Microwave Optics Research

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BRIGHAM YOUNG UNIVERSITY-IDAH0

DEPARTMENT APPROVAL

of a senior thesis submitted by

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ABSTRACT

MICROWAVE OPTICS RESEARCH

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The Physics Department x-band microwave optics equipment was originally intended for use in classroom demonstrations. I evaluated this equipment for use in research, determined additional equipment needed in order to perform attenuation and other experiments, and have used it to conduct research on the transmission properties of paper and other substances. The additional equipment includes a goniometer base and Radio Frequency absorbing foam apertures. This equipment was needed in order to create a standard procedure, take reasonably accurate measurements, and reduce undesired standing wave effects. I performed mathematical and experimental analysis to determine the necessary parameters of the new equipment. The new apparatus is comparable to setups featured in published journal articles and will give research opportunities to future students.
With this equipment I investigated the transmission properties of paper. I showed that paper acts as linear polarizer in two independent ways. A stack of paper edge-on as the incident surface is a known linear polarizer. After researching the conductive properties of paper, I predicted then demonstrated that microwaves incident on the face of a stack of paper is also a linear polarizer. The polarizing properties of paper have educational value for demonstrating polarization and relating the macroscopic to the microscopic.
ACKNOWLEDGMENTS

I would like to thank Todd Lines, my advisor for this project. I would also like to thank David Oliphant, Charles Andersen, and Andy Johnson for their help in obtaining and creating the necessary materials for the equipment, Phil Scott for writing much of the code used to gather and analyze data, and Josh Barney for his collaboration. I appreciate the entire BYU-Idaho Physics department’s role in my education. I thank Sam Nielson and Leslie Twitchell for time they spent answering my questions about paper. I especially thank my wife for her encouragement and patience with me as I’ve worked on this project.
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Chapter 1

Introduction

1.1 Project Background

The purpose of my project was originally to empirically investigate the interaction of microwaves with the atmosphere in a variety of conditions in order to test the computer software for atmospheric microwave transmission being developed by another student and to make possible other microwave optics experiments in the future.

The first part of this project consisted of cataloging and characterizing the existing microwave equipment that the Physics Department already had but that had been in disuse for some time. I determined some vital aspects of the equipment by performing several experiments such as a using a thin film-like interferometer to confirm the wavelength, a maximum detectable range experiment, and a beam shape experiment. I also checked manufacturer and government safety guidelines to resolve any safety concerns. The details of these experiments and observations have been documented in
BYU-Idaho Physics Department Microwave Optics Equipment (Appendix B), Thin Film Experiment for Determining Wavelength (Appendix C), and Microwave Beam Shape Map (Appendix D).

Using Beer’s law, [1]

\[ \frac{I}{I_o} = e^{-\alpha l c}, \]  

with a given attenuation coefficient \( \alpha \) one can determine the distance electromagnetic radiation of a given wavelength needs to propagate in order for it to be measurably attenuated. It can be easily shown that transmissions near 10 GHz are attenuated on the order of kilometers by oxygen and/or water vapor (See Appendix A). With the equipment on hand, only transmissions on the order of centimeters, meters, or at most, tens of meters maximum could be conceivably attainable (See Appendix B).

I then turned my attention to other materials, with higher attenuation coefficients with the hope of creating feasible experiments that could be used to test the computer model. I attempted to determine the attenuation coefficient and index of refraction for materials on hand for both the thin film and atmospheric transmission applications. The angles of highest transmitted intensity corresponded to a negative index of refraction for several textbooks and even a ream of plain printer paper. The discovery of a left-handed material would be very exciting however the amount of instrument uncertainty and extra variables in the setup rendered any measurements to be inconclusive for the time being.

Moving a target sample between the stationary transmitter and receiver dramatically changed the recorded intensity in a periodic fashion, suggesting standing waves were forming or that there was other interference was present between the transmitter, target sample, and receiver. This adds a much higher uncertainty to the
measurements of relative intensity needed to derive the attenuation coefficient of a given sample. Apparently the classroom demonstration equipment alone would not be enough to take the measurements needed.

This paper details the design process and construction of additional microwave optics equipment needed to perform quality microwave optics experiments.
Chapter 2

Design of the Apparatus

2.1 Basic Configuration

The main characteristics needed for a better experimental setup are a means of eliminating formation of standing waves and other interference as well as a stable structure that allows the transmitter and sample to be stationary with the receiver arranged to scan in a consistent manner. The basic design needed is not new. Several research groups have used variations of a stationary transmitter with the beam at normal incidence to a prism [2] [3] [4]. The receiver is placed on the end of an arm that rotates about the exit point of the beam from the prism to take data in the form of intensity vs. angle. The arms generally have tic marks for measuring distances and one arm is the pivoting arm of a goniometer to measure angles. Velazquez-Ahumada et al. [2] especially address a way to eliminate standing waves in this setup as follows:
The PVC mounting base was covered with adhesive copper foil, and pyramidal foam absorber was placed at both sides. This foam absorber prevents the formation of standing wave patterns between the horns and the mounting base. If standing wave patterns are present, the signal in the receiver would oscillate with the position of the receiver along the goniometer arm.

The oscillations mentioned were exactly what had been observed so it was decided that a variation of their setup pictured below in Fig. 2.1 [2] was needed.

![Experimental setup used by Velazquez-Ahumada et al. [2]](image)

**Figure 2.1** Experimental setup used by Velazquez-Ahumada et al. [2] Includes their microwave transmitter and receiver horns, goniometer base and arms, and RF absorbing foam base.

The main difference in the requirements for our experiment is the plan to test a variety of different targets of different shapes and sizes. It would be very inconvenient to have to machine all of our samples into identically shaped prisms to match the size of whatever hole were to be cut into the foam. Since the RF absorbing foam is expensive, it would be impractical to cut a new piece of foam and build a support structure for each target size. Therefore a variation of the usual setup was decided on. Instead of RF foam surrounding the target, two double-sided slabs of pyramidal RF foam with apertures in
them would be placed on each arm, one between the transmitter and the target, and the other between the target and the receiver as in Fig. 2.2.

**Figure 2.2** This is a rough drawing of the proposed goniometer with RF foam aperture setup. The test sample is in the middle of two RF absorbing foam apertures. The receiver pivots around the center of the sample in the plane of the table.

Given this basic design there were several parameters that needed to be determined before it was built including the type and quantity of RF absorbing foam needed, distances between the transmitter, sample, receiver, and foam apertures, the height of each of these above the table they rest on, and the shape and size of the apertures in the foam.

After researching several vendors and products, I chose a RF absorbing foam for a relatively good price that attenuates well for our frequency-12.5 ± 5 GHz (see Appendix C). Fig. 2.3 below shows the attenuation by this foam versus frequency from the manufacturer [5].
Figure 2.3 This shows the attenuation of the pyramidal foam used for the microwave apparatus over a range of frequencies [5].

Although this foam is not optimized for our frequency- it performs well compared to other foams that attenuate less than -15 dB over the whole range of frequencies. One of the most important features of this foam is its pyramidal shape. This feature reflects radiation in toward the foam again causing further attenuation and reducing reflections of the wave back on itself and thereby reducing the creation of standing waves.

The next question was how much of this RF foam to purchase. Having previously mapped the emitted beam it was apparent that the entire beam spreads so much as to be much larger than any of the target samples- including the RF foam- used in the published literature. This seems very curious when one considers that for visible optics any lens, aperture, or object tends to be many orders of magnitude larger than the wavelength or even the beam size form a laser. However, the most concentrated portion of the
unobstructed beam is essentially confined to the volume of a cylinder with its axis starting at the emitter horn with a length of 1m and a radius of 20 cm (see Appendix D). This is much more manageable but still considerably different than familiar visible optics.

The sheets of foam are sold in units of 0.6096m by 0.6096m. The foam needs to be mounted on a base with reflective foil behind it. Velazquez-Ahumada et al. [2] used copper foil but common aluminum foil is also an excellent reflector so I decided to use that instead. The two apertures need to be covered with foam on either side. One square of foam could be cut into four $\approx 30\text{cm}^3$ apertures. This wouldn’t be enough to fit the simple cylindrical approximation of the beam, much less the actual beam shape. Two sheets could yield four 0.3048m by 0.6096m pieces. Since most of the spread of the beam is actually parallel to the table and the bottom part of the beam dies off (see Appendix D) I decided to have the longer side be oriented horizontally and let the foam be lifted up to have its center aligned with the transmitter or receiver horn.

2.2 Mathematical Models

To reduce strange interference effects and to simplify the math it is important to maintain every portion of the apparatus far enough apart so that everything is in the far field or that incident waves are approximately parallel. A rule of thumb for this is about ten wavelengths, in this case about 30cm [2]. The conditions for determining the distance $R$ for the far field for a given aperture of largest dimension $a$ and wavelength $\lambda$ [1].

$$R > \frac{a^2}{\lambda} \quad \text{(2.1)}$$
Such distances being large enough to be close to infinity supports the manufacturers of a similar 10 GHz microwave apparatus which have “18 cm High Mounts -- Minimize tabletop reflections for improved accuracy” [6]. Therefore mounts at least this high should be used.

The next parameter I needed to determine was the shape and size of the apertures to cut into the RF foam. It is important to know how much microwave incident on aperture will diffract because greater diffraction spreads out the beam more, making it harder to detect and harder to associate with a given position. The two aperture shapes that would be easiest to fabricate would be a square or a circular hole in the foam. The following equations are solutions for the diffraction patterns for irradiance on a surface a distance $R$ from an aperture [1].

For a rectangular aperture

$$I(Y, Z) = I(0) \cdot \left( \frac{\sin(\alpha')}{\alpha'} \right)^2 \cdot \left( \frac{\sin(\beta')}{\beta'} \right)^2$$

(2.2)

where $\alpha' = kaZ/2R$ and $\beta' = kbY/2R$. For a square aperture $a = b$. The circular aperture results in the Airy disk pattern as follows:

$$I(\theta) = I(0) \cdot \left[ \frac{2 \cdot J_1(k \cdot a \cdot \sin(\theta))}{k \cdot a \cdot \sin(\theta)} \right]^2$$

(2.3)

where $J_1$ is a first order Bessel function of the first kind and $\theta = q/R$ where $q$ is the radial distance from the center of the Airy disk.

Plotting equations (2) and (3) with $I(0) = 1$ and equal values of $a$, $k$, and $R$ for both can be used to compare the diffraction through each shape. As an example, Fig. 2.4 below was plotted with the parameters of $a = .07$ m, $k = 2\pi/0.024$ m$^{-1}$, and $R = .3$ m.
Comparing the two equations shows that the circular aperture results in a more concentrated beam. The Maple GUI used to create these plots (see Appendix E) can be used to model diffraction through such apertures at a variety of distances once created. The diffraction patterns change more with changes in $R$ than changes in $a$ so even with fixed aperture sizes it will be important to model diffraction for different values of $R$.

### 2.3 Experimental Techniques

Having shown that a circular aperture is best, the most difficult part is choosing an appropriate aperture size in the foam. If it is too small the foam will attenuate too much and signal will not reach the receiver well or possibly diffract so much that the signal is spread out over too large an area to be useful. It the aperture is too large it would be like the foam was not even there and the problem of the standing waves would not be fixed, rendering the foam useless.
As I have already shown, diffraction through simple apertures is easy enough to model if the parameters are known. However, mathematically modeling standing waves between the transmitter, target, and receiver as a function of aperture size is too complex for the scope of this project. Instead, I performed several experiments to attempt to determine possible aperture sizes without cutting the expensive foam. The basic procedure of each experiment is to set up the microwave transmitter and receiver with the foam sheets between. I placed a book between the foam and the receiver and toggled between locations that result in a node or anti-node of a standing wave to fall on the receiver.

For each experiment I first measured the intensity with the beam off, the beam on with no obstruction, and the node and anti-node measurements with no foam. Then I measured intensity with nodes and anti-nodes for each aperture size, starting at zero and increasing the separation by 1cm increments. Using the LabView program “loswm.vi” (LabView Oscilloscope for Square Wave Measurements as shown in Appendix E) The two important things to pay attention to are how much the signal can pass through a given aperture size, and how much changing the position of the book varies the intensity for a given aperture size. An ideal aperture should have high transmission but low standing wave effects.

The first experimental setup is shown in the picture below in Fig. 2.5. I held the one piece of foam in place above the one shown to create the aperture. This creates a widening slit for an aperture. The error in slit sizes was considerable (perhaps as much as ± 2cm) since I didn’t fix the upper sheet of foam in place. The regular packing foam in
front of the transmitter helps some to concentrate the beam to reduce spread in the
direction of the slit.

![Figure 2.5](image1)

**Figure 2.5** Photograph of my first attempt to experimentally determine an adequate aperture size. The sheet of pyramidal foam on the right was held above the one supported between the two tables to create a slit. The size of the slit was measured with the meter stick.

I redid the experiment once the LabView program was improved (see Fig. 2.6). I also set it up so that the RF foam could be secured well for a given measurement. The foam slit in this experiment was perpendicular to the previous one and the distances were decreased to reduce the spread of the beam over the slit. This time the error was ±1 cm.

![Figure 2.6](image2)

**Figure 2.6** Photographs of my second attempt to experimentally determine an adequate aperture size.
The results this time with the improved LabView program, as shown below in Fig. 2.7, were much cleaner.

![Graph of second aperture experiment](image)

**Figure 2.7** Graph of second aperture experiment. Values at $x=-20$ record when the transmitter is off, $x=-15$ records when the transmitter was on with nothing between it and the receiver, $x=-10$ shows negative interference with the book only and $x=-5$ shows positive interference, again with no RF foam. All other values of $x$ correspond to the foam slit size with an error of ±5mm.

There was an interesting anomaly that some large aperture sizes (around 100mm+) have higher transmission than with the book and no foam at all. This could be fringe effects. In any case such aperture sizes are larger than ones we are considering.

One can see that in both cases aperture sizes below about 3cm or about one wavelength allow very little of the beam to reach the receiver. As expected, larger apertures transmit better but are more variable because standing waves form. The optimum design should balance between these two effects.

Having done these experiments, I decided to cut both of the foam sheets in half creating four 1ft by 2ft sheets. With these I conducted the following experiments with an
approximately square aperture. The procedure was essentially the same as before, only now the aperture shape is different as shown in Fig. 2.8.

![Figure 2.8](image)

Figure 2.8 Photograph of the third attempt to experimentally determine an adequate aperture size. The four sheets of pyramidal RF foam were used to create an approximately square aperture.

This test was performed twice with the book and then without the book to check transmission through the aperture itself and nothing else. The graphs for the second is shown below.

![Figure 2.9](image)

Figure 2.9 Graph of the data of the second square aperture experiment. Axes are the same as in Figure 2.7 Error in the x values is about ±5mm however it should be noted that in this experiment there appeared to me more error in the position of the book that was toggled to move the standing wave positions.
Compared to the slit experiment, these graphs indicate a higher attenuation, which is to be expected since the area of the aperture size is now an order of magnitude smaller. The square aperture experiments are therefore a better approximation than a slit of the circular apertures that need to be cut. Fig. 2.9 suggests that a good aperture size is that of 5cm by 5cm. This size has a noticeable transmission and the intensity does not change much with change in position of target. Interestingly, the strange high transmission readings seen with first apertures were not present. Finding conditions for high and low interference was more difficult which, even though it made this experiment harder, suggests that the RF foam works well.

I also conducted experiments with no obstruction of the beam other than the expanding square aperture. The purpose of this experiment is to model the attenuation of the aperture so as to predict attenuation by using two apertures as proposed. I conducted the experiment with the same procedure as above; only there was no book to toggle back and forth. The first test had the receiver at GAIN 1 and the second at GAIN 2. The corresponding graphs are shown below in Fig.s 2.10 and 2.11 respectively.
Figure 2.10 Graph of the test of attenuation of a square aperture in the foam. Receiver set to GAIN 1. Again the axes are the same as in Fig. 10 but with no 5s space because there was only one data point taken per aperture size. Error in the x values is about ±5mm.

Figure 2.11 Graph of the second test of attenuation by a square aperture in the foam. Receiver set to GAIN 2. Axes are the same as in Fig. 14. Error in the x values is about ±5mm.

Fig. 2.10 with GAIN 1 shows the voltage given from the receiver maxing out with no aperture and for square apertures 7cm on a side or larger. Fig. 2.11 shows GAIN 2 being used, allowing for more sensitivity since the output voltage did not reach its maximum. It also shows the anomalous brightness at 8cm or larger apertures we saw before. Such sizes are much larger than the 5cm aperture we are considering but the
behavior shown is interesting because it was completely unexpected. At 5cm with the more accurate GAIN 2 readings we see about a 15% transmission. Two 5cm apertures should result in about 14% and 2% transmission respectively. These are small, but using a proper gain setting, the modulated signal should still be easily visible with the “loswm.vm” program. Also, one would expect the transmission to actually be slightly higher with circular aperture, which diffracts less than a square one.

To stay in the far field with a 5cm aperture requires keeping at least 10cm away from the apertures which is very manageable. The predicted diffraction pattern at a distance of 30 cm is given below in Fig. 2.12. This shows that almost all the beam is kept within a 10cm radius of the axis. FWHM is at a radius of 4cm.

![Graph](image)

**Figure 2.12** Predicted diffraction pattern for a 5cm circular aperture. Units of the x-axis are meters and the y-axis represents relative intensity.
Chapter 3

Building and Testing the Apparatus

3.1 Goniometer Base

The core of the apparatus is the goniometer base. It provides the necessary structure to support each element and keep them at a measurable distance away from all other elements. It also measures angles between the incident and transmitted beam. It is shown below in Fig. 3.1.

![Figure 3.1 Photograph of the goniometer base with meter sticks inserted.](image)
The structure consists of three wooden boards with slits connected by swivels. They rest on a laminated angle wheel that serves to measure the angle between the two arms. Each board has a hole drilled through the center so that the base can be centered on the angle wheel and to observe how far the meter sticks are set into the base. The bottom board has a slit cut into it such that a meter stick can slide in and out of it, as does the middle board. The middle board, which is considerably smaller than the outer two, with the meter stick attached to it, can rotate independently of the other boards. To increase accuracy of angle measurements, a piece of cardboard or other thin sturdy material can be placed in the center of the under side of the meter stick.

The top board can also rotate independently so as to rotate a sample on it but can be secured if desired by wooden blocks about the size of the space between the outer boards. The dimensions of the base without the meter sticks are 29.5×30×8cm. This allows most samples to stay well within the far field of the microwaves at all times and provides a sturdy base.

The mounts created for our apparatus keep the transmitter and the receiver 30.5cm above the surface of the table so as to stay above the base and more than high enough to minimize reflections off the surface of the table as suggested by the Advanced Microwave Optics System [6]. These mounts, pictured in Fig. 3.2, straddle the meter sticks from the goniometer base allowing for easy measurement of distances.
These were the first pieces of equipment created for the microwave apparatus and were used in most of the experiments that were done to design and test the foam apertures.

### 3.2 Building of Foam Apertures

Having determined the parameters of the apertures in the RF foam they could then be constructed. The support structure needs to be sturdy, stable, and work as part of the goniometer base set. Pegboard was used because it is strong, thin, and conveniently perforated. Wooden blocks were used as support legs on the bottom of four sheets of 60.96x35.56 cm sheets of pegboard. In each of these holes much larger than the aperture size but small enough not to compromise the structure were cut to make way for the apertures. Slits were also added at the bottom-center so as to fit over the meter-stick arms of the goniometer base. A few additional small holes were drilled as well. See Fig. 3.3 below.
Each of these frames was covered with aluminum foil to act as a reflector on the upper 60.96x35.56 cm section. Holes for the aperture and for ties were carefully made in the foil as shown in Fig. 3.4.

The RF foam, which had previously had 5cm diameter circular apertures cut in the centers of each piece, was then carefully attached to each base using plastic ties that were punctured through the foam and threaded through holes in the foil and pegboard as shown in Fig. 3.5.
There are surely other ways to go about putting together the foam apertures. However, this method seemed best given the materials on hand. Also this arrangement allows everything to be completely disassembled without further damage to the foam by cutting and removing the inexpensive plastic ties. Four one-sided apertures could be made. The foam cut away from the centers can be replaced to make RF absorbing slabs. A combination of these or perhaps other configurations could be made according to the needs of future projects using these same components. The finished RF foam aperture is shown below in Fig. 3.6.

**Figure 3.5** Photographs of foam being attached to the base and the two bases being tied together with the same plastic ties.

**Figure 3.6** Photograph of one of the finished RF foam apertures.
3.3 Testing the Apparatus

Once I assembled all the components of the microwave apparatus it was time to test and characterize them. The biggest questions that needed to be answered were: do the foam apertures get rid of standing waves? Can enough of the beam make it to the receiver to be detected well? Can the beam be localized or is it diffracted over a large angular spread?

Determining whether or not the standing waves were extinguished was more difficult than I anticipated. The basic problem with having the standing waves is that a target between the transmitter and receiver will appear to have different transmittance as its position—but not width or any other variable—changes. I determined to move a book back and forth between the transmitter and receiver with and without the foam and compare the two results to the difference between having the transmitter on and off.

The first attempt was not done carefully and the variations in transmitted intensity compared to variations of turning the transmitter on and off did not decrease. Essentially it appeared that the standing waves were just attenuated only as much as the beam itself. The problem was that the beam was not always at normal incidence to the target book. The issue was solved, demonstrating the importance of careful alignment. Microwaves with their longer wavelengths allow for some small discrepancies but one should still take care to do things as well as possible.

If the microwaves are not at normal incidence to the target then some of the beam will be reflected depending on the angle. To eliminate this variable I took care to make sure that as I moved the target, it remained properly aligned with the other pieces of the apparatus. The setup for the improved experiment is given in Fig. 3.7.
The book placed at a convenient location then moved in increments of 5mm. Intensity was measured with losw.vm at each of these increments over a 10 cm range, which for this wavelength is essentially infinity. In each case intensity was measured without the book with the transmitter off and on. The data was normalized with the MatLab program set for compiling and normalizing data (see Appendix E). The resulting data from this test are shown in Fig. 3.8.
Figure 3.8 Plot of the normalized data for the test for standing waves. x=-10 is for when the transmitter is off, x=-5 is for when the transmitter is on without the book in the way. The red squares are without the foam, the black dots are with the foam apertures. Error in the measured x values is ±.5mm. Error in measured y values is the spread in the variation in y for each x taken in the original data (see Appendix F).

The intensity without the book varies noticeably periodically with a period of about half a wavelength as expected for a simple standing wave pattern. The transmitted intensity with the foam apertures remains nearly constant over the whole distance showing a lack of standing waves as hoped.

Fig. 3.8 shows the normalized data set and not the relative intensity of each one. The gain settings used for each set were different so a comparison of relative intensity could not be made in that experiment. At GAIN 2 the highest intensity measured with the foam is about .78% of the highest intensities measured at the same distances without the foam at GAIN 2. Although detectable the beam is highly attenuated. GAIN 3 should be used with the foam apertures in place. GAIN 4 might be used if trying to measure through a rather absorptive target however GAIN 4 tends to detect large levels of microwave background including cell phone and wireless internet signals. Comparing
transmittance with and without both foam apertures at GAIN 3 or 4 is undoable because the receiver needs to be at a large distance so that its voltage output does not saturate and the same distances with the foam the signal is undetectable or at best mired in static. Also it should be noted that changing the GAIN settings does not change the output voltage in a linear fashion. Even with the beam being highly attenuated it can still be detected well enough for many tests.

I also tested intensity as a function of angle for given distances for a variety of configurations to test angular spread. I ran the test with the goniometer base only, with a foam aperture on the transmitter arm, with an aperture on the receiver arm, and with both apertures. All of these were taken with GAIN 2. The losw.vm program had a hard time picking up the 100 Hz modulation over background when I used both apertures (see Appendix F). With the receiver set to GAIN 3 it worked very well (see Fig. 3.9). In the previous experiments, packing foam on the transmitter has helped consecrate the beam somewhat maybe acting as a waveguide. With the RF foam apertures in place, there was not room for any of the foam pieces I had. I cut one to size but its effects were minimal. Perhaps it was not long enough to archive incidence angles for total internal reflection down the length to the rectangular piece. For the data on all these experiments, see Appendix F. If the distances between the transmitter, receiver, and apertures were reduced, one would expect to see better results. However, due to the size of the foam apertures the range of motion of the goniometer arm would decrease to ±45° or less rather than ±90°.
Comparing the unobstructed beam to the beam passed through both apertures we see that instead of being spread out the beam is actually concentrated (see Fig. 3.9) or rather, most of the off-center portions of the beam have been blocked or absorbed.

**Figure 3.9** Plot of the normalized data Intensity vs. Angle. The red squares are without the foam, the black dots are with the foam apertures. Error in the measured x values is ±2°. Error in measured y values is the spread in the variation in y for each x taken (see Appendix F).

It should be noted that this is not comparable to the diffraction pattern predicted in Fig. 2.12, which is what intensity should look like on a plane perpendicular to the beam. I took data for the same conditions that Fig. 2.12 models (see Appendix F). The normalized graph for this observed diffraction pattern is Fig. 3.10.
The observed diffraction is a little more spread out than the predicted pattern for the same parameters with FWHM at about 8cm rather than at a radius of 4cm. Decreasing the distance to the aperture as long as it meets the Fraunhofer condition can reduce diffraction.

If for a given test setup the transmitted intensity is not high enough for the experiment to work the beam can be concentrated using a simple waveguide. Initially I created a waveguide slightly larger than the transmitter horn opening. It had a cardboard structure with the inner surface lined with aluminum foil. It was 4x4x10 cm. Since this convenient design seemed to work well I tried to create a waveguide/horn with the proper dimensions for x-band microwaves. I used the dimensions given from Rectangular Waveguide Dimensions - Microwave Encyclopedia - Microwaves101.com. [7] for x-
band waveguides: 2.286 x 1.016 cm. This was the same size as the cavity of the transmitter. I copied the dimensions of the transmitter horn as well to place on the end of 30 cm of waveguide so the waves leaving it would be nearly plane parallel. This waveguide and horn did not perform nearly as well as the first one. Fig. 3.11 compares the normalized intensity patterns with and without the waveguide.

![Graph of angle versus relative intensity for the beam with the waveguide (green) and without it (red) with the completed setup. The data shown has been normalized.](image)

**Figure 3.11** Graph of angle versus relative intensity for the beam with the waveguide (green) and without it (red) with the completed setup. The data shown has been normalized.

In summary, the foam apertures effectively eliminate the problematic standing waves. Although the beam is highly attenuated, it is localized enough to be detected well enough for many experiments.
Chapter 4

Results

4.1 General Procedure for Using the Microwave Optics

Apparatus

This project has resulted in the collection of information, and assembly of necessary equipment to perform a variety of microwave optics experiments. The Brigham Young University-Idaho Physics Department Microwave Optics Apparatus can be used to determine absorption, index of refraction, and perform other experiments with x-band microwaves. Appendix B contains an instruction manual for its use. The resulting setup is shown below in Fig. 4.1. This apparatus is comparable to those used in publications such Velazquez-Ahumada et al. [2] but has the advantages of being able to use samples of differing shapes and sizes, taking and storing data electronically, and the ability to be reconfigured for a variety of experiments.
4.2 Falsification of Paper as a Metamaterial

As stated in the introduction, my earliest attempts to determine experimentally the index of refraction of paper suggested that it might have a negative index of refraction. However, without a consistent way to take measurements and the standing waves problem, we could not be certain of our results. Using the procedure above, I preformed an experiment to determine the index of refraction of a sample of paper. Similar to the experiments of Velazquez-Ahumada et al. [2] performed on manufactured metamaterials, my target medium was a prism of known dimensions. As in Fig. 4.2, a beam with normal incidence to the prism will undergo only one deflection as it leaves a prism according to
Snell’s law [1] depending on the index of refraction $n$ of the material.

**Figure 4.2** Prism diagram demonstrating index of refraction [2].

Assuming that the index of refraction of air is 1 and that we have normal incidence on the prism solving Snell’s law for $n$ of the prism we get

$$n = \sin \theta_i / \sin \theta_t.$$ (4.1)

The angle the prism is cut at is $\theta_i$, and has a fixed positive value. The sign on $\theta_t$ is what determines the sign of $n$. Using a phonebook, which along with several textbooks and plain reams of paper had previously been appeared to have a negative index of refraction, I created a 20° prism. Using the new apparatus I measured the relative intensity over a ±45° interval at every degree (± .25°). Already knowing something about the paper’s polarization qualities that will be discussed in the following section, I rotated the transmitter and receiver 90° and redid the experiment. The results are charted below in Fig. 4.3.
Figure 4.3 Graph of relative intensity versus angle for a 20° paper prism for perpendicular or beam polarization orientations. Error bars in intensity values shown are range of intensities received for each data point.

Obviously the highest peak in each graph is positive. Each is at about 8° which gives us an $n \approx 2.5$. In one graph we see a small peak in the negative region but it is clear that overall the medium is not behaving as a left-handed material. Apparently early indications of negative indices were the result of measurement errors inherent in using only the transmitter, the receiver, a yardstick, chalk, and a protractor. The cause of the slight differences in shape of the curves is unknown but the following section addresses why we see here and in other experiments a transmitted intensity dependent on the orientation of the medium relative to the polarization of the beam.
4. Polarizing Properties of Paper

4.3.1 Background

While working on the above-mentioned project I came across interesting properties of paper as a medium for x-band microwaves. My first tests on microwave transmission through books or reams of paper indicated that paper might have unexpected optical properties. When I tried passing microwaves down the length of the book I noticed that if I rotated the book about its long axis the transmitted intensity changed dramatically.

The microwave beam is linearly polarized vertically directly from the transmitter [8] (see Appendix B). A book or stack of papers then acts as a polaroid-letting radiation through if the pages are perpendicular to the polarization and blocking radiation when they are parallel.

4.3.2 Theory

This phenomenon was actually observed in the earliest stages of microwave technology in the 1890s by J. C. Bose [9]. Although since that time paper has been shown to act as a polarizer for microwaves, it seems that few have sought to pursue or apply it other than quality control of paper products [10].

If paper is a polarizer, it must be conductive. However, a classroom multi-meter shows that paper is not conductive at all. Hair and Croucher [11] explain that it is actually quite difficult to measure the conductivity of paper due to contact resistance. They do show how it can be measured and list the conductivities for several kinds of paper and describe the conduction processes in the paper itself. Essentially, ions in water can travel along the small fibers that make up the paper. Also due to all the processing paper goes
through in its manufacture, paper contains sufficient quantities of metals so as to interact with microwave radiation [10].

![Figure 4.4](image)

**Figure 4.4** Fibers from soft and hard woods. Fibers such as these are used to make paper [11].

These conducting fibers, shown in Fig. 4.4, pressed flat into pages and stacked creating a condition for charge to flow along each page, but not in the direction perpendicular to the pages. This preferential direction for charge flow creates the conditions for polarization. When the incident radiation is polarized parallel to the pages, it moves charges and is thereby absorbed. When the incident radiation is polarized perpendicular to the stack of pages charge does not flow and the radiation is not absorbed but rather is transmitted.

Hair et al. [11] also explain how when paper is made, the majority of the fibers are aligned together in what is called the “machine direction” or “grain” of the paper. This is easy to observe when paper comes manufactured with some of the fibers dyed such as in Fig. 4.5.
Figure 4.5 Photograph of the back of a receipt with some of the fibers colored red. A mechanical pencil tip is included to for scale in the image. Note that most of the red fibers are oriented the approximately same way.

Long charge carrying anisotropic strands in a medium is the same general principal as given by Hecht [1] of a $H$-sheet or other Polaroid. I hypothesized that if each page in a stack of pages such as a book had the same machine direction then it should act as a polarizer as well if the beam were to pass through the cover of the book, or the face of each sheet of paper. This phenomenon, as far as I have been able to find out, is previously unobserved and unmentioned in the published literature. I took a book and turned it in between the transmitter and receiver and saw that this was indeed the case. I supposed that higher absorption occurred when the fibers in the pages were mostly parallel to the polarization of the incident microwaves but was unable to tell which way was the machine direction of the pages in the books I had.

Sam Nielson, the Curator of Special Collections & Archives of the David O. McKay Library, [12] taught me several methods of determining the grain of a given
sample of paper. In general the grain runs parallel to the spine of the book, the cover
grain going the same direction also. When this isn’t the case the book will tear itself apart
over time due to expansion by moisture. To test for the grain direction, one can bend but
not fold a given sample one way then bend it again perpendicularly. If the area of the
paper bent is about the same the grain will run parallel to the direction of the bend that
was easier to make. If one length is longer, larger torques may make it easier to bend and
ruin the comparison. This is the best non-destructive method.

A slightly destructive method is to slightly moisten the edge of the sheet. Ridges
will form and usually go away once the paper dries. The grain of the paper runs parallel
to the ridges since the paper tends to bend less in the direction all the fibers are oriented.
If this is inconclusive and a page can be sacrificed one can cut out strips of paper from
perpendicular directions in a page- preferably in slightly different shapes so that they can
be easily identified. Both should be lightly wetted. Both pieces will begin to bow but
each in a different direction. One piece will curl round its long axis and the other will
bow around the short axis. Each piece will have the fibers oriented perpendicular to the
bending as in Fig. 4.6.
With this knowledge I was able to observe that when the grain in a stack of papers is parallel to the polarization of the microwave beam there is more absorption than when they are perpendicular. In order for an object to be a linear polarizer it must be shown that there is a $\cos^2(\theta)$ dependence for transmitted intensity as the polarizer rotates through an angle $\theta$ as given by Malus’s Law [1].

### 4.4.3 Experimental Verification

The experimental setup was to suspend a target sample between the microwave transmitter and receiver on a surface transparent to microwaves. I placed the transmitter and receiver so the diodes are parallel and both are left stationary throughout the experiment. Then the sample is rotated $2\pi$ radians to show two periods of $\cos^2(\theta)$ if that dependence is present. If the intensity follows the $\cos^2(\theta)$ dependence then the target is a
linear polarizer. Data was taken using the programs outlined in Appendix E. For details on the specifics of the setup see Appendix F.

First this was done for five reams of Xerox printer paper bound together on the edges with tape. Five reams were used because one ream on edge is smaller in one direction than the size of the microwave beam (see Appendix D). Since the beam shape is not exactly uniform using one ream edge on changes how much of the beam is actually incident on the paper for a given angle. This would add another small angle dependence to the intensity pattern so, for purposes of proving it follows Malus’s law, enough paper was used so as to be larger than the main part of the beam. The experiment is shown in Fig. 4.7 and the results in Fig. 4.8.

Figure 4.7 Experiment to show that a stack of pages edge-on acts as a linear polarizer.
This experiment was done twice since the first resulted in the valleys of the curve being too muddled in background radiation to plot well. I did the experiment again with a higher gain setting. This setting resulted in a maximum voltage output being reached before the curve maxed out but showed the true shape of the valleys. The valleys are wider than the peaks which is not consistent with $\cos^2(\theta)$ but the periodicity is and the overall shape is still similar to $\cos^2(\theta)$. Recall that paper stacked edge on is a known linear polarizer since the 1890’s [9] and this experiment may be viewed as a quantification of Bose’s early observations. Since charge travels along the pages but not between them, a stack of pages edge on acts as a linear polarizer.

Next, I did the same experiment for four reams of paper lying flat so that the beam goes through the face of the pages. The experiment is shown in Fig. 4.9 and the results in Fig. 4.10.
Experiment to show that a stack of paper act as a linear polarizer due to the grain direction of the paper.

For this experiment the main peaks are consistent with the results of the previous experiment. There are other smaller peaks and valleys that are visible in the results. Perhaps this is the result of some variation in the directions of the fibers since they are likely to have a larger angular variation than the pages in a stack. Still, even with these
small variations the larger effect is consistent with the first experiment. However, a better comparison would be to see how each of these compares to a well-known linear polarizer.

The microwave optics classroom demonstration kit [8] has a linear polarizer, shown in Fig. 4.11 It is apparent that the parallel strips of metal are the long charge carriers that absorb incident radiation polarized in the same direction as the strips.

![Figure 4.11](image)

**Figure 4.11** Photograph of the linear polarizer from the IEC microwave optics kit.

With the same experimental procedure as before (Fig. 4.12) I obtained the results shown in Fig. 4.13.

![Figure 4.12](image)

**Figure 4.12** Experiment to observe Malus’s Law in a known linear polarizer.
The polarizing plate results in an intensity pattern most like $\cos^2(\theta)$. However, the valleys of the curve are still much wider and more uneven than the peaks like both experiments with paper only with a smoother curve. Malus’s Law assumes a perfect linear polarizer rotated through a perfectly polarized beam of light results in a $\cos^2(\theta)$ dependence for intensity. Inasmuch as the long charge carriers in the medium are not ideal nor infinitely long the resulting intensity pattern will deviate from $\cos^2(\theta)$. The more a given medium resembles an ideal linear polarizer the closer its intensity pattern will approach a $\cos^2(\theta)$ dependence.

Fig. 4.13 compares the normalized data for all of the experiments shown above with the convenient $\cos^2(\theta)$ curve, $0.0085 \cos^2((\theta \pi / 180) + (\pi / 4))$ for comparison.
Figure 4.13 Comparison of the Malus’s Law experiments and a $\cos^2(\theta)$ curve as shown.

Each of these curves has the same periodicity and nearly the same amplitude. If the polarizing grid from the kit is a linear polarizer then the same can be said for a stack of paper either through the pages or through the face of the stack. Paper is not a perfect linear polarizer but it is definitely a good enough linear polarizer so as to be easily recognizable as such.

As stated before, it was shown since the early stages of microwave optics that paper acts as a linear polarizer if the microwaves are incident on the edges of the pages [9]. To the best of the author’s knowledge, it is a new discovery that paper is a linear polarizer for microwaves going through the face of a stack of pages. In both cases, it is important that it be a stack of pages otherwise there is just not enough material to noticeably absorb the beam.

The polarization properties of paper for microwave radiation could be applied in many applications where a microwave polarizer is needed. Although paper is less durable
than other structures, it is usually inexpensive. One application could be quality control of paper itself since to measure grain direction or measure how well the fibers are oriented in a sample of paper. These and other applications will have to be the topics of others’ work, but an important application of the polarizing properties of paper is as an educational tool.

**4.3.4 Classroom Demonstration**

A microwave optics kit is a common piece of university physics lab equipment for classroom demonstrations. Most of these come with a wire comb of some kind for a linear polarizer such as the one I used in my experiment. These, of course, are still adequate for demonstrating how a polarizer works. Textbooks, or any reasonably sized stack of paper, can be equally useful to demonstrate polarization in general but have the added benefit of being able to show the mechanism of a polarizer on both macroscopic and microscopic levels.

For the demonstration, the only materials needed are a standard classroom microwave transmitter and receiver, and a regular sized textbook. Set up a standard classroom microwave transmitter and receiver about 40cm or so apart. The allowable range of separation depends somewhat on the gain setting, the quality of the equipment, and the size of book to be used. It is best to check the distances beforehand to insure that it is obvious if the microwave beam is being transmitted or absorbed by the book.

The microwave beam is polarized perpendicular to the surface the demonstration rests on. This is easily demonstrated while transmitting by rotating the transmitter 90°
about the axis of transmission. The receiver response will decrease to little or nothing. This step shows that the microwave beam is polarized.

Now place a textbook in front of the transmitter so that the binding is parallel to the beam as in the left side of Fig. 4.14. It is important to keep the book the same relative distance between the transmitter and receiver to avoid standing wave effects. This is most easily accomplished by ensuring that the book is in contact with the transmitter as in Figure 4.14. Rotate the book about the axis of transmission and observe the transmitted intensity. When the pages of the book are perpendicular to the direction of polarization the transmitted intensity is much greater than when the pages are parallel to the polarization. This happens because charge can flow in the plane of the pages but not between the pages. Incident radiation is absorbed when charge can flow. This is no different than the metal polarizer that likely comes with the kit. The charge flow direction is dictated by the visible, macroscopic, structure the polarizer.

Next, orient the book so that the cover is perpendicular to the beam. See the right side of Fig. 4.14. Rotate the book again and observe the change in intensity. When the binding of the book is parallel to the polarization, the beam is absorbed much more than when the binding is perpendicular to it. The polarizing mechanism is no longer the structure of the book, but the structure of the paper in the book. The fibers, which can carry charge have are oriented mostly in the direction of the book’s spine as stated before. Students could be asked to which way they think the fibers are oriented based on the observed intensities.
Figure 4.14 Photographs on the transmitter end of the stages of this classroom demonstration on polarization.

This demonstration, apart from being used to teach students about polarizers in general, can help students connect what they can see on an everyday scale to the microscopic level.

4.4 Opportunities for Future Research

My work in microwave optics research has laid the groundwork for further research in microwave optics in the BYU-Idaho Physics department. The actual course this research will take will depend on the interests of the students and of the advisor. T. Lines has expressed interest on several occasions in observing microwave propagation through snow packs to see how well it matches Norwegian computer models of it. T. Lines has also suggested possible research in low signal-to-noise ratio transmission, which would be primarily a computation problem [13]. The detection and data-recording program, “loswm.m” (Appendix E) is very good but could definitely be improved.
Further work could be done with the polarization properties of paper and wood. I performed some initial tests that strongly suggest that the grain of wood in general acts as a linear polarizer. Applications could include quality control of building materials; non-destructive tests of wood or wood based historical artifacts; and evaluation of living tree health.

The microwave optics apparatus could also be used to evaluate the claims of different professionally published papers about metamaterials. For example, Chen, Ran, Wang, Huangfu, Jiang, and Kong [14] claim that certain randomized structures could be metamaterials. Other publications have, in my opinion, dubious methods. For example, Iyer and Eleftheriades [15] use a target much smaller than the size of their beam (see Appendix D) and on a very reflective metal surface. Traditionally metamaterials for microwaves are made of circuit board materials [2] so I believe it would not be difficult at all for future students to study negative index materials.

I have noticed that certain materials, such as concrete can behave as a thin film for the microwaves. A thin film several centimeters thick, which in our case is only a few wavelengths, may be a novel way to study thin films. Biophysics students may be interested in applications such as checking for vital signs through solid walls [16].
Chapter 5

Conclusion

5.1 Project Summary

The finished Microwave Optics Apparatus will facilitate continued research in the Brigham Young University-Idaho Physics Department. I have used it to investigate the polarizing properties of paper, showing that manufacturing processes give paper a polarization effect in the machine direction of the paper, and demonstrate that paper does not exhibit a negative index of refraction as we first supposed. I have created and evaluated a valuable research tool for many future students who will be able to take what I have learned and apply it in several possible areas of interest.
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Appendix A

Atmospheric Attenuation of Microwaves by Water Vapor

The purpose of this analysis is to show mathematically whether or not microwaves from the Physics Department’s 10GHz microwave transmitter will be measurably attenuated enough by atmospheric oxygen and/or water vapor. The general form of the Beer-Lambert Law for attenuation of electromagnetic radiation is [1] [17]

\[ \frac{I}{I_o} = e^{-\alpha l c}. \]  

(1.1)

Where \( I/I_o \) is relative intensity, \( \alpha \) is the absorption coefficient, and \( c \) is concentration.

Assuming \( c \) is close to 1 for high concentration of absorbents or a best-case scenario, equation (1.1) becomes \( I/I_o = e^{-\alpha l} \). Assuming \( I/I_o = .9 \), or a 10% absorption as a detectable change after taking into account dispersion of the beam’s intensity over a large volume, the only thing needed to determine the path length \( l \) is \( \alpha \) which has units of Np/km. This means that \( l \) will be in units of km.
Meeks and Lilley [18] and Liebe, Rosenkranz, and Hufford [19] show that oxygen absorption is negligible for frequencies near 10GHz. The closest peak in absorption is for water at 22 GHz so it is the best bet to get enough absorption so as to be measurable. Cruz Pol and Ruf [20] give the following model to determine $\alpha$ near 22GHz that I have followed to determine the shortest-and therefore easiest to measure- $l$.  

$$\alpha_{\text{water}} = 0.0419 f^2 [T_L T_S + T_c]$$  \hspace{1cm} (A.1) 

$T_L, T_S,$ and $T_c$ refer to line strength, line shape, and continuum terms and are given by 

$$T_L = 0.0109 C_L P_{\text{H}_2\text{O}} \theta^{3.5} \exp(2.143(1 - \theta))$$  \hspace{1cm} (A.2) 

$$T_S := \frac{\gamma}{f_o} \left( \frac{1}{(f_o - f)^2 + \gamma^2} + \frac{1}{(f_o + f)^2 + \gamma^2} \right)$$  \hspace{1cm} (A.3) 

$$T_c = C_C (1.13 \times 10^{-8} P_{\text{H}_2\text{O}} P_{\text{dry}} \theta^3 + 3.57 \times 10^{-7} P_{\text{H}_2\text{O}}^2 \theta^{10.5})$$  \hspace{1cm} (A.4) 

where 

$$\gamma = 0.002784 C_W (P_{\text{dry}} \theta^{0.6} + 4.8 P_{\text{H}_2\text{O}} \theta^{1.1})$$  \hspace{1cm} (A.5) 

$\theta$ denotes the temperature ratio, $300/T$ where $T$ is the air temperature in kelvins; $P_{\text{dry}}$ denotes the dry-air partial pressure and $P_{\text{H}_2\text{O}}$ denotes the water vapor partial pressure, both in hectopascals; $f$ denotes frequency in gigahertz; and $f_o$ is the water vapor resonant frequency, i.e., 22.235 GHz. Equations ((2)-(6)) introduce the following parameters: water vapor line strength $C_L$, line width $C_W$, and continuum $C_C$. The above equations agree to within 0.5% with the L87 model over the spectral range of 15-40 GHz when $C_L = 1.0$, $C_W = 1.0$, and $C_C = 1.2$. 

So assuming a temperature of about 60 degrees Fahrenheit or $T = 288$, that leaves $P_{\text{H}_2\text{O}}$ and $P_{\text{dry}}$ which, assuming 100% humidity for highest absorption possible (density of
water in the air $q_{\text{water}} = 0.0132 \text{ kg/m}^3$) $P_{\text{H}_2\text{O}} = 17.54438400$ and $P_{\text{dry}} = 1006.838216$ when converted into hectopascals [21] [22].

Evaluating equation (1.1) for $l$ after obtaining all these constants yields $l = 20.7$ km. Even if $f$ were 22-right on the peak of the absorption line- $l$ would be 2.1 km. This is significantly longer than the maximum range of the equipment (see Appendix B). In order to hope to see anything with our equipment we would need an $\alpha$ of $\geq 2.1$ Np/km or 18.3 dB/km. Therefore the current microwave equipment is insufficient, even under ideal conditions, to measure attenuation by water vapor or oxygen in the atmosphere.
Appendix B

BYU-Idaho Physics Department

Microwave Optics Equipment Manual

B.1 Original Microwave Optics Kit

B.1.1 Microwave Transmitter

To power the transmitter use a DC power supply to provide 12V to 4mm blue sockets on the back. The output is rated at about 10 mW with a 2.8 cm wavelength (10.7 GHz) and experimentally (see Appendix C) shown to be 2.4 ± .4 cm (12.5 ± 5 GHz).
The maximum range of the beam in air detectable by the receiver alone is about 60m. In compliance with recommended instructions and FCC’s Electronic Code of Federal Regulations [23] and OSHA’s Nonionizing radiation [24] standards do not look into the beam, especially at close ranges. Also, no one should be exposed to the main beam for more than 6 minutes at a time. The main portion of the beam (see Appendix D) should be considered to be a cylinder with its axis starting at the emitter horn with a length of 1m and a radius of 20 cm. If there are objects inside this area be mindful that they may reflect the beam in other directions.

The possible configurations of the transmitter are given as follows below directly from the online instruction sheet MICROWAVE APPARATUS - 2.8cm, mini [25].

**Selector Switch Positions:**

- ‘OFF’ Transmitter does not transmit.
- ‘CW’ Transmits ‘Continuous Wave’ transmission (not modulated) of 2.8cm wavelength (or frequency of approximately 10,000MHz. or 10GHz.). As the unit is turn ON, a small red LED indicates that the unit is transmitting.
• ‘EXT’ A signal from a signal generator may be fed to the 4mm signal input sockets marked ‘EXTERNAL MOD’. This signal will modulate the transmission into pulses of CW at the frequency of the applied signal. If the modulating frequency is between 100Hz and 10kHz, the transmission can be heard as audible sound on the receiver.

• ‘100kHz’ The transmission is modulated by and internal oscillator at a fixed frequency of 100kHz. This pulse rate is used for ‘speed of light’ experiment. Also this can be considered to be a ‘carrier frequency’ which in turn can be modulated at a lower audio frequency (a frequency that can be heard by the human ear). If the microphone is inserted into ‘MIC’ socket, voice can be transmitted in this mode.

• ‘1kHz’ Transmission is modulated by fixed internal oscillator at a frequency of 1kHz. This setting is used for most experiments that require audible detection.

• ‘100Hz’ As above but at a low 100Hz frequency.

**SOCKETS:**

• ‘MIC’ Socket to accept the crystal microphone or other audio input signal to modulate the 100kHz carrier wave.

• ‘EXTERNAL MOD’ Sockets to accept an external modulating signal from a pulse source or a signal generator to modulate the CW directly.

**B.1.2 Microwave Receiver**

To power the receiver, insert a 9V battery. Switch left knob to ‘BATT’ to test the battery: if there is power, the ‘BATT. TEST’ light will turn on. The receiver horn seems to be
more sensitive than the diode probe if it is pointing at a source. Make sure to turn the receiver all the way to ‘OFF’ when not in use to conserve battery life.

The OUTPUT plugs can be easily connected to an oscilloscope or LabView program. The VOLUME CONTROL knob is jammed. Note that changing the GAIN setting does not change the output voltage linearly. The possible configurations of the receiver are given as follows below directly from the online instruction sheet MICROWAVE APPARATUS - 2.8cm, mini [25].

**SELECTOR SWITCH POSITIONS:**

- ‘OFF’
- ‘BATTERY TEST’ IF battery is operative, the small ‘BATT. TEST’ light will glow. If battery is flat, replace the battery (9V. type 216) or use alternative power source.
- ‘GAIN 1-4’ Select suitable level of gain to provide about half scale reading on the meter during an experiment.
• ‘VOLUME CONTROL’ When the signal is modulated so it can be heard, adjust to the desired volume of audio reception. The sensitivity of the audio alters with the gain setting.

SOCKETS:
• ‘OUTPUT’ Received signal may be fed into an oscilloscope or to another device.
• ‘DIODE PROBE’ When the Diode Probe is plugged in, the receiver in the horn is isolated and the reception indicated on the receiver is from the Diode Probe only. For some experiments finding nodal points or standing waves etc., the omnidirectional probe is more suitable for detection than the directional receiver horn.

B.1.2 Assorted Optics and Equipment

Other equipment includes a diode probe, shown in Fig. B.3 (a), which serves as a multidirectional probe and isolates the horn probe on the receiver when in use. Seems to be less sensitive to intensity but is not very directionally dependent but its orientation is sensitive to polarization.

The microphone is shown in Fig. B.3 (b). Initial tests suggest that this microphone does not work. A replacement should be obtained if audio transmission is desired.

Fig. B.3 (c) shows the paraffin wax lens in its aluminum frame. Although the wax seems to be somewhat scratched it still works. It has a focal length of about 13±2 cm.

There are three paraffin wax prisms. These are shown in Fig. B.3. (d). Two are white and one is a pale yellow. These prisms seem to be identical. The index of refraction
is about 1.3. There is a hollow acrylic prism, shown in Fig. B.3 (e). When empty this prism has a lower index of refraction than the others. Despite the fact that it seems to have been fractured and glued, it holds water with little or no leakage. This can be used as a mold for making wax prisms.

The other equipment shown in Fig. B.3 is self explanatory and works well except for the A.C. Adaptor which is an unnecessary piece of equipment if a DC power supply is used instead.

![Figure B.3](image)

**Figure B.3** (a) Diode probe. (b) Broken microphone. (c) Wax lens. (d) Wax prisms. (e) Hollow acrylic prism. (f) Large aluminum reflector plates. (g) Small aluminum reflector plate. (h) Diffraction grating. (i) Fiberglass linear polarizer (j) Hardboard beam splitter. (k) A.C. adaptor-240/12 V. AC
B.2 Goniometer Apparatus Instructions

B.2.1 Setup

The Brigham Young University-Idaho Physics Department Microwave Optics Apparatus can be used to determine absorption, index of refraction, and perform other experiments with x-band microwaves.

First set the angle wheel on a flat surface. For extra stability anchor it down with tape. Place the goniometer base over the angle wheel, secure it with tape, and insert a meter stick partially into each slot leaving the center hole clear. Center the cross of the angle wheel in the hole of the base such that the bottommost meter stick lines up with $0^\circ$ or other desired angle as shown in Fig. B.4 It may be helpful to tape the base to the angle wheel at this point for stability.

![Figure B.4 Photographs of how to orient the goniometer base.](image)

Then secure the meter stick that for the transmitter arm securely into the bottom slot of the goniometer base inserting it past the center hole. Use the center hole to note the value of the meter stick at the center. It is suggested to insert each stick so that the value for 10cm is visible in the center of the hole.
Secure the meter stick for the receiver arm securely into the middle board of the goniometer base inserting it past the center hole and orient it to a convenient location. Again, use the center hole to note the value of at the center. If angle measurements are not to be taken and only linear distances are to be changed a two-meter stick on the bottom slot may be more adequate. A two-meter stick in each slot might be used for a Michelson Interferometer or similar setup.

If rotation of the top board is not desired place blocks between the top and bottom boards out of the way of the motion of the receiver arm.

Set a RF foam aperture at a desired location on the transmitter arm. This can be as close as possible to the center. Place the other RF foam aperture on the receiver arm. If it is to be placed closer than 39.5 cm away from the center then it will restrict the range of motion of the arm.

Place the transmitter and receiver on their mounts and on their respective arms at desired distances greater than 10 cm away from the foam apertures to remain in the far field. If largest dimension of the transmitter horn is equivalent to \( a \) in equation

\[
I(\theta) = I(0) \cdot \left[ \frac{2 \cdot J_1 \cdot (k \cdot a \cdot \sin(\theta))}{k \cdot a \cdot \sin(\theta)} \right]^2
\]

then this is still a good approximation.

Set a DC power source to 12 V before plugging it into the microwave transmitter. Connect the DC source to the blue sockets on the transmitter. It does not matter which slot the positive or ground wire is connected to.

Set up a computer at least a meter away from the goniometer base, neither directly in front of nor behind the transmitter. Open loswm.vm with the DAQ connected. Use a
function generator to apply a 100 Hz square wave over the appropriate digital inputs. Connect the receiver output to the appropriate analog inputs on the DAQ (see DAQ assistant for help if needed). See Fig. B.4.

![Photograph of the complete microwave optics apparatus setup.](image)

**Figure B.4** Photograph of the complete microwave optics apparatus setup.

Center any sample directly on the center of the goniometer base. Take care with alignment.

### B.2.2 Recording Data

Type the desired file path into the dialog window then begin running “loswm.vm.” Press the reset button before each new data set. Check the receiver battery light then set it to the desired GAIN setting.

For each measurement taken (1) set the receiver to the desired angle and/distance (2) turn the transmitter to the 100 Hz modulation (3) use the function generator to adjust the square waves seen in the Waveform Graph so that two waves are completely visible
(4) press the Get Intensity button only when two full waves are visible. If the Enter button is used make sure to press it again to stop taking data. (5) Turn the transmitter off-not the DC power source unless doing so will change the transmitter’s position enough to skew the results. In such cases turn the DC power source on and off to turn the beam on and off. Only do this when absolutely necessary since this increases the risk of temporarily or permanently damaging the transmitter. (6) Adjust the value of the angle in “loswm.vm.” If distances are the variable it will still come out as numbers in the spreadsheet. If you enter the value in the text box rather than use the arrow keys then be sure to press the check button before proceeding. Note that using the arrow keys changes the angle value in increments of 5 units of angle or distance depending on what you are doing. (7) Adjust the receiver’s position being careful keep the aperture properly aligned. (8) Repeat for each desired data point. (9) When all the data is taken hit the STOP button. At this point “loswm.vm” will save the data in a spreadsheet. (10) Make sure to turn off all the equipment, especially the receiver.

NEVER let anyone be in the beam’s path, remembering that objects may reflect the beam in other directions.
Appendix C

Thin Film Experiment for Determining Wavelength

C.1 Procedure

Thin films are useful devices for creating interference but are especially difficult to make for visible wavelengths. However, it is much simpler to create a thin film and observe interference for longer wavelengths like microwaves.

First, set up the microwave transmitter so that the beam makes about a 30° incidence angle with the hardboard beam splitter (see Fig. C.1). Place the receiver about 20cm away from the transmitter without the diode probe so as to receive the reflected beam. Place one reflector plate between the transmitter and the receiver so that only the reflected beam is detected.
Before we create our thin film, we need to find the reflected beam. With the receiver set to GAIN 3 set the transmitter to the 100Hz modulation. Rotate the receiver until a maximum reception is found. Leave the equipment in that position and turn it off.

Next, place a second reflector as close as you can behind the hardboard. Turn the receiver to the 100Hz modulation and the receiver to GAIN 2. Slowly move the reflector back and notice the intensity change. When the distance between the two plates is about an integer multiple of one half wavelength there will be destructive interference and a minimum in the detected irradiance. Likewise when the separation is an integer multiple of a full wavelength, there will be constructive interference marked by a maximum irradiance. Measure the distance between maximum and minimum.

This distance between a maximum and a minimum is about $\lambda/2$ but since the beam was at an angle to the boards, it actually traveled a little farther. Taking this greater distance into account, for example using trigonometry or measuring the actual path of the beam between the two board positions rather than just the difference of the positions gives greater accuracy.
C.2 Results

The first time I preformed this experiment I found the wavelength to be 2.4 ± 0.4cm. The second time I measured 2.7 ± 0.4cm. The error could be reduced if the experiment were to be done extremely carefully. The transmitted wave is rated at 2.8 cm.

Note that technically, this is an interferometer and not a thin film but it is a good model for thin film interference. This is a modification of experiment 17 from the *Microwave Apparatus-Solid State* manual [8].
Appendix D

Microwave Beam Shape Map

D.1 Purpose

The purpose of this experiment is to create a spatial map of the shape of the beam emitted from the Physics Department’s microwave apparatus. This experiment focuses on the main part of the beam where its energy is most concentrated and its intensity represents a significant portion of the initial intensity. Experiment 2 from *Microwave Apparatus-Solid State* [8] *Specifications & Instructions for Use*’ handbook of experiments gives the below figure, approximating the beam shape.

![Beam shape diagram](attachment:beam_shape.png)

**Figure D.1** Beam shape diagram [8].
However, performing this experiment suggests that this is an oversimplification of the beam. The following is the procedure outlines a more thorough way to evaluate the microwave beam.

**D.2 Procedure**

Similar to Experiment 2 from *Microwave Apparatus-Solid State [8] Specifications & Instructions for Use*’ handbook of experiments, the relative beam strength is tested with reference to a plane perpendicular to the beam that is moved down the beams axis (see the Fig. D2 below from the manual).

![Figure D.2 Experiment diagram.](image)

The first step is to construct a reference grid. With a large sheet of paper, or several sheets glued together (avoid tape and especially staples which may interact significantly with the microwaves), draw a 90x70cm grid with the origin at the center with tick marks every 10cm. This represents the XY plane. Attach this grid to a mobile cart.

Set up the microwave transmitter so that it is aiming at the origin of the grid with no obstructions between it and the grid.
Prepare the receiver to use the diode probe. To avoid obstructing the beam with your body you can attach it to a long non-metal object such as a meter stick (see Fig. D.3 below).

![Figure D.3 Photograph of beam shape experiment.](image)

Start with the grid 10cm away from the transmitter. With the transmitter set to CW and the receiver set to GAIN 2 measure of the entire grid every 10cm in the X and Y directions recording the values (1 through 10 on a .25 scale, noting with an 11 for anything higher than 10) on the receiver’s meter for each point. Once relative intensity measurements have been made over the entire grid, turn off the equipment, carefully move the cart 20cm further away from the receiver (Z axis) and check that the transmitter is still centered on the origin. Begin transmitting and detecting with the same settings as before over the entire grid again. Repeat, moving the reference grid back 20cm each time
for about 2.5m or until you run out of beam detectable at these settings. Also, with the transmitter off, make note of the level of background microwave radiation.

**D.3 Results**

The values recorded for this experiment are in the Excel file beamshape.xlsx and values.xlsx. It should be noted that the error in all the lengths is ±2cm and the error in the values from the receiver meter is ±.25 ticks.

This is actually represents, assuming the beam is constant in time, a four-dimensional phenomenon: X, Y, Z, and the relative intensity. The file beamshape.xlsx contains a sheet with color-coded matrices.

Values from this matrix were used to create a matrix that could be used by the scatter3 plotting function in Matlab (see Appendix E). The first graph Fig D.4 (a) shows all the data points, including scaled down background levels. The second, Fig D.4 (b), only shows points that are greater than about 20% of intensity of the maximum. The only points that can appear are those that are measured directly so although the entire beam is not shown this gives a very good representation of its behavior.
Figure D.4 (a) Complete beam shape plot. (b) Scaled beam shape plot
The following graphs in Fig. D.5 are plots of the matrix of all the data gathered and give some idea as to the beam shape created prior to the graphs above.

Figure D.5 (a) Contour plot of data matrix. (b) 3D plot of data matrix.

We can see that the beam is not symmetrical. The bottom portion tends to die off and the intensity is found more in the upper half of the grid. Also, the left side of the
beam seems to be concentrated into a smaller area whereas the right side of the beam looks like it is more spread out. Nevertheless, as a low-order approximation, the main portion of the beam could be considered to be a cylinder with its axis starting at the emitter horn with a length of 1m and a radius of 20 cm.
Appendix E

Code

E.1 MatLab Code to Plot Beam Shape

“microwaveplot.m”

function microwaveplot( b )

% This function plots a 4 dimensional graph of the unaltered microwave beam,
% The background level is .5
% b is the factor to subtract from every value of intensity, for example
% b=.5 gets rid of the background, negative values increase the apparent size
% of the microwave background

hold on

importMatrix=xlsread('matrix4graph.xls')-.5; %matrix with all coordinates and values
m=importMatrix;

% this is how the matrix imported must be oriented

m = [0,0,0, 1;
    0,0,1, 2;
    0,0,2, 3;
    0,0,3, 4;
    0,0,4, 5;
    0,0,5, 6;
    0,0,6, 7;
    0,0,7, 8];

hold on

for n = 1:819
    n = 1:819 because there are 819 rows in the importMatrix
    scatter3(m(n,1),m(n,2),m(n,3),(m(n,4)-b)*100,round(m(n,4)-b),'filled')
end
E.2 Maple GUI for Diffraction through Square, Round, and Slit Apertures

Maple commands:

```maple
with(plots)
k := 2*Pi/lambda
lambda := 0.24e-1
beta := k*a*Y/(2*R)
alpha := k*a*Z/(2*R)
box := (sin(alpha)/alpha)^2*(sin(beta)/beta)^2
interactiveparams(plot3d, [box, Y = -.5 .. .5, Z = -.5 .. .5, axes = boxed], a = .2e-1 .. .22, R = 0 .. .75)
airy := (2*BesselJ(1, k*a*q/R)*R/(k*a*q))^2
interactiveparams(plot, [airy, q = -.5 .. .5], a = .2e-1 .. .6e-1, R = 0 .. .75)
B := (1/2)*k*b*sin(x/R)
slit := (sin(B)/B)^2
interactiveparams(plot, [slit, x = -1 .. 1], b = 0 .. .5, R = 0 .. 1)
```

E.3 LabView Program for Collecting Microwave Intensity

Data

“loswm.vi” front panel and block diagram.
When running “loswm.vi,” the microwave receiver outputs and a function generator set to 100 Hz square waves need to be connected to the appropriate DAQ inputs. The Waveform Graph is a digital oscilloscope screen triggered using the external function generator. The XY Graph displays data taken while the Get Intensity button is pushed. The Intensity Multiplier scales the Intensity data and the Angle (deg) controls what intensities measured are associated with a certain angle. If distances are measured instead of angles- units are not exported into the spreadsheet so just put the appropriate distance value in the Angle text box. The reset button clears the matrix to be outputted to a file and should be pushed before each new set of data is taken.

With the DAQ connected to the microwave receiver, the transmitter needs to be using the 100 Hz modulation. The program reads the values of the top of the square waves. Two complete square waves should be in the oscilloscope window when data is taken. If the signal is too weak the program may not record the correct values even if they are visible on the oscilloscope screen.

**E.4 IntensityAvgNorm.m**

“IntensityAvgNorm.m” Averages the intensities for each angle and normalizes the intensities. Requires input of a filename, starting angle, and angle increment. Calls SimpsonsForAvg.m (Needs NormalizeColumn.m)

```matlab
function IntensityAvgNorm(filename1,start,increment)
% Created by: Phil Scott 6/22/11
% This function takes in a matrix from excel and averages the 2nd-nth
% columns for a given value in the first column. This ONLY works if angles
% are seperated by a constant increment! This also calls a function to use
% Simpson's Rule to Normalize the data in the 2nd column.
% Read file into a matrix
A = dlmread(filename1);
```

82
% Get dimensions
[m,n] = size(A);

A = sortrows(A,1);
% Average the Intensity values for each given angle

for p = 2:n
    angle = start;
    q = 1;
    j = 0;
    sum = 0;
    for i = 1 : m
        if A(i,1) == angle
            sum = sum + A(i,p);
            j = j + 1;
        else
            Avg(q,1) = angle;
            Avg(q,p) = sum/j;
            sum = A(i,p);
            angle = angle + increment;
            q = q + 1;
            j = 1;
        end
    end
    % Last angle doesn't go into else statement so it gets put in the
    % matrix here
    Avg(q,1) = angle;
    Avg(q,p) = sum/j;
end
SimpsonsForAvg(Avg)
end

E.5 SimpsonsForAvg.m

“SimpsonsForAvg.m” Makes sure things are set up in order to start Simpsons Rule with an averaged matrix. Requires input of a matrix. Called in IntensityAvgNorm.m. Calls NormalizeColumn.m

function SimpsonsForAvg(A)
% Created by Phil Scott 6/24/11
[R, C] = size(A);
% Makes sure that simpson's rule will work. Needs odd amount of entries in matlab
if mod(R,2) == 0
    fprintf('Simpson's Rule requires an odd number of entries. The matrix\n    read from the file you gave has an even number of entries.\n    Would you like us to (a) delete the first data point, (b) delete the last data point, or (c) leave the matrix alone?\n    Input (and quite the program):\n    ',s');
    choice = input('and quite the program?\');
E.6 NormalizeColumn.m

“NormalizeColumn.m” performs Calculations for Simpson's rule for the second column of a given matrix. Requires input of a matrix and the number of rows in it. Returns Normalized matrix. Called in SimpsonForAvg.m and SimpsonsNormalization.m

function [A] = NormalizeColumn(A,R)
    % Created by Phil Scott 6/24/11
    % This program sorts the rows of a matrix in ascending order according to
    % the first column and integrates the data according to the second column.
    % The second column is then normalized so it integrates to 1 from now on.
    % Sorts Data- Column#
    A = sortrows(A, 1);
% Start the sum for simpson's rule

sum = A(1, 2) + A(R, 2);
for i = 2 : R - 1
% Finishes sum for Simpson's rule. Multiplies odd entries by 4 and even
% entries by 2
    sum = sum + 4 * mod(i + 1, 2) * A(i, 2) + 2 * mod(i, 2) * A(i, 2);
end
% Multiplying factor for Simpson's rule

h = (A(R, 1) - A(1, 1)) / (R - 1);
% Calculates the value of the integral

int = (h / 3) * sum;
% Normalizes the values in the second column
A(:, 2) = A(:, 2) / int;
% Displays the value of the integral for error checking.

int

end

E.7 SimpsonsNormalization.m

"SimpsonsNormalization.m" takes a matrix and ensures that everything is aright so it can
perform simpson's rule. No input/Output. Calls NormalizeColumn.m

function SimpsonsNormalization

% Created by Phil Scott 6/24/11
% This program reads a file into a matrix, checks to make sure the number
% of elements is sufficient for Simpson's rule, calls a function to perform
% Simpson's rule, and gives the user the option to save the result.
% Get a filename from the user
filename = input('What is the name of the file you would like to read in? (ex: Book1.csv)\n','s');
% Save the data from the file to a matrix
A = dlmread(filename);
% Tells how many rows and columns there are (R and C respectively)
[R, C] = size(A);
% Makes sure that simpson's rule will work. Needs odd amount of entries in matlab
if mod(R, 2) == 0
    fprintf('Simpson's Rule requires an odd number of entries. The matrix\n')
    fprintf('read from the file you gave has an even number of entries.\n')
    fprintf('Would you like us to (a) delete the first data point,\n')
    fprintf('(b) delete the last data point, or (c) leave the matrix alone?\n')
    choice = input('and quite the program?\n','s');
end
% Actions for program based on user's choice above

switch choice
    % Delete first row
    case 'a'
        A(1,:) = [];
        R = R - 1;
        fprintf('First row deleted. Continuing program\n')
    % Delete last row
    case 'b'
        A(R,:) = [];
        R = R - 1;
        fprintf('Last row deleted. Continuing program\n')
    % Do nothing and exit program
    case 'c'
        fprintf('Sorry for the inconvenience. Better luck next time.\n')
        return
end
end
% Calls a function to perform Simpson's rule, Normalize the second column,
% and return the results
[A] = NormalizeColumn(A,R);
% Gives the user the option to save and/or view the new matrix
choice2 = input('Would you like to (a) save the new matrix, (b) view the new matrix without saving, or (c) view and save the new matrix?\n','s');

switch choice2
% Save don't display
    case 'a'
        % Get filename to write to
        fprintf('What is the name of the file you would like to save the normalized matrix to? (ex: Book2.csv)\n')
        filename2 = input('normalized matrix to? (ex: Book2.csv)\n','s');
        dlmwrite(filename2, A)
        % Double checks to make sure the Normalized column integrates to 1
        [A] = NormalizeColumn(A,R);
% Display don't save
    case 'b'
        A
% Save and display
    case 'c'
        % Get filename to write to
        fprintf('What is the name of the file you would like to save the normalized matrix to? (ex: Book2.csv)\n')
        filename2 = input('normalized matrix to? (ex: Book2.csv)\n','s');
dlmwrite(filename2, A)

A

% Double checks to make sure the Normalized column integrates to 1

[A] = NormalizeColumn(A,R);

end

end
Appendix F

Accessing Data

Here is a semi-chronological list of the data files from Allen Andersen’s senior research with a short description of each. NOTE: “norm” in the name means that it is the normalized data set of the same experiment (see Appendix E). Unless otherwise stated, the error in the measurements is, for lengths ±.5 cm, ±.5 degrees, and the spread of the data points for a given intensity. To obtain any of the data files please contact Todd Lines at linest@byui.edu or Allen Andersen at allenlypro@gmail.com.

matrix4graph.xls- columns 1,2, and 3 represent x, y, and z positions (cm) respectively, column 4 represents relative intensity

foamguidee.xlsx- column 1 and 5 represent angles in degrees, column 2 represents relative intensity of unobstructed beam, column 3 is the relative intensity of the beam with a piece of packing foam placed in front of the transmitter as a waveguide, column 6=column3.

foamtest1num.csv-Tx w/ short packing foam guide distance to foam:40cm
Distance from foam to Rx gain2: 50cm Aperture Size – 1 cm increments, 5x places represent when the book changed position. Low to high, start w/ off, on., w/foam @0 low to high, then 1 through 7 cm

foamtest2.csv- Tx w/o short pfoam (pfoam designates packing foam) guide distance to foam:23 Distance from foam to Rx gain1: 39, -20off -15 on -10book low -5 book high, low to high

foamtest3.csv- square aperture. Tx w/o short pfoam guide distance to foam:20cmish. Distance from foam to Rx gain2: 30

foamonly.csv- square aperture. Tx w/o short pfoam guide distance to foam: 12
Distance from foam to Rx gain2: 34

foamonly2.csv- square aperture. Tx w/o short pfoam guide distance to foam: 12
Distance from foam to Rx gain1: 34

foamtest4.csv-square aperture. Tx w/o short foam guide distance to foam: 20
Distance from foam to Rx gain1: 40

aperturetest1.csv-Tx w/o short foam guide distance to foam: 40cm
Distance from foam to Rx gain1: 15-40. -15 off w/o foam, -10 on w/o foam, -5 foam with hole stopped. (all at 15 cm) Then 150(mm)+ w/ foam aperture

aperturetest2.csv-Tx w/o short foam guide distance to foam: 40cm
Distance from foam to Rx gain2: 15-40, -10 off w/o foam, -10 on w/o foam, -5 foam with hole stopped. (all at 15 cm) Then 150(mm)+ w/ foam aperture. Seems to include aperturetest1.csv data as well

aperturetest3.csv-Tx w/o short foam guide distance to foam: 40cm
Distance from foam to Rx gain3: 15-40. -10 off w/o foam, -5 on w/o foam, -5 foam with hole stopped. (all at 15 cm) Then 150(mm)+ w/ foam aperture

aperturetest4.csv-Tx w/o short foam guide distance to foam: 40cm
Distance from foam to Rx gain4: 15-40. -10 off w/o foam, -5 on w/o foam, -5 foam with hole stopped. (all at 15 cm) Then 150(mm)+ w/ foam aperture

aperturetestback.csv- Tx w/o short foam guide distance to foam: 40cm (foam set up backwards). Distance from foam to Rx gain2: 15-40. -15 off w/o foam, -10 on w/o foam, -5 foam with hole stopped. (all at 15 cm) Then 150(mm)+ w/ foam aperture

foil1.csv- (shiny side in) Tx w/o short foam guide distance to foam: 40cm
Distance from foam to Rx gain2: 15-40. -10 off w/o foam, -5 on w/o foam. (all at 15 cm) Then 150(mm)+ w/ foam aperture

angle1.csv- w/ foil. Tx w/o short foam guide distance to foam: 40cm. Distance from foam to Rx gain2: 22cm. -45 to 45. -10 off w/o foam, -5 on w/o foam. (all at 15 cm) Then 150(mm)+ w/ foam aperture

angle2.csv- w/ foil (shiny side in) Tx w/o short foam guide distance to foam: 40cm
Distance from foam to Rx gain2: 22cm. -45 to 45. -10 off w/o foam, -5 on w/o foam. (all at 15 cm) Then 150(mm)+ w/ foam aperture

angle3.csv-w/ foil (shiny side in) Tx w/ short foam guide distance to foam: 40cm
Distance from foam to Rx gain2: 22cm. -45 to 45. -10 off w/o foam, -5 on w/o foam. (all at 15 cm) Then 150(mm)+ w/ foam aperture

apcnbook1.csv-Tx w/o short foam guide distance to foam: 40cm. Distance from foam to Rx gain2: 16-40. -15 off w/o foam, -10 on w/o foam, -5 no book. (all at 15 cm) Then 150(mm)+ w/ foam aperture w/ book

apcnbook2.csv-Tx w/o short foam guide distance to foam: 20cm. Distance from foam to Rx gain2: 16-40. -15 off w/o foam, -10 on w/o foam, -5 no book. (all at 15 cm) Then 150(mm)+ w/ foam aperture w/ book

plexi1.csv- Tx w/o short foam guide distance to foam: 40cm. Distance from foam to Rx gain2: 20. 0-off 5-on w/o foam 15- w/ foam no glass 20 foam and plexiglass w/plastic25 foam and plexiglass no plastic

setupstest1.csv- with the completed setup, Tx at 30 cm from the center and Rx G2, 46 cm from the center. No foam apertures were used.

setupstest2.csv- with the completed setup, Tx at 30 cm from the center and Rx G2, 46 cm from the center. 1 foam aperture on Rx arm 39 cm from center

setupstest3.csv- with the completed setup, Tx at 30 cm from the center and Rx G2, 46 cm from the center. 1 foam aperture on Rx arm 15.5 cm from center

setupstest4.csv- with the completed setup, Tx at 30 cm from the center and Rx G2, 46 cm from the center. Both foam apertures on Tx arm 15.5 cm from center and on Rx arm 39 cm from center

setupstest5.csv- with the completed setup, Tx at 30 cm from the center and Rx G3, 46 cm from the center. Both foam apertures on Tx arm 15.5 cm from center and on Rx arm 39 cm from center

setupstest6.csv- with the completed setup, Tx at 30 cm from the center and Rx G3, 46 cm from the center. Both foam apertures on Tx arm 15.5 cm from center and on Rx arm 39 cm from center. Packing foam used as waveguide between Tx and RF foam

stwefcomp.csv-Tx and Rx G3 each 40 cm from center in a straight line (20 cm stick). When foam is used, each piece is at 25 cm from center. 0-variation between off and on with no foam, 5-book moved slowly back and forth over entire base w/o foam, 10-variation between on and off w/ foam, 15-book moved slowly back and forth over entire base w/ foam

stw1.csv-Tx and Rx G3 each 40 cm from center in a straight line (20 cm stick). No foam. 

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-10-off, -5-on w/o book, then every value after that corresponds to mm away from start. Due to some error in LabView input not all of the x-values are correct.

stw2.csv-Tx and Rx G2 each 40cm from center in a straight line (2m stick). No foam.
-10-off, -5-on w/o book, then every value after that corresponds to mm away from start.

stw3.csv-Tx and Rx G3 each 40cm from center in a straight line (2m stick). Each piece of foam is is at 25cm from center. -10-off, -5-on w/o book, then every value after that corresponds to mm away from start.

diffract.csv - test of Fig. 16. Tx 20cm from 1 aperture. Rx 30m past aperture. Perpendicular to beam -50 to 50 cm from center.

gdhmttest.csv- with the completed setup and 30cm xband waveguide w/ horn, Tx at 51cm from the center and Rx G3, 46cm from the center. Both foam apertures on Tx arm 15.5 cm from center and on Rx arm 29 cm from center

wvgdtest.csv- with the completed setup, Tx with 10cm waveguide at 31cm from the center and Rx G3, 46cm from the center. Both foam apertures on Tx arm 15.5 cm from center and on Rx arm 39 cm from center

wvgdtest2.csv- with the completed setup, Tx with 10cm waveguide at 31cm from the center and Rx G3, 55cm from the center. Both foam apertures on Tx arm 15.5 cm from center and on Rx arm 39 cm from center

gdhmttest2.csv- with the completed setup, Tx with 30cm waveguide and horn at 52cm from the center and Rx G3, 55cm from the center. Both foam apertures on Tx arm 15.5 cm from center and on Rx arm 39 cm from center.