Measurements of a Prototype 20 GHz Metamaterial Flat Lens

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***Abstract*— In this paper, we present measurements of a prototype metamaterial flat lens. Flat, lenses with short focal lengths are of particular interest due to their potential use in quasi-optical observing in space-based cubesat applications. Our metamaterial flat lens was manufactured by using 11 layers of RO3003 circuit board laminate with etched sub-wavelength-sized copper patterning. The copper patterning is designed in such a way as to maximize the transmittance of the lens while applying the correct phase shift across the lens plane to give the lens its focusing properties. The lens was measured by scanning a receiver horn through one axis of the image plane of a transmitting horn. This measurement demonstrated that the waist of the focused gaussian beam is 30% wider than ideal. It is suspected that this non-ideality is caused by phase error in the design process, though simulations would be necessary to confirm this. Further measurements will be useful to fully characterize the lens's focal properties and determine how much loss it incurs.**

I. Introduction

CubeSats may be an attractive prospective for those wishing to perform terahertz observations, due to the high atmospheric attenuation at these frequencies which makes ground-based observing difficult or impossible [6], and due to the often-prohibitive costs of other mission types which are able to observe from above the atmosphere. However, CubeSat missions come with their own set of design challenges, which particularly includes requirements for low weight and small form factor [2]. In particular, we would like to advocate for the use of metamaterial lenses as primary observing apertures in such systems, due to a number of advantages which help ameliorate CubeSats' particular challenges.

Metamaterials, which involve the structured embedding of metal elements within dielectric substrates, and metamaterial lenses in particular, have recently seen much advancement and development into the millimeter wavelength regime [3], [4]. The lenses which have been created so far are both thin and lightweight compared to a conventional lens of equivalent f-number, freeing up weight budget and making it easier to place and stow the lens, if a deployable design is necessary or desirable. Furthermore, these design techniques by Ref. [4] ensure that no anti-reflection coating is necessary to minimize reflection losses. Finally, such lenses have been found to theoretically have less than half a dB of loss, which is significantly better than that of a Fresnel zone plate lens, which, while flat and light, can exhibit on the order of 3 to 4dB or more of loss [5].

Here we have created and tested a metamaterial flat lens which operates at 20 GHz. The lens we present here is intended to act as a low-frequency prototype to test our design procedure. A successful design procedure should allow us to experiment with more expensive high-frequency designs, operating at 600 GHz or even above 1 THz.

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II. Lens Design

The lens is designed in a narrow bandwidth around 20 GHz, and is designed in such a way as to transform an incoming plane wave to a gaussian beam. This phase transformation is given by Refs. [4] and [1] as

$$\phi(r) = -\frac{\pi r^2}{\lambda R} \tag{1}$$

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

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

and w_0 is the waist of the focused beam at the focal plane. The focal length of the lens is given by f.

In the case of our lens, the diameter of the active area is 254 mm, and the focal length is 105 mm, making our lens an $f/0.41$ lens. These parameters in combination give the phase transformation shown in the top plot of Fig. 1.

Given this phase transformation, we subdivide the surface of the lens vertically and horizontally into pixels, each of square dimensions $\lambda/10$, which is, in this case, about 1.50 mm. Each of these pixels is assigned a single phase transformation based on the above equations. In our case, each pixel has 10 metal layers, with 10 copper squares of metal, stacked on top of each other and separated by 11 surrounding dielectric layers. The dimensions of each square may be picked freely. Then, using techniques as described in Ref. [4], each pixel is optimized to give the desired phase transformation and maximum transmittance. These optimizations work by automatically tweaking the dimensions of each metal square until the desired conditions for that pixel are met. Because each pixel is treated independently from each other pixel, this is relatively computationally simple, as it

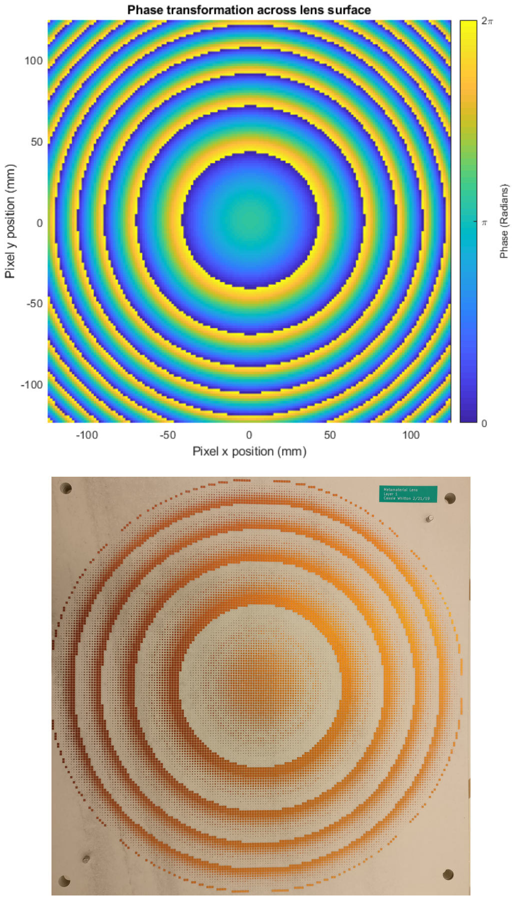

Fig. 1: The designed lens phase transformation (above) is compared with one layer of the manufactured lens (below). The layer's pattern is made up of thousands of copper squares.

only requires the optimization of around 5 free parameters (one for each layer of the lens, divided by 2 due to symmetry across its center) per pixel.

The lens was manufactured on RO3003 circuit board laminate with 760 mm thickness, with 1 ounce copper cladding. Due to manufacturing tolerances, the metal squares were constrained to be no smaller than 200 um in dimension, with at least 200 um between adjacent squares. A single layer of the manufactured lens is shown in the bottom half of Fig. 1. The layers were then stacked together, as shown in Fig. 2, using alignment holes that were drilled into the laminate layers during manufacturing. The completed lens is roughly 0.59 cm thick.

Though not directly relevant to this experiment, the lens is designed in such a way that it may be scaled from 20 GHz to 600 GHz. In doing so, the layer thicknesses and metal square sizes would be reduced by a factor of 30. Though this places much stricter tolerances on the manufacturing process, we have independently confirmed that there exist manufacturers with these capabilities.

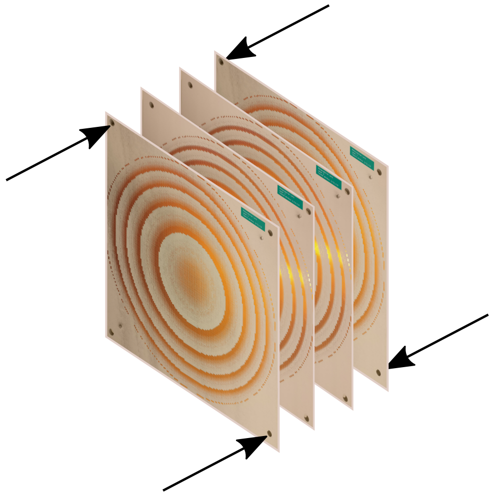

Fig. 2: Multiple layers of the lens are stacked together, aligned with guide-pins, and held together through boltholes at the corners. While this figure demonstrates only 4 layers, our lens has 11.

III. Experimental Setup

In order to test that the lens operates correctly, we performed a simple image-plane measurement. The physical setup for the experiment is shown in Fig. 3. To accomplish this, the transmitter (Tx) and receiver (Rx) were each placed 2 focal lengths away from the lens. We do this because placing the Tx $2f$ away from the lens causes its image to be $2f$ from the lens on the other side, as shown by the well-known lens equation:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \tag{3}$$

Here, d_o is the distance of the object from the lens and d_i is the distance of the image from the lens. Thus, the receiver directly measures the image of the transmitter. In addition, the resultant absolute magnification of the image is 1.

The transmitter and receiver each consist of a K-band pyramidal horn antenna with nominal 14 dBi gain coupled to a WR-42 waveguide. The transmitter is fed by a signal generator emitting a 20 GHz tone at -20 dBm. The receiver was connected to a power meter. The power meter only nominally operates up to 18 GHz; however, we tested that the power meter responded linearly to power input at 20 GHz. Therefore, while the absolute measurements of the power meter were likely incorrect, we are confident in the relative power measurements that it provided.

Once the transmitter's position was set, the receiver was scanned manually through the image plane until the point of maximum power reception was found. This was used as the zero-point for the measurement. The receiver was then manually moved up and down through the image plane in increments of a couple of millimeters. At each stopping point, the height of the receiver relative to its zero-point was recorded, along with the power measurement from the power meter.

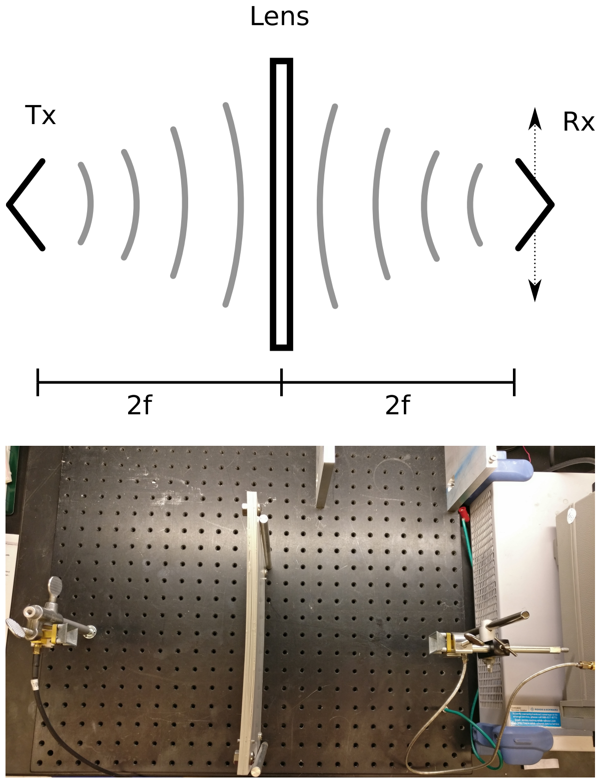

Fig. 3: A diagram of the test setup is display, with the realized setup displayed below it. The receiver and transmitter are both placed two focal lengths from the lens, such that the receiver sees an un-magnified image of the transmitter.

IV. Results

Plotted with red circles in Fig. 4 is the result of the image plane measurement as described above. The magenta line is the best gaussian beam fit to the measurement.

Plotted in blue is what we would expect to measure if the lens were acting as an ideal lens. This was calculated using the properties of the horn antennas, which we believe have beam waists of 8.4 mm at 20 GHz. By convolving the gaussian beam shapes of the two horns together, as described in Ref. [1], we expect the measured image to have an effective beam waist of approximately 11.9 mm.

The effective beam waist of the gaussian beam fit was 15.4 mm, which was about 30% wider than ideal. While we have not demonstrated that our lens focuses perfectly, we have demonstrated that it is functional as designed.

V. Conclusion

We have successfully demonstrated the focusing abilities of our 20 GHz metamaterial flat lens. However, the gaussian beam focus is 30% wider than ideal.

Further testing would be necessary to determine whether this is due to manufacturer tolerance error, phase error in the initial design, or an inaccurate estimate of the beam waists of the transmitter and receiver horns which were used. We suggest that a simulation of the designed lens, with its phase error included, could reveal whether or not the phase error was the cause. We also believe that a full near-field measurement of the lens would help to quantify the lens's performance in more meaningful ways.

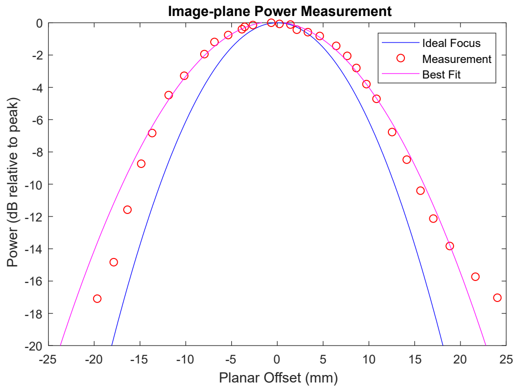

Fig. 4: Here is the plotted measurement of the image-plane scan compared to the expected beam measurement for an ideally focusing lens. The measured beam-width is about 30% wider than ideal.

In any case, we have demonstrated that our design process works well enough to accomplish an acceptable focus with our lens. We believe that scaling the lens to higher frequencies in the future is very achievable, as well as relevant. Doing so would allow their eventual application in CubeSat-based terahertz observations.

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