Characterizing Infrared Frequency Selective Surfaces on Dispersive Media

James Ginn[1], Brian Lail[2], David Shelton[1], Jeffrey Tharp[1], William Folks[1], and Glenn Boreman[1]

[1] CREOL - College of Optics and Photonics
University of Central Florida, Orlando, FL 32816, USA
[2] Department of Electrical and Computer Engineering
Florida Institute of Technology, Melbourne, FL 32901, USA

Abstract **—** With the emergence of frequency selective surfaces (FSS) and other passive planar antenna devices at infrared frequencies, 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 dispersive material properties in modeling is described. Measured and modeled results are provided as verification demonstrating the need to account for material dispersion in infrared FSS design.

Keywords **—** Frequency Selective Surfaces, Nanoscale device modeling.

I. 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, transmitted, or emitted radiation. The resonant properties of these structures depend both upon the FSS layout (dimensions and periodicity) and the properties of the materials used in the construction. Thus, by varying the FSS layout and material properties, it is possible to tune the FSS resonance to meet specific design requirements.

Since the 1960s, FSS structures have been successfully designed and implemented for use in radio frequency (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, 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 utilized in FSS fabrication exhibit measurable frequency dependent (FD) optical properties at IR. This measurable material dispersion can have a significant impact on the measured performance of the fabricated FSS and will degrade agreement between measured and modeled results when assuming static material properties. Furthermore, a large number of commercial electromagnetic solvers used in FSS characterization were developed specifically for RF application and, thus, allow only frequency independent material definitions, or provide only a limited means to account for dispersive materials.

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

II. FREQUENCY-DEPENDENT IR MATERIAL CHARACTERIZATION

Before modeling an IR FSS design, materials used for fabrication must be first characterized for their dispersive optical properties. While FD properties for many materials have been previously characterized and published, inconsistency in measurement approaches limit the utility of such results. Published material studies frequently characterize materials only in ideal situations, such as within a vacuum or as a bulk composition [5] or using mathematical models [6]. In addition, even if the material is studied in a similar configuration as the FSS to be modeled, variability in deposition techniques, layer intermixing, atmospheric conditions, material composition, and handling can render prior measured data inaccurate for modeling.

Clearly, for the highest possible accuracy when modeling FSS on dispersive materials, IR material properties must be characterized directly using the as-deposited materials or actual substrates.

Specifically, a J. A. Woollam Infrared Variable-Angle Spectroscopic Ellipsometer (IR-VASE) (Fig.1) was utilized to measure the IR properties of each material used in fabrication of the FSS over the wavelength range from 2 μm to 14 μm. For metals, deposition of the metal at a thickness greater than the skin depth on a known substrate, such as silicon, is recommended for accurate characterization of near bulk material properties. This is consistent with the metal thicknesses typically used in FSS designs; however, deposition at the exact fabricated metal thickness allow for representative results. To characterize dielectric stand-off layers, it is recommended to make measurements on the actual layer of material used in fabrication, before the application of electron resist. This facilitates both the determination of IR properties and the accurate measurement of the dielectric's thickness. The characteristics of each material are measured from samples, analyzed and fit to an oscillator model using software provided by the manufacturer, and stored in a shared network library as a spreadsheet file. Because most commercially available modeling software programs only accept material property definitions as complex dielectric constants, and not index of refraction, the measured data from the ellipsometer can also be converted for direct utilization by using the relationship

$$\widetilde{n}(\lambda) = \sqrt{\widetilde{\varepsilon}_r(\lambda)}\ . \qquad (1)$$

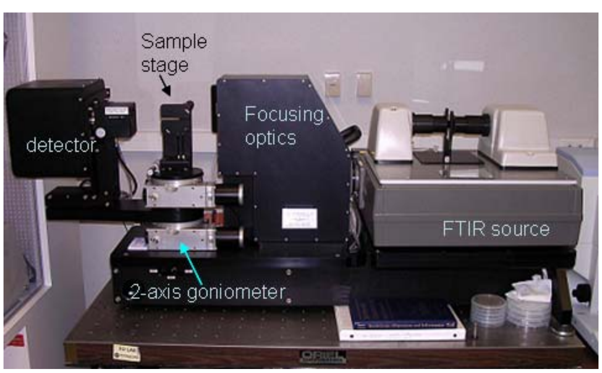


Fig. 1. IR-VASE.

As with any measurement apparatus, the IR-VASE is susceptible to both measurement and post processing errors. One of the capabilities of the IR-VASE analysis software is the ability to automatically determine both the standard deviation of the measured material response and material model errors. From these values and with proper deposition and analysis, optical properties from simple dispersive dielectrics and metals should be within ±5% of their actual values. As material model complexity increases, error will also increase.

III. IMPLEMENTATION

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 University'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 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. 2.

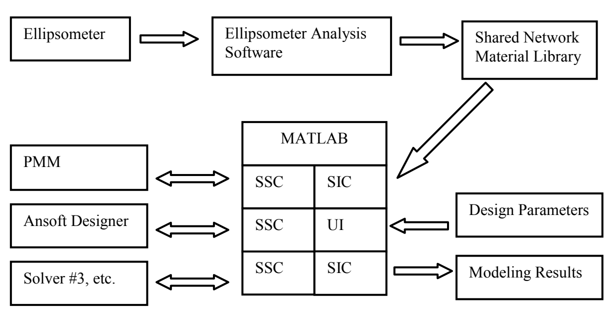


Fig. 2. Implementation of frequency-dependent modeling.

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 for modeling, 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 facilitates the process of design optimization by adding the ability to specify variable parametric sweeps and by allowing auto-rendering of the design in 3-D. This functionality is not available in some commercially available solvers, including PMM.

IV. EXAMPLE RESULTS: SQUARE-LOOP FSS ON ZIRCONIUM

For verification of the need to account for FD material properties in FSS modeling, a Manganese square- loop FSS on Zirconium (ZrO_2) with a Gold ground plane (Fig. 3) was fabricated and tested using a 3 μm to 14 μm spectroradiometer manufactured by Infrared Systems Development Corporation. The radiometer measures the surface emissivity directly [4]. In addition, the same design was modeled using PMM assuming frequency independent materials ($\varepsilon_r = 3.0272$, $\tan\delta = 0.023$, $R_s = 40\ \Omega$) and the developed MATLAB function following the process outlined in the previous sections with frequency dependent material properties. In addition, based on a ±5% variation in material properties, the maximum and minimum emissivty limits was calculated. Modeled results from Designer demonstrated acceptable agreement with results from PMM and, thus, are omitted. Fig. 4 is a plot of the modeled and measured emissivity of the square loop FSS. Neither PMM nor Designer support the calculation of emissivity directly, however, the developed MATLAB function calculates emissivity using the conservation of energy relationship

$$\alpha(\lambda) + \tau(\lambda) + \rho(\lambda) = 1. \quad (2)$$

With transmission τ set to zero due to the presence of the groundplane and with absorption α (unity minus reflection ρ) set equal to emissivity as a consequence of Kirchhoff's law. 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 μm to 6 μm, accurate prediction of the device's emissivity peak around 7 μm, and improved agreement of curve shape from 8 μm to 14 μm. Even with the inclusion of errors in the material measurements, the FD model demonstrates reasonable agreement with measured results.

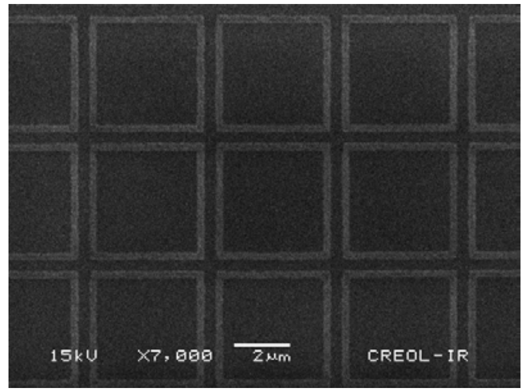


Fig. 3. SEM image of fabricated Square-Loop FSS on ZrO2.

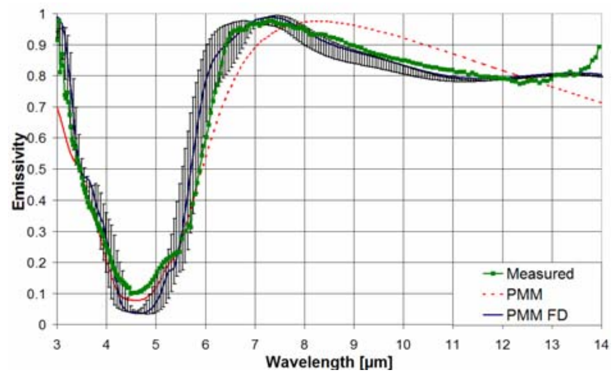


Fig. 4. Measured, frequency independent PMM, and frequency-dependent PMM results for square-loop FSS on ZrO2. Error bars represent total emissivity variation with material error.

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 facilitated by a MATLAB function has resulted in an overall increase of run time. 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 a spreadsheet file, generate of the function's GUI, and launch and close the desired solver. Overall, the longer runtime is acceptable due to the increase in model accuracy and additional program functionality.

Table 1. Comparison of runtime for a square-loop FSS using 100 frequency points.

	Frequency Independent	Frequency Dependent
Runtime	177s	552s

V. EXAMPLE RESULTS: SQUARE-LOOP FSS ON POLYMER

From the standpoint of mass production of an IR FSS, non-traditional stand-off layers, such as polymers, would be highly desirable for future designs to lower fabrication costs, reduce fabrication time, and allow for flexible substrates. Due to their composition, most polymers will exhibit significant frequency dependence and numerous loss bands at infrared. To evaluate FSS behavior on a polymer dielectric, another square loop FSS was modeled (Fig. 5) using both a fixed, lossless permittivity dielectric (ε_r = 1.5, tanδ = 0) and the complex permittivity of PC0G46GL measured from the IR-VASE (Fig. 6). PC0G46GL is a fluoropolymer based on polycarbonate and represents a potential plastic substrate candidate. While deposition of a PC0G46GL substrate is feasible, development of THE PROCESS capability requires considerable investment of engineering time and has not yet been implemented. With the modeling capabilities developed; however, it is now reasonable to predict the behavior of PC0G46GL both for design optimization and benefit evaluation prior to development of fabrication capabilities.

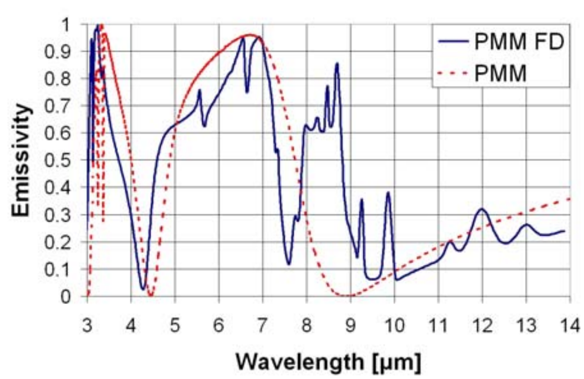


Fig. 5. Frequency independent PMM and frequency dependent PMM results for square loop on plastic.

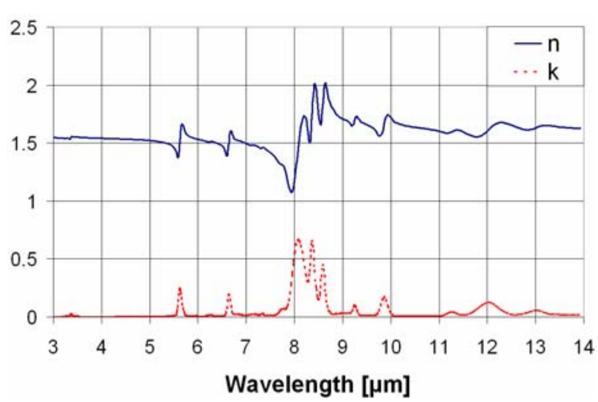


Fig. 6. Frequency dependent index of refraction (n,k) of PC0G46GL from ellipsometer.

When assuming a fixed permittivity dielectric, the square loop FSS was easily optimized for high emissivity from 5 μm to 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 μm to 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 IR 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 and investment risk.

VI. CONCLUSIONS

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

REFERENCES

[1] W. L. Schaich, G. Schider, J. R. Krenn, A. Leitner, F. R. Aussenegg, I. Pusçasu, B. Monacelli, and G. Boreman, "Optical resonances in periodic surface arrays of metallic patches," *Applied Optics*, vol. 42, no. 28, pp. 5714-5721, 2003.

[2] K. D.Möller, J. B.Warren, J. B. Heaney, and C. Kotecki, "Cross-shaped bandpass filters for the near- and mid-infrared wavelength regions," *Applied Optics*, vol. 35, no. 31, pp. 6210–6215, Nov. 1996.

[3] B. Monacelli, J. Pryor, B. A. Munk, D. Kotter, and G. D. Boreman, "Infrared frequency selective surfaces: design, fabrication and measurement," *Proc. SPIE,* vol. 5406, pp. 879-886, 2004.

[4] B. Monacelli, J. Pryor, B. A. Munk, D. Kotter, and G. D. Boreman, "Infrared frequency selective

surface based on circuit-analog square loop design," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 2, pp. 745-752, February 2005.

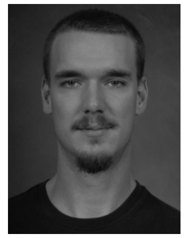
[5] J. E. Raynolds, B. A. Munk, J. B. Pryor, and R. J. Marhefka, "Ohmic loss in frequency-selective surfaces," *Journal of Applied Physics*, vol. 93, no. 9, pp. 5346- 5358, May 2003.

[6] E. Topsakal, J. Volakis, "On the properties of materials for designing filters at optical frequencies" *2003 IEEE Antennas and Propagation Society International Symposium*, vol. 4, pp. 635 – 638, 22-27 June 2003.

James C. Ginn received a BS and MS in Electrical Engineering from the University of Central Florida in 2004 and 2006. He is currently pursuing his PhD in Electrical Engineering at the University of Central Florida and is a member of the Infrared Systems Research group at CREOL. His current research interests include infrared reflectarray design and high frequency computational electromagnetics.

Brian A. Lail received the BS in physics from Furman University, MS in physics and electrical engineering and PhD in electrical engineering from New Mexico State University. From 2002 to 2005 he was with the Department of Electrical and Computer Engineering at the University of Central Florida. Since 2005 he has been an Assistant Professor in the Department of Electrical and Computer Engineering at Florida Institute of Technology, Melbourne, FL, teaching and conducting research in applied and computational electromagnetics.

David J. Shelton received a BS in Physics from the University of Evansville in 2005. He is currently pursuing his PhD in Optics from CREOL at the University of Central Florida and is a member of the Infrared Systems Research group. David is an NSF IGERT fellow. His current research interests include tunable nanoscale FSS design and fabrication as well as flexible substrate FSS fabrication.



Jeffrey S. Tharp received a BS in Physics from the University of North Carolina at Asheville and an MS in Optical Science and Engineering from the University of North Carolina at Charlotte in 2002 and 2004, respectively. He is currently pursuing his PhD in Optics at the University of Central Florida, CREOL: College of Optics and Photonics and he is a member of the Infrared Systems Research group. His current research interests include polarization modification using infrared frequency selective surfaces.

William R. Folks is a researcher at the University of Central Florida in Orlando. He received his BS from Eastern Michigan University in 1989 and the Ph.D. in physics from Kent State University in 1995. His research interests are in liquid crystal displays, infrared optics, terahertz applications, and optical engineering.

Glenn D. Boreman received the B.S. degree in optics from the University of Rochester, Rochester, NY, in 1978 and the Ph.D. in optical sciences from the University of Arizona, Tucson, in 1984. Since 1984, he has been on the faculty of the University of Central Florida in Orlando, where he is currently Trustee Chair Professor of Optics, Physics, and Electrical Engineering. He is coauthor of Infrared Detectors and Systems (New York: Wiley, 1996), author of Basic Electro-Optics for Electrical Engineers (Bellingham, WA: SPIE, 1998) and Modulation Transfer Function in Optical and Electro-Optical Systems (Bellingham,WA: SPIE, 2001). His research interests include infrared and millimeter-wave sensing, and the transition of radiofrequency concepts such as antennas and frequency-selective surfaces to optical frequencies using electron-beam lithography.

Prof. Boreman is a Fellow of the Optical Society of America (OSA) and of the Society of Photo-Optical Instrumentation Engineers (SPIE). He served six years as Editor-in-Chief of OSA's journal Applied Optics, and is a past member of the SPIE Board of Directors. Along with his students, he received the 1995 Kingslake Medal from SPIE.