Software for Project and Analysis of Frequency Selective Surfaces

Antonio L. P. S. Campos and Adaildo G. d'Assunção
Federal University of Rio Grande do Norte, Technological Center, Department of Communication Engineering, Av. Sen. Salgado Filho, 3000, Natal – RN, Brazil, 59072-970, antonio.luiz@pq.cnpq.br and adaildo@ct.ufrn.br
Robson H. C. Maniçoba and Lincoln M. Araújo
Federal University of Rio Grande do Norte, Department of Electrical Engineering, Av. Sen. Salgado Filho, 3000, Natal – RN, Brazil, 59072-970, robsonhcm@gmail.com and machado.lincoln@gmail.com

Abstract— **In this paper, a software for design and analysis of frequency selective surfaces (FSS) based on the equivalent circuit model is presented, with emphasis on teaching students in the interaction between FSS parameters. Tools to design FSSs and a tutorial with theoretical elements of the equivalent circuit method, applied to FSS, compose this software. The software can be used at FSS analysis and design course to consolidate the first theoretical and illustrated concepts.**

Index Terms — Frequency selective surfaces, equivalent circuit method, interactive computing, simulation software.

I. INTRODUCTION

Since the invention of the electronic computer there are two divergent opinions to show how this device should be used. One group saw the computer's principal use as a number manipulator: an extensive, ultrafast, and accurate calculator. A second group envisioned the computer as a symbol manipulator that might be taught to use logic and make decisions in a human fashion [1].

Frequency selective surfaces (FSS) are periodic structures in two dimensions that can provide frequency filtering to incoming electromagnetic waves. Traditional FSS structures have been investigated over the years for a variety of applications (e.g., frequency filters or diplexers in high performance reflector antenna systems, advanced radome designs, and smart surfaces for stealth applications) [2].

The analysis and design of FSS, and the calculation of their parameters, is inherently multidisciplinary, demanding knowledge of antenna, electromagnetic theory and FSS analysis and design disciplines. For example, when a parameter is modified in a FSS, this modification has some electromagnetic consequences, and hence also affects the frequency filtering.

In recent years, a number of electromagnetic simulation commercial software have appeared on the market, such as CST Microwave Studio®, Ansoft Designer®, and Ansoft HFSS®, and also a number of pedagogical software has been developed [3-9]. The main goal of such software is to avoid the tedious computation of the equations governing FSS theory.

In this paper, pedagogical software that emphasizes the understanding of the FSS parameters, using equivalent circuit model, is presented. The outline of the paper is as follows: in Section II, a brief

overview of the FSS theory is presented. The program is described in detail in Section III. Then, the equivalent circuit model is presented in Section IV. Results and comparisons are presented in Section V. Finally, Section VI concludes the paper.

II. FSS FUNDAMENTALS

A periodic array consisting of conducting patch or aperture elements is known as a frequency selective surface (FSS), or dichroic. FSS may have low-pass or high-pass spectral behavior, depending on the array element type (i.e., patch or aperture), similarly to the frequency filters in traditional radio-frequency (RF) [10]. A Two-dimensional planar periodic structure is shown in Fig. 1.
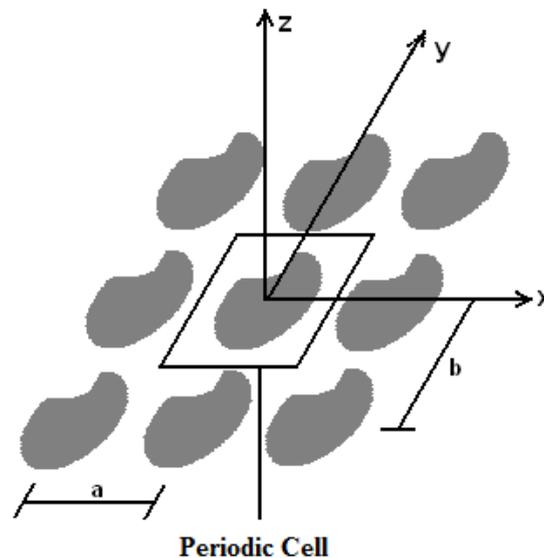

Fig. 1. Geometry of a two-dimensional periodic structure.

Many design parameters and principles are associated with the periodic structure, such as element shape, size, lattice geometry, dielectrics, grating lobes, and Wood's anomaly. Some of the most common element shapes are: circular, rectangular, dipole, cross dipole, Jerusalem cross, tripole, three- or four-legged dipole, ring, square loop and gridded square loop [10]. There are element formats that can be obtained from a combination or modification of simple elements such as those mentioned above, and elements of very complex shapes such as convolutional or fractals [11-13].

An FSS is a periodic array of aperture or patch elements, which are shown in Fig. 2. Aperture-element FSS reflects at low frequencies and transmits at high frequencies (similar to a high-pass filter), whereas the patch-element FSS transmits at low frequencies and reflects at high frequencies (similar to a low-pass filter) [11].

Several methods have been used to analyze FSS. One of the simplest methods is the equivalent circuit model [14, 15]. In this analysis the various strip elements that form a freestanding patch element in a periodic array are modeled as inductive and capacitive components on a transmission line. From the solution of this circuit, the reflection and transmission coefficients of the FSS are found.
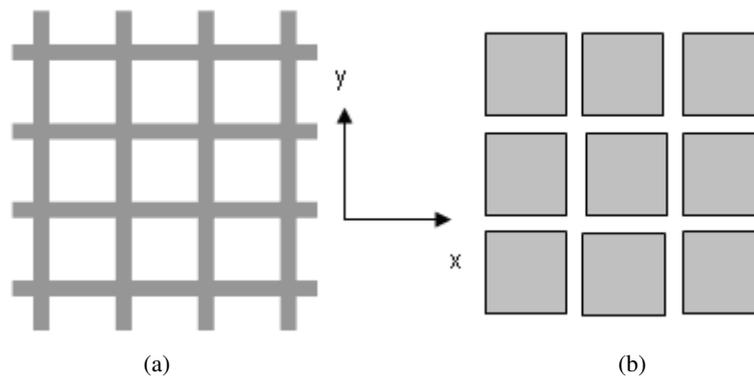
(a)   (b)

Fig. 2. FSS elements: (a) type aperture and (b) type patch.

III. SOFTWARE DESCRIPTION

The simulation software will be presented with an emphasis on the pedagogical point of view. The software is programmed in MATLAB®, which uses its own language sometimes called M-code or simply M, to facilitate both numerical calculations and graphical representations. The program analyzes an FSS mounted on a dielectric isotropic layer.

The graphical interface is a key point in this program. When the program is initiated, a selection menu displays the six possible FSS designs: square loops, gridded square loops, double square loops, quasi-square open loops, Jerusalem cross and square patch. Fig. 3 shows the main screen program.

The elements of the main design screen are:

- *Tool bar;*
- *Patch Shape;*
- *Picture;*
- *Dimensions;*
- *Selecting Frequency Parameters;*
- *Run Button;*
- *Save and Restore Workspace Buttons.*

In the upper side of the main screen, the tool bar shows menu button for documentation, when the user click in this button will appear the menu shown in Fig. 4. Chosen one of the structures, a pdf file is opened and the principal proprieties, equivalent circuit and mathematical model are presented.

The element *Patch Shape* comprises six options for element shapes to create the FSS. Each shape takes a different set of physical parameters and image for each of the options. Fig. 5 shows this item.

The *Picture* shows where each variable are in the shape and a type of element chosen. For example when the user chose the option square loop, the picture shown in Fig. 6 will appear in the main screen.
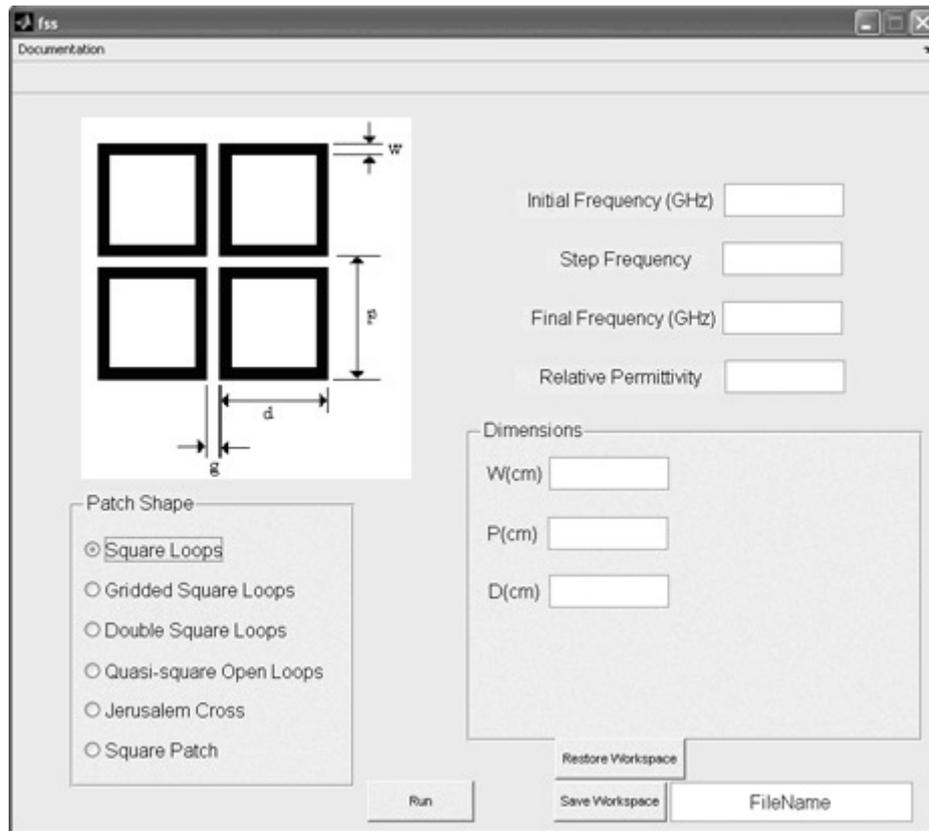
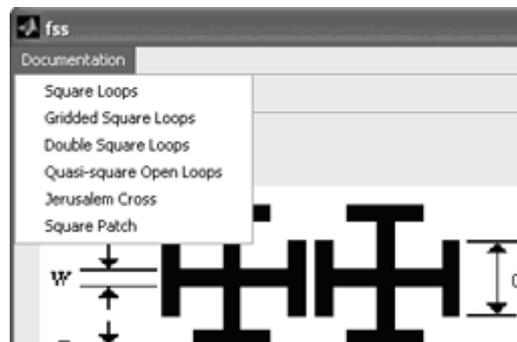Fig. 3. Complete layout of the FSS simulation software.

Fig. 4. Additional Information about each shape.
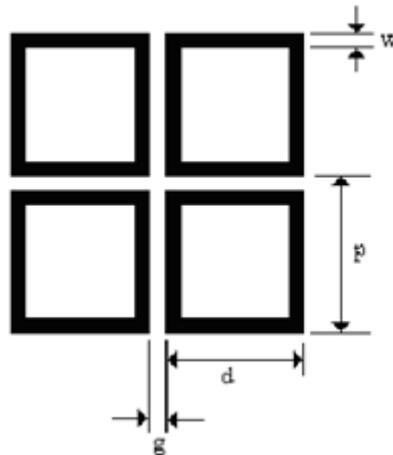

Fig. 5. Choosing a shape.

Fig. 6. Picture showing the physical parameters of the chosen geometry.

Dimensions comprise the set of variables or parameters required to do the analysis of the structure, these parameters are shown in the Picture item. For the option of square loop you can view the parameters shown in Fig. 7.

Fig. 7. Selecting physical parameters.

The element *Frequency Parameters* shows fields where frequency domain parameters and the relative permittivity of the substrate are placed. The user can take more information about each shape by menu Documentation, where the principal proprieties, equivalent circuit and mathematical model are presented. Fig. 8 shows this field.

When the user click on the button *Run Button*, the software analysis begins, one window with the S_{21} response of structure is plotted when the analysis finished.

The shape, parameters and results can be saved and restored anytime placing the file name and click on *Save Workspace Button* and to restore the data just place the file name and click on *Restore Workspace Button*.

Initial Frequency (GHz) [　　　]

Step Frequency [　　　]

Final Frequency (GHz) [　　　]

Relative Permittivity [　　　]

Fig. 8. Selecting frequency domain parameters and substrate relative permittivity.

IV. CIRCUIT EQUIVALENT METHOD

As mentioned earlier, the simulation software uses as analysis method the equivalent circuit model. This technique requires very limited computational resources when compared to full wave analysis methods, so it is useful to quickly predict the performance of that structures. The model also provides a useful physical view on how the FSS operates when its parameters are changed.

The starting point for the development of equivalent circuits for FSS structures is the representation of an infinite array of parallel conducting strips, developed by Marcuvitz [16]. The metal strips have zero thickness, a width, w, and periodicity, p. The plane wave illuminates the strips with an angle ϕ.

The inductive equivalent reactance is given as [16]:

$$\frac{X_L}{Z_0} = F(p,w,\lambda,\phi) = \frac{p\cos\phi}{\lambda}\left\{ln\left[\cos ec\left(\frac{\pi w}{2p}\right)\right] + G(p,w,\lambda,\phi)\right\} \tag{1}$$

where,

$$G(p,w,\lambda,\phi) = \frac{0,5\left(1-\beta^2\right)^2\left[\left(1-\frac{\beta^2}{4}\right)(C_+ + C_-) + 4\beta^2 C_+ C_-\right]}{\left(1-\frac{\beta^2}{4}\right) + \beta^2\left(1+\frac{\beta^2}{2}-\frac{\beta^4}{8}\right)(C_+ + C_-) + 2\beta^6 C_+ C_-} \tag{2}$$

$$C_\pm = \frac{1}{\sqrt{1\pm\frac{2p\sin\phi}{\lambda}-\left(\frac{p\cos\phi}{\lambda}\right)^2}} - 1 \tag{3}$$

$$\beta = \sin\left(\frac{\pi w}{2p}\right) \tag{4}$$

and λ is the wavelength.

At the same way, the incident magnetic field vector is parallel to the metal strips and it illuminates the array with an angle θ. The strips have periodicity, p, and a gap between the strips, g. The capacitive susceptance is calculated by [16]:

$$\frac{B_C}{Z_0} = 4F(p,w,\lambda,\theta) = \frac{4p\cos\theta}{\lambda}\left\{ln\left[\cos ec\left(\frac{\pi w}{2p}\right)\right] + G(p,w,\lambda,\theta)\right\} \tag{5}$$

The function $G(p,g,\lambda,\theta)$ can be solved by (1), Just change ϕ by θ and w by g.

Equations (1) to (5) are appropriated to wavelengths and incidence angles between the range: $p(1+\sin\theta)/\lambda < 1$. It can be used just to incident plane waves, TE or TM and it can not be used to

modeling of cross polarization [15].

To illustrate the method we will present the equivalent circuit method analysis for two structures: the square loop and the Jerusalem cross.

Periodic arrays of square loops are interesting for applications in frequency selective surfaces for dichroic reflector antennas. The modeling technique for this type of element is also based on the equations given by Marcuvitz [16]. These equations are particularly useful for the project in which the equivalent circuit can be easily modeled and the equations can be computed in personal computers. The method has some limitations, since it is generally useful only for normal incidence of plane waves and, as a scalar formulation, provides no information on cross-polarization. In Fig. 3 we can see the arrangement of the FSS with square loops and their physical parameters. Fig. 9 illustrates the equivalent circuit of this periodic array [17].
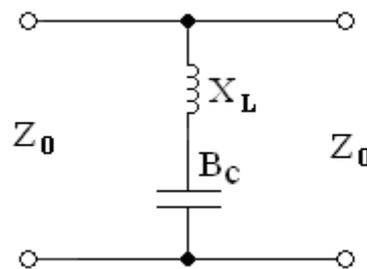

Fig. 9. Equivalent circuit of the square loop.

The reactance X_L is given by:

$$\frac{X_L}{Z_0} = \frac{d}{p} F(p, 2w, \lambda, \phi)$$ (6)

where the function $F(p, w, \lambda, \phi)$ was given in (1).

The susceptance B_C is given by:

$$\frac{B_C}{Z_0} = 4 \frac{d}{p} F(p, g, \lambda, \theta)$$ (7)

where g is the gap between the loops.

It can be seen that the impedance is reduced by a factor d/p. A thin dielectric substrate, on which the conductive elements are printed, causes an increase in the susceptance of the array while no effect on the inductive reactance is observed. Equation (7) is corrected to:

$$\frac{B_C}{Z_0} = 4 \varepsilon_r \frac{d}{p} F(p, g, \lambda, \theta)$$ (8)

The equivalent circuit model for the Jerusalem cross, consisting of a combination of two LC resonant circuits in series, as illustrated in Fig. 10 [15].
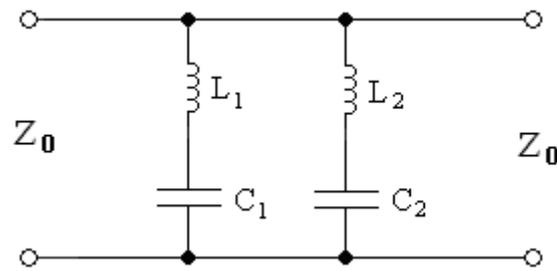
Fig. 10. Equivalent circuit of the Jerusalem cross.

The value of each inductive strip with width w, counting from L_1, is calculated using a conventional equation given by Marcuvitz. The susceptance B_1 is calculated as the sum of two susceptances B_g and B_d. B_g is the susceptance due to the capacitance between the capacitors final horizontal spaced of g, reduced by a factor of d/p. This susceptance is calculated as:

$$B_g = \frac{4d}{p} F(p, g, \lambda)$$

(9)

The susceptance B_d is given by the final capacitor spaced by $(p-d)$ and it is calculated as:

$$B_d = \frac{4(2h+g)}{p} F(p, p-d, \lambda)$$

(10)

The value of C_2 is not calculated directly using the analysis as described above, but from the assumption of a dipole resonance frequency f_3, such that, where is the resonant wavelength. From the value, C_2 is derived from the equation of the resonant circuit in series as:

$$f_3 = \frac{1}{2\pi\sqrt{L_2 C_2}}$$

(11)

The inductive reactance XL2 is due to strips of length d is calculated as:

$$\frac{X_{L_2}}{Z_0} = \frac{d}{p} F(p, 2w, \lambda, \theta)$$

(12)

V. RESULTS

To illustrate how the software works, we will make comparisons with the simulated results obtained by the software and measured results found in some references.

Fig. 11 illustrates a comparison between the results obtained with the software with the measured results presented in [17] for transmitted in dB. The dimensions of the structure were: $w = 0.47$ mm, $g = 0.25$ mm, $d = 5$mm, $p = 5.25$ mm, and $\varepsilon_r = 1.24$. The element was the square loop. Considering the resonance frequency, for measured results it occurs at 15.25 GHz while for simulated results it occurs at 15 GHz (error = 1.64%). Considering the bandwidth at − 20 dB, for measured results it was 2.03 GHz while for simulated results it was 2.06 GHz (error = − 1.48%). So, the results obtained by the software agree with the measured for prediction of resonance frequency and bandwidth.
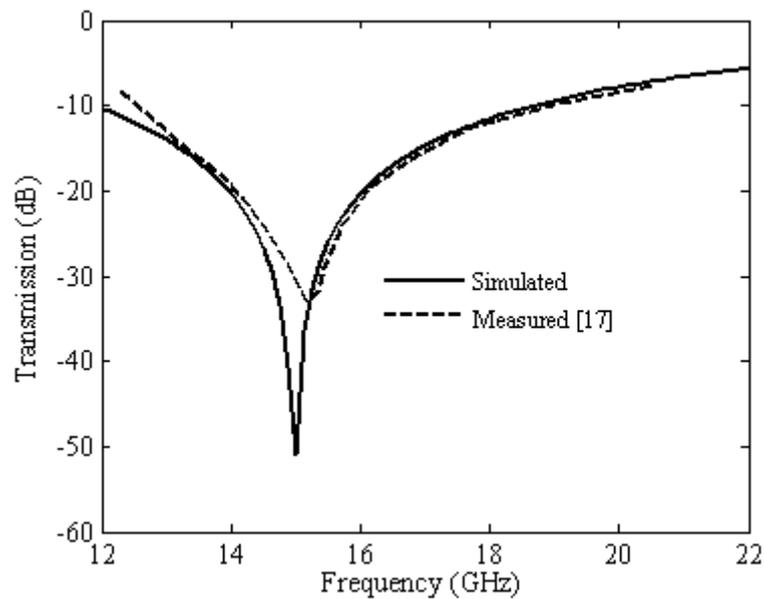
Fig. 11. Comparison between simulated and measured results of a square loop FSS.

Fig. 12 illustrates a comparison between the results obtained with the software with the measured results presented in [18] for transmission in dB. The dimensions of the structure were: $w1 = 0.15$ mm, $w2 = 0.15$ mm, $g = 0.60$ mm, $d = 3.70$ mm, $p = 5.05$ mm, and $\varepsilon_r = 1.24$. The element was the gridded square loop. Considering the resonance frequency, for measured results it occurs at 23.08 GHz while for simulated results it occurs at 23.18 GHz (error = 0.43%). Considering the bandwidth at – 20 dB, for measured results it was 1.49 GHz while for simulated results it was 1.31 GHz (error = 12.1%). Again, the results obtained by the software agree with the measured for prediction of resonance frequency and bandwidth, as well, the curve shape.
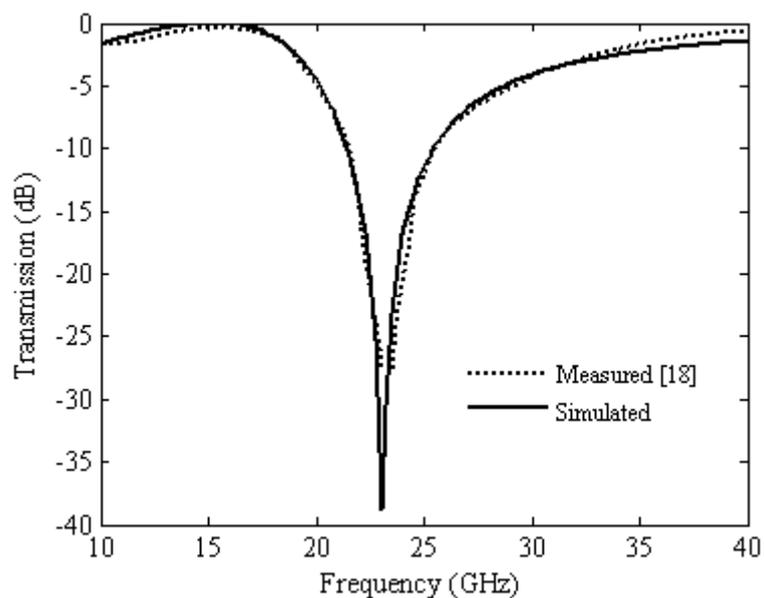

Fig. 12. Comparison between simulated and measured results of a gridded square loop FSS.

Fig. 13 illustrates a comparison between the results software with the measured results presented in [19] for transmission in dB. The dimensions of the structure were: *w*1 = 0.15 mm, *w*2 = 0.15 mm, *g*1 = 0.50 mm, *g*2 = 0.65 mm, *d*1 = *d*2 = 4.50 mm and *p* = 5.00 mm, ε_r = 1.24. The element was the double square loop. For simulated results, the first resonance occurs at 4.63 GHz and the second resonance occurs at 7.44 GHz. For the measured results [19], the first resonance occurs at 4.58 GHz and the second resonance occurs at 7.52 GHz. For the first resonance the error was – 1.09% and for the second resonance the error was 1.06%. The levels in the resonance frequencies differ by about 20 dB. This may be due to an inadequate process of measuring or because the equivalent circuit is an approximate method, or a combination of both, but a good prediction of the resonance frequencies and curve shape was achieved.

Typical frequency characteristics for transmission through a Jerusalem cross grid at normal incidence are shown in Fig. 14. The dimensions of the structure were: *w* = 0.90 mm, *d* = 4.95 mm, *p* = 6.50 mm, *g* = 0.21 mm, *h* = 0.30 mm and ε_r = 1.24. The main features of the response are the rejection frequency bands corresponding to resonances at *f1* and *f3*. For measured results [15], the first resonance occurs at 11.62 GHz and the second resonance occurs at 33.82 GHz. For simulated results, the first resonance occurs at 11.10 GHz and the second resonance occurs at 33.00 GHz. Considering the resonance frequency, for the first resonance the error was 4.48% and for the second resonance the error was 2.42%. As we can see, both numerical methods presented a good agreement.
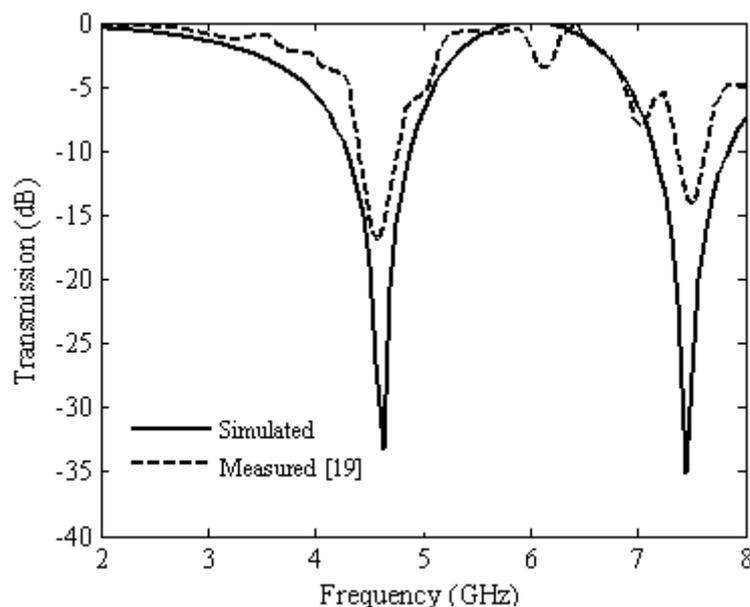

Fig. 13. Comparison between simulated and measured results of a double square loop FSS.
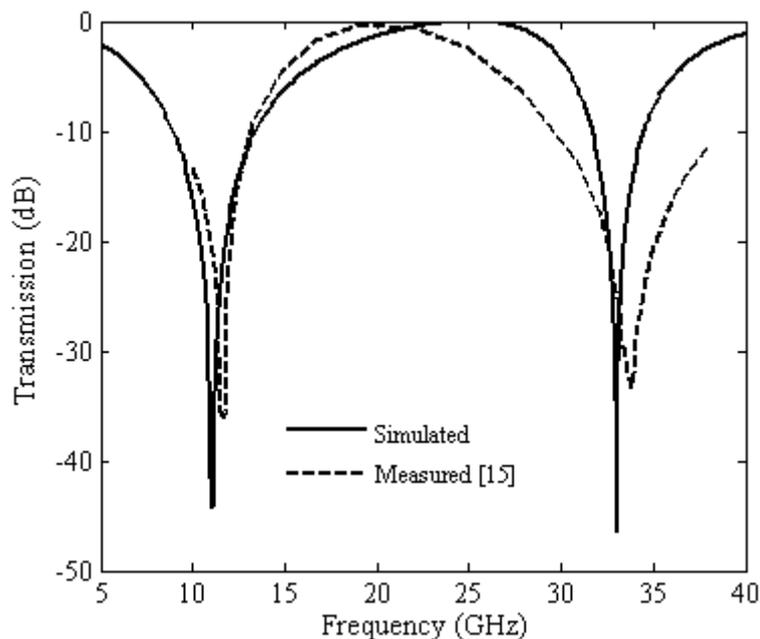
Fig. 14. Comparison between simulated and measured results of a Jerusalem cross FSS.

VI. EXPECTED RESULTS WITH THE SOFTWARE

The authors intend to use the software in the special topics course, frequency selective surfaces, given in the Post-graduate Program in Electrical Engineering and Computing, at Federal University of Rio Grande do Norte. The idea is to provide the software on the course webpage and apply lists of exercises that can be solved using the software. The lists will be directed to students so that they can understand how the physical parameters and the geometry of the structures influence the transmission characteristics of a FSS. This could be done with commercial softwares such as Ansoft Designer™ or CST Microwave Studio™, for example, which uses full-wave methods to perform the analysis of the structures, but the high cost of the license becomes our software very attractive. In addition, the low computational effort required by the equivalent circuit method allows a faster resolution of the lists of exercises. At the end of the semester, questionnaires will be used to diagnose the effectiveness of educational software use in the FSS.

VII. CONCLUSIONS

This work has described frequency selective surface simulation software, using equivalent circuit model, designed for student training. The authors hope that the software will improve students' knowledge of the relationships between FSS parameters. The tool provides students the opportunity to investigate FSS with different elements shapes, modifying its design parameters and obtaining the results for each of these modifications. The authors intend to use the software in a special topics course in 2012 year, given in the graduate program in electrical engineering and computing, at Federal University of Rio Grande do Norte. Together with lists of exercises the authors intend to improve student learning in the cited discipline.

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