Subwavelength Periodic Lattices for the Design of MMW Components using Ceramic Stereolithography

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Introduction

MMW systems have seen limited use in communications and remote sensing due partly to the lack of high-efficiency front-end components. At MMW frequencies, ohmic losses in metals become prohibitive and the cost of assembly of many small subcomponents is cumbersome and costly. In this paper we present a ceramic stereolithography fabrication process that enables construction of monolithic all-dielectric MMW front-end components and sub-systems. Many ceramics, such as alumina (Al2O3) used in this work, commonly provide loss tangents below 10^-5. The advent of ceramic stereolithography, a fully-3D ceramic fabrication process, has made it possible to construct all-ceramic parts with arbitrarily complex geometries. By adding a lattice substructure to the components, this process makes it possible to achieve a wide range of controllable dielectric contrast within the component itself allowing for efficient fabrication of those hardest-to-construct, variable-dielectric components such as planar and matched spherical lenses, photonic filters, isolated dielectric waveguides, etc.

Ceramic stereolithography is accomplished by substituting the polymer resin found in conventional stereolithography with a photoreactive ceramic suspension and operating the stereolithography apparatus in essentially the same manor. Strategies for SLA-compatible photopolymerizable ceramic suspensions of submicron ceramic powders were first developed at the University of Michigan, and have also been worked on by several academic groups worldwide [1]. The result is a “green” part, an essentially polymer part containing a high volume fraction of ceramic. The polymer fraction of the structure is removed through pyrolysis prior to the sintering. Though its potential is great, ceramic stereolithography has not yet found much microwave application. Further development in the area of ceramic stereolithography will prove to be an enabling technology in the MMW field.

Characterization of Ceramic Stereolithography

The facilities of the Advanced Ceramics Laboratory of the University of Michigan include a 3D-Systems SLA-250 stereolithography apparatus equipped with a 40mW HeCd UV laser with a 200µm beam. The system is loaded with a photoreactive acrylate-based highly-loaded alumina suspension. The UV penetration depth in the suspension is measured to be 30-40µm and high degree of laser overcure is required to achieve the minimum layer thickness of 100µm [2]. Due to multiple scattering in the suspension, the minimum curable linewidth, a_min, is measured to be 390µm. The errors in stereolithography are largely systemic, rather than random. Careful measurement and calibration can reduces these errors to very low levels. The remaining random errors in the stereolithography build process are small compared to those introduced by pyrolysis and sintering.

The “green” component produced in ceramic stereolithography contains only 50% ceramic by volume. The polymer portion is removed via pyrolysis at temperatures between 350 and 450°C and is sintered at 1600°C. Linear shrinkage is measured to be 20.8% ± 0.2% and is isotropic to within 0.1%. At surfaces, especially fine surfaces, there may be additional random linewidth error, Δa. In this process Δa is measured to be less than 30µm in each direction. The limitations and tolerances of the process will limit the achievable effective dielectric range.
Propagation in a Cubical Ceramic Lattice

The ability to control the effective dielectric constant of a structure composed of two or more materials is directly related to the ability to control the volume fractions of each. In many cases, this is achieved by merely controlling the porosity of a material; however, in order to achieve a wide effective dielectric range it is necessary to construct the ceramic in a mechanically stable structure, which in this case, has been chosen to be a periodic rectangular lattice (Fig. 1).

The effective dielectric tensor may of the rectangular lattice structure may be precisely controlled by controlling the linewidth dimensions (\(a_x, a_y, a_z\)) and the periodicity dimensions (\(L_x, L_y, L_z\)). When the dimensions of a structure are short compared to a wavelength the dielectric behavior can be analyzed in a quasi-static sense [3]. In the isotropic case in which \(a_x/L_x=a_y/L_y=a_z/L_z\) the effective dielectric constant can be approximated by

\[
\varepsilon_{\text{eff}} = \frac{1 + 2 \frac{a}{L} (\varepsilon_r - 1) \left(\frac{a}{L}\right)^2 (\varepsilon_r - 1)}{1 + 2 \frac{a}{L} (\varepsilon_r - 1) - 3 \left(\frac{a}{L}\right)^2 (\varepsilon_r - 1) + 2 \left(\frac{a}{L}\right)^3 (\varepsilon_r - 1)},
\]

where \(\varepsilon_r\) is the relative permittivity of the material.

In periodic media, planewave expansions are used to determine the propagation and dielectric behavior throughout [4]-[6]. The eigenvectors of the plane-wave expansion determine the electric-fields and electric flux density within a single period of the medium. From these fields, an effective dielectric tensor is computed. The low-frequency planewave solution shows that the quasi-static approximation produces a high estimate but is within 5% of the actual effective dielectric constant. Static finite-element analysis confirms this result (Fig. 2).

At frequencies away from DC, the planewave expansion shows that the structure exhibits the dispersive behavior of a photonic crystal. When the effective dielectric constant of the lowest propagating band is plotted versus normalized frequency, it is apparent that the dispersion characteristics can be divided into two regions. In the subwavelength region, where quasi-static methods may be applied, the medium can be approximated as being essentially non-dispersive. In the photonic crystal region, where planewave expansions and full-wave numerical techniques are required, the region must be treated as a 3D photonic crystal.

The constraints on the lattice parameter come from several sources. The most obvious constraint on the lattice is the minimum fabricatable linewidth within the ceramic stereolithography process. The cutoff between the subwavelength region and photonic crystal region is determined to be 35% of the dielectric wavelength as determined by the...
quasi-static approximation (Fig. 4). This quasi-static condition guarantees that the propagation velocity is with 5% of its nominal DC-value. The minimum linewidth constraint, $a_{\text{min}}$, is determined by the minimum linewidth of the process, and the upper bound of the periodicity is limited by quasi-static condition (2). The final constraint imposed on the lattice is due to the linewidth tolerance of the process. The tolerance constraint (3), ensures that the normalized error in the effective dielectric constant due to random linewidth errors, $\Delta a$, remains less than an acceptable normalized deviation, $P_e$.

$$a_{\text{min}} \leq a \leq L \leq \frac{0.35}{\sqrt{\varepsilon_{\text{eff}}}} \lambda_0$$ (2)

$$\frac{d\varepsilon_{\text{eff}}}{d(\frac{\pi}{L})} \frac{\Delta a}{\varepsilon_{\text{eff}}P_e} \leq L$$ (3)

These constraints allow a range of effective dielectric constants for each propagating frequency. The range of achievable dielectric constants is represented as a function of periodicity for each frequency (Fig. 5). Such diagrams give a graphical representation of the limits of quasi-static design. The region of achievable effective dielectric constants reduces for higher frequencies.

**Design of a Monolithic Luneberg Lens**

To demonstrate the capability of the proposed fabrication process, we consider a very complex antenna and feed structure. Despite its many applications, the Luneberg lens has been underutilized due to the difficulties in its fabrication. The Luneberg lens is a spherically symmetric inhomogeneous lens whose dielectric constant decreases radially outwards. The expense of the fabrication and the fragility of the product limit the use of Luneberg lens to controlled terrestrial applications.

Luneberg’s solution for the Luneberg lens requires a dielectric constant of 2 in the center which decreases quadracially to unity at the edge to create a focal point on the edge of the lens. This has been useful for most Luneberg lens applications since it allows the lens to be fed by a low-directivity horn, or the lens could be metalized and used as an RCS standard. In order to integrate the Luneberg lens with future ceramic systems, however, it is necessary to feed the lens with a ceramic waveguide. Gutman’s solution to the Luneberg lens provides for such a design. If $r_o$ is the radius of the lens, the solution creates a focal point within the lens at point $r_1$ [7]. The dielectric profile is given by

$$\varepsilon_r (r) = 1 + \left( \frac{r}{r_o} \right)^2 - \left( \frac{r}{r_1} \right)^2.$$ (4)
The advantage of creating an internal focal point within the lens is that it may be fed by high permittivity waveguide at that point. If required, the material behind the feed point may be removed entirely. It is also possible to feed the lens in multiple places which would create a multi-beam capability.

A 24 GHz Luneberg lens was designed to have a high dielectric constant of 5 at the core, and a low dielectric constant of 1.8 on the periphery. The fabricated result showed no sign of surface delamination or cracking. A low-permittivity “skirt” has been added to the non-radiating side of the Luneberg lens to add mechanical stability and to ease the fabrication process. The dielectric waveguide is fed through a diaphragm transition from a WR42 metallic rectangular waveguide. This primitive feed system provides a broadband match (better than 8dB) from 19-27 GHz with particularly good matches in the 10% windows about 19.5, 23, and 26 GHz. The measured radiation patterns are consistent expectation given the diameter of the lens. The slight asymmetry of the sidelobe patterns is the result of the partial fusion to the embedding material and will be corrected by using a coarser embedding ceramic. The results, however imperfect, verify the quasi-static design rules for strongly modulated subwavelength lattices constructed using ceramic stereolithography. The measured results of this and other prototypes will be presented.

This technology has application to many other technologies include planar lenses, focal plane arrays, guidance and coupling, and bandgap isolation. Ultimately, this technology can be used to construct complete all-ceramic subsystems which will be able to offer unparalleled efficiency and withstand extreme environments.

References
[1] F. Doreau, C. Chaput, T. Chartier. Adv. “Stereolithography for Manufacturing Ceramic Parts” Eng. Mater., vol. 2, pp. 493-496 (2000)
[2] K. C. Wu, Ph.D. Thesis, University of Michigan, 2005.
[3] S. Datta, C. T. Chan, K. M. Ho, and C. M. Soukoulis, “Effective dielectric constant of periodic composite structures,” Phys. Rev. B, vol. 48, 14936-43, 1993.
[4] S.-Y. Lin, V. M. Hietala, L. Wang, and E. D. Jones, “Highly dispersive photonic band-gap prism, Opt. Lett. vol 21, pp 1771-3, 1996.
[5] N. A. Nicorovici, R. C. McPhedran, L. C. Botten, “Photonic Band Gaps: Noncommuting Limits and the “Acoustic Band””, Phys. Rev. Lett. vol. 75, pp. 1507-10, 1995.
[6] N. Notomi, “Theory of light propagation in strongly modulated photonic crystals: Refractionlike behavior in the vicinity of the photonic band gap,” Phys. Rev. B, vol 62, pp. 10696-705, 2000.
[7] S. P. Morgan, “General Solution of the Luneberg Lens Problem,” J. Appl. Phys., Vol 29, pp. 1358-1368, September 1958.