Prototype Design of a Dielectrically Embedded Mesh Lens

Jeremy D. Whitton[1,*], Philip D. Mauskopf[1], Paul F. Goldsmith[2], Kristina K. Davis[1], Christopher E. Groppi[1]
[1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85283, USA
[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
*Contact: jeremy.d.whitton@gmail.com

Abstract—**Here we present a prototype design for a dielectrically embedded mesh lens consisting of stacked layers of printed circuit board (PCB) material and embedded copper elements. The dielectrically embedded mesh lens consists of layers of dielectric which contain sub-wavelength-dimension metal elements laid out in a grid fashion, and is both flat and lightweight. It has been demonstrated that the sizes of these metal elements can be varied according to their position in the apparatus, using models based on transmission line theory, to create a lens which focuses a plane wave at millimeter wavelength to a Gaussian beam with very low transmission loss, even without the use of antireflective coating. We present the phase design for our lens which was designed, using transmission line theory and electromagnetic modelling software, to operate at 20GHz. We further present an analysis of the transmission line components which will make up the lens.**

I. Introduction

There is currently a burgeoning field of research, both in industry and academia [2], into the use of CubeSats for remote sensing purposes, both active, for observing the Earth and other nearby systems from space, and passive, which can be used in addition for astronomical observations [1]. For remote sensing in astrophysical applications particularly, signal-to-noise ratios are very low, and so long integration times are often required. This problem is accentuated by the fact that CubeSats are small: 10cm x 20cm x 30cm, with a weight budget of 8kg, is a common CubeSat form factor [1], which puts tight constraints on the sizes of CubeSat systems, and especially lens or antenna apertures. This requirement can be ameliorated somewhat by the use of low-loss systems and antennas or lenses that have as large an aperture size as is feasible. One suggested way to maximize the signal obtained by a CubeSat is the use of inflatable antennas, deployable after the CubeSat is launched [3]. This technology is still, to some degree, in its infancy.

Another possible approach is to use a metamaterial lens as an aperture. Metamaterials, which involve the structure embedding of metal meshes within dielectric substrates, have recently seen much advancement and development [6]. Metamaterial lens technology is also quite recent, though there have been advancements made which allows them to be designed and fabricated to operate at millimeter wavelengths [4]. A metamaterial lens offers a number of attractive qualities for use in CubeSats: they can be made flat and thin (in contrast to a conventional geometrically curved lens), and therefore do not count heavily against the CubeSat's small weight budget. It also makes it easier to place and stow the lens, if a deployable design is necessary or desirable. Furthermore, these design techniques by [4], ensure that no anti-reflection coating is necessary to minimize reflection losses. Finally, such lenses have been found to, at least theoretically, have less than half a dB of loss, which is significantly better than that of a Fresnel zone plate lens, which can exhibit on the order of 3 to 4dB or more of loss [5].

In this paper, we wish to recreate the design procedure used by [4], to create a prototype design for a metamaterial lens. We have elected to design the lens for use at 20GHz using layers of RO3003 PCB material and copper, with the intention that the lens will be fabricated using existing well-known PCB fabrication techniques, rather than the more complicated photolithography and layering techniques used by [4]. It is hoped that this will provide a cost-effective method for prototyping and testing our design process before we move on to create lenses to operate at higher frequencies. Our lens is also designed with a focal length to diameter ratio of f/0.37, as compared to the longer-focal length f/3 design achieved previously, which we believe would be easier to design around for the purposes of CubeSat deployment.

II. Materials and Methods

A. Theory

The design for the lens is based primarily on quasi-optics and, in particular, the physics of Gaussian beams. The purpose of our metamaterial lens, like any remote-sensing lens, is to focus an incoming plane wave to a beam which converges at some focal distance *f*. In order to accomplish this, it is necessary for the phase of the incoming plane wave to be transformed to that of a converging Gaussian beam. This phase transformation is given by [4, 7] as

$$\phi(r) = -\frac{\pi r^2}{\lambda R}$$

where r is the distance on the lens plane from the lens center, and R is the radius of curvature of the phase front, given by

$$R(f) = f + \frac{\left(\frac{\pi w_0^2}{\lambda}\right)^2}{f}$$

and w_0 is the waist of the focused beam at the focal plane.

The way in which the lens then produces this desired phase shift may be described theoretically by transmission line (TL) theory. The lens may be subdivided in the plane of the lens into many TLs, each of which ideally produces a single phase shift determined by their distance from the center of the lens. This is realized by designing the embedded metal elements in the lens to lie on a grid pattern, aligning with these transmission lines, and choosing the size of the metal elements accordingly [4].

B. *Design Procedure*

Our design procedure closely follows that of [4] In order to perform these optimizations to find optimal TLs, we first require, as noted earlier, S-parameters of individual elements to be used in the TLs. There are two types of these: substrate layers, of g by g by l; and embedded metal element layers, which were modeled as metal squares within an area of vacuum. The dimensions of the vacuum area were g by g by m, where g is the grid distance between the centers of adjacent metal elements, m is the thickness of the metal element, and l is the thickness of a substrate layer. The dimensions of the metal element are b by b by m. The parameter b may be changed for every individual element in a TL according to the requirements of the optimizer.

Given these models, S-parameters were calculated using finite element methods in the commercially available software HFSS. To perform these calculations, Floquet ports were used, implying that our S-parameters represent the output transmission magnitude and phase, relative to the input, of a plane wave which goes through an infinite periodic array of identical models. The periodicity was given length scale g. S-parameters were calculated in this manner from both the substrate model and the embedded element model, and de-embedded to the appropriate dimensions of each. For the embedded elements, S-parameters were calculated across a sweep of 48 different b values, with b going from 0.02g to 0.98g.

This set of S-parameters was exported and loaded into Matlab, and converted into ABCD matrices. Matlab's nonlinear optimizer was used to optimize for sets of b values which produce maximal transmission and the desired output phase. Note that we choose to calculate the S-parameters of individual elements, rather than entire transmission lines, because in general, optimizations may take thousands of iterations or more. To do thousands of iterations in HFSS could take days to optimize for a single transmission line, whereas pre-calculating S-parameters for individual elements and combining them with transmission line theory means optimizations take seconds. The goal function to accomplish this optimization was defined as follows: given a set of b values, choose the ABCD matrix for the metal elements with those b values. Cascade them together

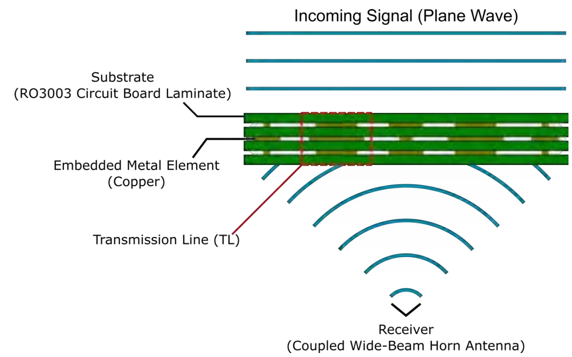


Fig. 1. Schematic diagram of metamaterial lens, not to scale

in the appropriate order, as in [8], with substrate ABCD parameters in between. Then find the S_{21} of the resulting transmission line. The function to be maximized is

$$\mathrm{mag}(S_{21}) \cdot \cos\left(\phi - \mathrm{ang}(S_{21})\right)$$

where ϕ is the desired output phase and $\phi - \mathrm{ang}(S_{21})$ will be referred to here as the phase error. In our case, this optimization was only performed for a single frequency, though it can in principle be extended to optimization over a particular bandwidth.

C. *Design Specifics*

With this procedure, we designed a lens according to the following specifications: the substrate dielectric is RO3003. The embedded metal elements are copper. The intended operating frequency is 20GHz. The grid spacing g is a tenth of a wavelength, equal to 1.5mm. The metal layer thickness is 35 microns, corresponding to 1oz copper cladding. The thickness of the substrate layers was constrained to 0.50mm (20 mil), which is a standardly available thickness of RO3003. The lens is composed of 10 layers of metal elements embedded within 11 substrate layers, as using fewer layers did not seem to provide sufficient transmission. The lens is a 30cm x 30cm square, with an 11cm focal distance. It is designed to couple to an antenna with a HPBW of 60 degrees: given our choice of focal length, this ensures it should capture about 99% of the beam power of the antenna. It was decided that 120 TLs would be optimized to be incorporated into the lens, which gives 1 TL

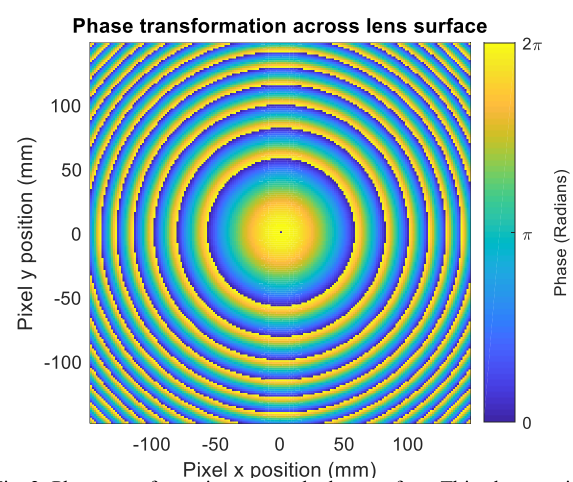
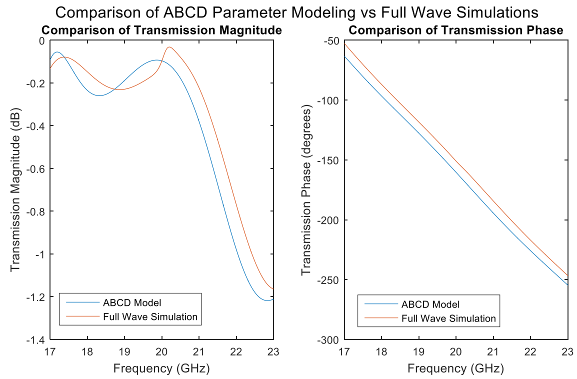


Fig. 2. Phase transformation across the lens surface. This phase varies rapidly at the edges of the lens due to its short focal distance.



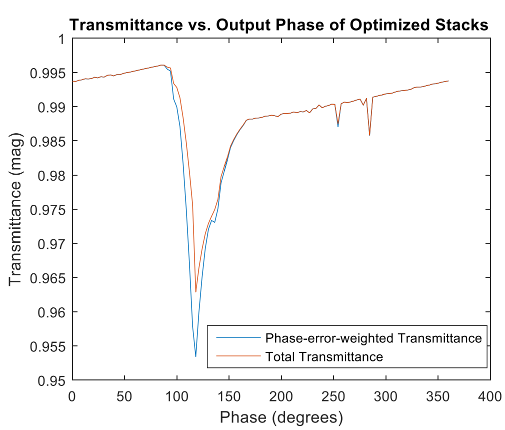
for every 3 degrees of phase shift between 0 and 360. In Fig. 2, the resulting phase design of the lens is depicted.

Fig. 3. Comparison of TL theory model vs. full wave simulation

III. Results

Given that our design relies upon the use of TL modelling in place of full wave simulations to determine the properties of our TLs, it was important to test is how well modelling the layering of substrate and metal elements with TL theory works. In **Error! Reference source not found.**, we show results comparing the S-parameters of our TL model vs. the S-parameters for the same structure obtained in HFSS via a full wave simulation. A number of optimized sets of *b* values were tested in this way, and this particular one exhibited the worst phase error. In spite of this, the phase error between the two is 8 degrees. We note also that the transmittances of the two models do not match perfectly, but are very close, generally off by no more than 0.2dB.

We also wanted to determine how high a transmission coefficient could be obtained across the range of desired output phases of our TLs. In Fig. 4, we demonstrate the transmittances of the 120 TLs which were optimized across an output phase range of 360 degrees. Across much of the range, the transmittance was above 98.5%; it was above 95% for the entire range. We note also that there is a distinct range of phases between ~100-150 degrees where the transmittance and phase-weighted transmittance drop sharply. This indicates that there is effectively a trade-off within this range between maximizing transmittance and minimizing the phase error. We found also, that, when using TLs with fewer than 10 layers, the reachable transmittance would in general drop lower. For example, with 8 layers of embedded elements, the transmittance was reduced to around 80%.



IV. Conclusion

We have here successfully designed TLs, using 10 layers of embedded metal elements, to be incorporated into a 20GHz lens design which have transmittances of over 95%. This falls somewhat short of the findings of [4], who were able to optimize for an average transmission of 97.5% across an entire 30% bandwidth. It may be that the optimization procedures previously used were more rigorous, and the procedures used here did not find global maxima within our parameter ranges. We also have no explanation for the significant drop-off in optimized transmittances between 100 and 150 degrees, and it is suggested that this could be studied in the future to determine if it is caused by non-rigorous optimization or some more inherent difficulty.

We do note that our design successfully constrained the thickness of the substrate layers to a single, standardly-available value, while the method in [4] required the optimization of the thicknesses of these layers. Our design has further been engineered to be simple to fabricate with standard PCB printing methods.

We also note that our simulation analysis of the transmission lines assumed periodicity in the lens plane of the structures which were tested. This means that our model may fail to take into account potential couplings between adjacent TLs which are different from each other.

Finally, we were unable to perform a full-wave simulation of the entire modeled lens, owing to unrealistic memory requirements. It is possible such a simulation could be performed by a supercomputer. It is suggested that future work will entail building a physical prototype based on the design procedure presented here, and measuring it to determine whether or not the 95% expected transmittance is realizable in practice.

Acknowledgments

This work was supported in part by JPL award SP.17.0001.003.

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Fig. 4. Over 95% transmittance is demonstrated over the lens surface

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