Characterization of Switchable Substrateless Frequency Selective Surfaces

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Abstract: In this paper, a new means for characterization of switchable substrateless frequency selective surfaces (FSS) was demonstrated with numerical and experimental approaches. The diodes model loaded active doubly periodic flat strip FSS acts as a dynamic screen, in which its surface reflectivity and transmittivity can be switched alternately and tuned through d.c. bias voltage control. The properties of FSS layer are characterized using a specially designed parallel plate waveguide (PPW) simulator that permits normal incidence excitation of the FSS under test and the responses are found between 3 to 5 GHz. It is shown that by means of d.c. bias control, the screen can be utilized in, (a) transmission mode as a dual band electromagnetic shutter, or, (b) reflection mode, as an amplitude shift keying (ASK) spatial modulator or dual band reflection canceller. In addition a hybrid de-embedding technique is employed to remove the influence the PPW simulator and reveal the true property of substrateless FSS. Typical experimental results are presented and validated against a new 3D electromagnetic (EM) modeling led de-embedding method for the composite FSS layer and PPW structure.

Keywords: Characterization, dual band, frequency selective surfaces (FSS), parallel plate waveguide, substrateless

1. Introduction

Frequency selective surfaces (FSS) have been widely used in a number of applications in communications systems. Many element geometries have been investigated ranging from dipole and square patch to circular loop to explore their unique properties [1]–[2]. The transmission and reflection coefficients of frequency selective surfaces (FSS), which can be usually constructed as planar two-dimensional periodic arrays of metallic elements with specific geometrical shapes, are dependent on the frequency of operation and may also depend on the polarization and angle of incidence [2]. For a variety of applications, it would be more attractive to have an electronically controllable tunability FSS for the selection of frequency as well as the transmission and reflection characteristics. Moreover, the possibility of having frequency bands at which a given FSS is completely opaque (stop-bands) and others at which the same surface allows wave transmission has became the interesting topic for the electromagnetic research in the recent years [3]-[6].

On the basis of the design of FSS structures, most part the applications using these structures require only passive printed conductors that usually be deployed on a dielectric substrate. Here the dependency on the substrate is high and hence the post-fabrication no possibility exists to change the frequency or polarization characteristics once designed and manufactured. Further, the relative applicable bandwidth of the surfaces is normally not more than few percents of the resonance frequency. Controllable metafilm has been introduced recently as one of the efforts to expand working frequency band [7]-[8], which includes a surface with certain amount of electrical small scatterers, turned by bias magnetic fields.

However, from the practical implementation magnetic field is more difficult to apply for large working area uniformly. Another effort is by integrating active frequency selective surfaces loaded with pin diodes into a single microwave low reflection layer with reflectivity as a function of diode bias current [9]. As compared with conductive polymer with tunable properties, this type of material does not require high biasing voltage or large devices to achieve large tunability.

Double periodic arrays of passive strip or slot dipole grids loaded with diodes are proposed here as a structure suitable for substrateless FSS layer [10]. In this paper, first the electromagnetic properties of FSS layer with switchable characteristic response are investigated with numerical approaches. The structure of FSS layer is comprised of conductive flat strip dipole array loaded with diodes model. The aim of investigation is to analyze the correlation of parameters of the diode when being driven by an external bias to the reflection and reflection characteristics of the structure. The equivalent circuit parameters of diode connected the pattern of conductive strip dipole are then analyzed numerically by 3D EM modeling. Then experimental investigations are performed using a PPW simulator that especially designed to permit normal incidence excitation of the FSS under test [11]. After performing 3D EM led de-embedding process using a hybrid de-embedding technique [12], the measurement results are then compared with the simulated results. The resulting structure is shown to have dual band properties in both transmission and reflection mode which are useful for a variety of applications including electromagnetic shutter, spatial amplitude shift keying (ASK) modulator, and narrowband microwave absorber. In addition, we show a means for modeling the entire FSS layer and PPW simulator test fixture as well as a method for test fixture de-embedding.

2. FSS Structure and Numerical Analysis

As discussed in [5], a lumped loaded planar strip equivalent of a wire dipole is used as a typical FSS unit cell and imaged to form a double periodic array of infinite extent. The imaged FSS array is then illuminated by an incident monochromatic plane wave. Inhomogeneous impedance boundary conditions are applied to each dipole of wire with lumped elements to balance the tangential vector components of the incident and scattered fields with the voltage contributions provided by the individual lumped elements. For thin wires, it can be assumed that the current has only a longitudinal component.

Starting with an integro-differential equation approach the current distribution on the wires is expanded in single/double periodic Fourier series according to Floquet's theorem. The current distribution is numerically solved by applying the method of moments. Having solved the current distribution of thin wires, the scattered field can be evaluated as a convolution of Green's function and is represented by the superposition of Floquet harmonics.

For numerical analysis, the switchable substrateless FSS structure is based on the structure in [10] comprised of a □/2-resonant frequency strip dipole center loaded with diodes. As shown in Fig. 1, each package of diode contains of 2 parallel RF Schottky diodes where the linear equivalent circuit of each diode is modeled as a lumped RLC boundary condition based on the data sheet of the diode [13]. R_S is the series resistor while Cj and Rj are the junction adjustable capacitor and resistor, respectively. The value of Cj and of Rj can be changed depending on the external bias current. In order to change the value of Cj and Rj experimentally, a d.c. bias control is applied across the lead of the diode.

The overall structure is illustrated in Fig. 2 consists of three flat copper strips each of length 49mm (including gap for modeled RF Schottky diode), width 4mm and spacing 50mm. A TE mode plane wave with electric field E parallel to the flat strips dipole and wave vector *k* perpendicular to the layer surface illuminates the FSS array at normal incidence obtaining the frequency response of the structure.

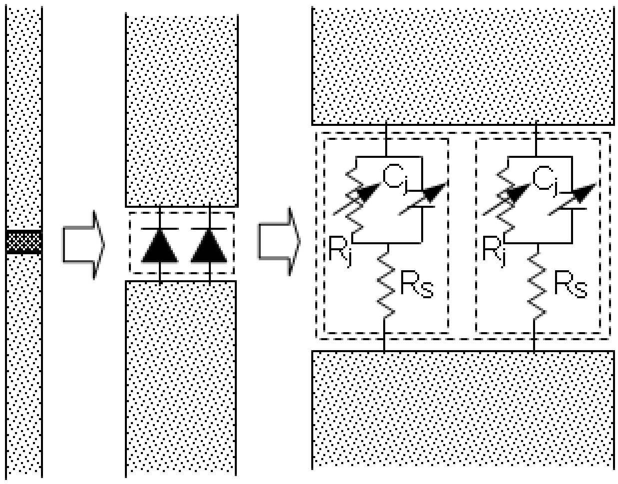

Figure 1 RF Schottky diode loading arrangement and equivalent circuit

Following the standard practice in all finite element method (FEM) simulations for infinite or periodic structure, the domain of computation is truncated by defining the electric wall on the sides that are perpendicular to the electric field E of plane wave. Hence, the absorbing boundary conditions are imposed on sides that are parallel to the electric field E. As provided in the simulation software, a convergence condition is determined to achieve sufficiently accurate results which is the difference in the electric field strength between the current and previous iterations to be less than a prescribed value. Whilst an adaptive meshing technique is set to automatically refine the mesh at locations where the error in the numerical result is large.

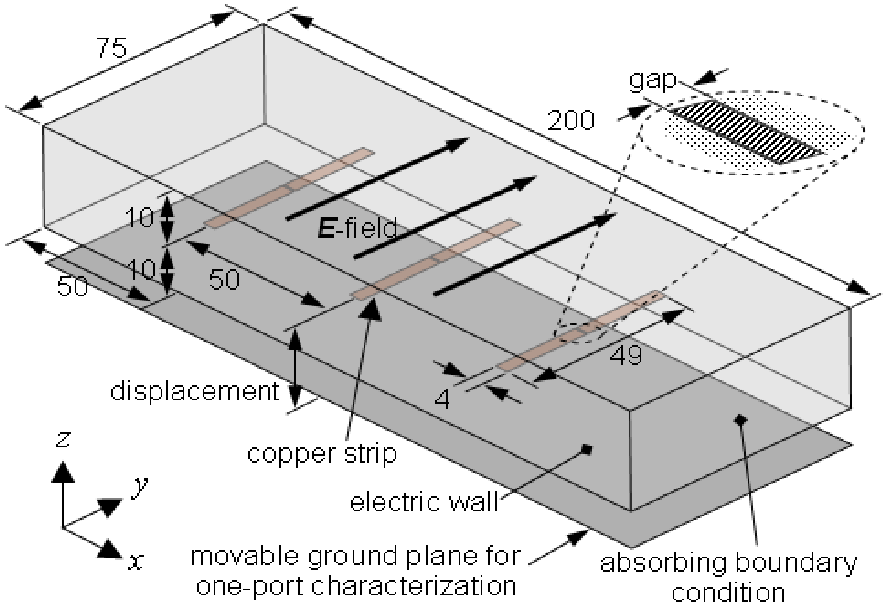

Figure 2 Overall substrateless FSS structure (units in mm)

3. Numerical Investigation and Characterization

3.1 Parametric Investigation of Tunable Components

In the numerical investigation of tunable components of the RF Schottky diode for the ON and OFF states, i.e. the values of Rj and Cj, as the effect of the forward and reverse biases, respectively, at first the structure with the equivalent circuit model shown in Fig. 1 is simulated with the resistance of R_S is set to be 6□, then the resistance of Rj is changed from 1□ to 100k□ with 0.7pF of Cj representing the forward bias (ON state) of the diode. The value of Cj is taken from the data sheet shown in Table 1.

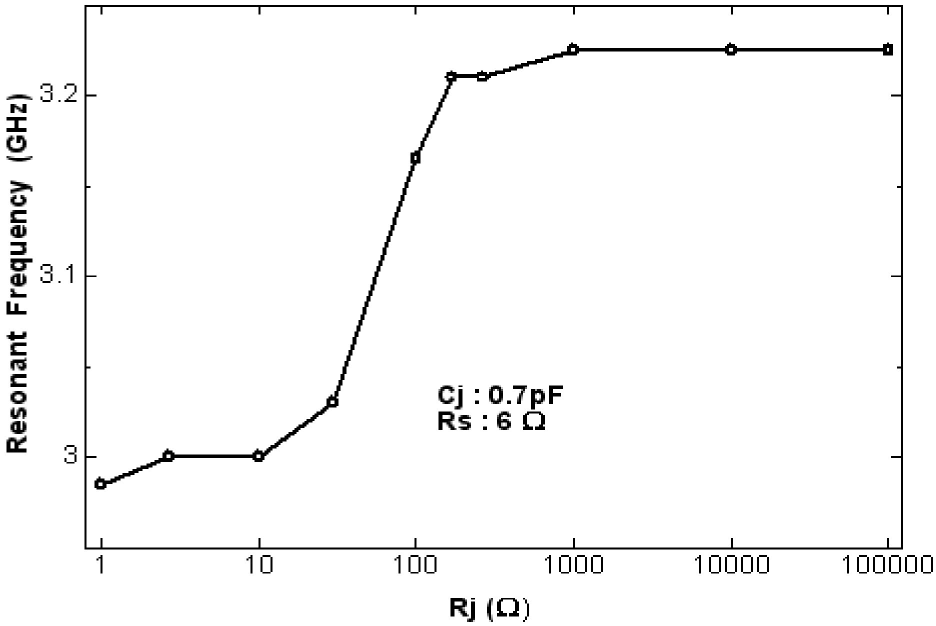

Figure 3 Simulated result of resonance frequency for substrateless FSS structure as a function of Rj (ON state)

Figure 3 depicts the dependence of resonance frequency of the structure on Rj value for the ON state. It is found that when the resistance increases from 1k□ to 100k□, the resonant frequency increases from 2.95GHz to 3.23GHz for the ON state which stands for the maximum tunability can be realized by this component. From the result, it is seen that for the ON state the value of Rj needs to be low enough□. It should be noted that the small varied value of Rj (less than 10□□) does not change the total impedance of structure appreciably, as a result the resonance frequency is relatively constant.

Similarly, the structure is then solved with the capacitance of Cj is varied from 0.001pF to 10pF; the resistance of R_S is set to be the same as the previous attempt and 1.2M□ of Rj representing the reverse bias (OFF state) of the diode.

Figure 4 plots the dependence of resonance frequency of the structure on Cj value for the OFF state. Here the value of Rj is chosen to be high enough to ensure that the diode is completely on the OFF state. From the result, in the comparison with Fig. 3 it seems that the resonance frequency ranges of the Cj controlled structure are wider than the range of the Rj controlled structure. It can be seen that when the capacitance increases from 0.001pF to 10pF, the resonance frequency decreases appreciably from 4.81GHz to 3.01GHz for the OFF state, which can be noted that the Cj controlled structure is more sensitive as a mean to control the frequency response than the Rj controlled structure. For the value of Cj from 0.01pF to 0.7pF, the resonance frequency decreases almost linearly with the capacitance in log–log scale.

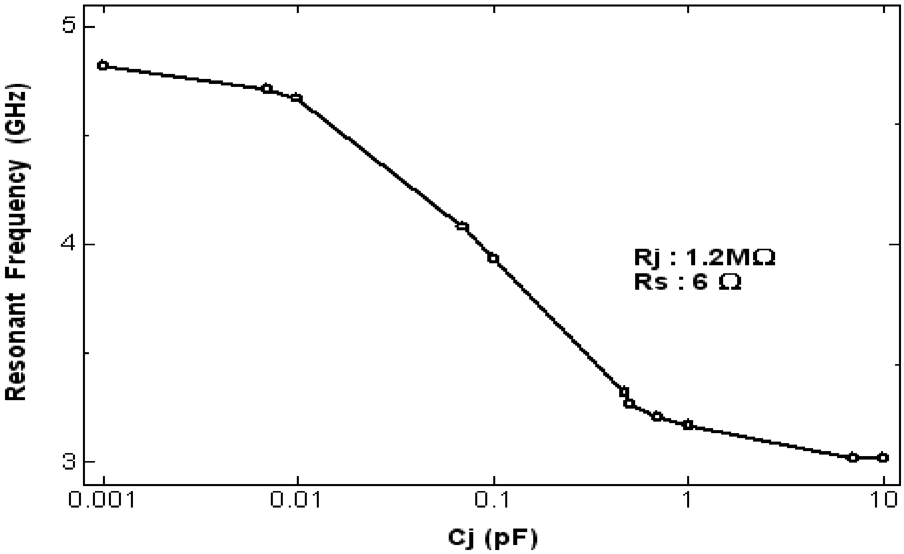

Figure 4 Simulated result of resonance frequency for substrateless FSS structure as a function of Cj (OFF state)

3.2 Two-port and One-port Characterization

The investigation of dual band properties of the proposed structure is carried out by numerically characterized the two-port response for two pair different values of Rj and Cj. By keeping the resistance of R_S to be 6, the values of Rj and Cj are chosen 2.7 and 0.7pF, respectively for the ON state, and 1.2M and 0.01pF, respectively for the OFF state. Figure 5 shows the simulated results for the both states. It should be noted that the value of Cj for the OFF state is set to be low enough making the diode completely switched off since for the OFF state the total impedance of the structure is more affected by the value of Cj than Rj. From the figure, it shows that the proposed structure has dual band properties allowing energy to be selectively transmitted or reflected. Another important issue required to analyze how far the difference between the reflected or the transmitted waves when the diode is switched on or off is the isolation of reflected and transmitted waves for the OFF state to the ON state. The isolation is defined as the ratio of the reflected (or transmitted) waves when the diode on the OFF state or ON state to the reflected (or transmitted) waves when the diode is on the ON state or OFF state, respectively. From Fig. 5, it shows that the isolation between ON and OFF states is 22.19dB @ 3.00GHz (0.2dB OFF state insertion loss) and 40.13dB @ 4.66GHz (0.1dB ON state insertion loss), respectively.

Next, one-port characterization of the switchable substrateless FSS is conducted by replacing the port 2 with a ground plane. The reflection characteristic of the proposed structure with a movable ground plane of 200mm width and 75mm height inserted at the reverse side in its ON and OFF states as illustrated in Fig. 2 is numerically investigated over a range of displacement between the backplane and the structure between 30mm and 60mm. The result of this simulation for 40mm displacement is plotted in Fig. 6.

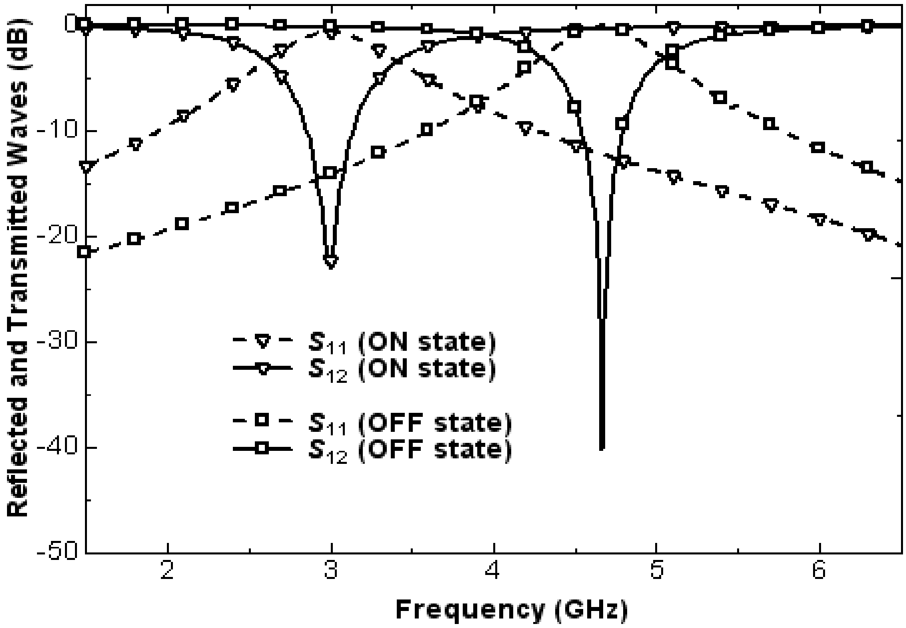

Figure 5 Two-port simulated result of transmitted and reflected waves of FSS structure for ON and OFF states

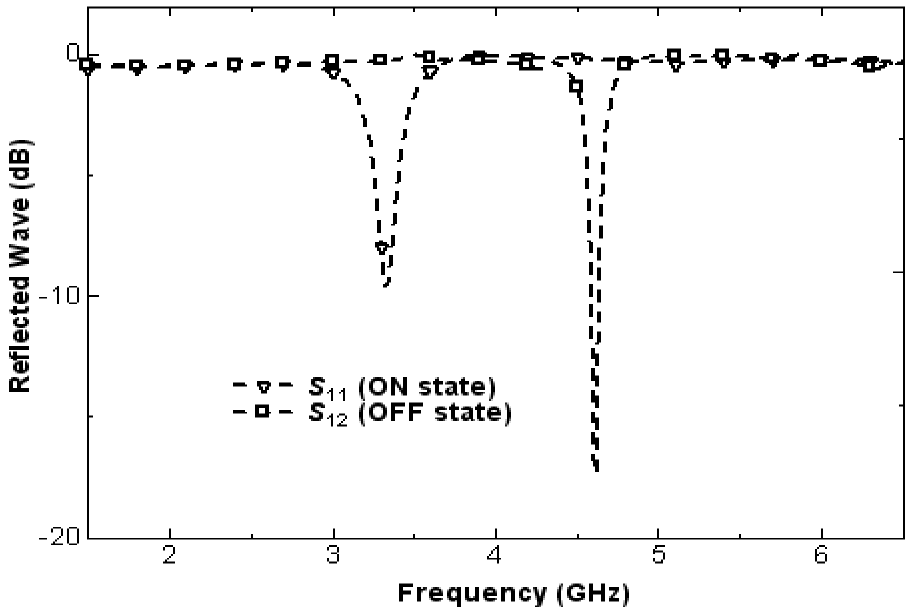

Figure 6 One-port simulated result of reflected wave of substrateless FSS structure for ON and OFF states (40mm displacement)

From the result, it shows that the metallic backplane placed behind the FSS structure causes the destructive interference of returned signals to port 1 attenuated by 9.56dB @ 3.33GHz (ON state) and 17.32dB @ 4.62GHz (OFF state).

5. Experimental Investigation

From the simulated result depicted in Fig. 4, it shows that the diode modeled by linear equivalent circuit requires at least 0.01pF of Cj to make the diode completely OFF. However, based on the data sheet [13], the minimum value of Cj that can be achieved is only 0.5pF. Since the minimum value of Cj based on the datasheet is too high to make the diode completely OFF, therefore, for practical implementation a beam lead pin diode HPND-4005 is proposed. From the datasheet [14], the proposed pin diode, which every package contains only of 1 diode, has the lowest junction adjustable capacitance Cj around 0.017pF that closed to the requirement, as well as the values of R_S and Rj. In order to be comparable to the experimentation, the numerical characterization is re-established accordingly for the FSS structure loaded with modeled HPND-4005 planar beam lead pin diodes.

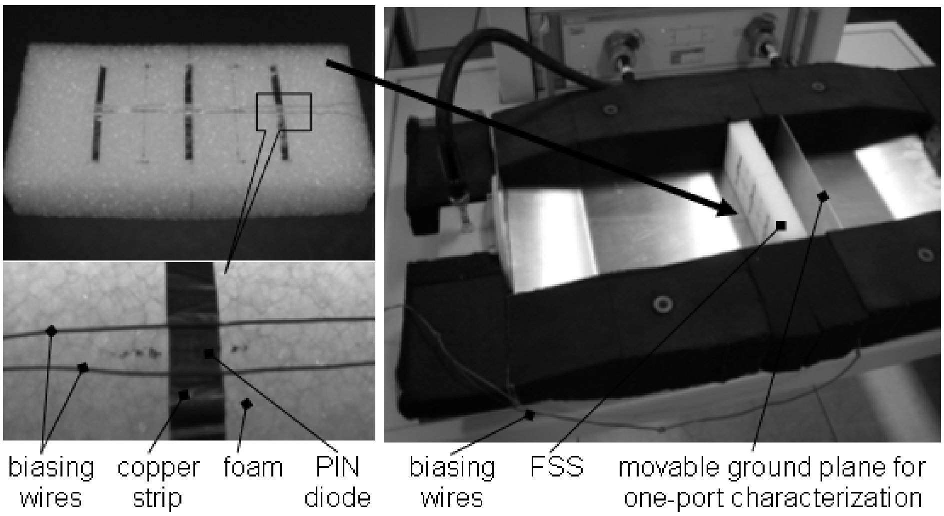

Figure 7 Fabricated switchable FSS structure and dismantled PPW simulator

Figure 7 (left) shows the picture of the fabricated switchable FSS structure for the experimental investigation. The structure is constructed from three copper strip dipoles of length 49mm (thickness 25μm), width 4mm, and spacing 50mm center loaded with the HPND-4005 planar beam lead pin diodes placed on the lossless foam (thickness 25mm and $\varepsilon_r \approx 1$) as a supporting substrate. The bias voltage is applied directly across the pin diodes using two parallel wires which are orthogonal to the applied incident field. Then, the FSS structure is placed inside the PPW simulator to have its transmission and reflection characteristics measured. Figure 7 (right) shows the dismantled PPW simulator used to perform characterization of the FSS structure normal incidence. It should be noted that conventional waveguide simulation methods are not applicable here, since they cannot be used to characterize the FSS structure at normal incidence. The incident wave is launched/received at coaxial input and output ports using coaxial to waveguide transducers. The PPW simulator that has taper length 100mm, plate length 400mm, plate width 200mm, and plate separation 75mm has been optimally designed to support a plane-wave normally incident beam [11].

The de-embedding result of two-port *S*-parameter measurements to investigate the dual band properties of the structure made for both ON and OFF states obtained according to the method described in [12], are depicted together with the simulated results in Fig. 8.

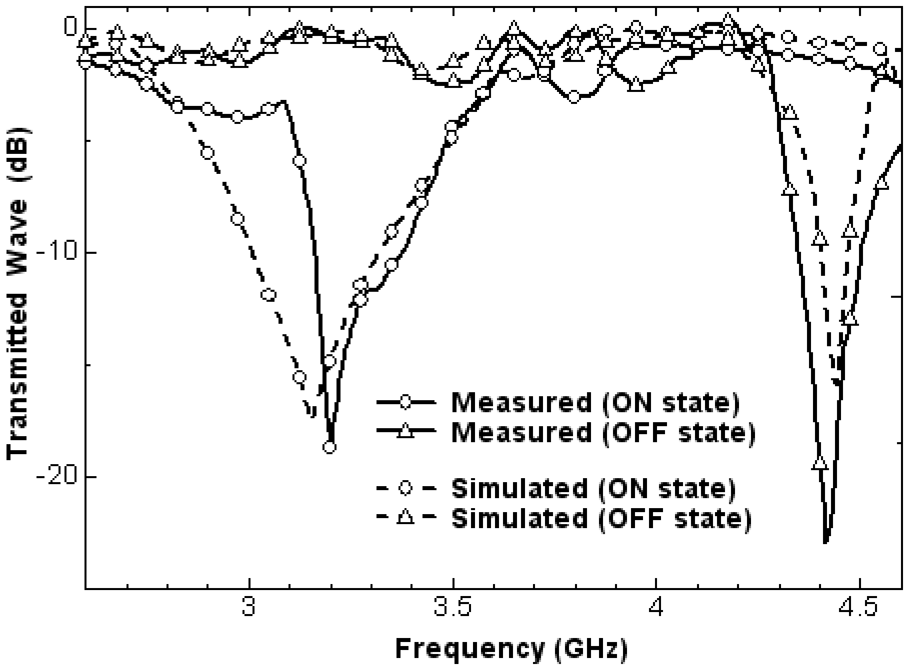

Figure 8 Measured and simulated results of transmitted wave of substrateless FSS structure for ON and OFF states

From the figure, it shows that the simulated results have a reasonable agreement with the de-embedded measured data. Fig. 8 also shows that when the diodes are forwardly biased (ON state), the FSS layer is transparent at 3.20GHz and when reversely biased (OFF state) it is transparent at 4.42GHz. The difference between the simulated and measured resonance frequencies is about 45 MHz for both states. Here, the isolation between ON and OFF states is 18.30dB @ 3.20GHz (0.7 dB OFF state insertion loss) and 22.98dB @ 4.42GHz (1.0dB ON state insertion loss), respectively.

To investigate further the one-port characterization of the switchable FSS, a 200mm width and 75mm height movable ground plane is inserted at the in reverse side of the FSS structure as shown in Fig. 7 (right). To obtain a perfect ground plane, the top and bottom sides of variable backplane are contacted to the upper and lower walls of PPW simulator. Similar to the simulation, the reflection responses of the structure in its ON and OFF states are measured over a range of displacement between the backplane and the FSS surface between 30 mm and 60 mm. The measured results leading de-embedding process to obtain the true electrical characteristics of the FSS structure are depicted in Fig. 9 together with the simulated results with approximately –30MHz variation in resonant frequency occurring for the measured ON state and –10 MHz for the measured OFF state relative to the 60mm displacement of backplane.

The results demonstrate that the presence of the metallic reflector positioned behind the FSS structure is leading to two frequency bands, 3.25GHz (ON state), and 4.35GHz (OFF state), where destructive interference is occurring leading to the signal returning to port 1 being attenuated by 12dB (ON stated) and 20dB (OFF state), respectively. This behavior suggests that the layer can exhibit the same functional behavior as a radar absorber in so far as the energy returned to the excitation source is reduced, albeit over a small frequency range. A second interesting feature of this arrangement is that at either 3.25GHz or 4.35GHz by toggling between ON and OFF states the incident signal reflected from the surface can be amplitude shift keyed.

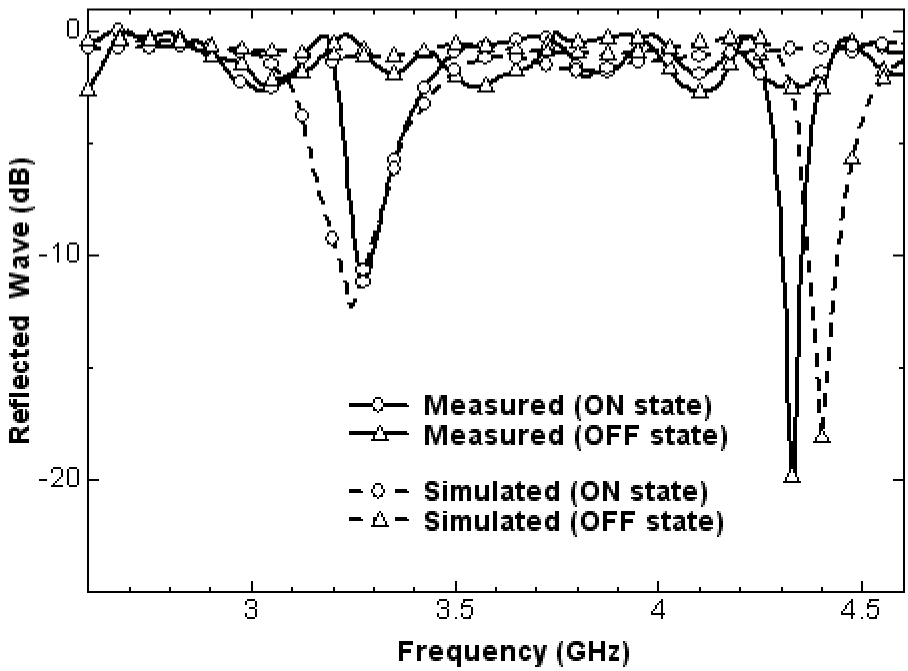

Figure 9 Measured and simulated results of reflected wave of substrateless FSS structure for ON and OFF states (60mm displacement)

6. Conclusions

The characteristic response of a flat strip substrateless FSS structure center loaded with diodes was investigated numerically and experimentally. It was demonstrated that the proposed structure can be operated as an electronic shutter allowing energy to be selectively transmitted or reflected with in excess of 18dB isolation between them at two distinct frequency bands both for numerical and experimental investigations. This feature should be useful for electromagnetic compatibility (EMC) energy control by acting as a spatial switch, or for agile radome applications. It was also shown that the inclusion of a metallic ground plane positioned behind the structure leads to destructive interference, again occurring at two distinct frequencies and chosen by whether the diode ON or OFF states is selected. It means that the structure can be dynamically switched to produce ASK backscattered encoded energy, or statically operated as a reflector or narrowband absorber in toggled between either of its two operating frequency ranges. Thus, the structure can be made to act as either a reflector, and absorber, or a modulation backscatter device. These properties could ultimately be exploited in RFID or agile radar cross-section applications.

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References

1. R. Mittra, C. H. Chan, and T. Cwik, "Techniques for analyzing frequency selective surfaces – a review," *Proc. of IEEE*, vol. 76, no. 12, pp. 1593-1615, Dec. 1988.
2. B. A. Munk, "Frequency Selective Surfaces: Theory and Design", *New York: Wiley*, 2000.
3. A. Tennant and B. Chambers, "Adaptive radar absorbing structure with PIN diode controlled active frequency selective surface," *Smart Mater. Struct.* vol. 13, pp. 122-125, Jan. 2004.
4. C. Mias, "Varactor-tunable and dipole-grid-based frequency-selective surface," *Microwave Opt. Technol. Lett.* vol. 43, pp. 508-511, Dec. 2004.
5. A. Munir, V. Fusco, and O. Malyuskin, "Tunable frequency selective surfaces characterisation," *in Proc. 38th EuMC*, Amsterdam, 2008, pp. 813-816.
6. A. Munir and V. Fusco, "Frequency selective surface with dual band switchable reflection and transmission," *Microwave and Optical Tech. Lett.* (to be published)
7. C. L. Holloway, M. A. Mohamed, E. F. Kuester, and A. Dienstfrey, "Reflection and transmission properties of a metafilm: With an application to a controllable surface composed of resonant particles," *IEEE Trans. Electromagn. Compat.* vol. 47, pp. 853–865, Nov. 2005.
8. E. F. Kuester, M. A. Mohamed, M. Piket-May, and C. L. Holloway, "Averaged transition conditions for electromagnetic fields at a metafilm," *IEEE Trans. Antennas Propag.* vol. 51, pp. 2641–2651, Oct. 2003.
9. T. K. Chang, R. J. Langley, and E. A. Parker, "Active frequency selective surfaces," *IEE Proc. Microw. Antennas Propag.* vol. 143, pp. 62-66, Feb. 1996.
10. A. Munir and V. Fusco, "Dual band switchable substrateless frequency selective surfaces," *in Proc. 2nd ICEEI 2009*, Bangi-Selangor, Malaysia, Aug. 2009 (to be presented).
11. A. Munir, V. Fusco and O. Malyuskin, "Parallel plate waveguide simulator design, characterisation and DUT de-embedding," *in Proc. IEEE AP-S 2008*, San Diego, USA, Jul. 2008, pp. 1-4.
12. A. Munir and V. Fusco, "A hybrid de-embedding technique and its application for FSS characterization," *in Proc. APMC 2008*, Hongkong, China, Dec. 2008, pp. 1-4.
13. "HSMS282x surface mount RF schottky barrier diodes data sheet," *Avago Technologies Limited*, 2006.
14. "HPND-4005 planar beam lead pin diode data sheet," http://www.avagotech.com/docs/AV01-0593EN

Biographies

Achmad Munir received the B.E. degree in Electrical Engineering from Bandung Institute of Technology, Bandung, Indonesia, in 1995, the M.E. and D.E. degrees in science and engineering from Yamaguchi University, Yamaguchi, Japan, in 2002 and 2005, respectively. From 2005 to 2007 he was a Research Fellow under JSPS fellowship programme with the Department of Electrical and Electronics Engineering, Faculty of Engineering, Yamaguchi University, Japan, working on the artificial materials research, particularly, artificial dielectric and artificial magnetic materials. From 2007 to 2009 he was a Research Fellow with the Institute of Electronics, Communications and Information Technology, Queens University Belfast, United Kingdom, involved in the experimental study of novel nonlinear artificial materials including high impedance surfaces and artificial magnetic conductor for the advanced EM applications. He joined the School of Electrical Engineering and Informatics, Bandung Institute of Technology, Indonesia, in January 2009 as a Lecturer. His research interests include linear and nonlinear artificial materials characterization and their applications for microwave devices.

Vincent Fusco obtained his Bachelors degree in Electrical and Electronic Engineering (First Class Honours) and his PhD in Microwave Electronics from the Queen's University of Belfast in 1979 and 1982 respectively. In 2000 he was awarded a DSc by Queen's University for his work on Advanced Front End Architectures with Enhanced Functionality, where since 1995 he has held a personal chair in High Frequency Electronic Engineering.

Professor Fusco's research interests include nonlinear microwave circuit design, and active and passive antenna techniques. The main focus for this research is in the area of wireless communications. Professor Fusco has pioneered many new concepts in self-tracking antenna technology. At present he is research director of the High Frequency Laboratories at ECIT www.ecit.qub.ac.uk, he is director of the International Centre for Research for System on Chip and Advanced Microwireless Integration, SoCaM.

Professor Fusco has published 350 scientific papers in major journals and in referred international conferences, and is the author of two text books. He holds several patents and has contributed invited chapters to books in the field of active antenna design and EM field computation. He is a Fellow of the Royal Academy of Engineering, Fellow of the Institute of Electrical Engineers IEE, Fellow of the Institute of Electrical and Electronic Engineers IEEE. In 1986 he was awarded a British Telecommunications Fellowship and 1997 he was awarded the NI Engineering Federation Trophy for outstanding industrially relevant research.