Novel Microceramic Structures for the Design of Monolithic Millimeter-Wave Passive Front-End Components

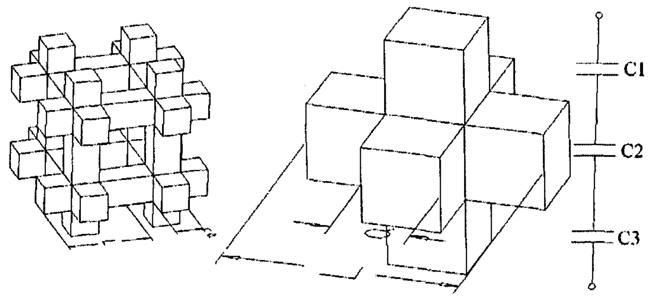
Karl Brakora*, and Kamal Sarabandi
Radiation Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan Ann Arbor, MI 48109-2122
E-mail: kbrakora@engin.umich.edu

INTRODUCTION

Development and production of millimeter-wave (MMW) technology has been hindered by the lack of suitable technology and techniques that would enable automated fabrication of monolithic subsystems with proper low-loss materials to occur. There is a need for novel fabrication methods for monolithic low-loss ceramic devices to control the dielectric behavior of simple passive MMW components such as waveguides, resonators, and antennas. Additionally, low-loss monolithic technology could be used to construct wide band multiple-beam and beam-steering antenna subsystems. The Rotman lens provides multiple simultaneous beams for array antennas allowing it to be used for multiple systems potentially operating at different frequencies. Such a monolithic low-loss ceramic lens array could offer unparalleled compactness and efficiency at MMW frequencies. The Luneburg lens is a spherically symmetric inhomogeneous dielectric lens whose dielectric constant decreases radially outwards. With a technology to construct complex dielectric profiles of arbitrary value using a low-loss ceramic, a Luneburg lens could be fabricated to be a cost-effective, efficient, extremely broad-band, light-weight, multi-beam antenna at MMW frequencies.

Ceramics provide significant advantages over other materials at MMW frequencies due to their very high Q. For instance aluminum oxide has a dielectric constant of 9.8 and a loss tangent of 0.00017 at Ka-band frequencies and titanium oxide has dielectric constant of 87 and a loss tangent of 0.00019 at X-band. But to exploit ceramic's full potential, a microstructure can be imposed on the ceramic to reduce and control the effective dielectric constant while maintaining the material's low-loss characteristics. New ceramic techniques have become available to do this. Thermoplastic CNC Machining and assembly blends ceramic powders into thermoplastic resins that can be finely machined using conventional CNC fabrication tools. Indirect Solid Freeform Fabrication can achieve very complex internal designs by casting any ceramic around wax molds created by high-precision ink jet deposition. Direct Ceramic Stereolithography [1] (Cer-SLA) offers an accurate prototyping method for three-dimensional macroscopic designs of arbitrary complexity.

This work proposes a technique to obtain a wide range of effective dielectrics by employing the Cer-SLA process to construct sub-millimeter scale regular periodic substructures of variable ceramic-to-air volume ratios. Low-frequency approximations are compared to simulated effective dielectric constants at millimeter-wave frequencies. The results may provide a basis for future design of arbitrarily complex dielectric profiles. Measured results and applications of this technique will be provided in the presentation.



a b

Fig. 1. (a) 8 periods of the cubical substructure, (b) one period of the cubical substructure with equivalent circuit

LOW-FREQUENCY APPROXIMATION

Two microceramic structures are proposed. The cubical substructure is an isotropic geometry selected because of the wide dielectric contrast achievable within the limitations of the Cer-SLA process (see Fig. 1a). The "log-pile" substructure is a uniaxial geometry attractive because of the simplicity of its construction in the Cer-SLA process (see Fig 2a). Both of the structures presented are designed to have spatial periodicities substantially smaller than a wavelength. Where the period is short compared with a wavelength scattering models become unnecessary, and a low-frequency approximation can be made [2]. In order to determine the effective dielectric constant of the structure, a single period is modeled as though it was between the plates of a capacitor. The area-to-length ratio and effective capacitance uniquely determines the effective dielectric constant of the period:

$$C_{eff} = C_o \varepsilon_{eff} = \frac{A}{L} \varepsilon_o \varepsilon_{eff}$$

Since the cubical substructure is isotropic, and since it can be shown that the effective capacitance over any period is invariant under translational movement to a different period, the apparent dielectric of any period of the cubical substructure is the local effective dielectric of the structure. A period of the cubical substructure is modeled by three series capacitors. Each series capacitor composed by the sum of two or more parallel capacitances representing the capacitance of the free space and high-dielectric volumes of the lateral slice (see Fig. 1b). The low-frequency approximation is a function solely of the width-to-period ratio, *a/L*.

$$C_o = \varepsilon_o L$$

$$C1 = C3 = 2\varepsilon_o \frac{L^2 - a^2}{L - a} + 2\varepsilon_o \varepsilon_r \frac{a^2}{L - a} \quad \text{and} \quad C2 = \varepsilon_o \varepsilon_r \frac{\left(2La - a^2\right)}{a} + \varepsilon_o \frac{(L-a)^2}{a}$$

$$\varepsilon_{eff} = \frac{C1 \,||\, C2 \,||\, C3}{C_o} = \frac{\left(1 + 2\frac{a}{L}(\varepsilon_r - 1) - \left(\frac{a}{L}\right)^2 (\varepsilon_r - 1)\right)\left(1 + \left(\frac{a}{L}\right)^2 (\varepsilon_r - 1)\right)}{1 + \frac{a}{L}(\varepsilon_r - 1) - 3\left(\frac{a}{L}\right)^2 (\varepsilon_r - 1) + 2\left(\frac{a}{L}\right)^3 (\varepsilon_r - 1)}$$

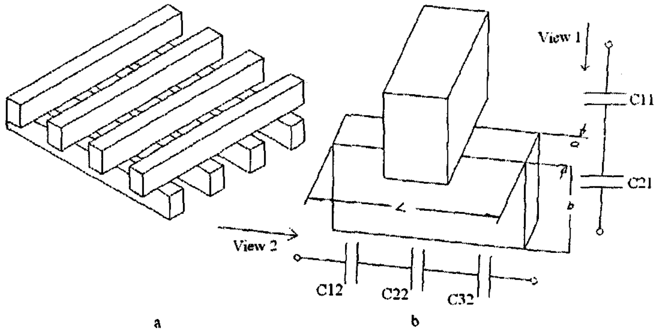


Fig 2. (a) Planar 16 periods of the Log-pile structure, (b) One period of the Log-Pile structure with circuit equivalent model

Owing to its uniaxial symmetry, the log-pile structure is anisotropic, and must be characterized from two directions (see Fig. 2b). The effective dielectric constant for E-field vectors in the directions shown as View 1 and View 2 in Fig 2b are determined in the same manner as it was for cubical form.

$$\varepsilon_{eff}^{1} = \frac{C11 \| C21}{C_{o1}} = \left(1 + \frac{a}{L}(\varepsilon_r - 1)\right)$$

$$\varepsilon_{eff}^{2} = \frac{C12 \| C22 \| C32}{C_{o2}} = \frac{\left(\varepsilon_r + 1 + \frac{a}{L}(\varepsilon_r - 1)\right)\left(2 + \frac{a}{L}(\varepsilon_r - 1)\right)}{2(\varepsilon_r + 1)}$$

The effective dielectric constants of these substructures in aluminum oxide are plotted as a function of a/L in Figs. 3 and 4.

NUMERICAL VERIFICATION

Ansoft HFSS 9.0 simulation software was used to make all simulated results. The simulated verification was conducted by modeling the transmission and reflection coefficients of a normal plane wave through a single-period thick, infinite slab. The infinite dimensions were modeled in simulation by the mathematically equivalent perfect TEM waveguide. The effective dielectric constant of the medium was then determined by the iteratively converging to the set dielectric constants satisfying transmission/reflection equations in layered media [3].

The approximation for the cubical form is accurate until the periodicity of the structure becomes nearly 40% of the free-space wavelength (see Figs. 5 and 6). The low-frequency approximation is seen to be valid for a log-pile structure with $b = L/2$ for L within 30% of the wavelength. Within the range of valid approximation, the results show that the simulated results agree with the low-frequency approximation to within 10% and the errors have the possibility of being corrected by minor compensation factors. The low-frequency approximation appears to be an acceptable tool to use in the design of these substructures.

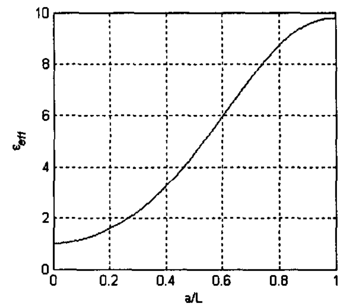


Fig. 3. Effective dielectric vs. a/L
for cubical structure
ε_r for $Al_2O3 = 9.8$

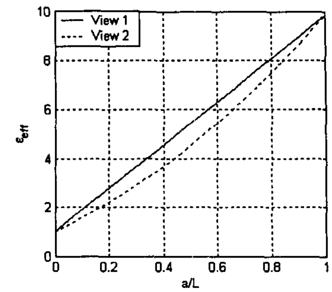


Fig 4. Effective dielectric vs. a/L
for log-pile structure
ε_r for $Al_2O3 = 9.8$

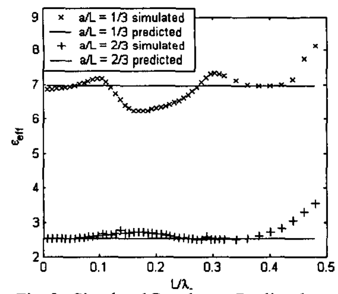


Fig. 3. Simulated Results vs. Predicted
For Cubical Structure

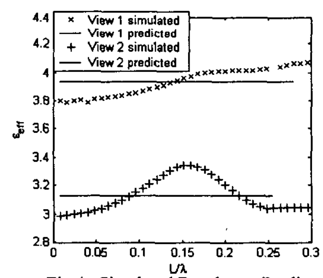


Fig 4. Simulated Results vs. Predicted
for Log-pile Structure
$a/L = 1/3$. $b/L = 1/2$

ACKNOWLEDGEMENTS

We wish to acknowledge Prof. John Halloran, director of the Advance Ceramics Laboratory of the University of Michigan, for his contribution of knowledge and equipment to this ongoing research.

REFERENCES

[1] Griffith, Michelle L. Halloran, John W. "Freeform Fabrication of Ceramics Via Stereolithography." ***Journal of the American Ceramic Society*****, Vol. 79, Oct. 1996.**

[2] Sarabandi, K. "Simulation of Periodic Dielectric Corrugation with and Equivalent Anisotropic Layer." ***International Journal of Infrared and Millimeter Wave, Vol. 11, No. 11, 1990.***

[3] F.T. Ulaby, R.K. Moore, and A.K. Fung. ***Microwave Remote Sensing: Active and Passive, Volume 1.*** **Addison-Wesley, 1981, ISBN 0-201-10759-7(v.1).**