Department of Electrical Engineering and Electronics, UMIST

Fourth Year Project Final Report Epilogue

High Power Gunn Diode Oscillators

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Acknowledgements

During the past nine months, the team has gained a great deal of support and advice for numerous elements of this project.

Firstly we wish to thank the project team supervisors, Dr. Bill Truscott and Dr. Rob Sloan, who provided the team with advice and the project with direction, particularly in the early stages, also they both spent an extensive amount of time helping with the simulations.

We would also like to express our gratitude to the sponsor company, e2v Technologies, for all support the company has given. In particular, we would like to thank Chief Engineer, Nigel Priestley for his coordination of the project and collaboration with the team. We would like to thank Philip Norton for his expertise used in calibrating the oscillator systems, and Bernard Whitworth for his superior manufacturing skills demonstrated during the manufacture of all components.

Finally we would like to give our thanks to microwave technician Keith Williams, for the time he spent with the testing team.

Without the support of those mentioned above, the achievements and success of this fourth year team project would not have been possible.

Chapter 1

Executive summary

The aim of the project is to build a Gunn diode oscillator consisting of four diodes coupled together using power combining techniques to achieve an output signal of 100 mW at 87 GHz. The objectives are to produce a single Gunn diode oscillator, and using the design of this system, produce a multiple Gunn diode oscillator, to provide power combining and achieve the desired output signal.

Two reports, the interim report and the final report, have to-date been compiled detailing the project. The interim report contains the research of the project including the uses of the oscillator system, physics of the Gunn diode, diode housings and the single diode oscillator design. The final report contains the optimisation of the single diode oscillator design, system simulations, the multiple diode oscillator design and results from the testing of the single diode oscillator. This document, the Epilogue, is the completion of the documentation of the project. It contains a summary of the simulations, optimisation of the power supply unit, testing of the multiple diode oscillator and the conclusion of the project.

Using power combining, an output signal of 94 mW has been achieved. The frequency of the output signal at 94 mW was measured as 84.5 GHz, not 87 GHz. The difference in operating frequency is a result of the effective length of the waveguide cavity, which is reduced because multiple diodes are inside it. The effective cavity length was not taken into consideration in the design calculations. Four diodes were not required to achieve power of 94 mW; tests illustrated that two diodes were sufficient when power combined, achieving 94 mW. Power combining was achieved with three diodes but the power of the output signal was very low. This low power output could be a result of the positions of the diodes and how they interact with each other.

Chapter 2

Introduction

The final report focuses on the design and manufacture of the multiple diode oscillator. The report contains the results from the testing of the single diode oscillator, and shows it functions as desired, and better than expected. Since the final report, the manufacturing of the multiple diode oscillator was completed.

A PSU (power supply unit) was built because each diode in the oscillator requires a different bias voltage to achieve power combining and optimum operation. The original design of the PSU is included in the final report. The optimisation and testing of the PSU has since been completed. Using the variable and independent voltage supplies of the PSU to bias the diodes, the multiple diode oscillator has been tested and the optimum operating set-up for the multiple diode oscillator has been investigated. Throughout the project, simulations of all of the components of the oscillator were carried out, since the final report simulations using more advanced models have been completed and the multiple diode oscillator and a diode system manufactured by e2v have been simulated, and their simulated performances have been compared.

The epilogue is a completion to the project; it details the testing and performance of the multiple diode oscillator, as well as the details of the PSU optimisation and a completion of the simulations. A conclusion of the project is given, outlining the project's success against the aims, objectives and the achievements of other similar projects. The Epilogue finishes with a consideration of further work that could, from this point, be carried out.

Chapter 3

Project progress

3.1 Simulation

3.1.1 Introduction

The conclusion about the simulations, drawn from the final report was that the Gunn diode model needed to be improved in order to obtain an accurate and useful simulation of a Gunn diode oscillator. The shortfalls of the simulations up to this point arise due to the complexity of the Gunn diode, making it difficult to model its behaviour and effects accurately in a simulation package. The steps taken to try to find a solution to this problem are discussed in this section, as well as an investigation of the backshort position and the radial line transformer designed and made by e2v Technologies.

The team is in a good position to use simulations of the oscillator design because all the components have been manufactured and the oscillator systems operates correctly. Because the oscillator is functioning, the simulations of the oscillator can be completed and compared with the results of the manufactured oscillator. This provides an opportunity to validate the accuracy of the simulations.

3.1.2 Gunn diode model

After discussions with e2v's Senior Engineer, Keith Newsome, it was decided that the team would create a Gunn diode simulation model using the exact dimensions of a Gunn diode and place a lumped port inside it to simulate the RF signal produced by the diode. The creation of this model started with a

GaAs substrate a with a diameter of 35 μm and a thickness of 2.5 μm. The lumped port was set up within the substrate and the Gunn diode brass package was placed below the substrate. Figure 3.1 shows a HFSS screenshot of the single diode oscillator designed by the team, the manufactured oscillator functions correctly.

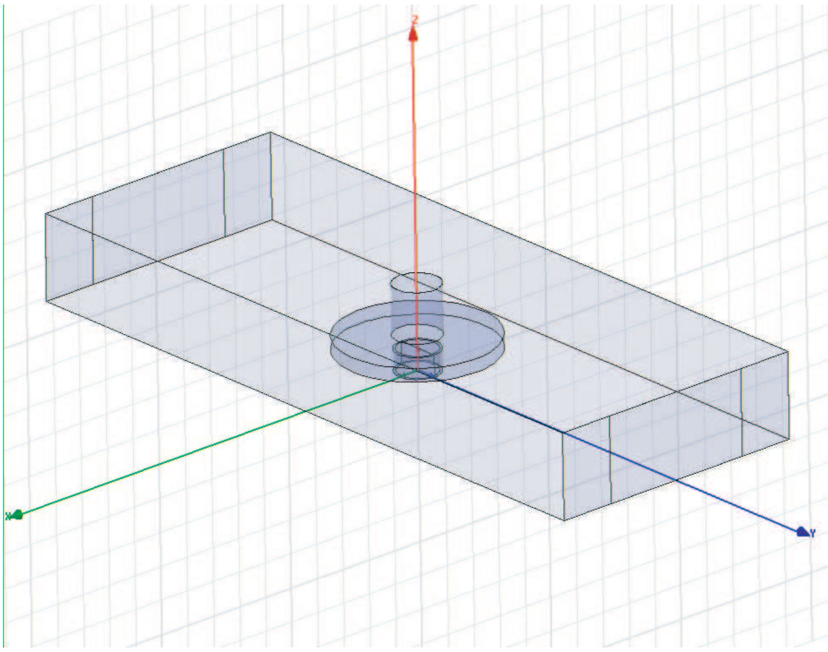

Figure 3.1: Single diode oscillator designed by the team

The operation of a Gunn diode oscillator is extremely complex and there are different theories about the function and effect of each of its components. The main components inside the waveguide cavity that affect the output of the Gunn diode are the RLT (radial line transformer) post and the resonant disc. From the research conducted earlier in the project it was known what results the simulation package should be producing. This research indicates that the response from HFSS should show that the phase angle crosses 0° at the fundamental frequency and again at the second harmonic frequency. In previous simulations this has not occurred and the results have varied and usually show that the phase does not cross 0° until the frequency exceeds 90 GHz. Figure 3.2 shows the response from the simulation using the improved Gunn diode model.

On the graph, figure 3.2, there are several phase changes which occur at the lower frequencies: 42 GHz, 45 GHz and 57 GHz. The first phase change at

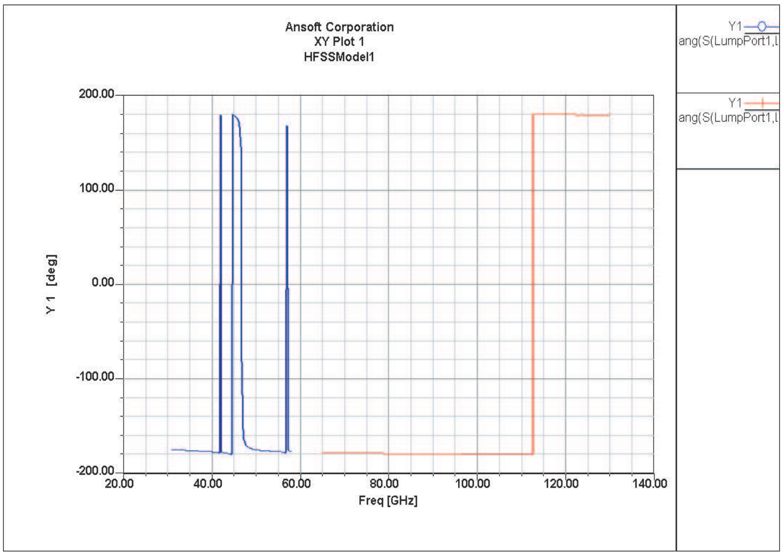

Figure 3.2: Response of single diode oscillator designed by the team

42 GHz is a sharp change and could be a rounding error. The second phase change occurs at 45 GHz, this is definitely a resonance as the peak at the top and bottom of the phase change rounds off; the point of resonance is the frequency at which the cavity and diode oscillate together, and at this point a phase change occurs, and crosses 0°. The resonant frequency determines the fundamental operating frequency, and simulated fundamental frequency of 45 GHz is relatively close to half of the value of the manufactured oscillator of 85 GHz. The third phase change at 57 GHz could also be a rounding error as the spike is very sharp.

Since the fundamental frequency was located at 45 GHz it is expected that there will be another resonance, the second harmonic, at twice that frequency, around 90 GHz. This was not seen on the initial plot from 30–90 GHz so another sweep was set up to run up to 130 GHz, this is shown as the red line in figure 3.2. A phase change occurs at 112 GHz but this value seems too high to be the second harmonic frequency. To verify whether this is a resonance, a polar plot was set up in HFSS. This plot showed that this phase change at 112 GHz is not a resonance because it does not travel around the plot but just stays at a value around 180°.

To conclude the findings when using an improved Gunn diode simulation model; there is a resonance associated with the GaAs substrate and the post of the radial line transformer at 45 GHz. There is no occurrence of a second resonance that should occur at the second harmonic frequency. Overall, for modelling the filter circuit, the simulation package HFSS has been a useful tool, but it has proved to be inconclusive when modelling the Gunn diode oscillator as a whole system. There are two possible reasons for this failure: firstly that HFSS does not work for this particular problem, or secondly that HFSS does work but the classic understanding of Gunn diode oscillators is wrong. It is more likely that the first reason is the explanation; HFSS does not work for this problem, so is not showing what we are looking for.

3.1.3 Filter Circuit

The radial line transformer used in the team's manufactured single device oscillator and multiple device oscillator was designed and made by Philip Norton of e2v Technologies. It was planned that the radial line transformer would be designed using HFSS.

The simulations of the resonant disc and RLT post were insufficient to investigate and optimise their design, and due to time restrictions the design could not be proved sufficiently. This highlighted the limitations of using a modelling tool in such designs and a hands-on, trial and error approach proved to be the most successful method for the resonant disc and RLT post. Earlier in the project, the team successfully designed the filter circuit using HFSS. The simulated filter circuit design can now be compared to the filter circuit designed and made by e2v.

The e2v filter circuit design consists of just one capacitor and one inductor, where as the filter designed by the project team consists of three capacitors and two inductors. e2v's design was created using knowledge and trial and error methods, no modelling tools were used.

The capacitors and inductors are cut-outs in the radial line transformer. The filter circuit design by e2v definitely works, this has been proven during the testing of the single device oscillator. Since the e2v filter circuit functions correctly, the investigation is about whether the design can be improved by using a modelling tool.

Firstly the filter circuit components of the e2v RLT were accurately measured and it was found that the diameter of the RLT cavity, the hole in which the RLT enters the waveguide, was 3 mm the gap between the capacitor and the waveguide housing was 0.08 mm. The filter circuit designed by the team had a RLT cavity diameter of 4 mm and a gap of 0.2 mm. To make the comparison between the two designs more accurate, the team's filter was redesigned with the same RLT cavity size and gap size as e2v's filter. The changes were made and the two designs were simulated in HFSS.

Figure 3.3 shows the results from e2v's design and figure 3.4 shows the results from the team's design.

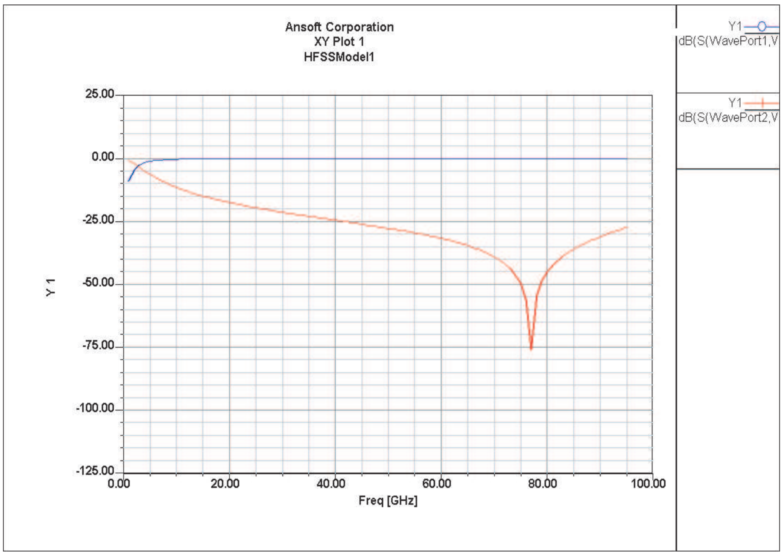

Figure 3.3: Response of filter designed by e2v

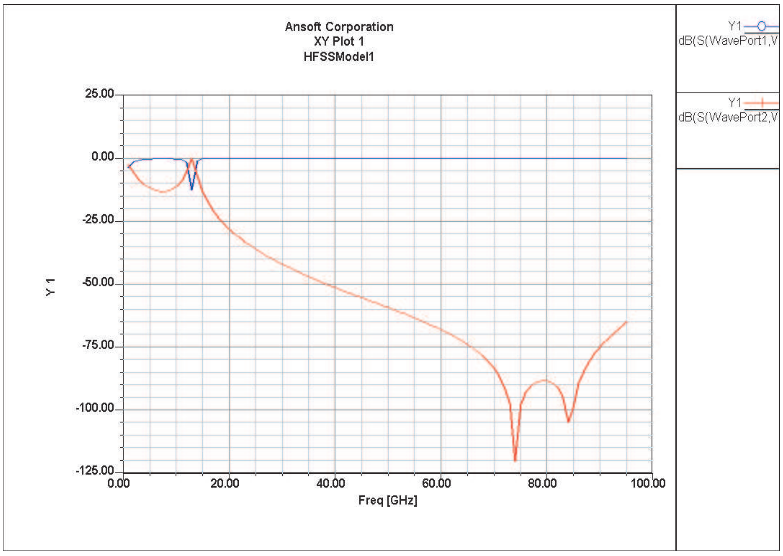

Figure 3.4: Response of filter designed by the project team

It is clear from the graphs that team's design has a better filter response.

The desired rejection value at the first and second harmonic frequencies must be below -20 dB. At the fundamental frequency (43.5 GHz) the rejection for e2v's design is -25 dB and for the team's design it is -50 dB. At the second harmonic frequency (87 GHz) the rejection for e2v's design is -33 dB and for the team's design it is -84 dB. Although the values achieved by the team's design are superior because the rejection is higher, the e2v design still fulfils the criteria that the rejection should be below -20 dB at both frequencies.

The filter designed by the team has a better response than the e2v design but it is not expected that changing the filter would improve the efficiency of the oscillator considerably. As future work it would be interesting to conduct an investigation into how much the filter affects the efficiency of the oscillator by manufacturing both designs and testing them in an oscillator.

3.1.4 Backshort

The signal produced by the Gunn diode can be considered as waves which are reflected by the back wall, back down the cavity of the waveguide. The position of the back wall can be varied and this modification is called the backshort. The backshort can be varied to optimise the performance of the oscillator. Several HFSS simulations were set up to study the effects of the backshort in terms of the phase angle of the wave travelling down the waveguide. The backshort was tested at different positions, resulting in the waveguide cavity being the following lengths: 8, 9, 10, 11 and 12 mm; for the frequency ranges 40–47 GHz and 80–94 GHz. Figure 3.5 shows the response for the backshort lengths for the frequency range 40–47 GHz.

At these lower frequencies the phase changes are spread out and occur at specific points. These phase changes occur at a point of resonance in the system. The point of resonance that is desired for the project is 43.5 GHz and the backshort length of 12 mm has a phase change at this frequency. The backshort also affects the phase changes for the second harmonic as illustrated in Figure 3.6.

At the higher frequencies the phase changes are more frequent. The phase change which occurs closest to the second harmonic at 87 GHz is a backshort length of 10 mm. The nearest phase change with a for a 12 mm backshort length occurs at 84 GHz and 90 GHz.

It can be seen from the graphs in figures 3.5 and 3.6 that the backshort length has a greater effect at the higher frequencies, 84–90 GHz, than at lower frequencies, 40–47 GHz. It seems the main function of the backshort is to adjust how the second harmonic frequency is fed back down the waveguide, and it

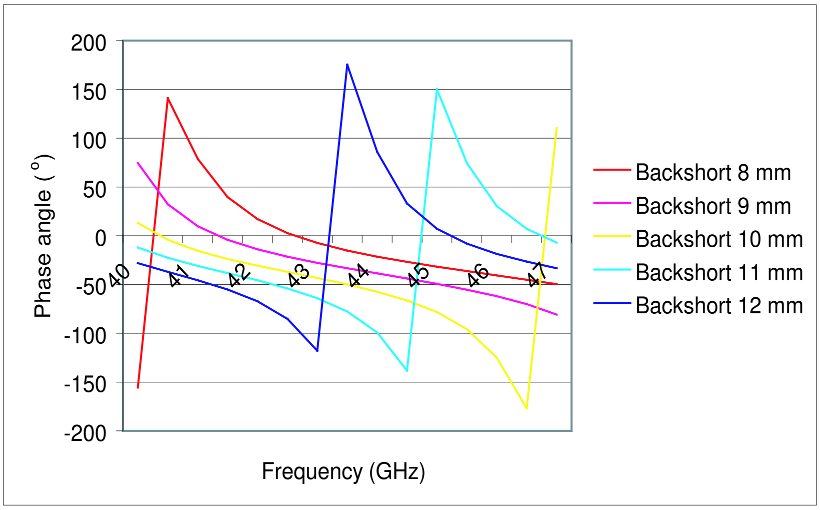

Figure 3.5: Phase angle for different backshort lengths from 40–47 GHz

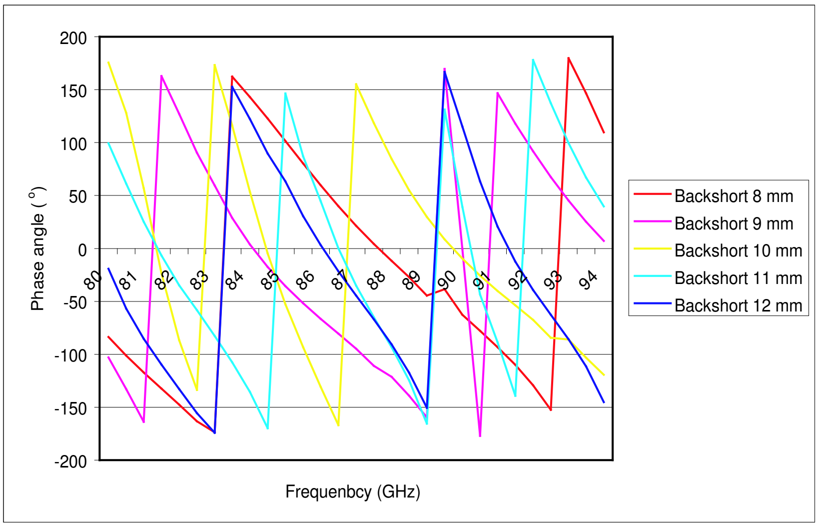

Figure 3.6: Phase angle for different backshort lengths from 80–94 GHz

is essentially a case of trying to find the position at which the fundamental and second harmonic frequencies match. It is easier to find this optimum backshort length in practice because the backshort is adjusted by hand, and clamped into position when the highest RF power is obtained.

3.1.5 Summary

The improved Gunn diode simulation model created in HFSS has proven to be inconclusive, particularly when simulated as part of the oscillator. This is probably because HFSS does not work for this particular problem. It is clear that further study into this area is needed to find a solution that can be used to create accurate simulation results.

The filter circuit designed by the project team using theoretical calculations and simulation software produced a better response when simulated in HFSS than the filter circuit designed by e2v. It was concluded that the improved filter circuit would not significantly affect the efficiency of the oscillator system.

The backshort has a greater effect on the phase of the waves at the second harmonic frequency than the fundamental frequency. When physically tuning the circuit, the optimum backshort length is determined by varying the backshort position until the power out of the oscillator is at a maximum, the fundamental and second harmonic frequencies are matched at this point.

3.2 Power supply

3.2.1 Introduction

The original requirement for the power supply was to provide four voltage supplies, with each voltage independent and variable, as biases for four Gunn diodes. The testing of the single diode oscillator demonstrated a power output of 50 mW at 85.05 GHz. As a result of the high power obtained from one diode, only two or three diodes are required in order to produce the target power of 100 mW depending on combining efficiencies. Due to time constraints and problems encountered with testing the PCB a number of modifications have been made to the PSU.

3.2.2 Modifications

Once the PSU was built, testing was carried out on the individual sections. Upon testing the PCB a number of errors were found with the circuit. Some of the tracks were shorted together resulting in the circuit malfunctioning. This problem was traced back to the schematic diagram from which the PCB was synthesised. These errors were corrected and the circuit was rebuilt using stripboard.

Another problem that was encountered was with the sample and hold amplifiers. The four voltages of the PSU are independent, so the value of each can be input in LabView independently. When the four different voltages were entered into LabView, the voltages were output to the appropriate sample and hold amplifiers. However, when these voltages were monitored with an oscilloscope, each of the outputs had a small step change. This change was found to be caused by a delay in the changing of the analogue voltage once the digital outputs changed. This meant that when an amplifier is selected by the demultiplexer the voltage for the previous amplifier will still be present on the analogue line and will continue to be output until the analogue line changes to the correct value. The delay was observed to be approximately 1 ms, and is illustrated in figure 3.7.

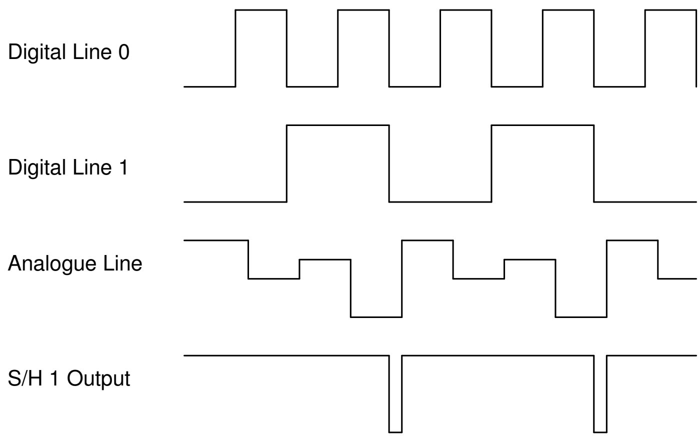

Figure 3.7: Sample and hold output example

To try to solve this problem the program with S/H amplifiers, the LabView program was modified to include a small wait command. This command was placed just before the “write to digital port” VI to prevent the demultiplexer selecting the next sample and hold amplifier before the analogue line had changed value. A wait command allows a time period to be specified, so the optimum delay could be obtained. The system was then tested with this modification with various wait periods, but this did not solve the problem. It did, however, reduce the period of the step change. The problem is that the time period could only be adjusted in the order of milliseconds, but the diodes are sensitive to voltage steps a much higher order.

After further testing it was found that by bypassing the inverting amplifier and connecting the analogue output from the data acquisition board to the analogue inputs on the S/H amplifiers the problem was solved. A new problem was created; the voltage regulators require a negative input voltage, resulting in only positive voltages being provided by the sample and hold amplifiers. Four inverting amplifiers could be positioned after the sample and hold amplifier as shown in figure 3.8, but this would mean the whole PCB would have to be redesigned, and with time being very limited this option was decided against.

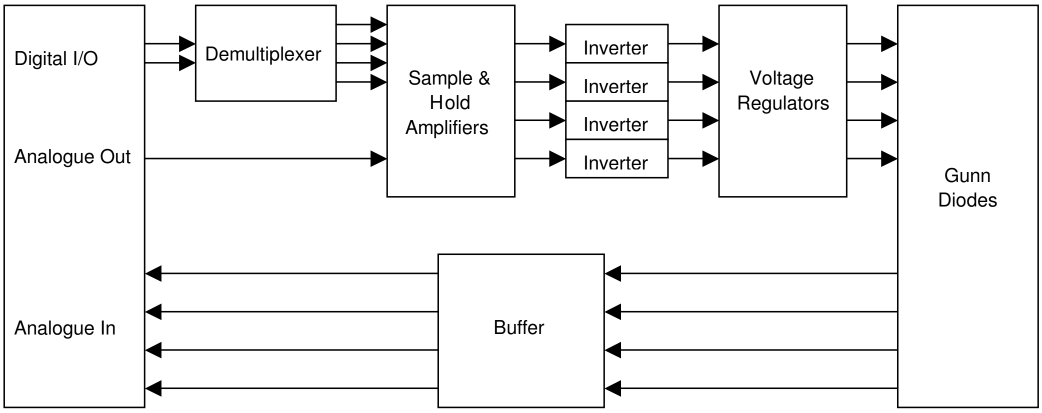

Figure 3.8: Possible solution using inverters

Another method was to use the two analogue outputs from the data acquisition boards and invert both of them, producing two of the three outputs. For the third output, a simple potentiometer could be used. Again this would have required significant changes to the PSU. A much simpler approach was chosen. Three 10-turn potentiometers were chosen to provide the adjustable inputs to the voltage regulators. This method is not be as precise as the data acquisition board, but having 10 turns means that sufficient control of the voltage is achieved.

Three voltmeters are used to monitor the bias voltages. This solution was the quickest and easiest to implement, but if more time was available for the project more work would have been done with the data acquisition board.

3.2.3 Summary

A number of problems occurred with the PSU. Due to the limited time, the solution to the problems to was to remove the data acquisition board from the PSU and use a number of potentiometers to control the bias voltages. The solution removed the accurate control of the voltages, for further work it would be advantageous to fix the problems with the data acquisition board.

3.3 Testing

3.3.1 Introduction

When the final report was written, the multiple diode oscillator was being manufactured, so no testing had started. The multiple diode oscillator is now complete, and testing of the multiple device oscillator has been done using the same test rig as for the single device oscillator, except the linear bench power supply was replaced by our own power supply, as described in section 3.2.

The testing was undertaken in two stages: firstly at e2v Technologies in Lincoln and secondly in the labs at UMIST. Four diode housings, G1 to G4,were available for the testing. These housings can be assembled into the oscillator in any combination or orientation.

3.3.2 Testing at e2v Technologies

The initial testing of the multiple device oscillator was carried out in the labs at e2v Technologies. This allowed e2v to see the manufactured system operating and enabled the team to become familiar with the testing procedure and ask questions, including the order in which the diodes should be turned on in a power combining oscillator.

Initially, the individual diodes were considered independently. Each diode was placed in the cavity and the test rig was attached. Next, the diode was biased and brought into oscillation. The angle of the diode relative to the cavity walls was adjusted until a maximum RF power output was observed, then the bias and backshort was adjusted until the peak power output from the diode was achieved.

Once the individual diodes were tested, two diodes were placed in the cavity. The diode furthest from the backshort was biased to give a high power output, then the back diode was switched on and the bias adjusted until locking and power combining occurred. During this initial testing session, power combining using the diodes G2 and G3 was achieved to produce a total output power of 94 mW at 84.53 GHz. At this point, the backshort length was 7.32 mm, and diodes G2 and G3 were biased to 5.26 V and 4.86 V respectively.

3.3.3 Initial UMIST testing

The testing session at e2v demonstrated that power combining could be achieved with the multiple device oscillator. The oscillator was set up in the optimum operating configuration determined during the e2v testing session, this enabled the team to compare our test equipment to e2v's equipment.

The team were unable to get the oscillators to lock using the same bias conditions as determined at e2v, indicating a discrepancy in the voltage measurement equipment at the two sites. After tuning the biases, the team were able to obtain a maximum of 86 mW of power when G2 and G3 were biased at 4.94 V and 4.85 V respectively. This is not as high as the power obtained at e2v, but it is a respectable power level, so the systematic testing procedure was begun across a limited range of bias voltages.

It was decided to start the testing with a similar test pattern as was used with the single device oscillator, keeping the backshort constant and varying the diode bias. The concept was adapted from a single diode to two diodes by creating an array of power readings and a separate, related array of oscillation frequencies. The raw results are included in appendix A.8.5. Figure 3.9 illustrates the power levels obtained for different bias conditions. Both graphs show the same data, but from different view points. The arch shape on the graph illustrates that the diodes only lock together under similar bias conditions, this was predicted in the final report.

By this point, the team had developed a good feel for the testing methods for a multiple device oscillator, and decided to move on to a larger scale systematic test of the oscillator which is described in detail in the following sections.

3.3.4 UMIST test method

This method describes the assembly and set up of the power combining Gunn diode oscillator, setting up from scratch, and the method used to determine the optimal operation parameters. The results of these tests are described in section 3.3.5.

1. Insert the Gunn diodes into the Gunn diode housing blocks using the insertion tool and a jeweller's screwdriver.

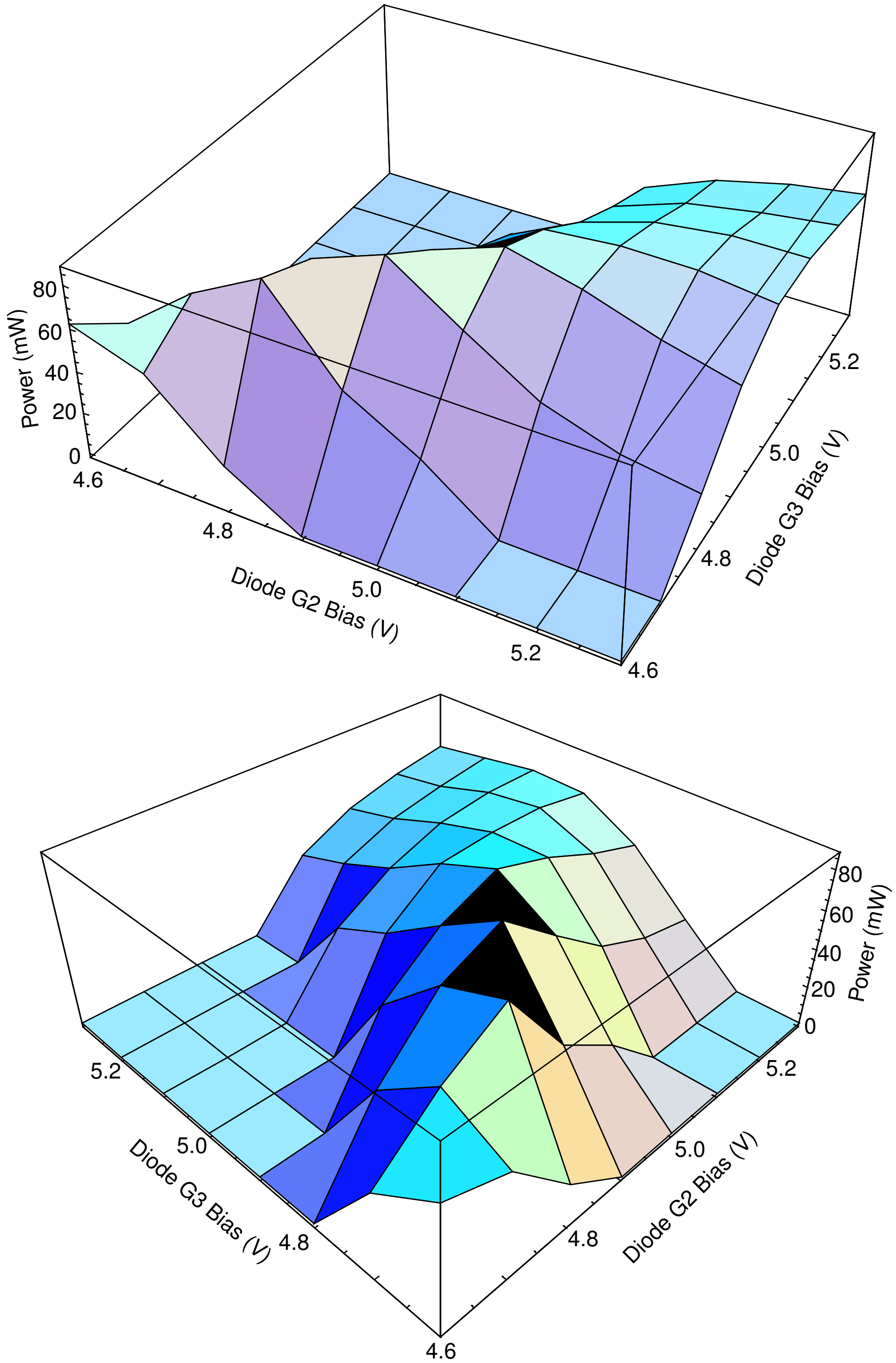

Figure 3.9: Power levels for varied G2 and G3 bias voltages

2. Assemble the oscillator comprising of the backshort housing, *one* Gunn diode housing and the second harmonic waveguide block. Bolt securely together.

3. Set up the test equipment as shown in figure 4.30 and described in the method of section 4.3.3.1 of the final report.

4. By tuning the backshort length, the position of the Gunn diode and the position of the radial line transformer in the housing block, determine their optimum positions for maximum RF power output.

5. Record the operating frequency and power output over the voltage operating range of the oscillator.

6. Repeat from step 2 with the remaining Gunn diode housing blocks. Sample test results are shown in figures 3.10 and 3.11.

7. Choose two Gunn diode housing blocks with similar bias-frequency characteristics. Reassemble the Gunn diode oscillator with both of these two blocks.

8. The backshort length has little effect on the oscillation frequency of the front Gunn diode, instead the distance between the Gunn diodes is significant for the front diode. Therefore, with the front Gunn diode turned off, tune the backshort length to find the optimum power output for the rear Gunn diode.

9. For each Gunn diode measure and record the operating frequency and power output over the voltage operating range of the oscillator with the other Gunn diode turned off. Results are shown in figures 3.12 and 3.13.

10. To power combine: Turn on the front diode and wait until stable oscillation is achieved, then turn on the rear diode. It is unlikely at this stage for the frequencies to lock and power combining to be achieved because the frequencies need to be matched by adjusting biases. When the frequencies do not lock, this will be indicated by a noisy spectrum on the analyser display. When the two frequencies are locked then the spectrum will just display the signal at the oscillation frequency and the images brought about by the use of the W-band mixer.

11. With the front diode bias set at 4.0 V increase the rear diode from 4.0–5.5 V and record the frequency and power output when the frequencies lock together. Increasing the bias of the front diode, repeat all these

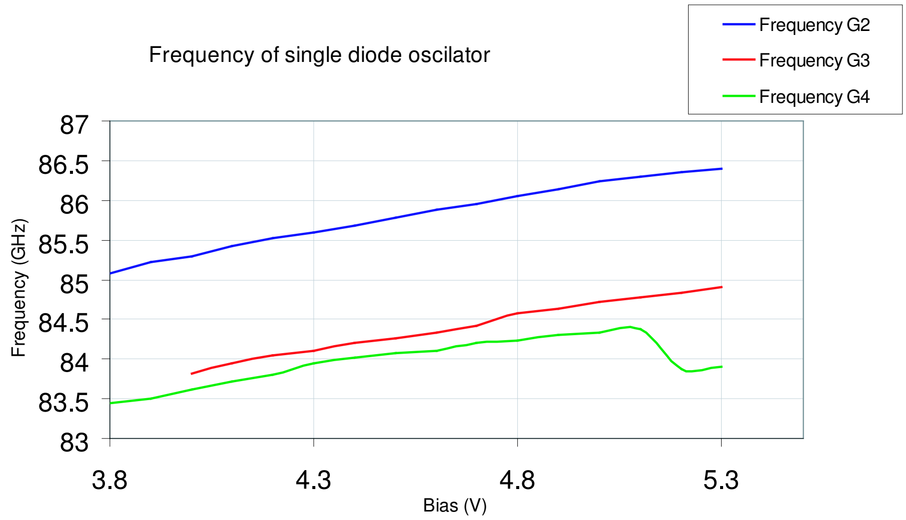

Figure 3.10: Single diode oscillator frequency

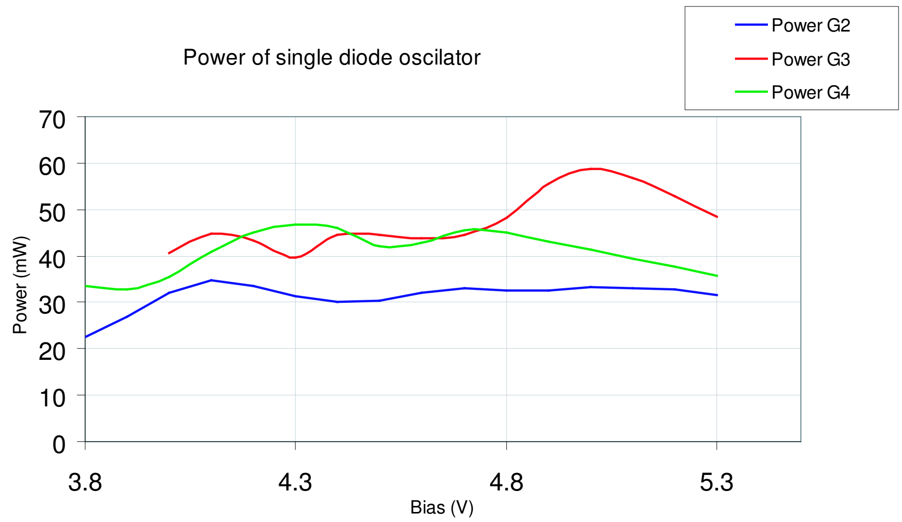

Figure 3.11: Single diode oscillator RF power

measurements until the front diode bias is 5.5 V. The results are shown in appendix A.8.6 and figures 3.15 and 3.14.

12. The results taken in part 10 should determine the optimum bias settings to give maximum power output whilst power combining both Gunn diodes.

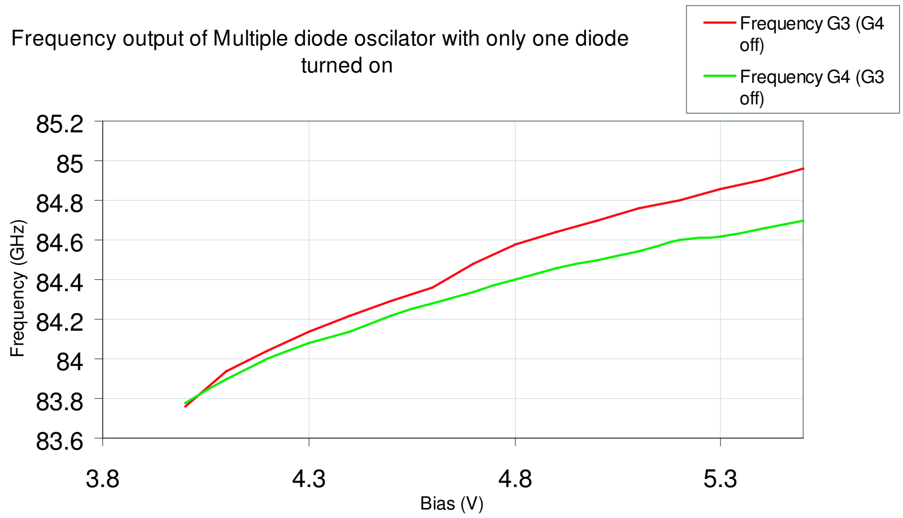

Figure 3.12: Single diodes biasing in a multiple diode cavity: Frequency

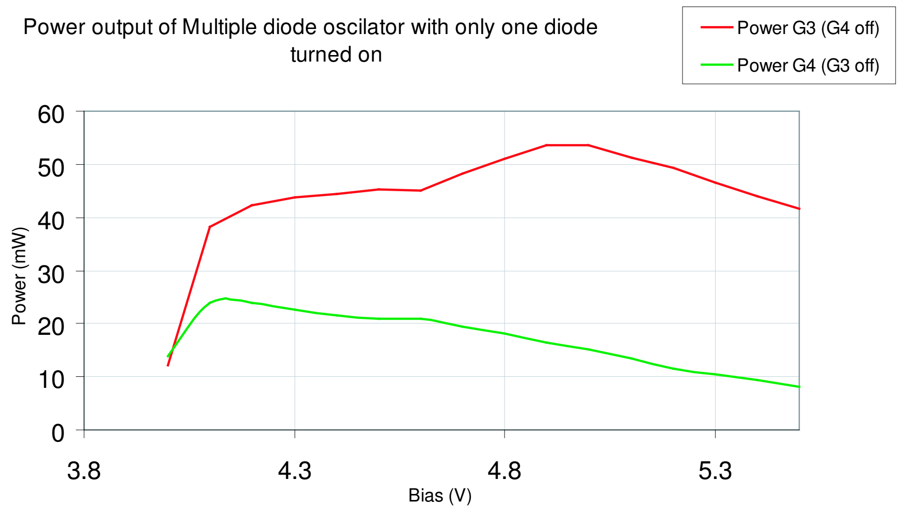

Figure 3.13: Single diodes biasing in a multiple diode cavity: Power

3.3.5 Results

Results for the test method described in section 3.3.4 are presented here. The results tables for all the graphs presented in this section are given in appendix A.8.

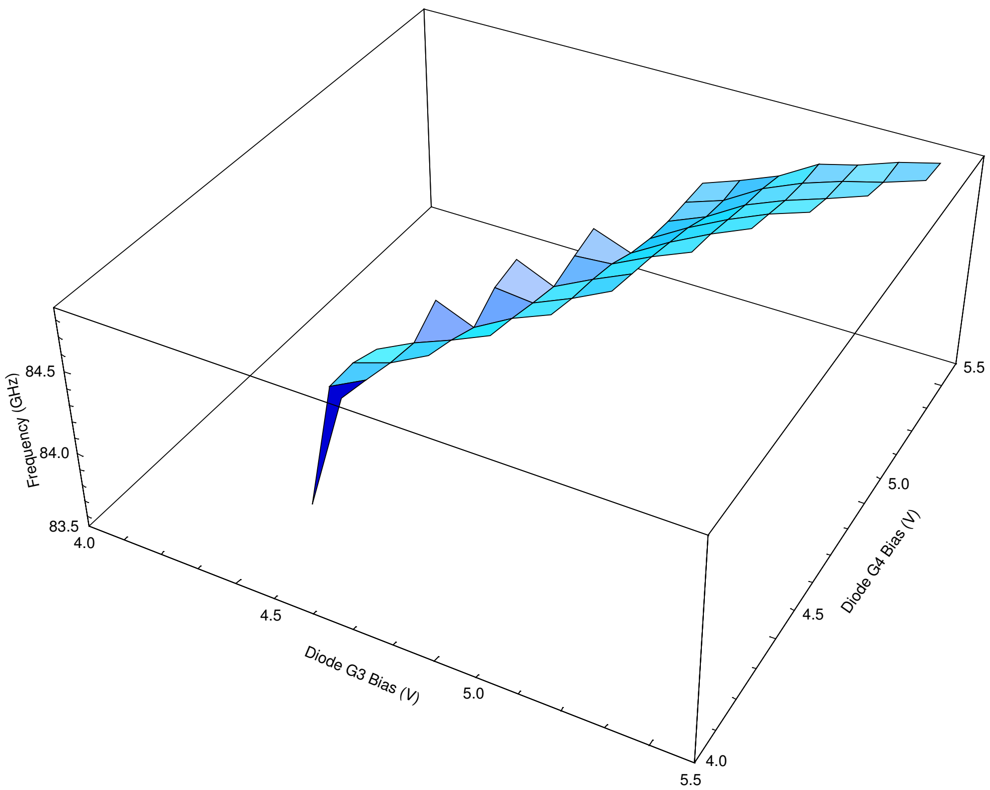

Figure 3.14: Frequency of oscillation whilst power combining

For the single diode oscillators, the optimum backshort length was found to be 9.9 mm. For the multiple diode oscillator, the optimum backshort length is 10.6 mm. This length gives maximum RF power output from the Gunn diode.

It can be seen from figure 3.10 that Gunn diode housing blocks G3 and G4 have similar bias-frequency characteristics. Based on this, power combining was attempted using these two blocks, G3 in front of G4. Figure 3.11 shows that the expected power output of both G3 and G4 should be similar. However, when placed in a multiple oscillator configuration, it is shown in figure 3.13 that the power output of G4 is much less than when G4 was assembled in the single device oscillator. This drop in power output can be attributed to the location of G3 which attenuates the propagation of the electromagnetic wave through the waveguide.

Figure 3.10 and figure 3.12 both suggest that in order for the two diodes to operate at the same frequency (and therefore power combine efficiently) G4 will have to operate at a bias of approximately 200 mV higher than that of

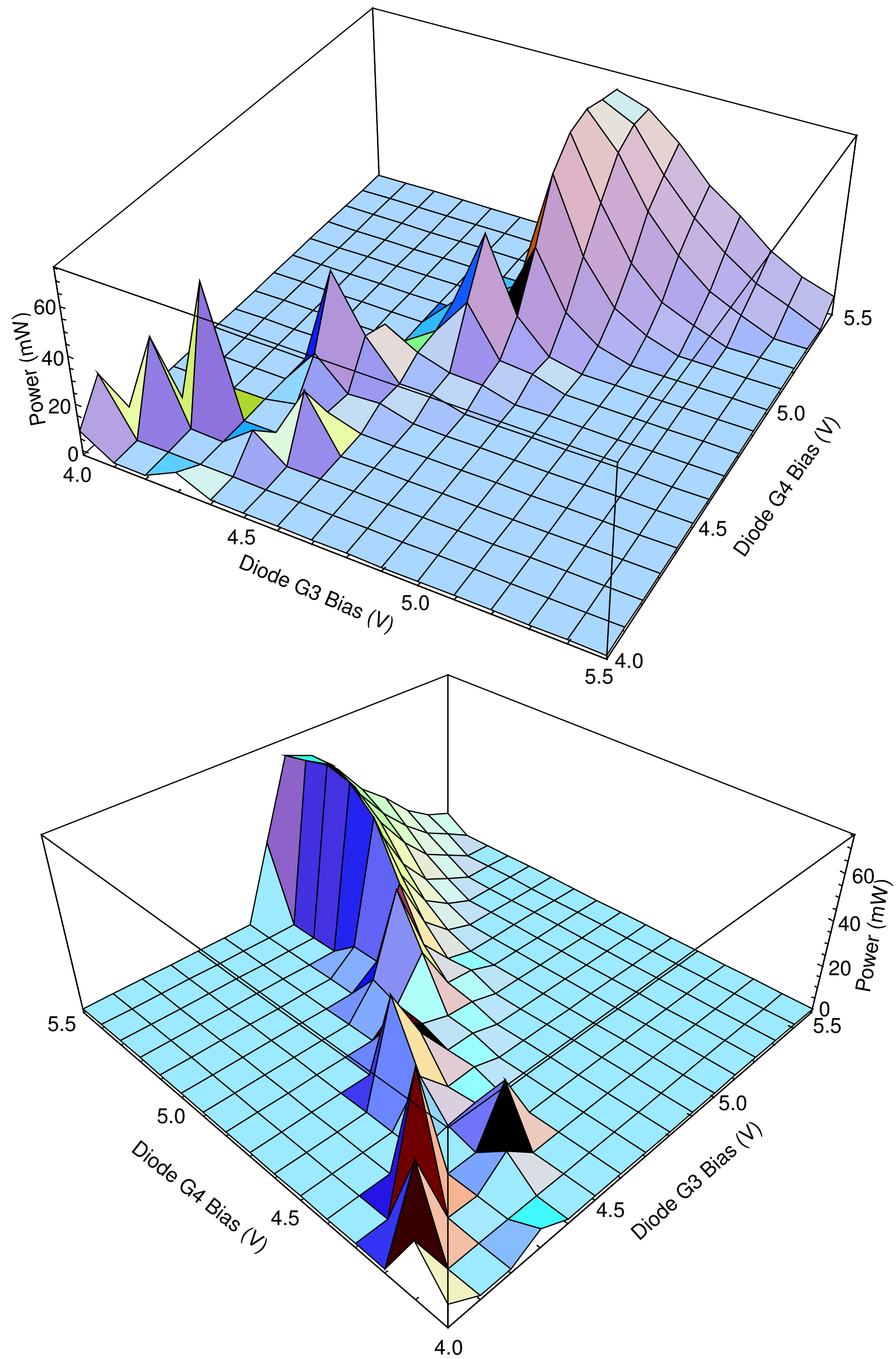

Figure 3.15: RF power whilst power combining

G3.

Figures 3.15 and 3.14 show three dimensional graphs of the power output and frequency of oscillation of the multiple Gunn diode oscillator at different bias voltages. When the operation frequencies of the two Gunn diodes do not lock together the power output is assumed to be zero for the purposes of these graphs.

The optimum Gunn diode biases for power combining are found to be when the bias of G3 is 4.8 V and G4 is 5.3 V. The power output at this setting is 73.62 mW at a frequency of 84.24 GHz. As predicted, the bias voltage of G4 is set slightly higher than that of G3 for this optimum position. It can also be seen that generally, the bias of G4 has to be greater than that of G3 in order for the frequencies to lock.

3.4 Conclusions

We have successfully demonstrated power combining at the second harmonic using a Gunn diode oscillator, achieving 94 mW of RF power at 84.53 GHz. During the testing, conditions for frequency locking have been determined and trends have been found linking diode bias to oscillation frequency and power.

Much of the tuning of the project could not be accurately mathematically calculated due to minute differences in devices introduced during the manufacturing process. This limits the potential of using such power combining devices in commercial products.

It has been determined that whilst simulation is very useful in the design of such systems, it cannot model the system completely. This project will be useful when deciding what parts of a system to simulate in future oscillator designs.

Since this project will be expanded upon as part of a terahertz imaging system, the requirements of that project should be considered. Acceptable excitation frequencies for that system are in the range 83–91 GHz. Our RF frequency of 84.53 GHz satisfies this requirement.

Appendix A

Electronic information

This section provides various digital documents that may be of interest to the reader. In order to view this appendix, place the included CD into an appropriate drive in your computer. If your computer is set to use Windows Autoplay, the menu should be loaded automatically. If not, please follow these steps to load the menu:

Windows 95 or above including NT

1. Insert the CD into an appropriate drive.
2. Click the Start button.
3. Choose Run.
4. In the resulting dialog box, type `D:\index.html` replacing `D` with the letter of your CD drive.

Other operating systems

1. Insert the CD into an appropriate drive.
2. If required, mount the CD.
3. Start a web browser.
4. Enter the following URL: `file:///path-to-cd/index.html` where `path-to-cd` should be replaced with the actual path to the CD for your operating system and hardware.

A.1 Project plan

Planning is important for any project, especially so for a long-term project such as this one. Careful attention was paid to the project time plan, copies of which are available on the attached CD.

A.2 Records of the meetings

As the project was progressing, regular meetings were organised between the team members and the supervisors. Agendas were created for these meetings, and minutes were recorded for reference. These documents can be found organised chronologically on the attached CD.

A.3 Financial accounts

A copy of the accounts for the project, both with and without personal time estimates, are available on the attached CD.

A.4 Presentation slides

A presentation was organised to allow us to demonstrate to e2v Technologies the current level of our understanding of the project and discuss the aims and objectives for the project. It was also designed to introduce the project team and set the scene for some questions to be asked. The slides used in the presentation are available on the attached CD, as are the slides used for the formal project presentation in January.

A.5 PHP source

Source listings for the PHP scripts used to create the project web site are included on the attached CD. Discussion of why PHP is used in the site is provided in the interim report and expanded upon in the final report.

A.6 Technical drawings

Mechanical drawings for various methods of waveguide construction are provided in this section.

A.7 Project logs

A log was maintained containing all issues that arose during the project to track their progress and ensure resolution. A log of all communications with e2v was also created to help to facilitate a professional relationship between the team and e2v, and avoid excessive contact that may waste everybody's time. Both logs are available in this section on the CD.

A.8 Experimental results

Raw data from the testing of the oscillators is presented in this section.

A.9 HFSS simulations

As described in all three reports, HFSS was used to simulate parts of the oscillator. The HFSS files used in the simulation are included in the attached CD for your reference.

A.10 Power supply

The schematic and PCB layout for the power supply unit for the multiple device oscillator is available for viewing here, along with information on the LabView modules used to build the control interface to the PSU.

A.11 Main reports

A copy of the final report including this epilogue are also included on the attached CD for reference, along with a copy of the interim report.