Flat Lens Antenna Technology for Free Space Material Measurements

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Abstract— **Free space material measurements at VHF and UHF bands require antennas that are necessarily large and heavy to accommodate the long wavelengths in these bands. Large antennas make measurement less practical and more expensive. This paper presents a new flat lens antenna technology, which enables significant reductions in size and weight compared to conventional wide bandwidth horn antennas. These new antennas utilize artificial dielectric loading combined with lossy materials to give directivities similar to much larger and heavier horns. This paper also presents the direct application of these antennas for free space dielectric material characterization. Example measurements of dielectric specimens are shown with a pair of 200 MHz to 4 GHz antennas.**

I. INTRODUCTION

Wireless and radar technologies at UHF and VHF frequencies require directive antennas for research, testing, and quality assurance. VHF/UHF wavelengths are in the range of several feet (10 cm to over 1 m), leading to present horn antenna technology that is large and heavy. For example, a conventional 0.2 - 2 GHz, dual-ridge horn weighs upwards of 20 lb. (9 kg) and is approximately 38” long x 37” wide x 27” tall (1 m x 0.9 m x 0.7 m). This size and weight make these antennas challenging to mount on rails or rotation stages or robots for scanning measurements. In field measurements, large antenna size and weight also complicate transport and storage of the measurement equipment. Even in a research or a manufacturing setting, these large antennas require space that may not be easily available.

“Measurement grade” antennas are desired for testing in laboratories, anechoic chambers, factories, or outdoor environments. To make these tests more practical and cost effective, smaller and lighter antennas with the same electromagnetic performance of conventional horns (i.e. directivity and bandwidth) are needed. The increasing use of automation and scanning also dictate a maximum size and weight for an antenna to be suitable. Many environments are often less than ideal. Dust, moisture, and electrostatic shock are all problems that can plague conventional horn antennas in certain settings. Thus, a new technology is also needed to withstand these conditions while still resulting in smaller and lighter weight antennas.

The work described in this paper is of a new flat lens antenna technology, or FLAT, that meets the above goals of reducing size and weight without degrading antenna directivity. The antenna designs presented here also are inherently rugged, making them suitable for harsh environments where moisture or dust is present. They are constructed with novel composite manufacturing methods that make them mechanically tough. And most of the conductive components of these antennas are encapsulated so there is minimal risk of electrostatic shock damaging transmitter or receiver electronics.

To demonstrate some of the utility of these flat lens antennas, this paper also presents their use in a free-space material measurement application. Free space material measurement methods provide broad band information about the dielectric or magnetic properties of materials [1]. They can also do this non-destructively for a wide variety of materials – both low loss and lossy. However, the use of free space methods has been limited at UHF frequencies in part due to the large size of the physical aperture of antennas in this range. The antennas presented here are somewhat smaller and allow for more reasonable specimen sizes to be measured. Example free space measurements are shown of material samples that are as electrically small as 1.6 wavelengths across.

In this paper the data presented are of some typical building materials used in either homes or commercial buildings. Knowing the dielectric properties of such materials is important for development of wireless communication applications and equipment within a typical house or office structure.

II. FLAT LENS ANTENNA TECHNOLOGY

Miniaturization has been a consistent theme in antenna research over the past several decades. Some of these efforts have focused on the idea of making an antenna thin in the propagation direction so it can be mounted conformal to a wall or vehicle. For example, magneto-dielectric metamaterials or metaferrites have been developed for reducing antenna thickness [2]. Such solutions can be wide band, but they also add significant weight to an antenna. Non-magnetic artificial materials such as electromagnetic bandgap (EBG) materials or double negative metamaterials (DNM) have also been explored to further miniaturize resonant antennas [3]. Unfortunately, these resonant metamaterials have very complex behaviors and have been effective only over narrow bandwidths.

In the test and measurement applications of interest here however, conformal is not a needed advantage while wide bandwidth is a necessity. Moreover, reduced weight is a significant need along with general size reduction. The innovation presented here is therefore not about making antennas that are thin in the propagating direction. Instead, the main idea of the flat lens antenna technology (FLAT) is to reduce the size in a dimension perpendicular to propagation. Maintaining a reasonable length parallel to the direction of propagation ensures that the antenna can still have useful directivity.

Figure 1 shows two hardware implementations of this idea. The larger antenna in this image operates from 200 MHz to 4 GHz and the smaller antenna from 500 MHz to 6 GHz. The polarization direction is designated by ‘E’ in the image and is parallel to the plane of the antenna. The propagation vector is shown in the image by ‘k’. Both these antennas are just over 2 inches (just under 6 cm) wide. The 200 MHz antenna is 30 x 20 inches (76 x 51 cm) and the 500 MHz antenna is 16.5 x 10 inches (42 x 26 cm).

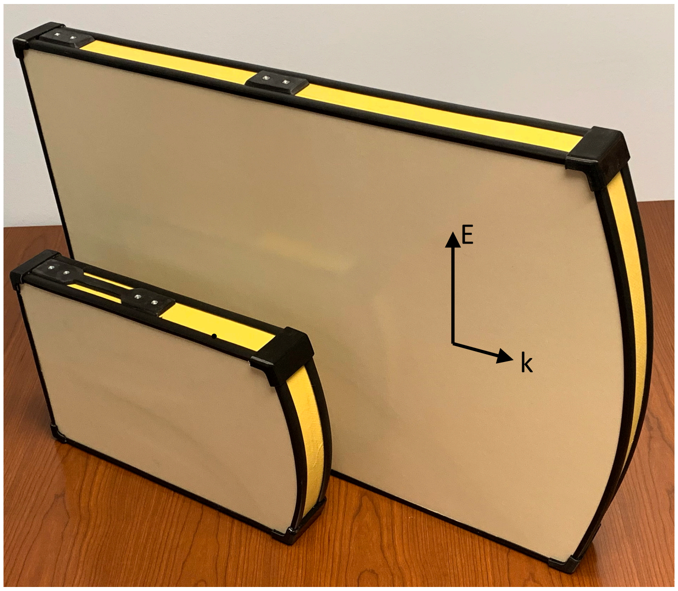

Figure 1. Photograph of two different FLAT antennas. The polarization is parallel to the plane of the antenna (E) and the forward direction of propagation is designated by k

Besides shape, another key design element of this antenna technology is that it incorporates anisotropic dielectric loading. Unlike many of the resonant metamaterials described in the literature, the metamaterial loading used in these antennas is below resonance so that it has wide band performance. This dielectric loading is used in two internal regions of the antenna shown in Figure 2. Towards the front where energy propagates out, it is in the form of a low-loss dielectric gradient that acts as a lens to control the antenna gain. In particular, it modifies the forward traveling wave to have a less curved phase front as it exits the antenna. The loading is created by a conductive pattern of metal on thin substrates stacked up with foam layers to create an artificial dielectric metamaterial that is very light weight.

Towards the back of the antenna, lossy anisotropic dielectric material is incorporated to reduce back-propagating energy that is not directed into the feed. This lossy dielectric is manufactured from a pattern of carbon loaded polymer material deposited on foam substrates and is also very light weight. This lossy loading significantly improves the antenna front-to-back gain ratio. But it does this at the cost of some antenna efficiency. These FLAT antennas tend to have efficiencies around 40 percent. This is not a problem for most measurement situations. However, it does make them unsuitable for high-power scenarios. The obvious benefit is the overall reduced size. Thus, these antennas do not have the same realized gain as a conventional dual-ridge horn. But they do have roughly equivalent directivities making them ideal for measurement applications. The novel design elements described here are patent pending.

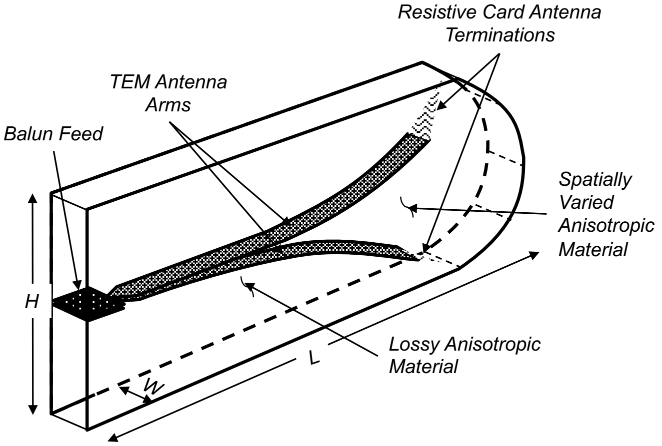

Figure 2. Internal design of FLAT antenna including lossy and non-lossy artificial dielectric matamaterials.

Some key physical and electromagnetic parameters of the 200 MHz version of the FLAT antenna are compared to published manufacturer data of two conventional dual-ridge horns in Table 1. Another key element of these antennas is that they are constructed primarily from composites and foam rather than the aluminum used in a conventional horn. For this reason, they are approximately a fourth of the weight of most equivalent horns.

Measurements of the forward and backward gain from a 200 MHz FLAT antenna are shown in Figure 3 along with the VSWR in Figure 4. These data were measured in an outdoor range by placing a large ground plane in front of the antenna to image it. The measured reflection data is analyzed by applying the well-known Friis equation to calculate gain [4].

Table 1. Comparison of 200 MHz FLAT antenna to commercial dual-ridge horns designed for same frequencies

	FLAT200	Conventional Horn 1	Conventional Horn 2
Length	**30"**	38"	38.5"
Width	**2.25"**	38"	37"
Height	**20"**	24"	29"
Weight	**8 lb**	22 lb	26 lb
Frequency	**0.2 – 4 GHz**	0.2 - 2 GHz	0.2 - 2.5 GHz
F/B Ratio	8 - 30 dB	7 - 25 dB	? - 25 dB
Gain	-2 - 12 dBi	6 - 14 dBi	2 - 12 dBi
VSWR	< 2.4	< 2.4	< 3

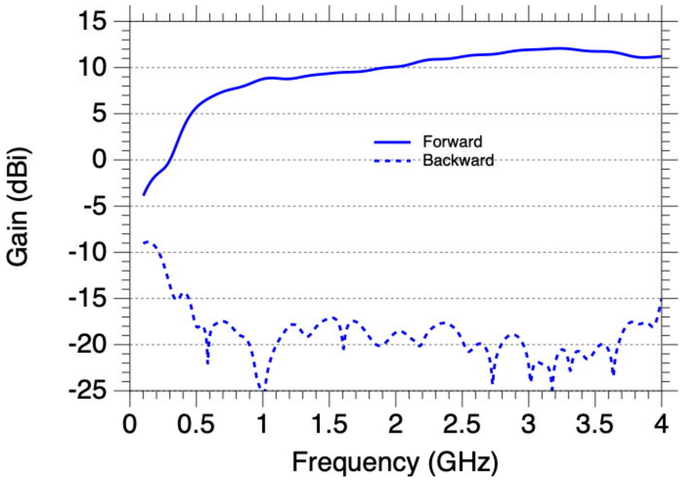

Figure 3. Forward (solid line) and backward (dashed line) gain from a 200 MHz FLAT antenna measured from a groundplane range.

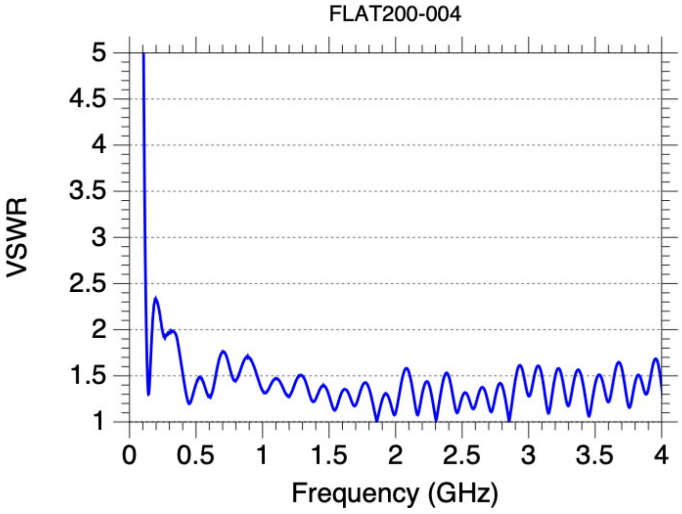

Figure 4. Voltage Standing Wave Ratio of FLAT200 antenna showing wideband performance

As described above, a significant characteristic of these antennas is that they maintain directivity even with the dramatic reduction of the one dimension. This is accomplished in part by the internal lossy dielectric materials, which result in a typical efficiency of the FLAT antennas of about 40 percent. To illustrate this, both the antenna gain and the directivity measured on a FLAT200 antenna are shown in Figure 5. These results were obtained with a spherical near-field method [5] and they compare well to the ground-plane method shown in Figure 3. As these data show, the directivity is 4 or 5 dB higher than the gain and is at a level similar to conventional wide band horn antennas.

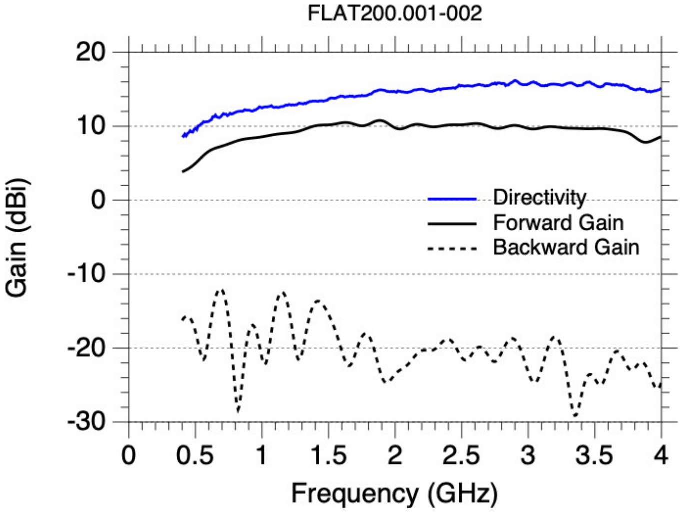

Figure 5. Nearfield measured Gain and Directivity for a FLAT200 antenna showing about 4 or 5 dB difference.

III. FREE SPACE MATERIAL MEASUREMENTS

A. Methodology

The concept of material measurements with these FLAT antennas is based on using them as "spot probes". The idea of a compact probe for free space microwave material measurements goes back at least several decades. In the mid 1970s, Musil, Zacek, et al. used dielectric rod antennas to measure transmission through a material specimen [6]. They used their probes to successfully obtain the dielectric permittivity of silicon specimens at millimeter wave frequencies. More recently wide band spot probes were used successfully to extract dielectric and magnetic materials at frequencies down to as low as 2 GHz [7]. In the present work FLAT antennas are used in a similar way but at much lower, UHF frequencies.

A photograph of the measurement setup is in Figure 6, which shows two FLAT antennas placed on either side of a material specimen. The specimen in the photo is 4 x 4 feet (1.2 meters square) and the separation from the end of each antenna to the specimen is approximately 3 feet (0.9 m). Not shown is a two-port vector network analyzer used as the microwave source and receiver for collecting scattering parameters. Calibration is done with response and isolation measurements. For transmission, the response calibration is a clear site (no specimen) and is the primary reference measurement. The isolation is done with a same-size conductive sheet in place of the specimen, and it helps to account for energy that may spill around the finite sized specimen. Thus, the calibrated data from a specimen under test is given by,

$$S_{21}^{cal} = \frac{S_{21}^{raw} - S_{21}^{iso}}{S_{21}^{res} - S_{21}^{iso}}, \quad (1)$$

The response and isolation calibration by itself is insufficient for eliminating all the various measurement errors. Thus, an additional step of time domain gating is used on the calibrated data to isolate the desired signal from multipath and other undesired scatter. For the data in this presentation the measured signals were transformed into time domain via a Fast Fourier Transform and a 2-nanosecond time domain gate was applied before transforming back into frequency domain.

Figure 6. Photograph of two FLAT antennas on either side of a material specimen

B. Measurement Examples

Two common building materials were measured: plywood and sheet rock (gypsum wall board). The measured transmission amplitude of these two materials in the 400 MHz to 5 GHz frequency band are shown in Figure 7. The sheet rock material is relatively low loss while plywood has moderate losses. These characteristics are apparent in their relative transmission amplitudes. Specifically, the plywood has significantly more insertion loss even though it is of similar thickness to the sheet rock. There is also some ripple apparent in the measured signals, which is likely due to over illumination of the specimen resulting in moderate edge diffraction errors. This ripple could be reduced by either increasing the size of the measured specimens or by constructing an aperture wall of similar material. At the lowest frequency of 400 MHz, the lateral dimensions of the specimens are only 1.6 wavelengths across, so over illumination errors are not unexpected.

Taking the transmission amplitude and phase and applying a standard iterative dielectric inversion method [1] gives the real and imaginary permittivity data shown in Figure 8. In this plot, solid lines represent the real permittivity while dashed lines are the imaginary permittivity or dielectric loss. The somewhat more lossy characteristics of the plywood are evident in the increased imaginary permittivity versus the sheet rock (dashed lines). The real part of the plywood permittivity (solid black line) also shows some apparent dispersion (non-trivial slope) in this frequency range, while the lower loss sheet rock's real permittivity (solid blue line) has a reduced slope.

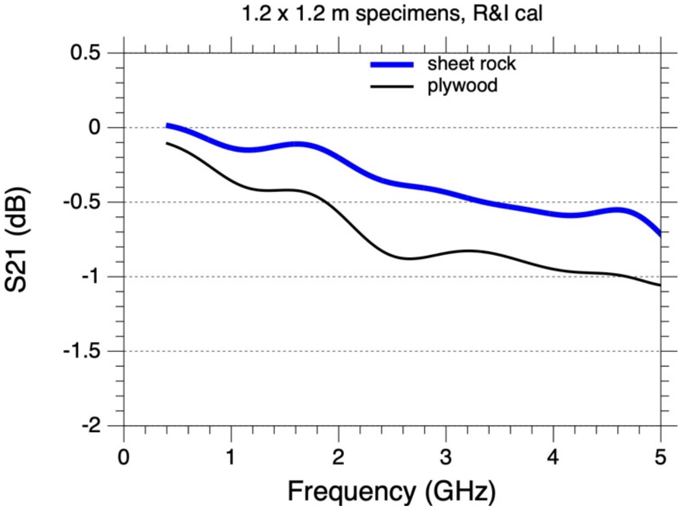

Figure 7. Transmission amplitude of 1/2 inch (1.3 cm) plywood and 3/8-inch (1 cm) sheet rock materials

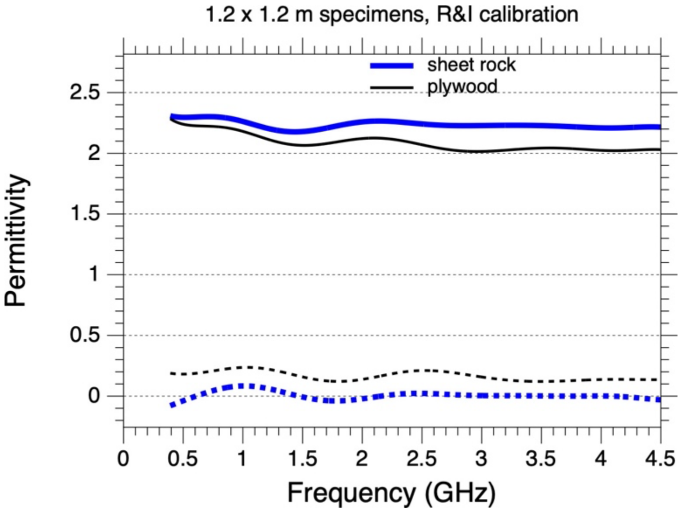

Figure 8. Real (solid lines) and imaginary permittivity (dashed lines) of several common building materials

Often for S21 measurements to determine dielectric properties, the calibration can be simplified to just a response calibration that is the ratio of the sample transmission to that of a clearsite. To show what happens when a simple response calibration is used instead of a response and isolation method with this fixture, Figure 9 shows the inverted real and imaginary permittivity of the same sheet rock and plywood, but with just the response-only calibration. The most noticeable difference with the results in Figure 8 is the large deviation in the real permittivity at frequencies below 1 GHz. This anomalous effect is caused by over illumination which then modifies the effective phase of the measured signal. In the response and isolation method, this is accounted for by the isolation calibration. The disadvantage of including the isolation calibration is that it does add some additional ripple across the band, presumably due to edge diffraction from the edges of the metal isolation standard.

The best way to have both minimum ripple and no over illumination effects is to have a larger specimen. However, that is not always a realistic solution. It is also possible to minimize ripple and over illumination effects by mounting the specimen into a larger apertured wall of similar material. Though that also adds additional complexity to the measurement procedure and may not always be practical.

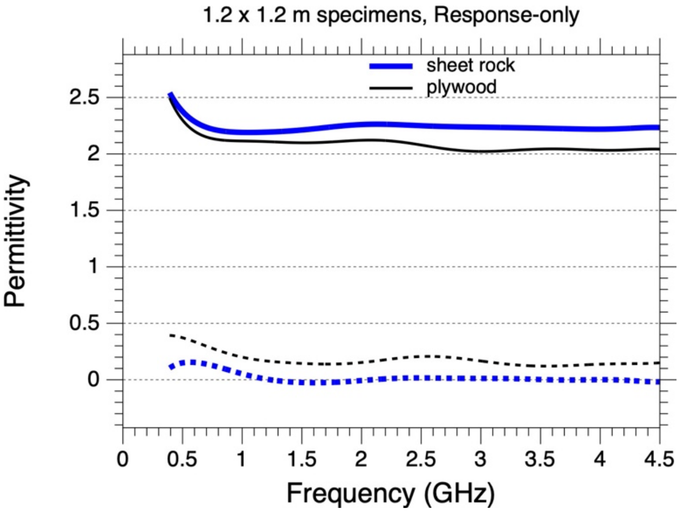

Figure 9. Real and imaginary pemittivity with response-only calibration (no isolation subraction)

Another common building material that can also impact wireless signals propagation is window tint. It often consists of thin sputtered or evaporated metal layers on a polymer substrate. An example measurement of the transmission through commercial window tint is shown in Figure 10, and this particular specimen has an insertion loss close to 9 dB. Two curves are shown in this plot, the solid line was calibrated with just a response (clearsite) while the dashed line was calibrated with both a clearsite and a metal sheet isolation measurement. Similar to the dielectric samples, the additional isolation calibration adds additional ripple to the measured amplitude.

Using the measured amplitude and phase of the S21 data, the real and imaginary sheet impedance can be inverted for the window tint using the standard methods [1]. This inverted data is shown in Figure 11, which shows the real impedance as a solid line and the dashed line is the imaginary impedance, also known as the reactance. In this case the reactance is a positive number indicating a slightly inductive characteristic. Unlike the dielectric specimens, the response-only calibration results in a more accurate inversion. This is because the phase data primarily influences the reactance, which is relatively small for this specimen. Instead, the amplitude ripple is the dominant error source and the response-only calibration results in a lower level of ripple. Thus, when specimens are electrically small, the appropriate choice of calibration method depends on the relative importance of phase versus amplitude to the inverted properties.

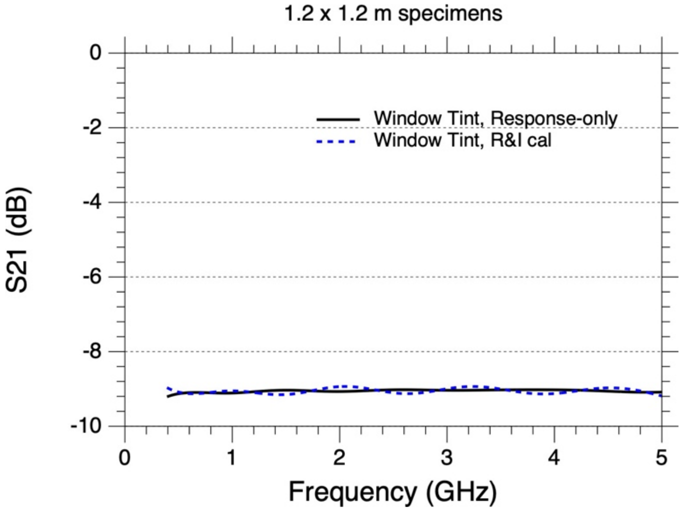

Figure 10. Transmission coefficient through a commercial window tint measured both with response-only (solid line) and response and isolation calibrations (dashed line)

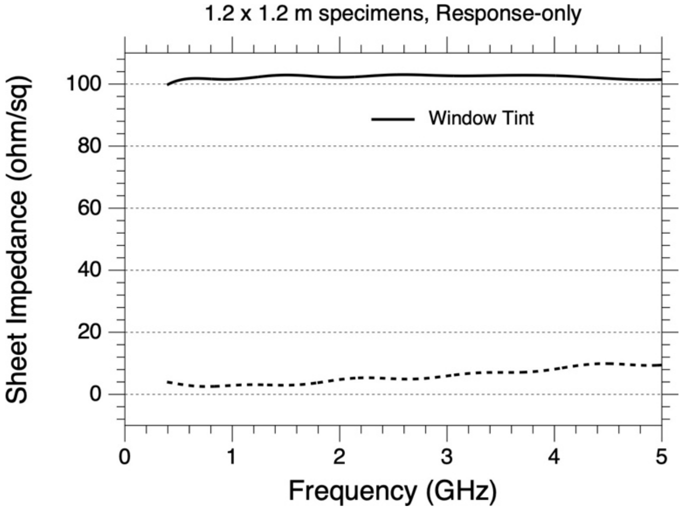

Figure 11. Real (solid line) and imaginary (dashed line) sheet impedance of a commercial window tint

I. CONCLUSION

This paper presents a new flat lens antenna technology, which results in antennas that are smaller and lighter than conventional dual-ridge horns. Even with this significant reduction in physical characteristics, they still have bandwidth and directivity that are similar to conventional wide band horns. While their low efficiency prevents them from high power applications, their good directivity and fast ring-down makes them excellent for instrumentation applications such as materials measurement.

The application of these antennas for determining dielectric materials at UHF frequencies is also demonstrated. A pair of FLAT antennas was used to measure both dielectric and resistive materials, and their dielectric permittivity or sheet impedance was successfully inverted. The relative effectiveness of a response and isolation calibration versus a response-only calibration was also explored on these measurements. The large wavelengths at low frequencies lead to a desire toward being able to measure electrically small specimens, and the free space measurements shown here were successful even on specimens that were only 1.6 wavelengths across at the low end of the measurement band.

ACKNOWLEDGEMENT

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