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An Active Annular Ring Frequency Selective Surface

Paul S. Taylor, Edward A. Parker, and John C. Batchelor, *Senior Member, IEEE*

***Abstract*—Offering good performance in terms of all polarizations affected and good angular stability, the ring element is a popular choice in frequency selective surface (FSS) designs. This paper introduces a topology for two-state switching of a ring based FSS. The two states offered by the surface enable it to be either transparent or reflective at the frequency of interest. A design targeted at the 2.45GHz WLAN band, and intended for the control of the electromagnetic architecture of buildings (EAoB), is realized both by simulation and measurement, the results of which are presented and evaluated.**

***Index Terms*—Active frequency selective surface, annular ring, electromagnetic architecture, FSS**

I. INTRODUCTION

AS more devices become wireless and the demand for such is on the increase, particularly in the built environment, then the Electromagnetic Architecture of these spaces needs to be considered. Modern construction materials offer improvements in building thermal efficiency and UV protection. This is often achieved by a metallic coating or loading and can be greatly detrimental to the building EA. Another consequence of the convenience of wireless connectivity is security, particularly where unbounded signals might radiate beyond their intended boundaries. Containing these signals would greatly enhance security.

Modifying the Electromagnetic Architecture of Buildings (EAoB) and therefore controlling their spectral efficiency and security can be achieved by the application of frequency selective surfaces (FSS) [1]-[5]. A passive FSS although suitable for some applications might be considered to be restrictive, as it offers no flexibility once installed, whereas an Active FSS (AFSS) allows the potential for some element of control by changing the behavior of the surface. This allows for reconfiguration in the event of time or frequency dependant propagation requirements, or the actual physical movement of boundaries such as dividing walls or temporary partitions.

Many element types are used in FSS designs, from simple dipoles to complex fractal and convoluted structures. The propagation characteristics of the built environment can be complex, with signals arriving at any angle of incidence or polarization, due to diffraction, reflection and scattering, and the element type selected needs to be appropriate. An added complication is that these environments are often dynamic with the movement of equipment, furnishings and people continually changing the propagation characteristics of the space. Singly polarized elements such as dipoles only offer frequency selectivity in the plane of the element; dual polarization is achievable with crossed dipoles and related structures but, as with most elements, their performance suffers at oblique angles due to the grating responses which are angle of incidence dependent [6], [7]. A popular choice of rotationally symmetrical geometries offering good stability to angle of incidence is the loop family of elements, and particularly the annular ring [8]-[11]. These features make it a good choice for, but not restricted to, applications in the built environment.

Achieving two-state switching of a dipole based surface utilizing semiconductor switches, such as PIN diodes is a recognized technique, and has also been applied to other element types [12]-[16]. The term *two-state* means that the surface, for a patch element design, can be configured to a reflective or transparent state at the frequency of interest by application or removal of a control signal, usually a dc bias.

This paper presents a novel technique targeted at the WLAN band of 2.45GHz, for two-state switching of a ring based AFSS design, whilst still maintaining appropriate performance for the applications previously outlined. Section II demonstrates how two-state operation of the design is realized by exploiting the resonances [17]-[20] that are achievable with split-ring elements. Simulations using CST Microwave Studio^{TM} (CST MWS^{TM}) are used to verify the basic operation of the design. Section III looks at the implementation of the PIN diode switching elements and deals with the transparent distribution, from an RF point of view, of the dc control signal. Section IV details the construction and practical measurements of an actual functional prototype surface at angles of incidence up to 45^o with a linearly polarized source at rotation angles of 0^o, 22.5^o, 45^o and 90^o. Simulations using CST MWS^{TM} are included for comparison, and the results are discussed. The paper closes with concluding remarks that summarize the design and measurements.

II. TWO-STATE ANNULAR RING FSS DESIGN

A. Theory of Operation

Fig. 1(a) illustrates the performance of a two-State dipole FSS where the surface behaves as a conventional FSS array in its reflective state with the elements open and in a transparent state by connecting the rows of dipole ends together, usually with semiconductor switches such as PIN diodes. This results in an inductive surface with a high-pass filter response. Providing the high-pass band is low enough in frequency then negligible loss is experienced at f_r in the transparent state, as shown in Fig. 1(a).

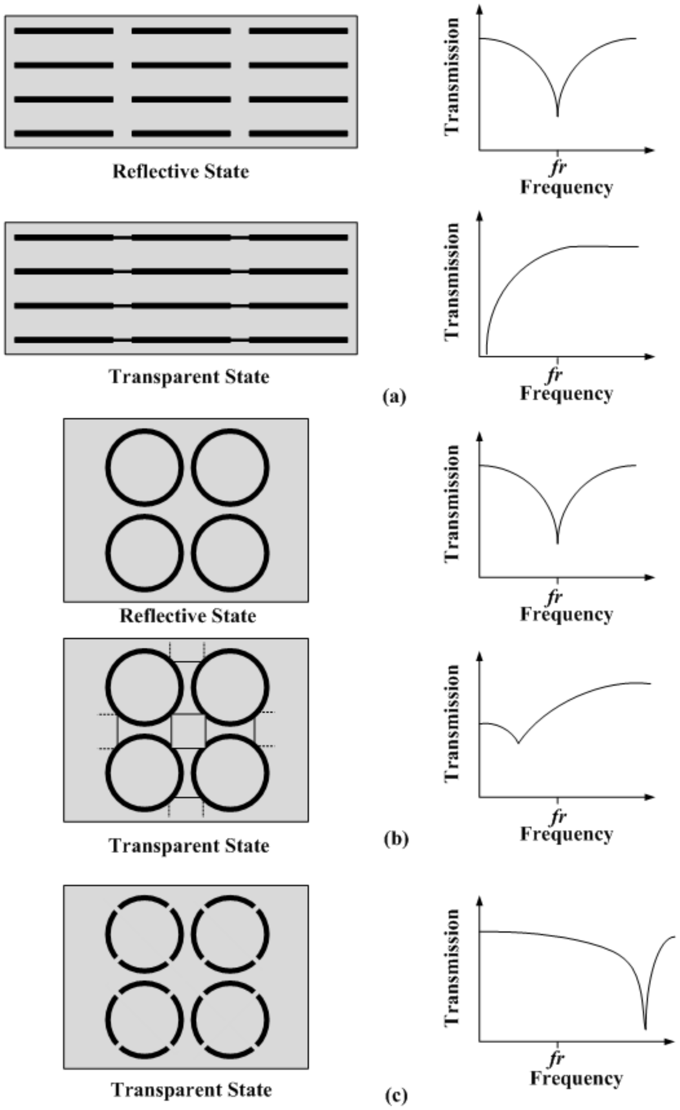


Fig. 1. Development of a two-state ring surface from the dipole structure of (a), the shorted ring version of (b) and the final open-circuited structure of (c).

Initial experiments have shown that applying a similar technique to an annular ring FSS resulted in a lowering of the surface's resonant frequency, but with the response being rather broad and lossy, and also falling within the original stop-band as shown in Fig. 1(b). Another approach, and the method adopted here, was to remove the fundamental resonance by introducing discontinuities in the elements. This is achieved by open-circuiting the rings into four sections, with the breaks being orthogonally positioned at 45°, 135°, 225° and 315° respectively. This results in a transparent surface that is no longer resonant at its original design frequency. Reconnecting these breaks in the conductors returns the surface back to its reflective state. Fig. 1(c) demonstrates the basic principle of operation. It is worth noting that for the transparent state the surface still exhibits a resonance, which is at approximately twice the fundamental design frequency, with each unit cell being made up of four $\lambda/2$ elements at this frequency. This resonance is considered far enough removed from the target band as not to be problematic.

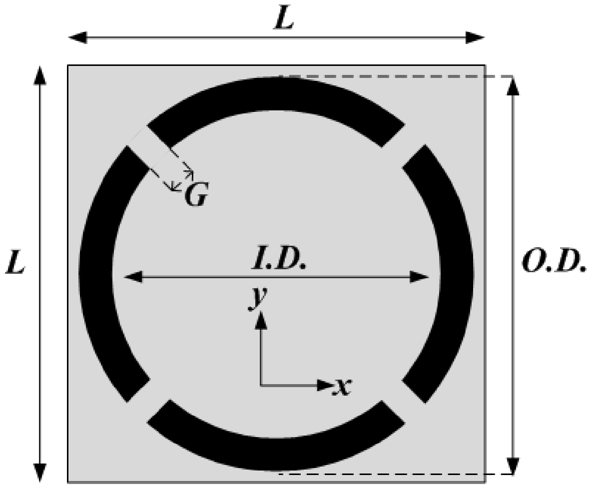
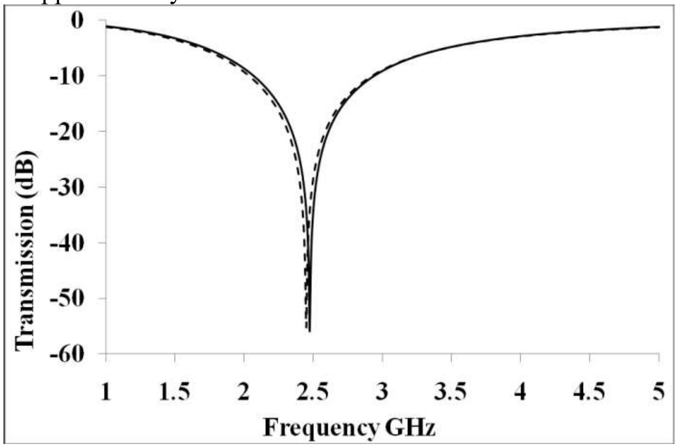


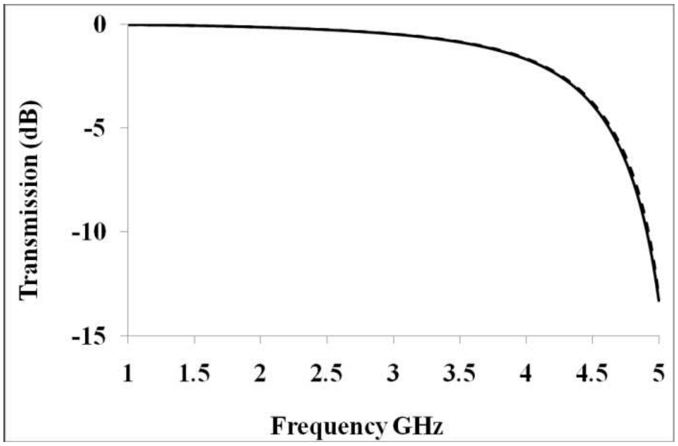
Fig. 2. A unit cell of the experimental surface.

B. *Experimental Structure*

Shown in Fig. 2 is a unit cell for a design frequency of 2.45GHz, its dimensions are: *L* = 38.16mm, *O.D.* = 36.8mm *I.D.* = 32.8mm and *G* = 1.5mm. These dimensions result in a closely spaced array on a square lattice. The close spacing is advantageous in terms of both angular stability and also distribution of the biasing control signal. The design and associated simulations include a 0.17mm thick polyester substrate with $\varepsilon_r = 3$ and $\tan\delta = 0.04$. All metallic elements are of 0.015mm copper. Initial simulations were carried out using this structure, where *ideal* switches were assumed, that is switches were either open or closed at points *G*, and introduced no additional strays or losses to the surface. The dimension *G* is dictated more by the component package used rather than a critical dimension. Simulation results for this structure at normal incidence are given in Fig. 3, and show a pronounced stop-band at 2.45GHz for the ON state and a 1dB transmission loss for the OFF state, with the OFF state resonance at approximately 5GHz.



(a)



(b)

Fig. 3. (a) ON and (b) OFF state simulation results for TE —— and TM ---- polarizations at normal incidence for the structure of Fig. 2

III. PIN DIODE SWITCHING AND CONTROL

A. PIN Diode Switch

PIN diode switching is an established and reasonably efficient technique in RF and Microwave circuits, and is used here. Fig. 4 shows a PIN diode structure and simplified equivalent circuits for when the diode is forward and reverse biased.

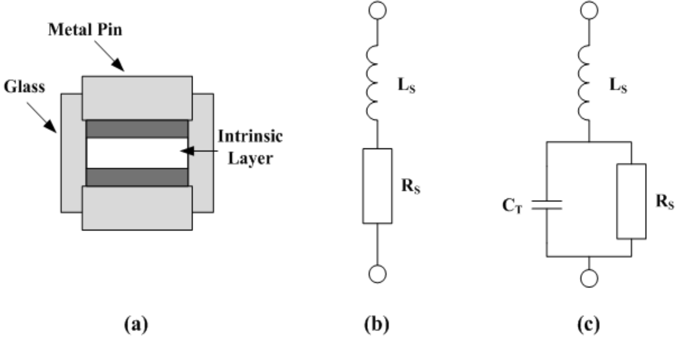


Fig. 4. (a) PIN diode structure, with its forward bias equivalent circuit in (b) and reversed biased in (c)

In the forward bias condition the diode presents a resistance R_S in series with the package inductance L_S. The reverse bias condition the circuit becomes a parallel combination of R_P and C_T in series with L_S. C_T is actually a combination of the device junction capacitance C_J and its package parasitic. At frequencies above about 10MHz and up to several GHz the equivalent circuit is a good approximation to a resistance whose value is controlled by a dc or low frequency control current. The HMSP3862 [21] from Avago has been used in this application. The device is actually a series connected pair of diodes in a SOT-23 package with an OFF capacitance of 0.3pF and an ON resistance of 1.5Ω. This results in a device with C_T 0.15pF and R_S 3Ω for a series connected pair. The surface topology required four devices per unit cell.

B. Control Signal Distribution and Isolation

In AFSS designs any additional control or bias lines if not correctly isolated from the resonant surface will impact upon its operation and performance. Suitably chosen inductors achieve the required isolation. Inductors when used as RF chokes present a high impedance at the design frequency whilst allowing a dc path for the PIN diode control signal. For choke applications, owing to the presence of stray reactances, the blocking impedance rises above $2\pi fl$ as the minimum self resonant frequency (SRF) of the device is approached [22]. It is acceptable, and even advantageous, to exploit this feature as a greater impedance is presented by the device and consequently improved isolation is achieved.

The SIMID 0603 series of inductors from EPCOS [23] offer a suitable component. With an SRF of 2.5GHz, the 56nH inductor was the selected device. Normally this value of inductance would present an impedance of approximately 860Ω at 2.45GHz, but as we are operating to just below its SRF a greater value is achieved. Presented in Fig. 5 is an SRF measurement performed on an EPCOS 56nH inductor using a HP8722ES vector network analyzer (VNA). It clearly shows the SRF peak, and the device presenting an impedance of approximately |Z|= 4.5kΩ at the design frequency of 2.45GHz.

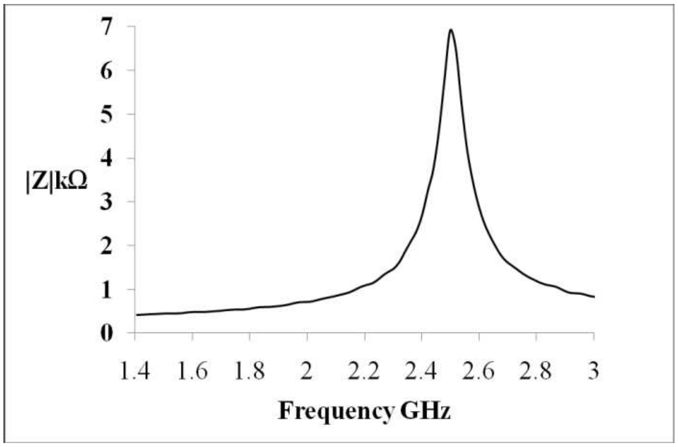


Fig. 5. Inductor impedance |Z| response

Providing we have good isolation of the control signal, in the interest of efficiency and also economy, where practical it makes sense to use the FSS elements themselves as current carrying conductors for the control signal. The topology is such that providing the correct polarities of the PIN diodes are observed then the biasing can be applied in either a row or column format. The latter is adopted here. Conveniently, the spacing between adjacent elements supports an 0603 inductor with no additional tracking required. Shown in Fig. 6 is a schematic representation of a 2x2 array.

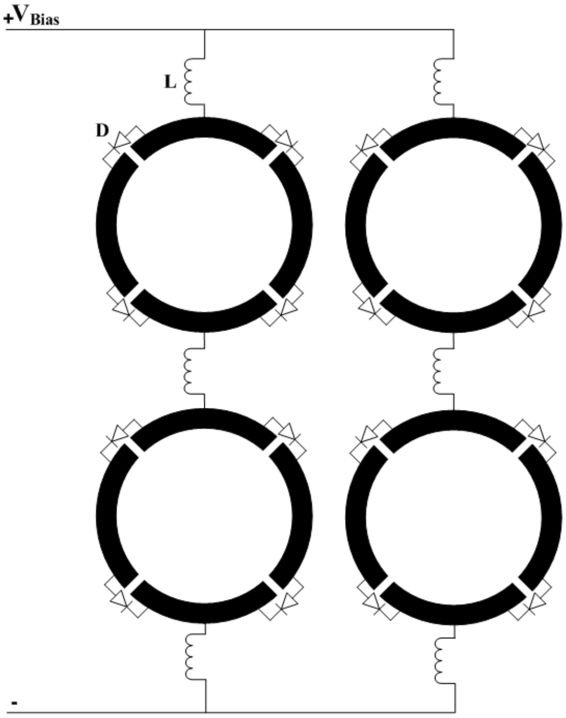


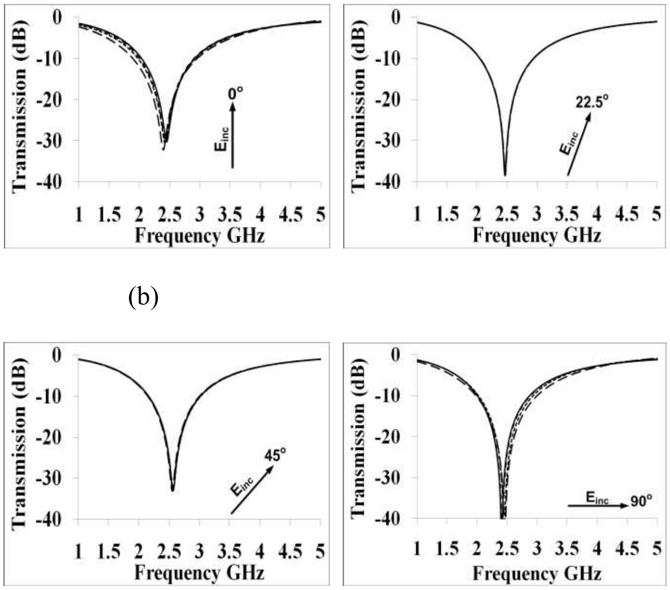
Fig. 6. Schematic representation of a 2x2 array, detailing the surface topology and component locations. L = 56nH inductor, D = HMSP3862 PIN diode.

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. *Simulation Results*

With the component values and their associated strays known, these were incorporated in the structure shown in Fig. 2. The values for the PIN diode were: 0.15pF for the OFF state capacitance and 3Ω for the ON state resistance and an impedance of 4.5kΩ for the bias line inductor was also included. Fig. 7 and 8 show the simulated results for both ON and OFF states of the surface illuminated with a linearly polarized source at rotation angles of 0^o, 22.5^o, 45^o and 90^o at incidence angles of 0^o - 45^o in 15^o increments. The rotation angle is the angle between the y axis and the E vector in the plane of the array. They clearly show a good stop-band at the design frequency and good angular stability, with increasing angles of incidence at all polarization angles.

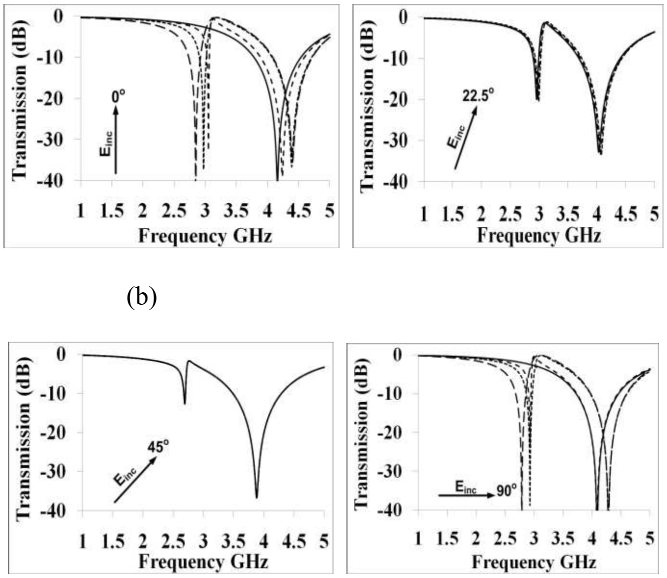
It is evident from the results that the OFF state capacitance of the PIN diodes has the effect of lowering the 5GHz surface secondary resonance by approximately 1GHz when compared with that of an ideal switch as previously shown in Fig. 3(b). The OFF state simulation results of Fig. 8(a-d) show an additional unwanted narrow-band response at approximately 2.8GHz. Although this null was quite deep in cases, its bandwidth was sufficiently narrow that it was not expected to be observable in practice. Its origin is a weak resonance corresponding to a current distribution mode approximating that for an un-segmented ring – simulations show that its exact frequency is moderately sensitive to the gap width *G*. Note that there are slight differences between Figs. 7(a) and 7(d), and also differences between Figs. 8(a) and 8(d), though in both cases the E vector is parallel to a side of the lattice square. This is related to the attached chokes along y.



(a) (b)

(c) (d)

Fig. 7. ON state simulation results for TE incidence at angles of, 0° ——, 15° ----, 30° ····· and 45° — — — .



(a) (b)

(c) (d)

Fig. 8. OFF state simulation results for TE incidence at angles of, 0° ——, 15° ----, 30° ····· and 45° — — — .

B. *Prototype FSS Fabrication*

The surface tested was a 5x5 array on an axial lattice fabricated using standard printed circuit board (PCB) photographic and wet-etch techniques, which resulted in a 25 element surface of 200x200mm requiring a total of 100 diodes and 30 inductors. For mechanical stability the test surface was backed with a 12mm thick sheet of polystyrene foam ($\varepsilon_r = 1.04$). Shown in Fig. 9 is the constructed test surface.

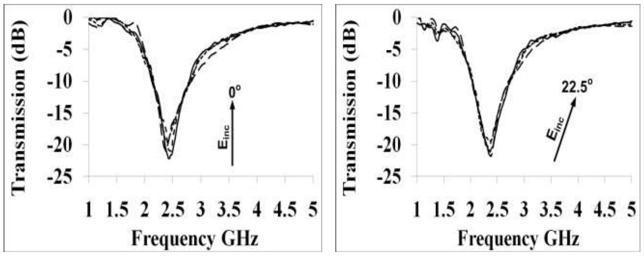
Fig. 9. Close-up view of the constructed prototype test surface

C. *Prototype FSS Measurements*

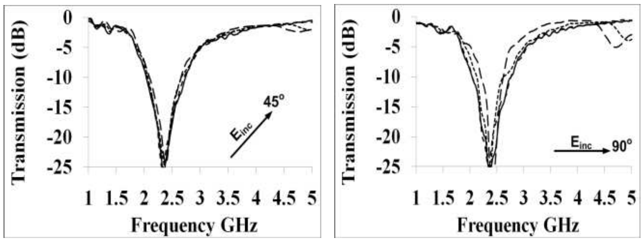
A dc bias voltage, V_{Bias}, of 17 volts, current limited to a total forward current of 200mA was required for the prototype surface. The supply current is divided equally over five columns, resulting in approximately 40mA per column. In the OFF state, no bias was applied.

The measurement set-up consisted of a plane-wave chamber equally divided by a microwave absorber loaded rotatable screen, thus allowing for angle of incidence transmission measurements. The screen has a centrally located adjustable aperture that accepts the surface under test. A pair of Rohde and Schwarz HL050 broadband log-periodic antennas and a Hewlett Packard 8722ES VNA were used for the transmission system.

To ensure consistency in the measurements a transmission calibration was carried out with an open aperture before each measurement. Figs. 10 and 11 show the results for the prototype surface. For the ON state the stop-bands are at approximately 2.45GHz, with a rejection of ≥20dB, and good stability for increasing angles of incidence. For the OFF state, with increasing angles of incidence a loss of between 1 and 3.5dB is experienced at 2.45GHz. As anticipated the transmission null at 2.8GHz is much reduced when compared with the simulation results.

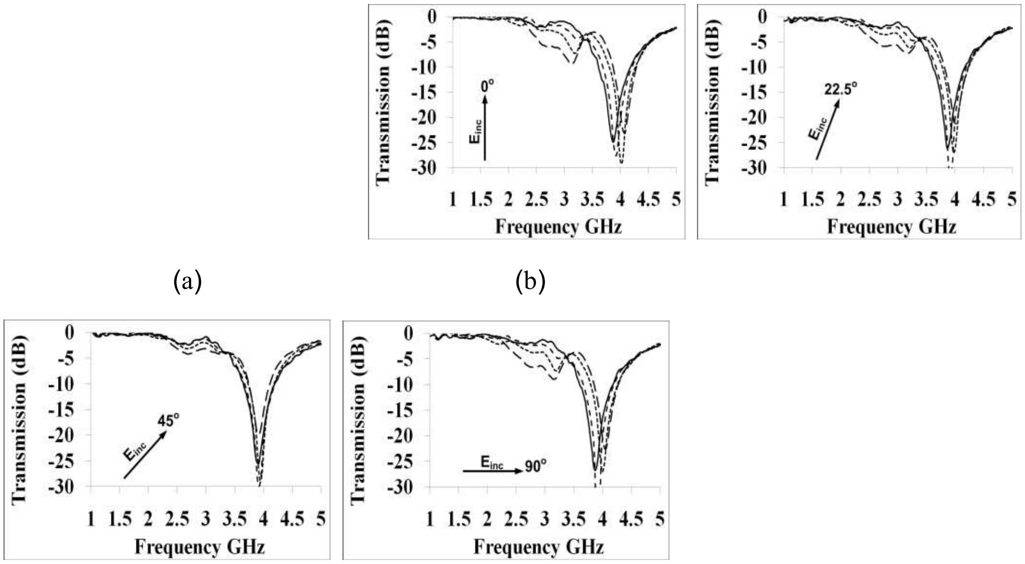


(a) (b)



(c) (d)

Fig. 10. ON state measurement results for TE incidence at angles of, 0^{o} —, 15^{o} ----, 30^{o} ····· and 45^{o} — — — .



(a) (b)

(c) (d)

Fig. 11. OFF state measurement results for TE incidence at angles of, 0^{o} —, 15^{o} ----, 30^{o} ····· and 45^{o} — — — .

D. Discussion of Results

Table I contains a summary of the simulated and experimental results including the -10dB bandwidths. Comparing the results shows good centre frequency stability near 2.4GHz for all polarisations at the angles of incidence measured, with any minor differences being attributed to tolerance of manufacture of the test surface. The centre frequency rejection was ≥ 20dB for the test surface, which is comparable with non-active surfaces. The OFF state insertion loss varied over a range of 1–3.5dB, with the worst case being 0_{45} and 90_{45}, but was much reduced when compared with the simulations of Fig 8(a-d). This was expected, as very narrow FSS responses are often attenuated [24] - the main contributor to loss at 45^{o} being the minor resonance at approximately 2.8GHz encroaching into the pass-band. As previously shown, the OFF capacitance of the PIN diodes significantly lowers the overall frequency response. A PIN diode with a lower value of capacitance would effectively increase the frequency of the unwanted response and consequently reduce these OFF state losses. Applying a reverse, as opposed to a zero bias offered no improvement in the surface OFF state performance.

The -10dB bandwidth was 1060-420MHz, dependent upon polarization and angle of incidence. Significantly it was lower than the simulated results, which would suggest that the ON resistance of the PIN diodes was less than the 1.5Ω per device quoted, resulting in a higher Q surface and hence narrower bandwidth. With a PIN diode effectively being a current controlled variable resistor, this is a feature of the device that might be used to give the surface an amount of bandwidth control.

V. CONCLUSION

This paper has presented a novel method of two-state switching of a ring FSS structure, both through computer simulation and practical measurements. A prototype 5x5 two-state ring FSS structure has been designed and fabricated, targeted at the WLAN band of 2.45GHz. The prototype surface was constructed using readily available materials and components and measured. Performance was in good agreement with computer simulations for both its ON and OFF states. Good stability for angle of incidence, at least up to 45^{o}, and at all rotation angles was also demonstrated. Although the rings were in this case set on a square lattice for symmetry, the same biasing arrangement is certainly feasible for modified lattice geometries [25], giving different reflection bandwidths – an issue of secondary importance here – and others with higher grating lobe onset frequency. In the interest of energy conservation, the ON state current and hence the power consumption, may be reduced below the 40mA in section IV *C*, but below about 10mA the signal attenuation in the operating band centred at 2.45GHz would be reduced. Furthermore, the power requirements are lower for small finite size FSS [26]. The surface presented here could be of interest to applications in both the built and other environments. One application is communications control between adjoining rooms in a building, by the simple operation of a switch, or a more intelligent control system.

TABLE I
SUMMARY OF SIMULATED AND MEASURED RESULTS

		Rotation Angle$_{\text{Angle of Incidence}}$ (Degrees)															
		0_0	**0_{15}**	**0_{30}**	**0_{45}**	**22.5_0**	**22.5_{15}**	**22.5_{30}**	**22.5_{45}**	**45_0**	**45_{15}**	**45_{30}**	**45_{45}**	**90_0**	**90_{15}**	**90_{30}**	**90_{45}**
Center Frequency (GHz)	**Simulated**	2.45	2.46	2.47	2.52	2.46	2.46	2.46	2.47	2.56	2.56	2.56	2.55	2.44	2.41	2.55	2.6
	Measured	2.44	2.46	2.4	2.38	2.4	2.4	2.42	2.43	2.41	2.44	2.4	2.41	2.38	2.36	2.36	2.42
Rejection (dB)	**Simulated**	-35	-35	-35	-35	-38	-38	-38	-38	-33	-33	-33	-33	-35	-35	-33	-32
	Measured	-22	-21	-20	-21	-21	-20	-20	-22	-25	-25	-24	-24	-25	-25	-25	-30
-10dB Bandwidth (MHz)	**Simulated**	870	890	940	1060	900	900	900	890	850	840	860	850	860	870	910	1000
	Measured	680	640	660	680	700	700	700	680	700	680	600	580	720	720	500	420
OFF state insertion loss at 2.45GHz (dB)	**Simulated**	-1.7	-1	-2	-4.5	-3	-3	-3	-3	-4	-4	-4	-4	-1.7	-2	-2.3	-4.5
	Measured	-1.5	-1	-1.7	-3.5	1.6	1.7	1.7	3.4	1.5	1.5	1.6	2.6	-1.6	-1.1	-1.7	-3.5

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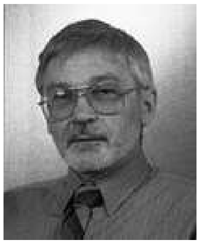

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