Design and Analysis of Reconfigurable Frequency Selective Surfaces using FDTD

Khaled ElMahgoub, Fan Yang, and Atef Z. Elsherbeni

Center of Applied Electromagnetic System Research (CAESR), Department of Electrical Engineering, University of Mississippi, University, Mississippi, USA
kelmahgo@olemiss.edu, fyang@olemiss.edu, atef@olemiss.edu

Abstract: In this paper, a finite-difference time-domain with periodic boundary condition (FDTD/PBC) algorithm is used to design and analyze a reconfigurable frequency selective surface (RFSS). The FSS is reconfigured using two techniques; the first technique is based on using diodes and the second technique is based on changing the orientation of the grid of the FSS mechanically. Simulation results are provided to validate this concept of RFSS.

Keywords: Finite-difference time-domain (FDTD), periodic boundary condition (PBC), frequency selective surface (FSS).

1. Introduction

There has been a significant amount of interest in frequency selective surfaces (FSS) over the years, as they have been investigated for a variety of applications, such as electromagnetic (EM) filters, radomes, absorbers, artificial electromagnetic band gap materials, and many other applications [1]. In most FSS applications, the geometry and material parameters have been designed to produce a static frequency response. However, several groups have investigated the possibility of tuning or reconfiguring an FSS so that its frequency response can be shifted or altered altogether while in operation. This can be accomplished either by changing the electromagnetic properties of the FSS screen or substrate, by altering the geometry of the structure, or by introducing elements into the FSS screen that vary the current flow between metallic patches. In the first class of reconfigurable FSSs (RFSS), the frequency response of the FSS is changed by altering the electromagnetic properties of the substrate, which can be accomplished by many means such as using ferrite as the substrate material and applying DC bias across it, or by using a liquid dielectric as a substrate [2]. The second RFSS class is based on the micro-electro-mechanical systems (MEMS) technology. The metallic elements of the FSS are designed to be able to change orientation or position. The final class of RFSS to be considered, incorporates circuit components into the metallic screen that can be used to vary the current between metallic elements [3].

In this paper, two techniques are used to design an RFSS. The first technique is based on using a diode between the metallic parts of the FSS elements. The diode is switched between two states (ON and OFF states) to change the frequency response of the FSS. The second technique is based on mechanically changing the grid arrangement of the FSS elements from axial to skewed grid with different skew angles. The design and the analysis are done using FDTD/PBC algorithm described in [4] which is based on the constant horizontal wavenumber approach [5]. The diode is simulated using the actual diode current-voltage equation in the presence of both axial and skewed FSS grids, which will provide more accurate simulation results compared to simulating the diode as
an open circuit (OC) for the OFF state and a short circuit (SC) for the ON. Numerical results are provided to prove the validity of the design.

2. The Proposed Design

The FSS structure consists of dipole elements. The basic geometrical dimensions of the dipole are: length 12 mm, width 3 mm, and gap 1 mm (the gap is used for mounting the diode). The periodicity is 15 mm in both x- and y-directions as shown in Fig. 1. The substrate has a thickness of 6 mm and relative permittivity \( \varepsilon_r = 2.2 \). As shown in Fig. 1, the FSS has two control parameters which increase the degree of freedom of the reconfigurability. The first control parameter is the diode which has two states, ON or OFF. The diode acts as a short circuit connecting the two arms of the dipole in the ON state, while in the OFF state it acts as an open circuit. Due to these two states the current distribution on the dipole will change from one state to the other, leading to changes in the frequency response. The advantage of using the FDTD/PBC is to implement the diode using the actual diode current-voltage equation (1), which will give more accurate results compared to simulating the diode as OC or SC. The diode current is characterized by voltage-current relation as shown [6]:

\[
I_d = I_0 \left[ e^{(qV_d/kT)} - 1 \right],
\]

where \( q \) is the absolute value of the electron charge in coulombs, \( k \) is the Boltzmann's constant, \( I_0 \) is the saturation current of the diode and \( T \) is the temperature in Kelvin. The values used in the simulations are as follows: \( q = 1.602e-19 \) C, \( k = 1.38066e-23 \), \( T = 300 \) K, \( I_0 = 1e-14 \) A.

The second control parameter is the movements of different rows of the FSS as shown in Fig. 1(b). These mechanical movements can be done using a stepper motor or MEM structure. The movements will change the grid orientation of the FSS which in turn will affect the frequency response of the FSS.

![Diagram](image)

Fig. 1. The geometry of the proposed RFSS: (a) axial case, (b) skewed grid case.
3. Numerical Results

In this section, full-wave EM simulations are performed using the diode equation in FDTD to simulate different FSS configurations. The algorithm developed in [4] was used to simulate the structure with different skew angles while using the diode equation for generating accurate results. To completely study the proposed FSS, different configurations are simulated. As shown in Table 1, the structure is illuminated by normal and oblique incident plane waves, the two states of the diode are studied, and different values of skew angles are used. The structure is excited by a TE\textsuperscript{z} plane wave using cosine modulated Gaussian pulse centered at 8 GHz with a bandwidth of 16 GHz for normal incident case ($k_x = k_y = 0 \text{ m}^{-1}$). While for oblique incident case ($k_x = 20 \text{ m}^{-1}$, $k_y = 0 \text{ m}^{-1}$), the structure is excited using cosine modulated Gaussian pulse centered at 8.5 GHz with a bandwidth of 15 GHz. In the FDTD simulations, 3,000 time steps and a Courant factor of 0.9 are used. The top and bottom boundaries of the computational domain are terminated by the convolutional perfect matched layer (CPML) as presented in [6]. The FDTD grid cell size is $\Delta x = \Delta y = \Delta z = 0.5 \text{ mm}$.

![Fig. 2 Normal incident ($k_x = k_y = 0 \text{ m}^{-1}$) with different skew angles, (a) diode OFF, (b) diode ON.](image)

![Fig. 3 Oblique incident ($k_x = 20 \text{ m}^{-1}$, $k_y = 0 \text{ m}^{-1}$) with different skew angles, (a) diode OFF, (b) diode ON.](image)

From Figs. 2 and 3, the changes in the frequency response can be noticed. The effects of the two configurations parameters are observed. Turning on the diode shifts the reflection coefficient peak from almost 13 GHz to 7.5 GHz. In addition, changing the
skew angle of the grid of the FSS introduces a frequency shift in the reflection coefficient. The different frequency values of the peak of the reflection coefficient (total reflection) are stated in Table 1.

The new design provides two degrees of freedom in the reconfigurability. A large frequency shift can be obtained by turning on the diode, while a finer frequency shift can be obtained by changing the grid skew angle. However, it is worthwhile to illustrate that some practical considerations should be taken in fabricating such design. For example, the diode biasing networking should be considered, and especially in the case of FSS many diodes are used. The second issue is the implementation of the mechanical movement and the control of these movements.

Table 1: different simulation cases

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Diode State</th>
<th>Skew Angle (°)</th>
<th>Incident $k_x$ (m⁻¹)</th>
<th>Position of Reflection Coefficient Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OFF</td>
<td>90°</td>
<td>Normal $k_x = 0$</td>
<td>13.36 GHz</td>
</tr>
<tr>
<td>2</td>
<td>ON</td>
<td>90°</td>
<td>Normal $k_x = 0$</td>
<td>7.53 GHz</td>
</tr>
<tr>
<td>3</td>
<td>OFF</td>
<td>75.06°</td>
<td>Normal $k_x = 0$</td>
<td>13.92 GHz</td>
</tr>
<tr>
<td>4</td>
<td>ON</td>
<td>75.06°</td>
<td>Normal $k_x = 0$</td>
<td>7.69 GHz</td>
</tr>
<tr>
<td>5</td>
<td>OFF</td>
<td>68.19°</td>
<td>Normal $k_x = 0$</td>
<td>14.37 GHz</td>
</tr>
<tr>
<td>6</td>
<td>ON</td>
<td>68.19°</td>
<td>Normal $k_x = 0$</td>
<td>7.83 GHz</td>
</tr>
<tr>
<td>7</td>
<td>OFF</td>
<td>90°</td>
<td>Oblique $k_x = 20$</td>
<td>13.27 GHz</td>
</tr>
<tr>
<td>8</td>
<td>ON</td>
<td>90°</td>
<td>Oblique $k_x = 20$</td>
<td>7.54 GHz</td>
</tr>
<tr>
<td>9</td>
<td>OFF</td>
<td>68.19°</td>
<td>Oblique $k_x = 20$</td>
<td>14.32 GHz</td>
</tr>
<tr>
<td>10</td>
<td>ON</td>
<td>68.19°</td>
<td>Oblique $k_x = 20$</td>
<td>7.84 GHz</td>
</tr>
</tbody>
</table>

4. Conclusion

A new RFSS design was introduced. The reconfigurability of the design is based on two techniques, the first is based on controlling a diode state and the second is based on controlling a mechanical movement to change the skew angle of the FSS grid. The design was simulated using FDTD/PBC algorithm (full-wave EM simulator), while taking into account the actual model of the diode and different skew angles. The simulations were efficient in both memory usage and computational time. The results showed that the design provides a wide range of reconfigurability and a large degree of freedom in controlling the FSS frequency response.

References
