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Development of a Terahertz Leaky-Wave Antenna using a Parallel-Plate Waveguide

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ABSTRACT

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Because of a growing bandwidth problem within wireless communications, the terahertz (THz) spectrum is being investigated as a possible technology for short-range, high-bandwidth communications. For this reason, it is worth implementing known communications technologies within the radio frequency (RF) and microwave bands, such as antennas, in the terahertz band. One such technology is the leaky-wave antenna.

Leaky-wave antennas have been in use within the RF and microwave bands since the 1940’s. The leaky-wave antenna is a travelling wave antenna in which a fast wave with a phase velocity greater than the speed of light, $c$, propagates through a waveguide. This fast wave is allowed to leak out of the waveguide via an opening along the length of the waveguide.

A THz leaky-wave antenna is implemented using the TE$_1$ mode of a parallel-plate waveguide (PPWG). Various plate separations are used during this project in order to show the leaky-wave effect for different dispersion relations. Using a commercial THz time domain spectroscopy (THz-TDS) system, the input of the waveguide is a broadband THz signal. The expected output from such an input
would be dispersed in the frequency domain. This is particularly interesting because it allows the leaky-wave antenna to act as a THz demultiplexer by separating a broadband signal into individual frequency components that vary with angle.

Our measured experimental results show that the waveguide indeed produces a dispersed output matching the analytical result. The propagation angle of lower frequencies is closer to perpendicular to the waveguide, with the cutoff frequency of the PPWG at the normal. Higher frequencies are transmitted closer to the axis of the waveguide.

Since the phase-matching condition for a leaky-wave antenna can work in either direction, this THz leaky-wave antenna can also receive radiation. Our results show that when operating in this orientation, the receiving angle matches the angle of transmission from the transmitter setup for each frequency. This again shows agreement with the analytical result from leaky-wave antennas. Using the leaky-wave antenna in this manner, we see the potential for THz frequency domain multiplexing.

Varying the plate separation of a PPWG changes the dispersion relation. Since the angle of leaky-wave propagation depends on the dispersion, by varying the plate separation, one can vary the angle of the leaky-wave along the length of the waveguide. We implement such a waveguide in order to focus a chosen frequency to a point. Simulations of the field intensity show that this is possible. By mapping out
the field intensity for each design frequency, our results validate this concept by showing that the field focuses within the plane of propagation.

To the best of our knowledge, this work shows for the first time that these types of antennas can be implemented within the THz spectrum in order to transmit and receive THz signals.
Acknowledgments

Recently I heard a quote that I have come to love. It’s attributable to Jim Gordon, inventor of the Maser and a giant over the last 60 years within the field of photonics. The quote goes like this: “There is no limit to what can be achieved if it doesn’t matter who gets the credit.”

I am by no means claiming great achievement with this thesis. The quote is applicable in that there is a large group of people whose names will not be on the front of this thesis, but through their support of me they deserve all the credit.

First and most obvious is my committee. Dan has been a wonderful advisor and always supportive of me, even when my ideas of research timelines didn’t always match up with reality. I have nothing but the utmost respect and admiration for him.

Doug and Kevin have both acted as mentors, examples, and sounding boards for me over the past year and for that they have my appreciation. They are both great experimentalists and I have always enjoyed any chance I’ve had to hear them talk about their work or the work of others.

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## Contents

Acknowledgments ................................................................................................................. v

Contents ................................................................................................................................. 1

List of Figures .......................................................................................................................... 2

Introduction .............................................................................................................................. 4

1.1. The Terahertz Spectrum ................................................................................................. 4

1.2. The Bandwidth Problem and Future THz Communications .......................................... 6

1.3. THz Generation, Detection, and Time Domain Spectroscopy ......................................... 6

Leaky-Wave Antennas ............................................................................................................ 10

2.1. History and Theory of Leaky-Wave Antennas ............................................................... 10

2.1.1. The THz Parallel Plate Waveguide .......................................................................... 13

2.2. Experimental Implementation of the Leaky-Wave Antenna ........................................... 15

2.2.1. Design ...................................................................................................................... 15

2.2.2. Experimental Setup ................................................................................................. 17

2.2.3. Analytical and Experimental Results ...................................................................... 21

2.3. Measuring Field Intensity as a Function of Aperture ...................................................... 24

2.4. Using the Leaky-Wave Antenna to Receive Radiation .................................................. 26

2.4.1. Theory and Experimental Setup ............................................................................. 26

2.4.2. Results ..................................................................................................................... 29

Aiming the Leaky Wave Antenna by controlling the Dispersion ........................................... 31

3.1. Varying the Plate Separation to Control Dispersion ...................................................... 31

3.2. Design of the Focusing Leaky-Wave Antenna ............................................................... 33

3.3. Simulations of the Leaky Wave Antenna ...................................................................... 34

3.4. Experimentally Mapping the Focused Radiation ............................................................ 37

Conclusions ............................................................................................................................ 42

References ............................................................................................................................... 44
List of Figures

Figure 1.1 The Terahertz Spectrum ................................................................. 5
Figure 1.2 Typical THz Time-Domain Spectroscopy Setup ............................ 8
Figure 2.1 Leaky-Wave Antenna .................................................................... 11
Figure 2.2 Angular Radiation .......................................................................... 12
Figure 2.3 Leaky-waveguide frequency dispersion ........................................ 13
Figure 2.4 PPWG Leaky-Wave Antenna .......................................................... 15
Figure 2.5 PPWG Leaky-Wave Antenna Design ............................................. 17
Figure 2.6 Sample Time Domain Pulse from T-Ray 2000 ............................... 18
Figure 2.7 Sample Frequency Domain Pulse from T-Ray 2000 ...................... 19
Figure 2.8 Setup for Leaky Wave Transmission .............................................. 20
Figure 2.9 Analytical result for Leaky Wave radiation ................................... 21
Figure 2.10 Spectral Analysis for Leaky Wave transmission (example) .......... 22
Figure 2.11 Leaky Wave Transmission ........................................................... 23
Figure 2.12 Peak Electric Field vs. Aperture width, \( b = 2 \text{ mm} \) ................. 25
Figure 2.13 Peak Electric Field vs. Aperture width, \( b = 4 \text{ mm} \) ................. 26
Figure 2.14 Leaky Wave Antenna as Receiver ................................................ 27
Figure 2.15 Setup for receiving Leaky Wave radiation ................................... 28
Figure 2.16 Leaky Wave Receiver ................................................................. 29
Figure 3.1 Focused Leaky Wave Antenna Design .......................................................... 32
Figure 3.2 Focused Leaky Wave Antenna Implementation ......................................... 34
Figure 3.3 Simulation of Focused LWA – 100 GHz ...................................................... 35
Figure 3.4 Simulation of Focused LWA – 170 GHz ...................................................... 36
Figure 3.5 Simulation of Focused LWA – 300 GHz ...................................................... 37
Figure 3.6 Setup for mapping electric field of focused LWA ...................................... 38
Figure 3.7 Field intensity at 100 GHz for Focused LWA ............................................. 39
Figure 3.8 100 GHz Field Intensity with Simulation .................................................. 40
Figure 3.9 Field intensity at 170 GHz for Focused LWA ............................................ 41
Chapter 1

Introduction

In this brief introduction, background information will be provided to give context to the supporting foundation of this experiment.

1.1. The Terahertz Spectrum

Over the past century the electromagnetic spectrum has opened up more and more to scientists [1]. One can imagine the spectrum, as we know it today, divided into two main parts. The lower end encompasses all radio waves and microwaves, up to frequencies around 100 GHz. The higher end encompasses X-rays, UV, Visible light, and infrared all the way down to the mid-infrared, which reach down to about 10 THz. The rationale for this division is a difference in technology. Radio waves and microwaves are typically generated using electronic methods such as antennas or solid-state devices. The higher end is generated using photonic methods [2-3].
In between these two regions lies the Terahertz (THz) spectrum. The THz band roughly encompasses the range from 100 GHz to 10 THz, bridging the gap between microwaves and the mid-infrared. For scale, 1 THz is equivalent to 300 μm in wavelength, 1 ps in period, and 4 meV in energy.

Figure 1.1 The Terahertz Spectrum
THz lies on the EM spectrum between microwaves and Infrared, at the intersection of electronics and photonics. Courtesy of THz Science and Technology Network. www.thznetwork.net

Apart from giving a more complete picture of the electromagnetic spectrum, the THz spectrum has many unique properties. THz is a non-ionizing radiation and has the ability to penetrate a variety of non-conducting materials. Many chemical and biological molecules have distinctive absorption and emission spectra within the THz band. It also allows for time-resolution studies on the picosecond level. For these reasons, THz applications are being sought out in many areas such as biology, medicine, security, and communications [4-10].
1.2. The Bandwidth Problem and Future THz Communications

A particular area of interest lies in short-range, broadband communications. In recent years, there has been tremendous growth in the usage of mobile computing. This has resulted in large amounts of wireless data usage. In coming years, as this growth continues, the question of bandwidth availability will begin to be a real concern [7-11]. The expectation is that by 2020 the data rate demand will be on the order of multiple 10’s of Gbit/s [7]. With current wireless technology, which lies below 300 GHz where regulation is in full force, it will not be possible to meet such a demand [7]. The investigation of the frequency range above 300 GHz for wireless communications crosses into the THz range. With that in mind, there is a growing interest in developing communication technologies such as multiplexers, demultiplexers, and frequency selectors for the THz band. This project has been on the development and characterization of one such technology, the leaky-wave antenna, which shows potential for these types of functions. The approach has been to take a known technology in the RF and microwave spectrum and then apply it to the THz region.

1.3. THz Generation, Detection, and Time Domain Spectroscopy

Traditionally, the THz region was referred to as the THz “Gap” since it was largely unexplored due to the lack of technologies to generate and detect these frequencies. Electronic methods for generating microwaves tend to break down on the low end and optical technologies for generating mid-IR also cease to function at
the high end [2, 12]. Over the past few decades, however, this “gap” has started to 
fill in. Methods for the generation and detection of THz radiation have been in 
development and have become an active area of research.

Several common methods of THz generation and detection now exist, 
including second order nonlinear processes such as optical rectification and 
difference frequency generation (DFG), electron accelerators, backwards wave 
oscillators and free-electron lasers, quantum cascade lasers (QCL’s), and photo-
conductive antennas (PCA’s) [2, 12-15]. We use photoconductive antennas in our 
research for both generation and detection. One can measure the entire electric field 
of the THz pulse by delaying the optical pulse that hits the detector. In this way, a 
THz time domain spectroscopy (THz TDS) system can be achieved. Our research 
uses THz TDS to investigate phenomena within this spectrum.
Figure 1.2 Typical THz Time-Domain Spectroscopy Setup

A typical THz TDS setup consists of a femtosecond pulsed laser beam which is split into emission and detection beams. Each beam impinges on a photoconductive antenna which either generates or receives THz radiation. The Electric Field is mapped out by delaying the detection beam in time with an optical delay to measure the field at each instant in time. [http://fir.u-fukui.ac.jp/thzlab/index_files/Eng_THz_TDS.htm](http://fir.u-fukui.ac.jp/thzlab/index_files/Eng_THz_TDS.htm)

In a typical THz TDS setup, a femtosecond laser, often Ti: Sapphire, is used for both detection and generation. The optical beam is split, with each beam going to a separate PCA. The generation beam hits a voltage biased PCA, which generates a single cycle broadband THz pulse. Using parabolic mirrors or lenses (made from Teflon in our case) the THz pulse is focused onto the detection PCA. By inserting a delay stage into the path of the optical detection beam, one can scan over time and measure the amplitude of the electric field of the THz pulse with respect to time. Since we then have the full field, we have all phase and frequency information as
well so that both absorption and dispersion can then be measured. The frequency content of the THz pulse is found by taking the Fourier transform of the field [2, 12, 16].

In this project, we have used a commercially built THz TDS setup by Picometrix Inc. This commercial setup is fiber-coupled to allow for maneuverability of the THz emitter and detector.
Chapter 2

Leaky-Wave Antennas

This section will discuss the history and theory of the leaky-wave antenna and present our results for implementing such a device for the first time within the THz spectrum.

2.1. History and Theory of Leaky-Wave Antennas

Leaky-wave antennas are a type of travelling wave antenna that has been used in the microwave and RF spectra since the 1940’s [17-18]. In a leaky-wave antenna, a travelling wave is guided along a main waveguiding structure and radiates outward azimuthally from the axis of the waveguide [19].
Figure 2.1 Leaky-Wave Antenna
An early example of a leaky-wave antenna was a rectangular waveguide with a continuous slit cut along one of its sides [20].

The travelling wave inside the waveguiding structure is a fast wave, with a phase velocity greater than the speed of light. Only a closed structure like a waveguide can support a fast wave. This is because the phase velocity of the wave inside of the waveguide exceeds that of the free space wave, which leads to an effective refractive index which is less than 1 [18-19]. As an example, for a waveguide consisting of two parallel plates separated by a distance $b$, the effective index of refraction goes as:

$$n_{eff} = \sqrt{1 - \left(\frac{c}{2bf}\right)^2}$$

For leaky-waves, the free space wave and the guided wave must satisfy the following phase-matching condition:
\[ k_0 \sin \theta = k_{\text{waveguide}} \]

Where \( \theta \) is the angle between the normal to the waveguide and direction of free-space propagation [18]. This is because of the mismatch between the phase velocities inside of the waveguide and in air.

\[ \]

\[ \]

**Figure 2.2 Angular Radiation**

The angle \( \theta \) is defined as the angle relative to the normal of the waveguide. This is shown here for a parallel plate waveguide (PPWG).

Because the phase constant of these waveguides changes with frequency, the direction of the leaky wave also changes with frequency, allowing the antenna to be scanned by varying the frequency. What this means is that if the input is broadband, then the leaky waveguide will act like a prism, with a dispersed output, with higher frequencies lying closer to the axis of the waveguide. This is essentially then a frequency-domain demultiplexer, taking a broadband input and separating individual frequency components by angle.
If the input to a leaky-wave antenna is broadband, then the output is dispersed.

The earliest examples of these waveguides were rectangular waveguides with a slit cut along the length of one side to allow for radiation to leak out. The rectangular waveguide excites the TE$_{10}$ mode. For RFs and microwaves, these leaky rectangular waveguides have been the standard for many years. However, such a leaky wave antenna has yet to be implemented in the terahertz (THz) spectra because suitable waveguides for the THz region have been difficult to come by.

2.1.1. The THz Parallel Plate Waveguide

A waveguide is any device that propagates the EM wave without significant loss to the intensity or spreading of energy [1-2]. For radio and microwaves, the most common type of waveguide is often a hollow metal pipe or a coaxial cable. For optical and infrared frequencies, silica fiber optics are the standard waveguides. In
the THz region, there is not yet a standard go-to waveguide for long-range propagation. While many waveguides have been and are still being developed, the parallel plate waveguide has shown some of the most promise [21-22].

With the parallel plate waveguide, there are two common modes that we tend to use, TEM mode and TE$_1$ mode. In TEM mode, the electric field is polarized perpendicular to the plates, while the magnetic field is polarized parallel to the plates. The analytic form of the field corresponding to this mode is a Gaussian shape [1, 21]. When operated in TEM mode, the PPWG exhibits very low loss and almost no dispersion, which means it will not work for the leaky-wave antenna, since dispersion is necessary.

In TE modes, the electric field is polarized parallel to the plates with no restriction on the magnetic field. The analytic form of the field for TE modes is alternating sines and cosines. The lowest order, TE$_1$, is a single a half-sine wave with nodes on either edge of the waveguide [1, 23]. The TE$_1$ mode can transmit THz with controllable dispersion, which for our purposes is very useful [23]. The dispersion is due to the cutoff frequency of the mode, which is related to the plate separation, $b$.

\[ f_c = \frac{c}{2b} \]

This dispersion allows us to implement the PPWG with TE$_1$ mode as a leaky-wave antenna if we were to cut a slit into one of the plates. Combining the phase-matching relation with the dispersion of the TE$_1$ mode, the emission angle of leaky waves from the PPWG can be derived:
\[ \sin \theta = \sqrt{1 - \left( \frac{c}{2bf} \right)^2} \]

To explore and characterize this effect, the parallel-plate waveguide leaky-wave antenna was developed for the THz spectrum.

![Diagram of PPWG Leaky-Wave Antenna](image)

**Figure 2.4 PPWG Leaky-Wave Antenna**

In \( \text{TE}_1 \) mode the electric field is polarized parallel to the waveguide. This allows for controllable dispersion since there exists a cutoff frequency related to the plate separation, \( b \).

### 2.2. Experimental Implementation of the Leaky-Wave Antenna

#### 2.2.1. Design

To observe leaky waves, we constructed a modular THz PPWG with various plate separations. The THz leaky-wave antenna was made by using two aluminum
plates, one with a slit cut through the middle, separated by plastic spacers at the four corners.

The two aluminum plates were each 5 cm by 5 cm by 0.8 mm (1/32” stock aluminum thickness). A groove of varying width was cut through the middle of one of the two plates for a length of 4.2 cm. The size of the aluminum plates was chosen for three reasons. The width of 5 cm is much larger than a typical beam size of 1 cm, allowing for good coupling efficiency. A length of 5 cm is long enough to allow for guided wave modes without edge effects. A small thickness was chosen in order to closely approximate the ideal, infinitely thin, leaky wave antenna. This is to minimize any surface modes that may exist as the wave passes from waveguide into free-space. The length of the slit was enough to allow for leaky-waves along the majority of the length, yet still providing structure since the “leaky” plate remained a single piece. It is necessary that the slit not go all the way through the plate, since we needed for the pulse to couple in as TE$_1$ mode. Therefore, the antenna must be a complete PPWG at the front where the pulse hits it in order to excite TE$_1$ mode.
Figure 2.5 PPWG Leaky-Wave Antenna Design
The leaky-wave antenna consists of two parallel plates, with a slit cut through one. The plates are held together by plastic spacers at the four corners.

Plastic spacers were made to hold the two plates together at the corners and provide structure. The spacers were interchangeable and made to sizes of 1, 2, 3, and 4 mm. This allowed for characterization of the leaky wave antenna with various dispersion relations, since the angle of the leaky-wave depends on the plate separation.

2.2.2. Experimental Setup

The setup for this experiment consisted of the commercial THz TDS system by Picometrix for generating and detecting THz radiation. This setup in particular was used because the emitter and detector were fiber-coupled, allowing for easy
manipulation of detector position in order to fully characterize the leaky-wave radiation. This system generates a broadband band THz pulse using photo-conductive antennas that are excited using a fs Ti:Sapphire Laser.

![Figure 2.6 Sample Time Domain Pulse from T-Ray 2000](image)

Our THz TDS system produces a single cycle broadband THz pulse.
Figure 2.7 Sample Frequency Domain Pulse from T-Ray 2000

Our THz TDS system produces a single cycle broadband THz pulse with a bandwidth of about 0.5 THz.

The broadband pulse is passed through a confocal lens arrangement using 6 cm and 10 cm focal length Teflon lenses. This allowed for the beam size of 1 cm to be equal for all frequencies as they were coupled into the PPWG.

The THz pulse coupled into the PPWG in TE\textsubscript{1} mode and leaky-wave radiation was transmitted angularly from the normal to the waveguide. This leaky-wave radiation was then measured at various angles. A focusing lens was used in order to focus a particular frequency onto the detector, since each frequency is emitted as plane waves at a particular angle.
Figure 2.8 Setup for Leaky Wave Transmission

THz is emitted from the fiber-coupled photoconductive antenna, then is focused using a confocal lens setup with teflon lenses. The focused beam is coupled into the waveguide in TE$_1$ mode.

By taking the Fourier transform of the electric field data from this setup, one can analyze the frequency content. The leaky-wave frequency data was normalized by dividing by the Fourier transform of a pulse that passed straight through the PPWG. The rationale for this is two-fold. First, we only wish to look at frequencies that actually couple into and out of the waveguide, which will depend on the plate separation. Second, since the original pulse is more concentrated at lower frequencies, it allows us to see which frequency in particular shows a peak at the particular angle at which we are observing.
2.2.3. Analytical and Experimental Results

One can rearrange the previous leaky wave equation to solve for frequency. This is the analytical result that experiment should match.

\[ f = \frac{c}{2b \sqrt{1 - (\sin \theta)^2}} \]

Plotting this for the four different values of \( b \) yields the following graph.

![Graph showing the frequency of radiation vs. angle from the normal to the waveguide.](image-url)

**Figure 2.9 Analytical result for Leaky Wave radiation**

The plot shows the frequency of radiation vs. angle from the normal to the waveguide. 0 degrees corresponds to cutoff frequency. As angle increases, so does frequency, with the result more apparent at smaller plate separations.
As is shown, the dispersion has a greater effect as $b$ is reduced. We see more curvature to the plot of $f$ vs. $\theta$ for smaller plate separations.

For analysis, we found the spectra at various angles for each plate separation. We normalized the frequency domain data by dividing by the spectra from a plane parallel plate waveguide with the same plate separation. This ensures that we looking at the peak from the leaky-wave effect. An example of this is shown in figure 2.10.

![Figure 2.10 Spectral Analysis for Leaky Wave transmission (example)](image)

The plot above shows the unnormalized frequency domain data and the normalized data for one angle ($52^\circ$) using 1 mm plate separation. The normalization factor is also shown. This is the spectra that is transmitted from a plane parallel plate waveguide with the same plate separation.
For each angle and plate separation, we recorded the peak frequency from the normalized spectra. The results are shown in figure 2.11. For several of these points we've included error bars to show the full-width half maximum of the peak from the normalized spectra.

![Graph showing Leaky Wave Transmission](image)

**Figure 2.11 Leaky Wave Transmission**

THz radiation was measured at each angle and a frequency peak was found corresponding closely to the expected leaky wave frequency. This plot shows the transmission results for four plate separations.

The expectation is that the experiment would show a peak at each particular frequency corresponding to the leaky-wave angle as shown in the analytical result.
What we see is good agreement between our experimental results and the analytical results that were predicted from the equation. The measurements ranged from $10^\circ$ to $72^\circ$. Larger angles than this ran into the problem of the detector lying along the axis of the waveguide itself and seeing surface modes from the shield used to prevent radiation directly from the waveguide. These results demonstrate that the PPWG can be used to transmit Leaky-wave radiation in the THz range. This shows good potential as a THz frequency-domain demultiplexer.

2.3. Measuring Field Intensity as a Function of Aperture

The peak of the electric field was also measured at various angles with respect to a varying slit aperture width, $w$. Apertures of 1, 3, 5, and 7 mm were used for plate separations of 2 and 4 mm. Varying the slit width does not affect the form of the electric field of the leaky-wave, only the magnitude. As shown below, the peak of the electric field increases as aperture width is increased. This field enhancement is more pronounced at higher angles. This is due to the fact that as the angle is increased, the detector can see more frequencies. Since the percentage of the power that is leaked increases with aperture, it should be possible to design a leaky-wave antenna that radiates the majority of the power. In our work, we have only used a uniform slit width. Perhaps with a slit width that increases along the length of the waveguide one could maximize the efficiency of radiation. This is a measurement that we do not have, however. This would be a difficult measurement to take since the radiation is diffracted outside of the plane of the slit, defined as the $y$ direction in
our experiments. What can be seen in figures 2.12 and 2.13 is that the peak of the field increases as we increase the aperture size.

Figure 2.12 Peak Electric Field vs. Aperture width, $b = 2$ mm
Shown are measurements of the peak of the electric field at 3 different angles ($30^\circ$, $45^\circ$, and $60^\circ$) for a leaky wave antenna with plate separation of 2 mm.
2.4. Using the Leaky-Wave Antenna to Receive Radiation

2.4.1. Theory and Experimental Setup

Using the PPWG Leaky-wave antenna as we have shown could be considered akin to a THz demultiplexer, in that it takes in a broadband pulse and disperses it into single frequency components that can be detected by varying the angle of the detector. A THz frequency-domain multiplexer, a device that combines multiple single frequencies into a single broadband pulse, has yet to be realized. In a first step towards this however, we reversed the leaky-wave antenna and have shown that it
can receive radiation through the slit and transmit it through the “front” of the PPWG.

Figure 2.14 Leaky Wave Antenna as Receiver
The THz pulse couples in through the slit and is then detected from the front. The mode matching condition dictates that the frequency that couples best into TE₁ mode will be the same frequency that would couple out at the specified angle.

In this experiment, we use the same broadband pulse as before, focused with the confocal lens arrangement to a beam size of 1 cm. The beam couples into the slit and is guided out of the PPWG.
Figure 2.15 Setup for receiving Leaky Wave radiation

THz is emitted from the fiber-coupled photoconductive antenna, then is focused using a confocal lens setup with teflon lenses, the same as before. The focused beam is now coupled into the waveguide through the slit. The detector is then placed at what had been the front of the waveguide.

In the first experiment, the electric field of the beam was parallel to the plates of the waveguide, allowing for TE$_1$ to be the dominant mode. In this setup, the initial mode is actually going to be TEM since the slit is perpendicular to the electric field. Since TEM mode propagates with zero dispersion however, the beam passes through the slit into the waveguide without dispersion [22]. Once the beam passes into the waveguide, the electric field is now parallel to the plates and TEM mode of the slit becomes TE$_1$ mode of the PPWG. Since TE$_1$ mode can be approximated as a bouncing wave, we expect the angle of the beam to play an important role [24, 25].
2.4.2. Results

We scanned the output of this leaky-wave “receiver” by varying the angle of the beam with respect to the device. We find that output exhibits a peak at the same angle that was predicted for leaky-wave transmission. That is, at each angle the frequency that best couples into the PPWG is the same frequency that would be radiated out at that angle in leaky-wave transmission. These results are shown below.

![Figure 2.16 Leaky Wave Receiver](image)

**Figure 2.16 Leaky Wave Receiver**

THz radiation was measured at each angle and a frequency peak was found corresponding closely to the expected leaky wave frequency. This plot shows the receiver results for four plate separations.
No normalization is used in this instance because coupling into the waveguide only occurs at the leaky-wave frequency. These results show that this leaky-wave receiver could function as a THz frequency-domain multiplexer by using multiple THz inputs at different angles one should be able to measure a combined output consisting of the added frequency components.
Chapter 3

Aiming the Leaky Wave Antenna by controlling the Dispersion

This section will describe a variation on the leaky wave antenna. We combine the concept with previous demonstrations that vary the index of refraction inside the waveguide by varying the plate separation. This concept is known as artificial dielectrics.

3.1. Varying the Plate Separation to Control Dispersion

It has been demonstrated that by utilizing the dispersion of the TE$_1$ mode of the PPWG, this particular structure can be used as a 2D artificial dielectric [26]. By varying the plate separation, $b$, one can create interesting devices such as gradient lenses and band pass filters for THz [27-28]. Utilizing this property and the phase-
matching condition of the leaky-wave antenna, we implemented a THz leaky-wave antenna designed to focus a single frequency.

Figure 3.1 Focused Leaky Wave Antenna Design
By varying the plate separation, $b(x)$, we can change the angle of radiation. In choosing a focus point and a design frequency, we can solve for the plate separation. This focused leaky-wave antenna should focus the design frequency at the chosen point.

By choosing a focal point, $(x,z)$, in relation to the waveguide and a design frequency, $f_0$, one can analytically solve for the plate separation as a function of $x$, $b(x)$. 
\[ b(x) = \frac{c}{2f_0} \sqrt{1 + \left(\frac{L-x}{z}\right)^2} \]

### 3.2. Design of the Focusing Leaky-Wave Antenna

Using this relation for plate separation, we constructed a focusing THz leaky wave antenna. First, the top plate with a slit was used from the previous experiments since this plate did not require any variation along the \( x \) direction. For the bottom plate, we designed the correct shape in AutoCAD and had it 3D-printed in plastic with 25 \( \mu \)m resolution. Since 25 \( \mu \)m is well below the diffraction limit of THz radiation, this was an acceptable tolerance. In order to make the bottom plate conductive so that it could act as a waveguide, it was coated with a thin layer of conductive Nickel spray paint. The top and bottom plate were then joined with plastic spacers. Two focusing leaky waveguide antennas were constructed to focus frequencies of 100 GHz and 170 GHz respectively. Each was 5 cm by 5 cm in area to allow for easy implementation into the previous setup. The focal point for the 100 GHz model was chosen to be at \( x = 5 \) cm and \( z = 5 \) cm, that is, in the plane of the end of the waveguide, 5 cm from the top plate. For the 170 GHz model, we chose a closer focal point 3 cm away from the edge of the waveguide. This is because the spectral amplitude decays for higher frequencies.
Figure 3.2 Focused Leaky Wave Antenna Implementation
We used the exact same setup as before, except now we setup the detector to raster scan over a chosen area. The focused leaky-wave antenna is made from a metal top plate and a 3D printed bottom plate coated in conductive paint.

3.3. Simulations of the Leaky Wave Antenna

For this aspect of the project, there does not exist a nice analytical equation for comparison, so we ran simulations for several different designs to see if each
frequency would focus to the chosen point.

![Figure 3.3 Simulation of Focused LWA – 100 GHz](image)

The origin here refers to the center of the waveguide. The field intensity at 100 GHz does focus to the chosen point 50 mm above the edge of the waveguide. Simulation courtesy of Yasuaki Monnai, University of Tokyo.

As can be seen in figure 3.3, the field intensity at 100 GHz does converge to the focal point 5 cm above the edge of the waveguide as expected. Simulations were also run for the 170 GHz design. A simulation was also run for a 300 GHz design, even though this was not implemented experimentally. This was to show that this concept would work for higher frequencies than our THz TDs can produce. These results are shown in figures 3.4 and 3.5.
Figure 3.4 Simulation of Focused LWA – 170 GHz
For this design, the focal point was chosen to be at 30 mm above the edge of the waveguide. Simulation courtesy of Yasuaki Monnai, University of Tokyo.
For this design, the device was scaled down to be 30 mm long. Here the chosen focal point was 30 mm above the edge waveguide. This design was not implemented experimentally since the spectral amplitude of our THz TDS is very low around these frequencies. Simulation courtesy of Yasuaki Monnai, University of Tokyo.

3.4. Experimentally Mapping the Focused Radiation

To implement this experimentally, it was necessary to raster scan across a window in order to map out the electric field at every point. The setup was as shown in figure 3.6.
Instead of varying the receiver angularly, the receiver is raster scanned across a window in order to map out the field at every point. From the Fourier transform of the field, we are able to get the intensity of the desired frequency at each point.

To characterize this radiation for the 100 GHz model, scans were taken every 5 mm along a grid of points from $x = 3.5$ cm to 7.5 cm and $z = 3$ cm to 6 cm. Since the radiation would be coming from many different angles at each point there was not an optimal angle for the receiver as in the previous experiments. In order to best split the difference, the receiver was set at a 45° angle. The corresponding plot of the field intensity at the design frequency of 100 GHz is shown below.
Figure 3.7 Field intensity at 100 GHz for Focused LWA
The device was designed to focus 100 GHz at the point (5 cm, 5 cm) in the x-z plane. As shown, at 100 GHz, the field is seen to narrow at the designated point.
Figure 3.8 100 GHz Field Intensity with Simulation

We show here the Experimentally measured field intensity plotted on top of the simulated field. We see consistent narrowing at the focal point for both experiment and simulation.

What we see in figures 3.7 and 3.8 is narrowing of the field at the expected point. We do not see a much larger enhancement of the field intensity at the focal point. This is because while the antenna focuses in the x-z plane, the radiation is diffracting in the y direction. Also, the radiation emitted from further down the waveguide has smaller amplitude than it does at the front. This is because the slit-width is uniform, yet the total radiation is decreasing along the length, so that the radiated amplitude is smaller as x increases. Even so, this plot shows excellent agreement with the designed intention and with the simulated result from figure 3.3. The plot for 170 GHz, figure 3.9, shows excellent focusing to the designed point.
Again we see that the overall amplitude of the radiated beam decreases with $x$, but even so the narrowing to the chosen point is apparent. It could be possible to increase the focusing by using a slit width that increases with $x$, but for demonstration of principle it is not necessary.

Figure 3.9 Field intensity at 170 GHz for Focused LWA
The device was designed to focus 170 GHz at the point (5 cm, 3 cm) in the x-z plane. We see a sharp narrowing towards the focus point.
Conclusions

We have demonstrated here for the first time a THz leaky wave antenna. This was done by using the PPWG and allowing radiation to radiate azimuthally out from one of the plates. This leaky-wave radiation is dispersed angularly with low frequencies more perpendicular to the waveguide and higher frequencies closer to the axis of the waveguide. In this way, the leaky-wave antenna functions as a THz demultiplexer by dispersing a broadband pulse.

By changing the plate separation, one can control the cutoff frequency of the PPWG, and therefore change the dispersion of the leaky-wave radiation. Making the plate separation smaller rotates higher frequencies towards the normal as lower frequencies are cut off. By increasing the aperture of the antenna with a wider slit, one allows more radiation to leak out of the PPWG. This follows a mostly linear relation as slit width is increased.
We also demonstrated that the PPWG leaky-wave antenna can be used to receive radiation through the leaky-wave slit. At each angle, the frequency that best couples into the PPWG through the aperture is the same frequency that would be radiated outward at that angle in leaky-wave transmission. This shows promise as a THz multiplexer. The obvious next step for this project is to do just that. By using multiple THz inputs with the Leaky-wave antenna as a receiver, one could potentially demonstrate frequency-domain THz multiplexing for the first time. Our hope is to be able to demonstrate this at a future point.

By combining the concepts of artificial dielectrics with the leaky-wave mode matching condition, we were also able to demonstrate a leaky-wave antenna with a gradient plate separation. This was used to focus a designed frequency to a chosen point. The importance of this is to show that the unique properties of the TE₁ mode can be utilized to control the leaky-wave dispersion.

Other work on this project could include further improving the coupling efficiency of TE₁ of the PPWG in to the leaky-wave mode and further utilizing gradient plate separations to create novel leaky-wave effects.

All of these results suggest that the THz leaky-wave antenna could have interesting applications as a frequency-agile THz source, with possible applications in the realm of THz communication technology.
References


