm thick, with $\varepsilon r = 3.0$ and loss tangent $\delta = 0.04$ was used for all the designs presented here. The FSS consisted of a 5 × 5 array of square loop slots in a square lattice of periodicity p = 37mm. The sides of the squares (L) were 29 mm in length, and the slot width w was 0.3 mm. The dimensions of the biasing circuit lines at the rear were: A = 27.6mm, B = 3.6mm, C = 30.3mm, D = 32.8mm, E = 32.4mm, F = 1.5mm, G = 16.8mm, H = 5.0mm. The circuit contained 4 diodes per square loop slot, connected in series within a cell and simultaneously connected to the 5 cells in a column, making 20 diodes in series per column. The five columns had different feed lines that could be controlled independently if desired. Photographs of the rear side of the 5 × 5 slot array and a single cell of the array are shown in Fig. 2(a) and (b). BAR64-02 silicon PIN diodes with forward resistance $R_s = 2.1$ ohms and capacitance at 0 volts of $C_s = 0.17$pF were employed for the switching. CST Microwave Studio was used for simulations of the design with diodes added as lumped capacitor/resistor for the OFF/ON states. The very thin dielectric substrate increased significantly the meshing process and computational requirements. All the FSS structures here were simulated as infinite arrays.

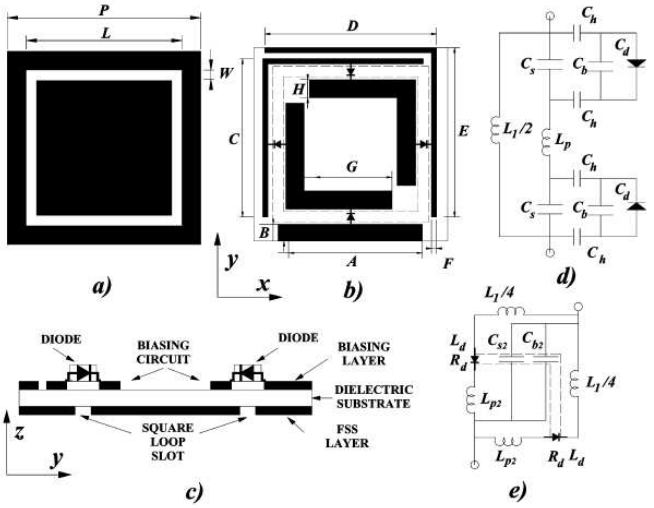
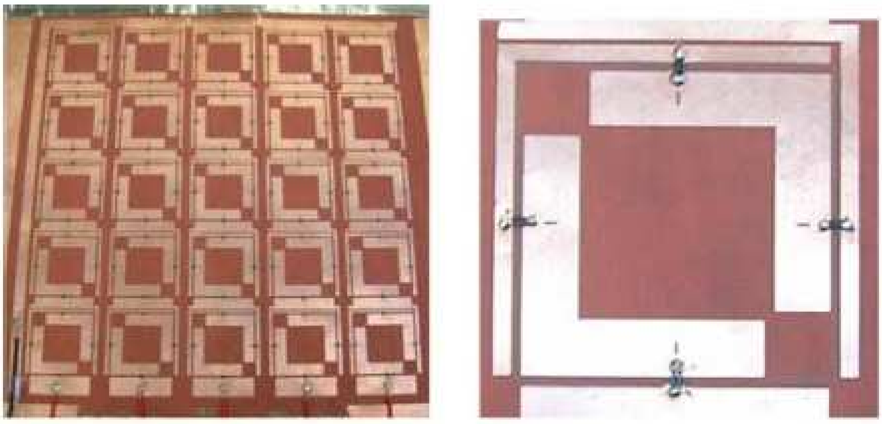


Fig. 1. Unit cell of the active FSS: (a) Front view with the square loop slot, (b) rear view with the biasing circuit, (c) magnified section view of the structured, (d) equivalent circuit model for the FSS with diodes switched OFF, (e) simplified equivalent circuit model for FSS with diodes switched ON.

B. Measurements

Measurements were carried out using two log periodic antennas at 0.6 m from a 3 × 3 m absorbing panel containing the FSS. The system was calibrated relative to an open aperture of approximately 190 × 190 mm in the centre of the panel. Fig. 3 shows the measured transmission response of the switchable FSS with the diodes OFF, at normal wave incidence angle, and at 45° in TM and TE. At normal incidence, the bandpass was centered at around 2.5 GHz with insertion loss of 0.6 dB and a -10dB fractional bandwidth of 75%. At TE45°, the insertion loss increased to 1.2 dB and the -10dB bandwidth decreased to 43%. At TM 45°, the insertion loss was 0.6 dB and the -10dB bandwidth increased to 84%. In all three measurements, the insertion loss for the 2.4 GHz to 2.5 GHz Bluetooth band was kept below 1.7 dB. The response when the diodes were in the ON state is shown in Fig. 4. Transmission levels were well below -18dB for normal incidence, TE45 and TM45. Simulations compared well with the measurements, showing good angular stability and polarization performance. In the simulations, diodes were found to be the largest contributors to the insertion losses of the FSS, with the diodes in the OFF state adding over 0.3 dB. In addition, as infinite arrays were simulated while finite FSS were measured, much of the discrepancy between the simulations and measurements in Figs. 3 and 4 is likely to be due to edge effects.



(a) (b)

Fig. 2. (a) Rear side of the 5 × 5 array (b) a magnified view of a unit cell.

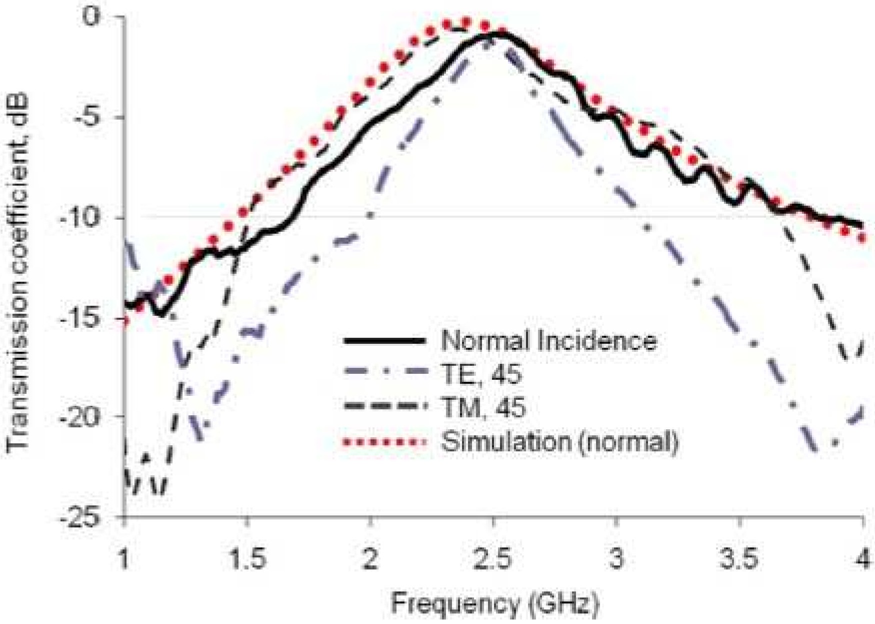


Fig. 3. Simulated and measured transmission response of the active FSS with diodes switched OFF.

C. Analysis of the Active FSS Simulations were run to analyze the effect of the biasing circuit on the performance of the FSS. The main findings are summarized as follows.

—The FSS was stable to angle of incidence for both vertical and horizontal polarization. The difference in resonance frequency between the two polarizations in the OFF state was less than 1%.

—The lossy dielectric substrate attenuated any possible resonance due to the vertical and horizontal lines of the biasing circuit, particularly in the ON state.

—Fig. 5 shows transmission response of the FSS with the diodes in the OFF/ON state, and also the FSS without the biasing circuit but with the diode's characteristic capacitance/resistance connected directly to the slot FSS. The bias lines were found to behave mainly as parallel capacitors (C_b in Fig. 1(d)), decreasing slightly the resonant frequency in the OFF state and by 8% in the ON state, reducing the ON/OFF transmitted power ratio by 2 dB.

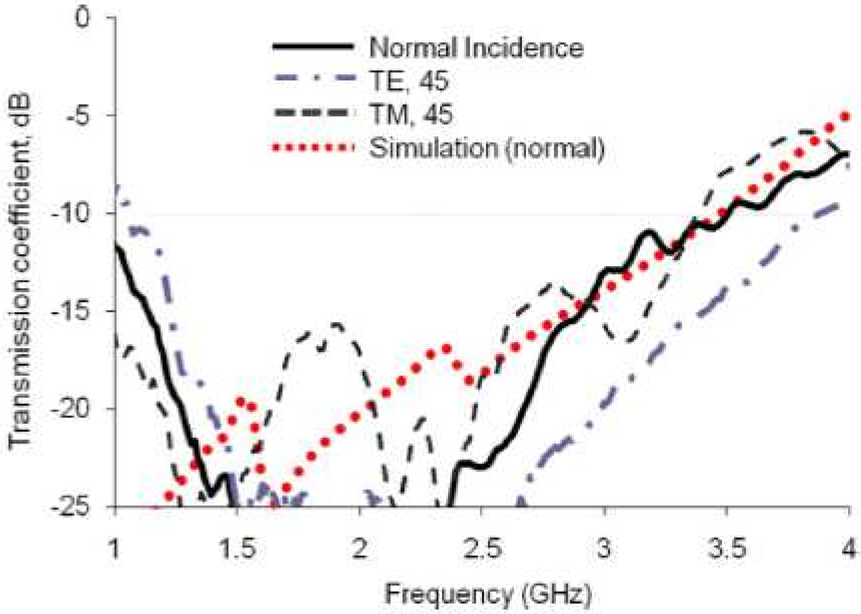


Fig. 4. Simulated and measured transmission response of the active FSS with diodes switched ON.

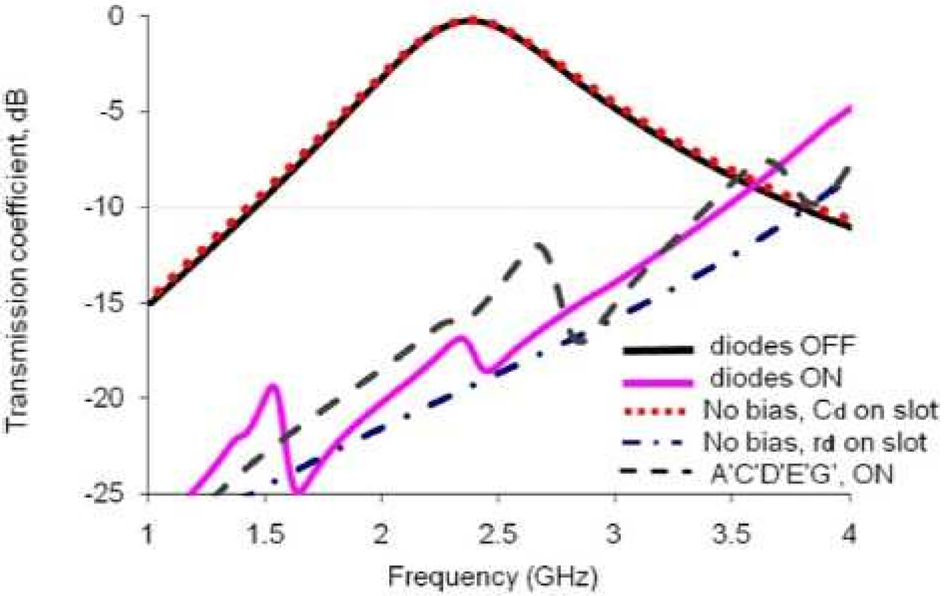


Fig. 5. Simulated and measured transmission response of the active FSS configuration with diodes switched ON.

Fig. 6. Two cascaded layers of the switchable FSS separated by polystyrene foam, one layer rotated by 90 degrees.

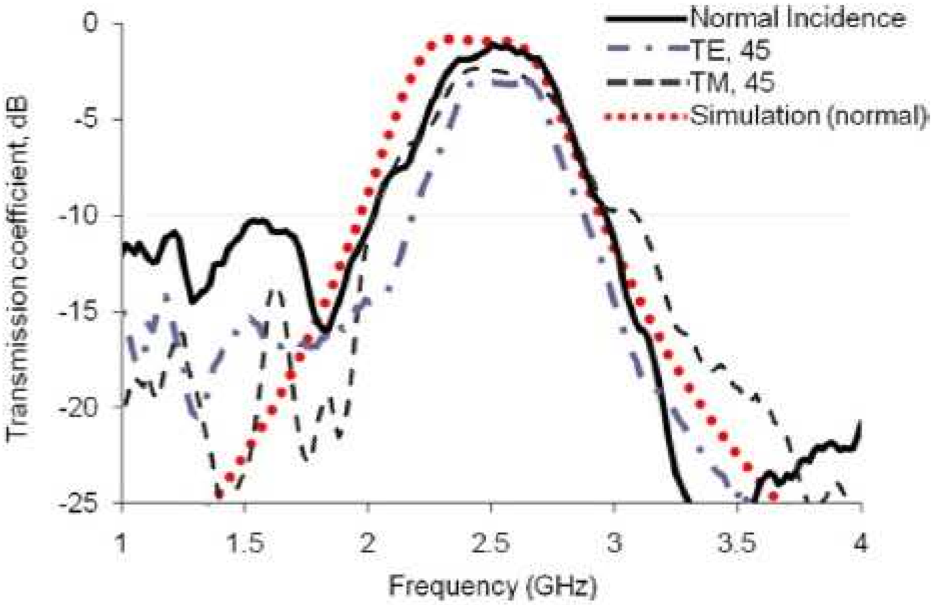


Fig. 7. Measured transmission response of the two cascaded layers of the active FSS with diodes switched OFF.

–A reduction in the length of A, C, D, E and G (Fig. 1(b)) to the minimum length needed to connect the diodes (A’ = 15mm, C’ = D’ = 17.5mm, E’ = 19.5mm, G’ = 15mm) degraded the ON state performance of the FSS by 2 dB (Fig. 5 as A’C’D’E’G, ON). It also reduced capacitance C_b, increasing slightly the resonant frequency. Equivalent circuit models for switchable square loop slots were described in [16], [17]. Using that model and the findings described in this section, a simplified equivalent circuit model of our active FSS design with the diodes in OFF states is presented in Fig. 1(d), where: L_1 is the inductance created by the metallic grid at each side of the slot ($L_1/2$ corresponds to the two sides in parallel), C_s the capacitance of the slot, C_h the capacitance between the biasing circuit and the FSS and C_b the parallel capacitance added by the biasing lines. The diode adds C_d, r_d and L_d to the circuit, behaving mainly as C_d in the OFF state [9]. C_h can be omitted as it has very low impedance at 2.5 GHz. In addition, the inductance of the centre patch L_p could be disregarded in the OFF state due to its low impedance value compared to C_s and C_d [16], [17]. The resonant frequency of the active FSS with diodes in the OFF state would be:

$$\omega_0 = \frac{2}{\sqrt{L_1 C_1}} \qquad (1)$$

where

$$C_T = C_s + C_b + C_d \qquad (2)$$

Fig. 1(e) illustrates the slot created when the diodes are switched ON and its simplified equivalent circuit model. The square slot is split in four sections and the capacitance of C_s and C_b reduced to C_{s2} and C_{b2}. The inductance of the patch L_{p2} should now be taken into account as it is in series with $L_1/4$. The main effect of the diodes and the biasing circuit was a reduction in the electrical length of the slot from the typical 0.5 λ to 0.45 λ.

III. CASCADING ACTIVE SQUARE LOOP SLOT ARRAYS

A. Design and Measurements

Two cascaded FSS arrays can be regarded as a basic Fabry-Perot interferometer (FPI) [21], [24]. FPI behave as high Q filters, with very narrowpassbands at frequencies where the sum of the path length phase between the layers, and the phase of the surface reflection coefficient satisfies a specific condition. In order to improve the filter selectivity, two layers of the active FSS were separated by a polystyrene foam layer, by a distance S of 20 mm (0.16 λ) as illustrated in Fig. 6. In addition, one of the layers was rotated 90 degrees, improving the control capabilities of the surface and allowing individual switching of columns in one layer and rows in the second one. Fig. 7 shows the transmission response of the cascaded FSS with the diodes switched OFF. There is a clear improvement in the roll-off rate and width of the band-pass peak compared with the single layer structure described in Section I (Fig. 3). The bandwidth of the -10dB passband has decreased to 40%, 27% and 40% at normal incidence, TE45° and TM45°respectively. At normal incidence, the insertion loss is 1 dB at 2.5 GHz and below 2 dB between 2.35 GHz and 2.7 GHz. At TE45°, the insertion loss is now 3 dB at 2.5 GHz and under 3.4 dB from 2.4 GHz to 2.7 GHz. AT TM45, the insertion loss is less than 2.7dB between 2.35 GHz and 2.5 GHz. Simulations and measurements showed that diodes contributed to over 0.5 dB of the insertion losses at normal incidence. The losses might be reduced by using higher quality diodes such as those employed in [26]. The transmission response of the cascaded active FSS with the diodes in ON state is shown in Fig. 8. At 2.5 GHz the transmission levels dropped to -25dB, -23dB and -17dB at normal incidence, TE45 and TM45 respectively. Across this range of illumination angle, the difference in transmission coefficient between the diode OFF and ON states was over 14 dB for the 2.4 GHz to 2.5 GHz Bluetooth frequency band. It is worth considering that in mobile communications and wireless local area networks in the built environment, comparatively small reductions in signal interference can give very significant reductions in the system outage probability. In [25], for example, a 15 dB increase in the carrier-to-interference ratio has been demonstrated to reduce the outage probability by a factor of almost 30.

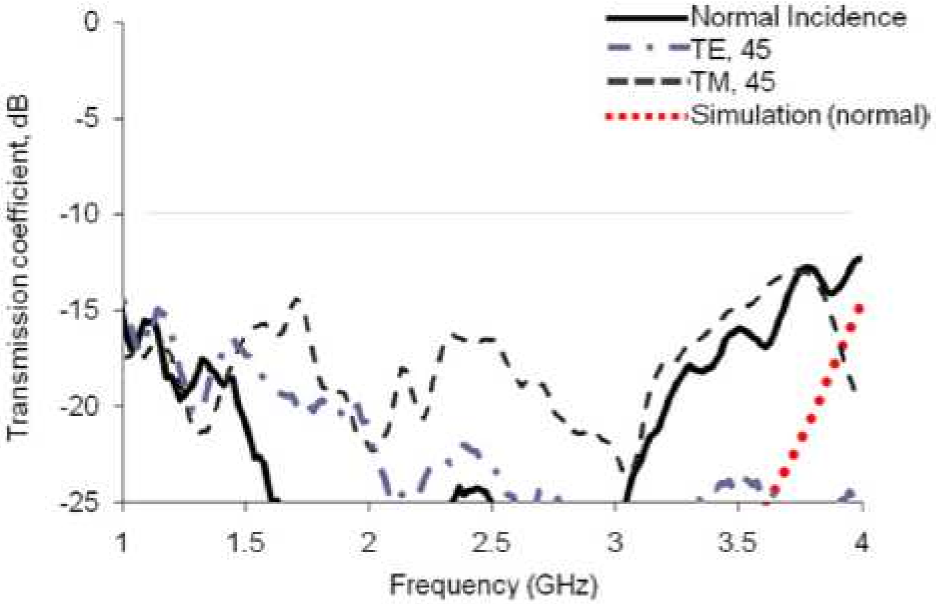


Fig. 8. Measured transmission response of the two cascaded layers of the active FSS with diodes switched ON.

IV. CONCLUSIONS AND DISCUSSION

Active frequency selective surfaces with diodes capacitively coupled to slots arrays via a very thin, flexible substrate have been presented. A switching structure using square loop slots has been demonstrated and analyzed. In addition, two cascaded layers of the active FSS improved the roll-off rate and widened the passband peaks, while maintaining a similar ON/OFF power ratio. Simulations as infinite arrays compared well with measurements of the 5 × 5 array for the two configurations presented here. The main aim of this research work is to control electromagnetic propagation in buildings by modifying their Electromagnetic Architecture. The relatively small number of elements employed makes the structure attractive for applications to small apertures in buildings, reducing the cost of installation and maintenance. The methodology described has been filed as Tunable Surface filing no. GB 0902380.6

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