Modeling Infrared Frequency Selective Surfaces with Frequency Dependent Materials

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Abstract: With the emergence of infrared frequency selective surfaces (FSS), the increasing need for accurate characterization using numerical modeling prior to device fabrication has exposed limitations in the traditional modeling procedures used for lower frequency FSS designs. To improve full-wave FSS models at IR, a procedure to measure and integrate frequency dependent material properties in modeling is described. Measured and modeled results are presented for a square loop FSS on a ZrO_2 dielectric and modeled results are presented for a similar design on a plastic substrate, illustrating the need to account for frequency dependent material properties for accurate prediction of FSS performance.

Keywords: Frequency Selective Surfaces, Nanoscale device modeling

1. Introduction

A Frequency Selective Surface, or FSS, is made up of a periodic arrangement of resonant structures for the purpose of spectral modification of reflected or transmitted incident radiation. The resonant properties of these structures are largely dependent on both the structure's layout, in terms of structure dimensions and periodicity, and the structure's material properties. Thus, by varying a structure's layout or material properties, it is possible to tune the resonant point of an FSS to meet specific design requirements.

Since the 1960s, FSS structures have been successfully designed and implemented for use in RF applications. With growing interest in adapting low frequency antenna layouts for infrared (IR) applications, several FSS designs have been fabricated and tested including designs using dipoles [1], crosses [2], and square loops [3]. To limit the need for repetitive fabrication and testing, many commercially available numerical electromagnetic solvers have been successfully used to model and characterize FSS designs at IR [4]. One of the greatest limiting factors of IR FSS modeling, however, has been the assumption that materials at IR exhibit electromagnetic properties independent of frequency. Traditionally a valid assumption at RF, the majority of materials common to FSS fabrication exhibit measurable frequency dependence (FD) at IR - resulting in significant modification of the device's resonant characteristics. Furthermore, most commercial electromagnetic solvers used in FSS characterization require frequency independent material definitions exclusively or provide only a limited means to account for frequency dependence.

To overcome this limitation, this paper presents a procedure to account for FD material properties in IR FSS modeling. Material measurement using an Ellipsometer and integration of FD materials in existing commercially available full-wave modeling packages is discussed. In addition, the paper includes analysis showing significant improvements in modeled results.

2. Implementation

Before modeling an IR FSS design, materials used for fabrication must be first characterized for their FD electromagnetic properties. While FD properties for many materials have been previously published, inconsistency in measurement approaches, variable material deposition techniques, and erratic frequency characterization requires direct measurement of materials for the highest accurate modeling possible. Thus, a J.A. Woollam Infrared Variable-Angle Spectroscopic Ellipsometer (IR-VASE) was utilized to measure the optical properties of each material used in fabrication of the FSS. For metals, deposition of the metal at a desired thickness on a known substrate, such as silicon, is recommended for accurate characterization. For dielectrics, characterization of the actual piece used in fabrication before metallization is recommended - both for determination of optical properties and accurate measurement of the dielectric's thickness. Optical properties of each material are measured from as-deposited samples, analyzed using software provided by the manufacturer, and stored in a shared network library spreadsheet.

To carry out modeling, a MATLAB function was created to utilize the measured FD material properties. The MATLAB function consists of three major components – User Interface (UI), Solver Independent Code (SIC), and Solver Specific Code (SSC). The UI component of the code provides the interface necessary for user input and real time presentation of results. The SIC component interprets the users input, reads FD material properties from the shared network library, and creates result files and directories. The SSC component provides functionality to interface with a specific external electromagnetic solver and to interpret the results generated by the solver. The function's layered approach is desirable as it allows for easy integration of multiple electromagnetic solvers without changing the UI or SIC. Currently, Ohio State's Periodic Method of Moments (PMM) and Ansoft Designer, both Method of Moments solvers, are supported.

Solutions for frequency dependent material designs are realized using frequency point by point simulation. To improve performance, programs are provided with a template specifying initial geometry. Step modeling is achieved by populating the desired template with material properties at each frequency step and calling the necessary solver. In the function's current implementation, PMM setup files, written in FORTRAN, are directly modified at each step, whereas Designer setup files utilize a proprietary file format and require modification using VBScript to directly interface with the modeling program. Results are then stored for each frequency step in a spreadsheet and the UI is updated in real-time. A summary of the program is provided in Fig. 1.

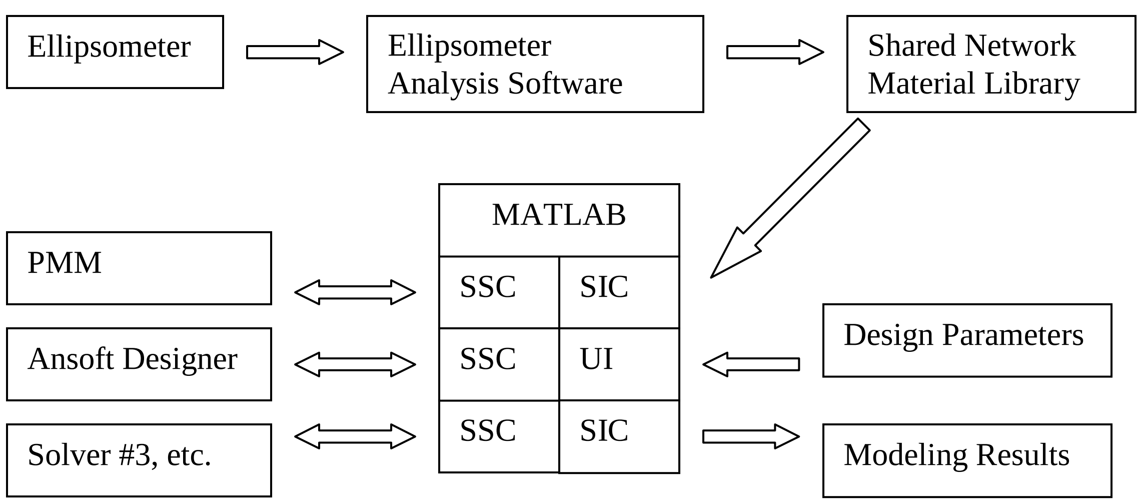

Fig. 1. Implementation of frequency dependent modeling.

In addition to support for FD materials, the developed MATLAB function further enhances all of the solvers by adding new capabilities. Most significant of this new functionality, especially from the standpoint of the user, is the fact that parameter input, user interfaces, and results are all presented identically regardless of the chosen solver. Neutral presentation is desirable to lower the learning curve necessary to model, such as the need to learn FORTRAN for PMM or the Ansoft product UI for Designer, and improves post processing and sharing of data between solvers. The function also adds the ability to specify variable parametric sweeps and auto-renders the design in 3-D - functionality not available in some commercially available solvers, including PMM. Current plans include support for additional solvers, auto-generation of geometries, adaptive solving, and design optimization.

3. Example Results

For verification of the need to account for FD material properties in FSS modeling, a square loop FSS on ZrO_2, (Fig. 2) was fabricated and tested using a Radiometer. In addition, the same design was modeled using PMM assuming frequency independent materials and using the MATLAB function following the process outlined in the previous section. Fig. 3 is a plot of the modeled and measured emissivity of the FSS. From the figure, the FD model provides an improved indication of the device's measured behavior over the frequency independent model including a better bandwidth match from 3-6 μm, accurate prediction of the device's resonant point around 7 μm, and improved agreement from 8 to 14 μm.

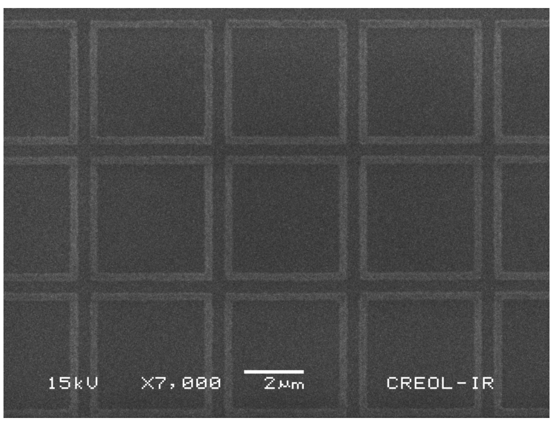

Fig. 2. SEM image of fabricated square loop FSS on ZrO_2.

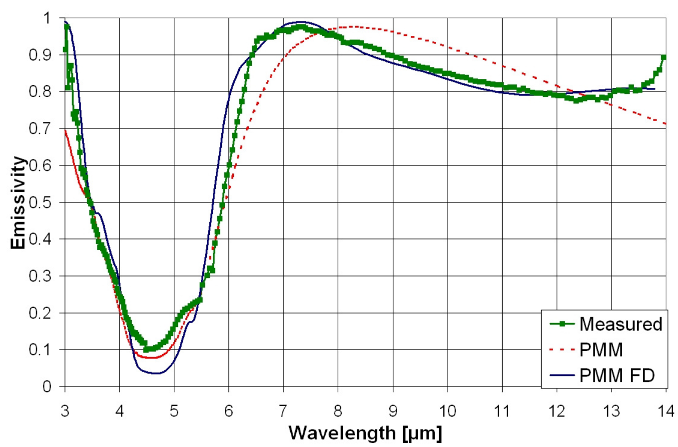

Fig. 3. Measured, frequency independent PMM, and frequency dependent PMM results for square loop FSS on ZrO_2.

From the standpoint of mass production of an IR FSS, non-traditional stand-off layers, such as plastics, would be highly desirable to lower fabrication costs, however, most plastics exhibit significant frequency dependence and numerous loss bands at infrared. To evaluate FSS behavior on a plastic dielectric, another square loop FSS was modeled (Fig. 4) using both a fixed, lossless permittivity dielectric and the complex permittivity of a sample plastic measured from the Ellipsometer (Fig. 5). When assuming a fixed permittivity dielectric, the square loop FSS was easily optimized for high emissivity from 5 – 8 μm simply by scaling existing designs and models. Running the same models using the developed MATLAB function and accounting for the frequency dependence of the plastic, the FSS retains some of its original behavior with the introduction of a high emissivity band between 8 – 9 μm and a sharp dip in emissivity around 7.5 μm. From a design standpoint, this new behavior can significantly change the potential applications of the FSS by effectively expanding the device's emissivity band and introducing an undesired dip in the middle of that band. Even with the measured optical properties, predicting these new trends before testing is clearly problematic when using only a frequency independent model. By including material frequency dependence, further design optimization can occur with a reasonable expectation of accuracy and, thus, a reduction in the need of costly fabrication and measurement.

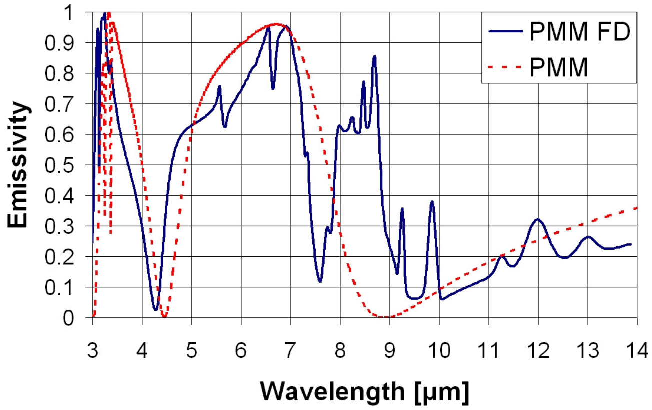

Fig. 4. Frequency independent PMM and frequency dependent PMM results for square loop on plastic.

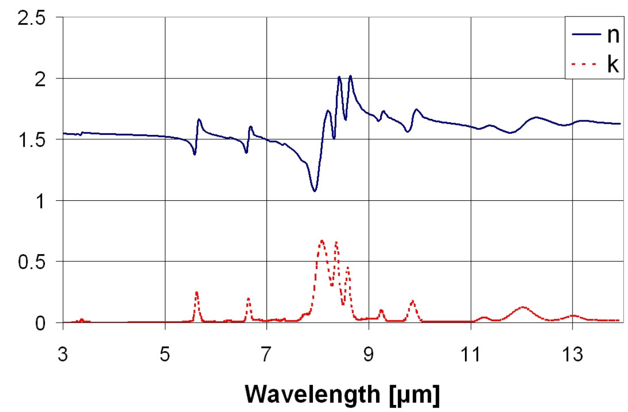

Fig. 5. Frequency dependent index of refraction (n,k) of plastic dielectric from Ellipsometer.

In addition to modeling results, run time data for the model from Fig. 3 was also collected for each program and summarized in Table 1. As expected, the use of frequency dependent materials through a MATLAB function has resulted in an overall increase of run time, however, the increase can largely be attributed to additional time required to copy the measured permittivity values from the shared drive, extract the results, save the results to an spreadsheet file, generate of the function's GUI, and launch and close the desired solver. Designer especially suffers due to the required reliance on VBScript and the need to scan the temporary results directory to find solution data. Overall, the increased runtime is acceptable due to the increase in model accuracy and additional program functionality.

Table 1. Comparison of run times for a Square Loop FSS using 100 frequency points.

Program	Frequency Independent Runtime	Frequency Dependent Runtime
PMM	177 s	238 s
Designer	552 s	1291 s

4. Conclusions

A procedure for the accurate characterization of a frequency selective surface design for use at infrared frequencies has been developed using frequency dependent materials. The procedure requires the use of an Ellipsometer and a custom MATLAB function to interface with several commercially available electromagnetic solvers. Comparison of modeled and measured data for FSS designs on ZrO_2 substrate and plastic substrate illustrate the significance of accurately modeling material properties versus frequency in performance predictions.

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