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Communications

Switchable Frequency Selective Surface for Reconfigurable Electromagnetic Architecture of Buildings

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Abstract—A frequency selective surface (FSS) that is electronically switchable between reflective and transparent states is tested. It can be used to provide a spatial filter solution to reconfigure the electromagnetic architecture of buildings. The FSS measurements show that the frequency response of the filter does not change significantly when the wave polarization changes or the angle of incidence changes up to $\pm 45^\circ$ from normal. The FSS is based on square loop aperture geometry, with each unit cell having four PIN diodes across the aperture at 90 degree intervals. Experiments demonstrated that almost 10 dB additional transmission loss can be introduced on average at the resonance frequency, for both polarizations, by switching PIN diodes to ON from OFF state.

Index Terms—Active frequency selective surface (FSS), electromagnetic architecture, frequency selective surface (FSS), oblique incidence, PIN, security, stability, switchable.

I. INTRODUCTION

In large buildings and offices, frequency re-use methods are required to enhance the spectral efficiency and capacity of wireless communication systems. This observation has led to the concept of electromagnetic architecture of buildings [1], [2]. Passive bandstop frequency selective surfaces (FSSs) can be used to enhance the electromagnetic architecture of a building, and hence to improve spectral efficiency and system capacity, but switchable FSSs can provide a better reconfigurable solution. If switchable FSSs are placed in strategic locations of a building, they can be reconfigured remotely and rapidly, which is not possible with passive FSSs [1]. This paper describes an electronically-switchable FSS, with a highly stable frequency response, useful in such applications.

Recently, a considerable amount of research is carried out in the field of switchable FSS to achieve a reconfigurable frequency response for different applications [2]–[12]. Among different methods to obtain a variable FSS frequency response, the PIN diodes are mostly used to switch an FSS between ON and OFF states. Most research has been car-

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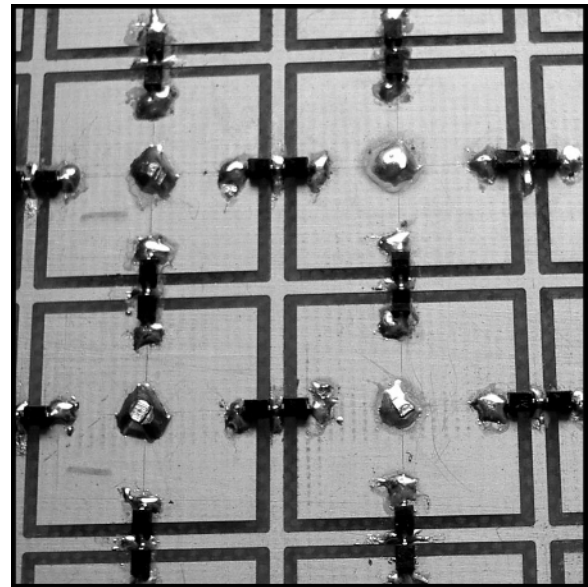


Fig. 1. The front close-up view of the switchable FSS prototype.

ried out on bandstop FSSs, such as arrays of metallic dipoles, which have a switching device (e.g., diode) placed between the arms of the dipoles. Conversely, their bandpass version consisting of an array of slots is not suitable for the inclusion of active elements as the bias applied to the devices will short across the metal surface. Recently, an attempt was made to design an active band pass FSS using two FSS layers [8]. In this design, one of the FSS layers is a standard bandstop active FSS which is placed in front of a passive bandpass FSS with a thin layer of PCB. This design is quite complex and require accurate design tools and high manufacturing accuracy. In order to alleviate these constraints, a single layer switchable FSS is presented in this paper. Its frequency response does not change significantly with polarization (TE and TM) and angle of incidence (up to $\pm 45^\circ$ from normal) and can be used to electronically reconfigure electromagnetic architecture of buildings.

Switchable FSS Prototype: The FSS tested here is based on the theoretical design given in [11]. These theoretical results have predicted a frequency response that does not change significantly with polarization (TE and TM) and angle of incidence up to 60° . An FSS with 25×15 elements was fabricated based on the theoretical design. The overall size of FSS prototype is $45 \text{ cm} \times 30 \text{ cm}$. The thickness of the FR4 substrate was 1.6 mm. Figs. 1 and 2 show the front and rear close-up views of the switchable FSS prototype, respectively. There are four PIN diodes in each unit cell. Positive dc biasing is applied from the front side of FSS. The diagonal negative dc bias lines on the reverse side are joined together on the border of the FSS prototype. It can be seen in reference [12] that crossed shape bias lines produced stable frequency response at oblique angles only for TE polarization (while unstable for TM), therefore diagonal biased lines were preferred in this particular design.

II. MEASUREMENT SETUP

Transmission: Fig. 3 shows the measurement setup for the switchable FSS prototype. HyperLog 7060 log periodic antennas from Aar-

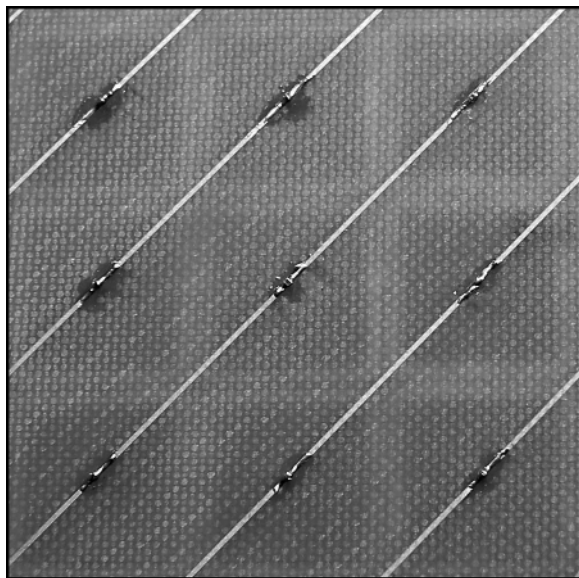


Fig. 2. The rear close-up view of the switchable FSS prototype.

iona were used for the measurements [13]. These antennas operate between 700 MHz to 6 GHz and were well suited for the experimentation. The antennas were connected to a vector network analyzer (Rohde & Schwarz ZVC, 20 KHz to 8 GHz). The measurement procedure for each set-up included a reference measurement without the FSS in the window. The instrument was then calibrated for transmission over the frequency range. This means that the subsequent measurement was relative to the transmission through the aperture. In this way any diffraction around the edges of the finite metal sheet were included. Furthermore, the influence of reflections from the floor was studied by putting in absorbing material, which did not make any detectable difference in the measurement. Personnel moving around in the room more than a meter and a half away from the set-up did not affect the result, which lead to the conclusion that other reflections did not cause any major errors. To measure the oblique incidence performance of FSS prototype, the antennas were kept stationary while the position of FSS aperture was changed for each angle of incidence. Straight lines were marked on the floor for each angle of incidence by considering the initial position of the FSS aperture (in metal frame) as a reference (normal incidence). The metal frame having FSS aperture was carefully rotated to align it exactly to the marked lines on the floor (for each angle of incidence, see Fig. 3). This experimental arrangement was found to have sufficient positioning accuracy to provide repeatable measured results. To measure both TE and TM polarizations, the antennas were rotated around their axes by 90° .

Reflection: Reflectivity measurements were carried out using a standard NRL (Naval Research Laboratory) arch [14], which is housed within an anechoic chamber. The measurement system is illustrated in Fig. 4 and consists of two wide band horns, covering 2–18 GHz, connected to an HP8510C automatic vector network analyzer (VNA). Rohde and Schwarz HF906 double ridged waveguide horn antennas were used [15]. The switchable FSS sample under test was supported on a low density expanded polystyrene table, which was surrounded by 12 inch pyramidal absorbers. The system was calibrated using a response/isolation technique (vector error correction). The isolation measurement was carried out by first removing the polystyrene table and sample so that the horns were illuminating the chamber absorber directly. For the response measurement the table was replaced and a metal plate was positioned so that its center was on the axis of rotation of the

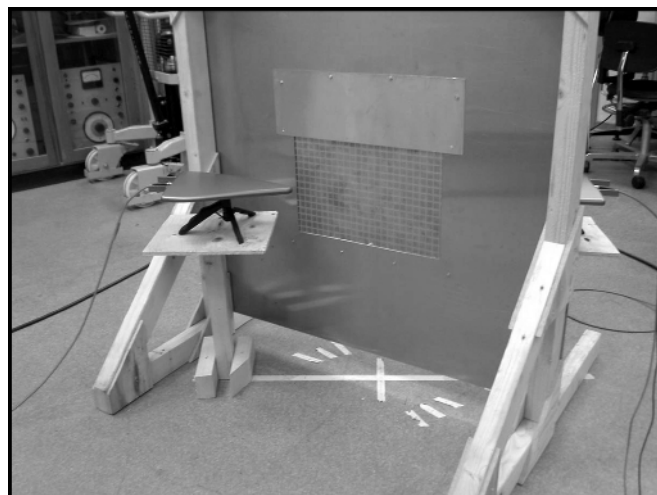


Fig. 3. The transmission measurement setup showing the switchable FSS fixed in a metallic frame between two log-periodic antennas.

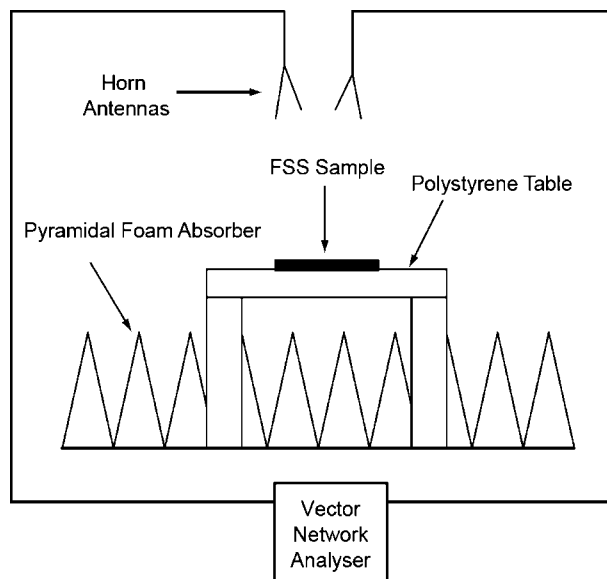


Fig. 4. The block diagram showing the reflection measurement setup.

arch arms which carry the wide band horns. This resulted in a calibration which gave a dynamic range of better than -55 dB across the entire frequency range and this was deemed sufficient to assess the performance of the FSS. To improve the measurements further, the time domain gating feature within the VNA was used to reduce any erroneous scattering. In order to carry out oblique incidence measurements the supporting arms of the arch were rotated to the appropriate angle using accurate predetermined fixings and the horns were rotated through 90° each depending on the polarization needed. The previously described calibration was repeated for each angle and polarization.

PIN Diodes Biasing: A total of 1500 Philips (BAP51-03) [16] diodes were used in the fabrication of FSS prototype which is relatively costly even when cheaper diodes were used. However, the cost may be further reduced by using technique described in references [2], [7]. In a practical situation it is envisaged that an active FSS would be used as a small aperture within a conducting wall, rather than applying the FSS over the entire wall or room. This would reduce the costs of the FSS and this approach was investigated successfully in [7]. To switch these PIN diodes from OFF to ON state, a forward voltage of 2

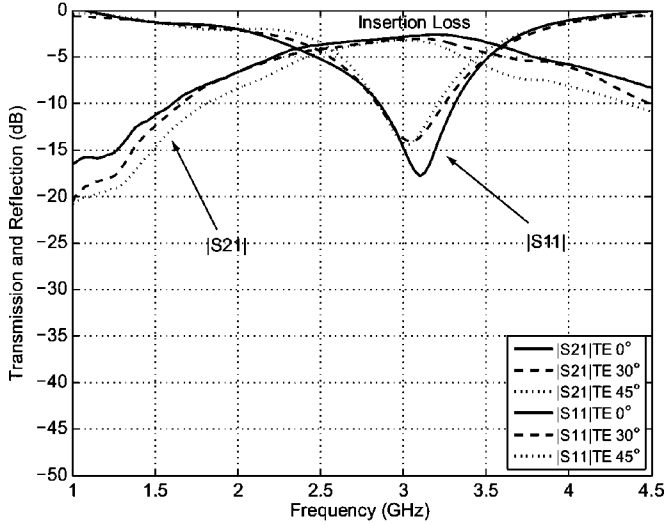


Fig. 5. Measured transmission and reflection characteristics of switchable FSS for perpendicular polarization (TE) when the diodes are in OFF state.

V was applied to the FSS prototype in both transmission and reflection measurements. The biasing of the diodes is accomplished such that all the diodes are electrically in parallel. To forward bias them the power supply is set to deliver a current of 2 A, which is divided among the diodes giving each a bias current of about 1.3 mA. A further increase in current did not affect the attenuation. No voltage was applied in the reverse bias case.

III. MEASURED RESULTS

A. Perpendicular (TE) Polarization

PIN Diodes OFF: Fig. 5 shows the measured transmission and reflection characteristics at 0° , 30° and 45° incidence angles for perpendicular polarization (TE incidence) when the PIN diodes are in OFF state. The resonance occurred at 3.2 GHz for 0° , with a -17.5 dB reflection. The insertion loss at this frequency for 0° is 2.6 dB. At 30° and 45° incidence angles, the resonance frequency slightly shifts downward to 3.1 and 3.05 GHz, respectively, both with a reflection coefficient of -14 dB. The insertion losses for these incident angles are 2.6 and 2.6 dB, respectively.

Comparing the theoretical results in [11], the measured resonance frequency is shifted upwards by about 0.6 GHz. The average transmission loss in theory is 0.7 dB as opposed to 2.6 dB in measured results. There are three main causes for the higher values of measured transmission loss: dielectric losses, diode losses and the reflection losses due to physical presence of diodes and the soldering material on FSS surface. The shift in resonance frequency from 2.45 GHz (theoretical) to 3.2 GHz (measured) may be due to: (a) lower value of dielectric constant of the substrate used for the fabrication of active FSS; (b) inaccuracies in the parameters values in the diode model; (c) extra inductance added by the dc interconnecting lines on the border of finite FSS (rear side); and (d) the soldering material used in FSS fabrication. The other reason is the extra inductance added by the continuous diagonal bias line as opposed to Fig. 2 in [11], in which the bias line has a small discontinuity.

PIN Diodes ON: Fig. 6 depicts the measured transmission and reflection coefficients for perpendicular (TE incidence) polarization when the diodes are in ON state. For 0° , 30° and 45° incidence angles, the reflection coefficient is close to 1 dB while the transmission loss is 11.5, 13, and 14.6 dB, respectively. Therefore, at 0° , 30° and 45° incidence angles, the transmission loss can be switched by 8.9, 10.4, and 12.0

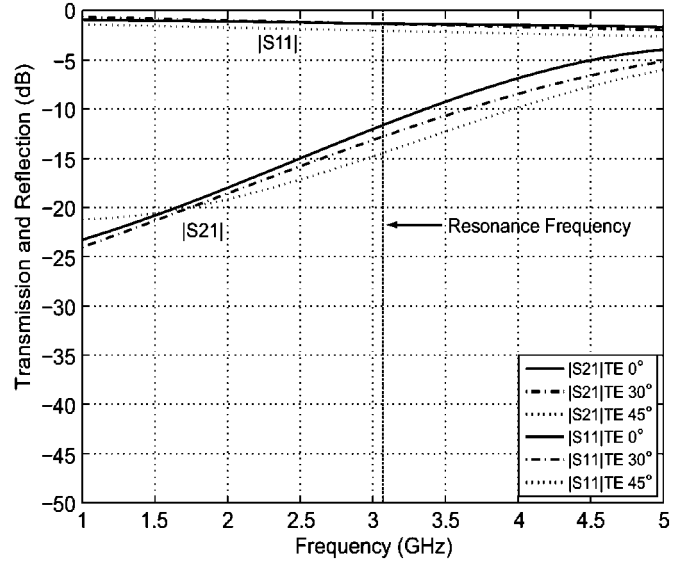


Fig. 6. Measured transmission and reflection characteristics of switchable FSS for perpendicular polarization (TE) when the diodes are in ON state.

dB, respectively, by switching PIN diodes from OFF to ON state. As far as the amplitude variation is concerned, although the transmission response varies over the measurement frequency range, the actual used bandwidth is much smaller than this (IEEE802.11b). The frequency variation over this bandwidth is much smaller and so would not be an issue in the application it is intended for.

B. Parallel (TM) Polarization

PIN Diodes OFF: Fig. 7 shows the measured transmission and reflection characteristics at normal and oblique incidence angles for parallel polarization (TM incidence). The resonance and insertion loss at normal incidence are the same as in TE case, as expected from the symmetry of the unit cell. The change in the resonance frequency is also the same as in TE case while the reflection coefficients at 30° and 45° are -21 dB and -28 dB, respectively. The transmission losses for these angles of incidence are 2.4 and 2.3 dB (due to Brewster effect), respectively.

PIN Diodes ON: Fig. 8 depicts the measured transmission and reflection coefficients for perpendicular (TM incidence) polarization. For 0° , 30° and 45° incidence angles, the reflection coefficient is close to 1 dB while the transmission loss is 14, 13.5, and 12.2 dB, respectively. Therefore, at 0° , 30° and 45° incidence angles, the transmission loss can be changed by 11.4, 11.1, and 9.9 dB, respectively, by switching PIN diodes from OFF to ON state.

The use of any FSS design to control wireless coverage in a building environment depends on many factors, such as transmitting source power, receiver sensitivity, room layout, distance between sources and building construction materials. It is not proposed that entire rooms be coated with FSS. This is discussed in [8] in which a simple path loss analysis shows that >30 dB transmission loss may be required for an FSS wall, which this FSS design would not provide. The potential in FSS designs is in the use as a small aperture embedded in a shielded room, as discussed and demonstrated in [8]. In this case and with full recognition of the factors mentioned above, this FSS design offers a practical solution.

IV. CONCLUSION

In this paper, experimental results for a single-layer switchable FSS are presented. PIN diodes along with square apertures are used.

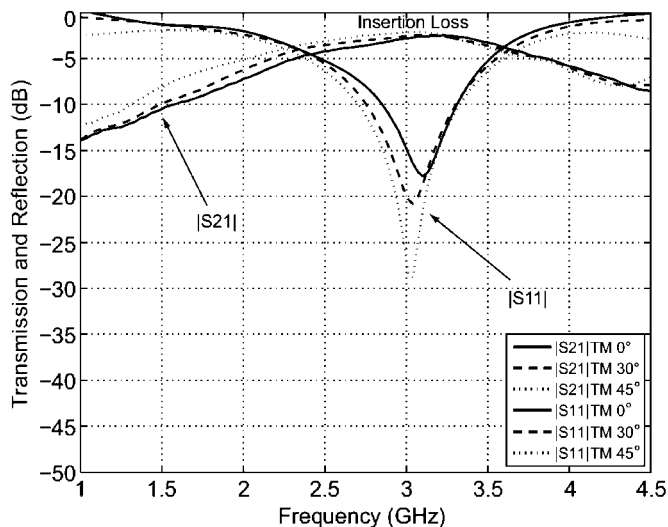


Fig. 7. Measured transmission and reflection characteristics of switchable FSS for parallel (TM) polarization when the diodes are in OFF state.

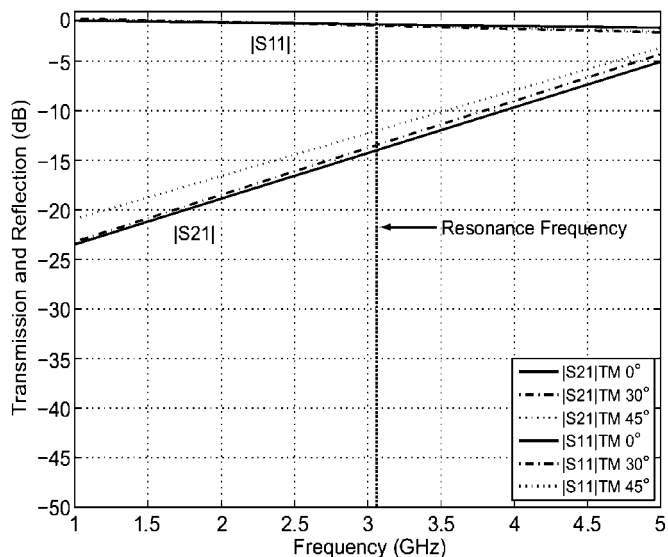


Fig. 8. Measured transmission and reflection characteristics of switchable FSS for parallel polarization (TM) when the diodes are in ON state.

The prototype FSS has shown a stable transmission response for both TE and TM polarizations. Experimentally, an average additional transmission loss of 10 dB is achieved for both polarizations at normal and oblique incidence, by switching PIN diodes between forward and reverse bias. Further isolation may be obtained by using a dielectric having low loss tangent, better quality PIN diodes and dual layer FSS architecture. Beside other applications, it may find use in electronically reconfiguring electromagnetic architecture of buildings.

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