Department of Electrical Engineering and Electronics, UMIST

Fourth Year Project Interim Report

High Power Gunn Diode Oscillators

Michael Gaskill
David Headland
Jamie Higginbotham
Ruth Irwin
Andrew Nelms
Raymond Wan

Supervisors:
Dr. R Sloan
Dr. WS Truscott

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Chapter 1

Executive Summary

The aim of this project is to produce a high frequency, high power output signal by applying a direct current (DC) input signal to a system; producing a radio frequency (RF) oscillator; the system is built using Gunn diodes. The research, results and conclusions of this project will be used by a number of engineering groups, primarily a research group in UMIST and e2v Technologies, to improve the functionality and capability of Gunn oscillator systems. These Gunn oscillator systems include car radar and terahertz radiation imaging systems.

The Gunn diode is a complex electronic device, which can operate in a region known as the negative differential resistance region (NDRR). When the device is operating within this region it exhibits negative resistance characteristics; as the input voltage increases the current through the diode decreases. This phenomenon is due to the band structure of Gunn diodes, which cause electrons to move to higher energy bands as the voltage across the diode is increased, resulting in the electrons gaining a higher relative mass and moving at a slower speed. When the Gunn diode is operated in this region, it can be made to output a high frequency oscillating signal due to the production of domains that propagate internally across the diode.

There are two types of Gunn diodes, differentiated by the material the diode is manufactured from. These two types of diode are gallium arsenide and indium phosphide. The diodes exhibit different behavioural characteristics, gallium arsenide diodes are being used for this system since they have a longer life and are less prone to disturbance due to external conditions. There are a number of circuit configurations that can be used. Two of these configurations, waveguide and planar circuits, are most commonly used. The waveguide configuration confines the output signal well, has low attenuation losses and acts as a heat sink for the diode, so is the chosen circuit configuration.

The diode must be operated within the NDRR to produce an RF output signal. The diode is maintained in this region of operation by the bias voltage, which is applied to the diode along a path known as the radial line transformer. The radial line transformer is a complex device that acts as the bias circuitry for the diode; the components and their magnitudes are crucial. Gunn diodes generally produce an output signal frequency between 30 and 50 GHz; the requirements of the project are to produce a signal whose frequency is 87 GHz. To achieve this high frequency, the second harmonic of the output signal is extracted. A filter circuit and the waveguides are used to remove and dispose of other harmonics that are undesired. Gunn diodes consume a large amount of power, but they have low energy efficiency, so much of this power is dissipated as heat, resulting in the output power of the Gunn diode being small. The requirements of this project mean that power from a number of diodes must be combined to produce a power signal of a sufficient magnitude.

A simulation tool is being used to support the design of this oscillator system. The simulator tool is being used to model the interaction of electromagnetic fields that are produced inside the waveguide as the output signal propagates along it. The system is going to be manufactured, so designs for the waveguide and radial line transformer must be produced, including diagrams for the machinist to use to manufacture these components.

Problematic issues faced within this project include the dissipation of heat from the Gunn diode and a large amount of testing required for familiarisation, understanding and verification of the system.

The project is mostly up to date with the time plan. The actions so far have included understanding the Gunn diode, choosing the type of Gunn diode and the circuit configuration for the system, understanding circuit biasing (the radial line transformer is partially designed), choosing second harmonics and designing the waveguide appropriately (the initial waveguide designs have been given to the machinist), deciding on the method of power combining and learning to use the simulation and testing tools.

Chapter 2

Introduction

2.1 Aims and objectives

The aim of this project is to build Gunn diode oscillator that can achieve a power output of 100 mW at 87 GHz oscillation frequency.

Such an oscillator could be required to combine the power from four Gunn diodes to total a maximum power output of 100 mW.

As the project has progressed it has become increasingly apparent that the major objective of the project is to achieve the power combining of the Gunn diodes at 87 GHz. The power output objective is now considered to be secondary to this.

2.2 Project purpose

The Gunn diode is a relatively cheap and readily available device. They are often used for DC to microwave conversion; no additional complex circuitry is required to create an oscillator. The low voltage requirements make them suitable for a wide range of applications and allow them to be used in a variety of different environments. The devices are currently being used in many systems including car radar and terahertz imaging.

There are a variety of different radar systems available, each performing slightly different tasks. These tasks include movement sensors, distance measurements, ABS (anti-lock braking system), automatic cruise control (ACC) (e2v Technologies 2003*a*) and collision avoidance. Mercedes offer a "Distronic" proximity-control system on their S-class range of vehicles. This system uses a 77 GHz Doppler radar located behind the front grille. This sensor is linked to an electronic control and braking system. The sensor measures the distance to the vehicle in front, the system will calculate the minimum safe distance between the two vehicles, and will adjust the car's speed to maintain this safe distance. Mercedes stress that this is not a safety system as it is not designed to avoid collisions, but is designed as a comfort feature. Mercedes are also developing more sophisticated systems, which can detect the road edge, lane markings, gauge the condition of the road, and from this provide more control over the vehicle.

Gunn diodes are being used in terahertz radiation systems; a Gunn oscillator creates a signal which is amplified up to terahertz. Terahertz. imaging is a technology similar to that of X-rays, used to produce an internal image of an object from measurements acquired by non-intrusive processes (Galbraith & Zhang 2002). The properties of terahertz radiation allows the radiation to penetrate deep with high accuracy to produce better images than those produced by the other currently available radiation imaging systems. The imaging is suitable for use in many industries, and is already being used for medical imaging.

Other systems which use Gunn diodes include frequency modulated continuous wave (FMCW) radar sensor heads, local oscillators/carrier generators for microwave video distribution and systems (MVDS), point to point links or other communication applications, these systems are all being developed by e2v Technologies (e2v Technologies 2003*a*). The research and analysis completed during this project is going to be used by a number of groups, including e2v Technologies and a UMIST research group, to achieve higher performances from Gunn diodes to improve and increase the performance of systems based on Gunn diodes.

2.3 Project sections

2.3.1 Research

In order to find out more information about Gunn diodes and how they can be used to produce oscillations research needed to be carried out. A number of methods were used to obtain this information. The primary method was to use papers published in journals, magazines, and conference proceedings. Searches were carried out using the IEEE Xplore website (`http://www.ieeexplore.ieee.org/`) and the PDFs of the relevant papers downloaded. Relatively few books were available that covered the subject of Gunn diodes, but a number of books were found or recommended that covered the topic of microwaves. These books and papers were quite useful in understanding the fundamental concepts and to gain better knowledge in this field.

2.3.2 Simulation

Simulation software, used for the design process of a system, is a useful tool for engineers because it can save time and money. The other benefit for this project is that it will give an insight into the operation and theory of waveguides and how to optimise their performance. A high level of detail can be obtained from the simulations because they can generate results that are not experimentally measurable. Simulation software does however have limitations, because the calculations it performs are based on theories and laws; the results may not demonstrate the exact behaviour of a real system.

The software chosen for this project is High Frequency Structure Simulator (HFSS). HFSS models electromagnetic fields in 3-dimensional structures, so the waveguide can be simulated and investigated using this. Waveguide theory is complex and has many variables, each part of the system is critical because even a small change can affect the system a great deal. These slight changes can be simulated in HFSS and the knowledge gained can be applied to the oscillator built by the team. Simulations will be carried out for the single diode oscillator and the power combining oscillator.

2.3.3 Building

A major part of the project at this stage is to build a single device. The aim of building the single device is to gain a basic understanding of how these devices are constructed and an understanding behind the precise measurements required.

The design has been broken down into three main elements namely the waveguide, the Gunn housing and the backshort. These elements will all be manufactured in high grade brass because it can be machined to a close tolerance giving near-net shapes, this is critical for the accurate measurements required.

At this stage of the project the building of the single device is on schedule with the initial design prepared. Although, due to the machining facilities being short-staffed, the actual building will fall slightly behind schedule. Optimistically the device should be ready by mid-January, so results achieved from tests performed on the device can be used for the presentation at the start of February.

2.3.4 Testing

After any device has been built, it requires testing to make sure it conforms to the specifications. Generally, testing should be used as a method to confirm calculations and decisions made during the design phase. For this project, however, it will also be used as a point to do some empirical tuning of the radial line transformer (see section 3.6 on page 34 for more details).

Tests that will be performed on the completed oscillators include:

- Spectrum analysis.
- Radio frequency power measurements.
- Phase noise measurements.

Further details are provided in section 3.7 on page 37 and section 3.11 on page 50.

2.4 Document overview

1. Section 3.1 gives an insight into the fundamentals of the Gunn diode. The characteristics of Gunn diodes and the reasons behind their behaviour are described. A brief outline of the fabrication process is also given.

2. An important issue which must be considered is to analyse the safety for the team members involved with the project. Section 3.2 looks at implementing a safe system of work, by implementing risk assessments. It describes what risk assessments have been completed and highlights the potential hazards. To conclude this section, copies of the risk assessments are attached in the appendices.

3. Section 3.3 explains what simulation tools we are using, describes the reasons for choosing to simulate the design, the results already obtained and the proposals for future simulations which will be carried out.

4. Gunn diodes can be made of various semiconductor materials. Section 3.4 outlines the similarities and differences between the two most common Gunn diodes. Arguments for and against these two types of Gunn diode are presented and the choice of material stated.

5. Section 3.5 explains the need for a circuit to confine and transfer the microwave power of the Gunn diode. The circuit configurations, waveguide and planar, which could be used to fulfil this role are introduced. The choice of circuit configuration is justified and further explanation of this circuit configuration, is provided.

6. The radial line transformer is the circuit to bias the Gunn diode; it comprises of a filter and a resonant disc and is situated above the diode. Section 3.6 describes the radial line transformer and how it operates.

7. Section 3.7 looks specifically at the Gunn diode oscillator provided by e2v Technologies. A test procedure is outlined for investigating the bias voltage-frequency characteristics of such an oscillator together with the results of the test on the available model. Preliminary conclusions are drawn as a point of comparison for any future designs of the oscillator.

8. The principles of fundamental and second harmonics are introduced in Section 3.8 and an explanation of why we have chosen to use the second harmonic of the Gunn diode is given.

9. In order to practically obtain high power levels from high frequency oscillators, several individual oscillators must be combined together in such a that the power from each individual oscillator constructively contributes towards an overall RF power. Section 3.9 discusses the requirements to successfully achieve this power combining.

10. The Gunn diode requires cooling due to the amount of power it dissipates and its small size. In section 3.10, the considerations for cooling the oscillator are described and a chosen method of action is outlined.

11. In order to investigate the performance of Gunn Diode Oscillators, test procedures must be set. Section 3.11 outlines some of the tests that should be made, to verify the correct function of an oscillator device. Proposals are made to research test methods that have not yet been investigated.

12. Section 3.12 describes the building of the single Gunn device using the various ideas raised from the research. The chapter describes the

major aims and what is hoped to be achieved by building such a device. An explanation is also given of each individual part and how their magnitudes were determined. A statement on the preferred material and what stage the building progress is at is also given.

13. A web site was created in order to share information about the progress of the project between group members and any interested third parties. Section 3.13 describes how the web site was created and what information is present within it.

2.5 Existing devices

There are currently no power combing Gunn diode oscillators available commercially, but there are single diode oscillator systems that can be purchased. Gunn diodes are ideally suited for use in oscillators and are typically used in waveguides. The waveguide, Gunn diode and other components for the system can be bought separately but some companies, such as e2v Technologies, will design and deliver the complete system to suit the customer's needs. In these circumstances the waveguide will normally be custom built for the particular application (as well as the radial line transformer and other components). It is also possible to buy pre-manufactured waveguides in standardised sizes.

A waveguide is chosen by the band in which it operates, for instance if the application was for a 90 GHz oscillator a WR-10 waveguide would be chosen as it operates in the W-band (75–110 GHz). Figure 2.1 on the next page (WiseWave Inc 2003) shows the dimensions of a pre-manufactured waveguide that can operate in a number of frequency bands.

Our project design will differ from the commercially available devices because all of the components in the system shall be custom built to suit the application. Also, the team hopes to successfully design and build a power-combining oscillator that will be unique and that fulfils the specification of the project.

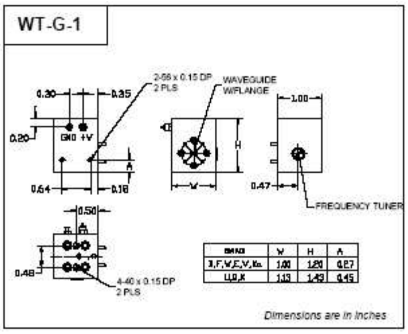


Figure 2.1: Dimensions of a pre-manufactured waveguide

Chapter 3

Project progress

3.1 Overview of Gunn diodes

3.1.1 The Gunn effect

A Gunn diode is a two terminal device, typically made from Gallium Arsenide (GaAs). Just like a normal diode they exhibit non linear I/V behaviour, but have a negative resistance characteristic. The I/V curve in figure 3.1 on the facing page shows the negative resistance region, where as the voltage is increased the current falls. This negative resistance region occurs due to the energy band structure of GaAs. The band structure of GaAs is quite complex but "for realistic electron energies ($E < 2\,\mathrm{eV}$) only the lowest conduction band needs to be considered" (van Zyl, Perold & Botha 1998). The shape of this conduction band is a curve containing several distinct valleys, as shown in figure 3.2 on page 12.

These valleys can be approximated to two parabolas, the central Γ-valley and the satellite L-valley as shown in figure 3.3 on page 13.

The effective mass of an electron, $m*$, is given by equation 3.1:

$$m* = \frac{\eta^2 k^2}{2E} \tag{3.1}$$

Where:

η Efficiency.

k Wave vector.

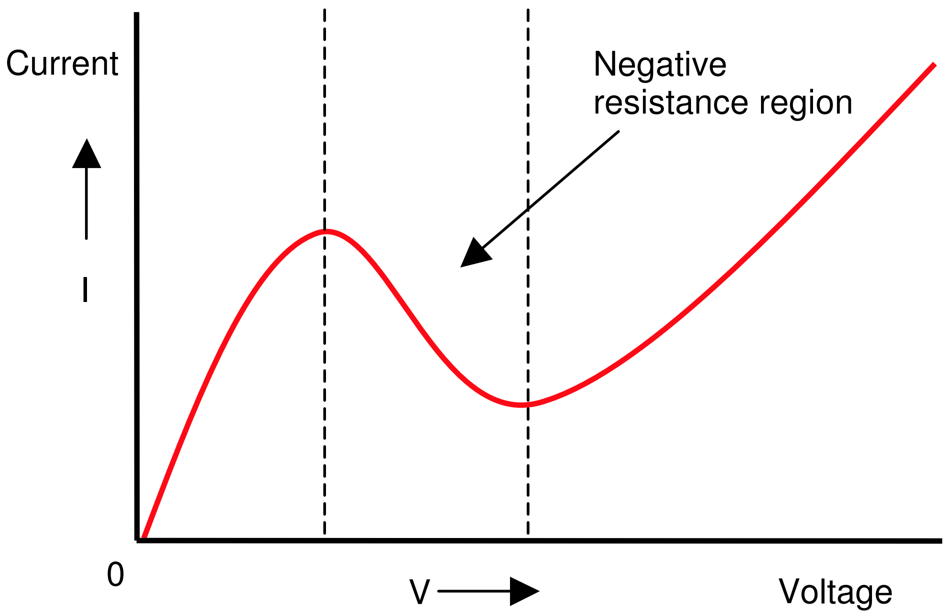


Figure 3.1: Negative differential resistance

E Electron energy.

As the central valley curve has a much sharper slope than the satellite valley, this means that the effective mass of an electron in the central valley is smaller than the effective mass of an electron in the satellite valley. Therefore, the mobility of the electrons in the satellite L-valley will be much less due to the higher effective mass. When no bias is applied electrons will occupy the lower Γ-valley as they do not have sufficient energy to reach the higher satellite L-Valley. However, when a bias is applied some of these electrons will gain enough energy to move from the Γ-valley up into the satellite valley. The promoted electrons have a higher effective mass, so have less mobility leading to a slower average drift velocity. Thus, the current decreases as the voltage increases creating a negative differential resistance region. When a sample of GaAs is biased at the negative resistance region, Gunn domains can be formed. These arise due to small perturbations in the net charge. This causes the electric field distribution to change, giving rise to different drift velocities at different points in the sample. Electrons at one point will travel faster than electrons at a second point causing a build up in one area and depletion in another, creating a Gunn domain. This domain grows as it propagates through the sample from the cathode towards the anode, where it

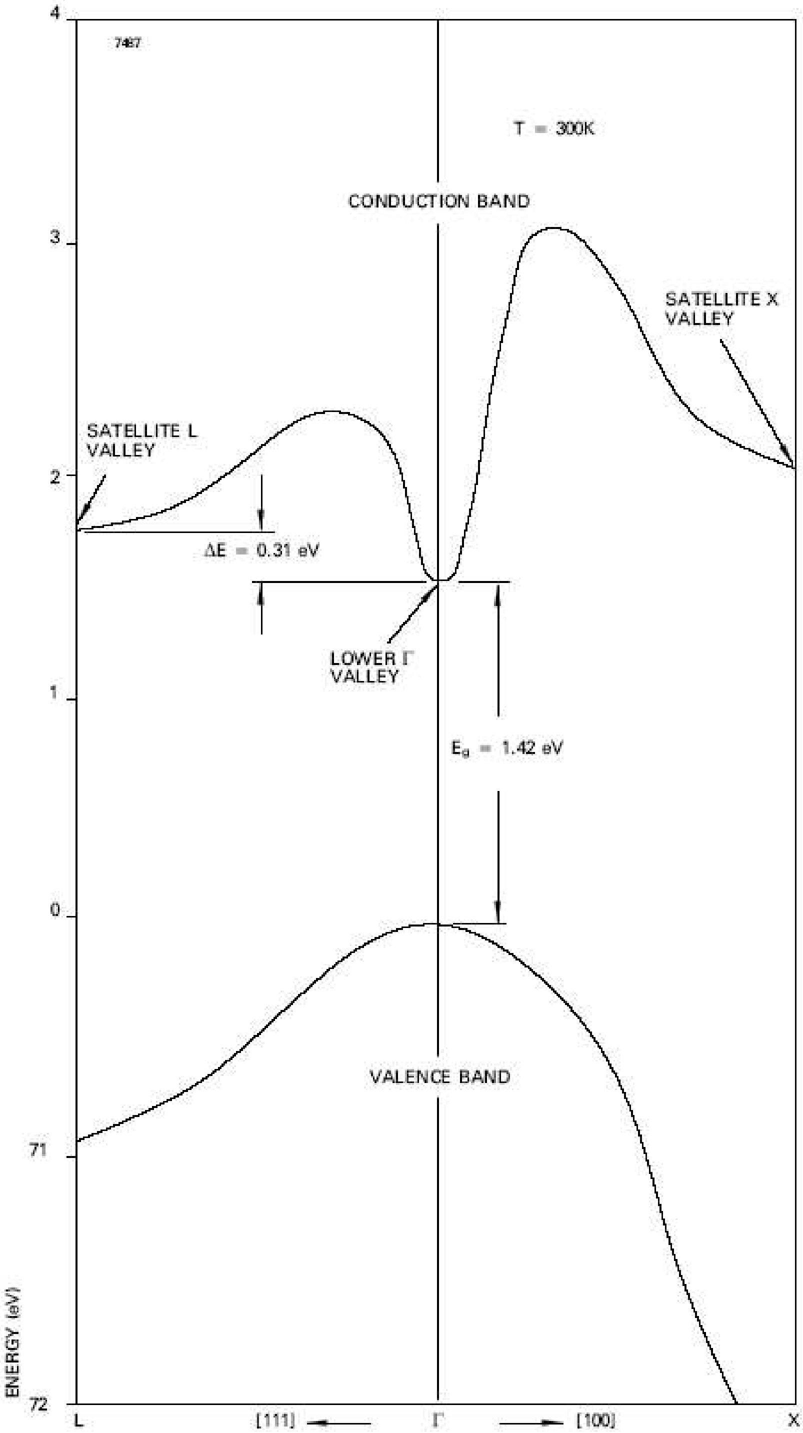


Figure 3.2: The band structure of GaAs

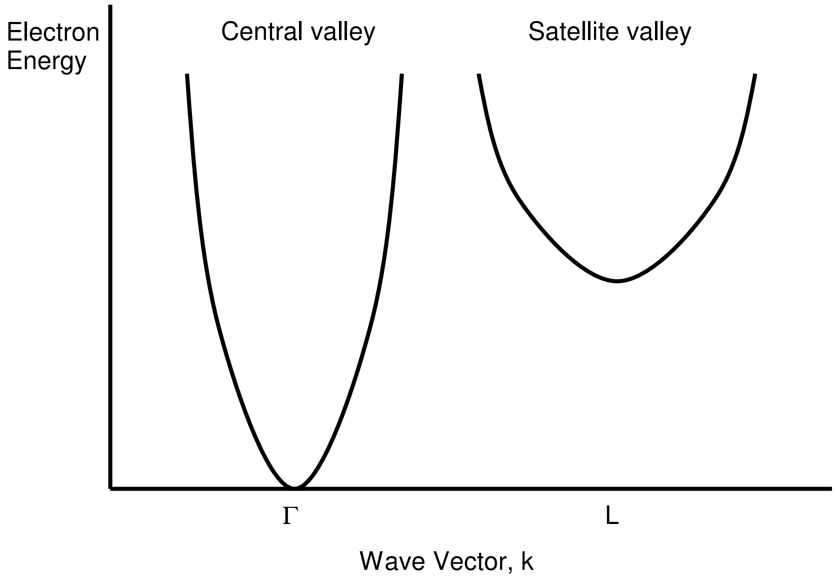


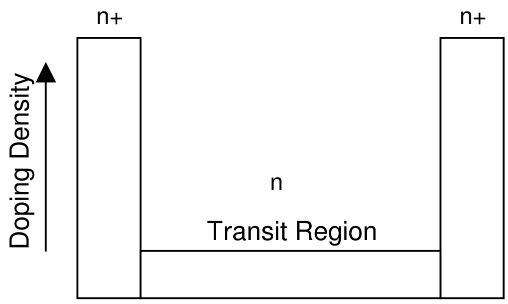
Figure 3.3: Simplified band structure of GaAs

is then absorbed. This means another domain can be formed, this successive formation of Gunn domains leads to oscillations. The frequency of oscillation therefore depends on the distance the domain needs to travel before reaching the anode, and also the DC bias. The DC bias will affect the drift velocity of the domain and so will affect the frequency.

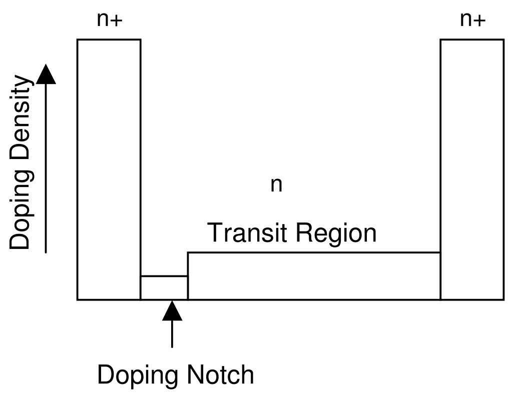
3.1.2 Fabrication of Gunn diodes

Gunn diodes are often made from GaAs, they consist of three layers, a relatively low doped transit region that is situated between two highly doped contact regions. This forms a n+→n→n+ structure, as shown in part (a) of figure 3.4 on the following page. These three layers are often grown using a molecular beam epitaxy process. The individual diodes and contacts can then be defined by standard masking and etching procedures.

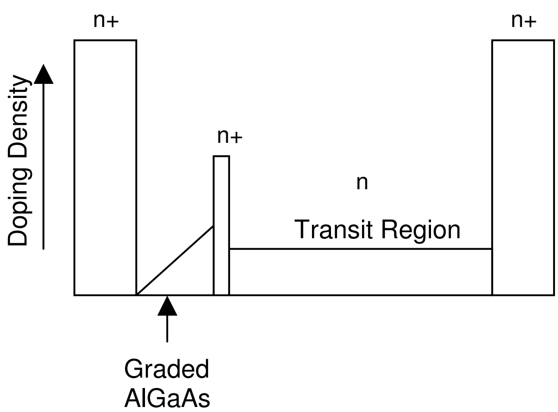
As mentioned earlier, the frequency depends on the distance the Gunn domain needs to travel before being absorbed at the anode, therefore it depends on the length of the transit region of the diode. When electrons are initially injected into the cathode they remain in the Γ-valley and don't immediately gain enough energy to be promoted to the upper satellite L-valley. This delay means that the electrons don't enter the low mobility state immedi-



(a) Structure of a conventional Gunn diode



(b) Structure of a Gunn diode with a doping-notch



(c) Structure of a graded-gap Gunn diode

Figure 3.4: Structure of various types of Gunn diode

ately, so there is a delay in the formation of the domain. Subsequently there is a "dead zone" by the cathode region of the diode, which reduces the efficiency of the diode as the length that the domain can grow within is shorter. This, therefore, leads to a reduced power output. The existence of the "dead zone" affects high frequencies and there is a rapid fall in power at frequencies greater than 60 GHz, so often the second harmonic component has to be used as explained in section 3.8. This drawback of the "dead zone" can be overcome by reducing it size, this can be achieved in a number of ways:

One method is to use a doping notch, as shown in part (b) of figure 3.4 on the preceding page, which will produce a high electric field in the notch. This stronger electric field will accelerate the electrons faster allowing them to gain enough energy to transfer to the satellite L-valley more quickly.

A more efficient method is to inject high energy "hot electrons" directly into the transit region, a graded-gap Gunn diode uses this technique, as shown in part (c) of figure 3.4 on the facing page. "Hot" electrons are injected with enough energy to jump from the Γ-valley directly into the L-valley. This results in domain formation very near to the cathode allowing it to grow almost instantly.

The diodes are often enclosed in a small cylindrical package with a screw thread. The diode is then wire bonded to the base and the top lid of the package. The screw based package allows the diode to be mounted extremely easily into its target environment, and also offers a low thermal resistance so heat can be transferred to its surroundings with little difficulty.

3.2 Health and safety

3.2.1 Introduction

For any project large or small, safety is an important issue which must always be considered. Having a team member injured could put a halt on the project and cause it to fall behind schedule. Therefore implementing a safe system of work is critical for this project, for this project the use of risk assessments is employed.

In industry the law requires employers to carry out risk assessments. The person most suitable to complete a risk assessment is the person who is going to perform the task where there is a risk, because they are most familiar with the equipment and can ensure that any risks are efficiently understood and controlled.

A risk assessment weighs up all the potential hazards which could cause harm to personnel, property and equipment; it identifies the existing control measures, and then classifies the probability and severity of the hazard. The results of the assessment, groups the hazards into three categories: 'high, medium and low'. In the event of a hazard being in the high group, action must be taken to reduce the risk and suitable control measures are put in place which remain effective throughout the project.

The UMIST protocol for risk assessments for such a project is freely available from the institutes's intranet. The intranet provides guidance for completing risk assessments for the workplace, with the intention of making it a logical process to understand (UMIST Safety Office 2003).

One of the main reasons for completing a risk assessment is to identify and eliminate the risk. Therefore the risk assessment should be carried out before anyone is exposed to the risk, so that the necessary control measures can be put in place first. The second reason for completing a risk assessment early is to highlight any necessary controls needed which can be catered for in the design stages.

Once a risk assessment has been completed it is of no benefit unless the information is used properly. Consequently, it is necessary to have copies made and distributed to all team members informing them about the risks and how they must be controlled.

3.2.2 Activities

The activities for this project were split into several different areas varying from working alone to performing a range of tests. Each particular task was deemed to require a risk assessment. There are three main risk assessments which were completed at this stage of the project:

1. Working on personal computers.
2. University out of hours working.
3. Testing microwave devices.

3.2.2.1 Working on personal computers

The first two activities (1 and 2) are of minimal risk but are required to demonstrate an appreciation of this safe system of work. The assessment for "work on a computer" raised issues of sitting correctly at the computer and taking breaks during extensive periods of use.

3.2.2.2 University out of hours working

The second assessment was for using the university facilities out of normal working hours, one reason for working at this time is to take advantage of the specialist software which is only available in University. The main issue raised in this assessment is working alone, so notifying campus security that team members are working in the building and having a mobile telephone to make emergency calls reduces the potential risks.

3.2.2.3 Testing microwave devices

The third assessment is of major importance due to the project being involved with the use of high frequency radiation. The purpose of reviewing this hazard is to look at the effects of exposure to RF fields and assess its possible impact on human health. Such an assessment is necessary for limiting exposure to RF fields during the testing of a Gunn diode device.

Protective measures include engineering controls, administrative controls, and personal protection. Where surveys of RF fields indicate levels of exposure in the workplace are in excess of limits recommended for the general population, action should be taken to protect personnel.

Engineering controls should be applied, where possible, to reduce RF emissions to acceptable levels. Such controls include good safety design, and where necessary the use of interlocks or similar protection devices. For this experiment the supply should always be isolated when making alterations to the system.

Administrative controls that can be used to reduce exposure are access restrictions, allowing only authorised personnel around the test bench and displaying a suitable non-ionising radiation warning sign around the test area.

Protective clothing, such as conductive suits, gloves, and safety shoes, may be used for this project. Their use should be confined to ensuring compliance with exposure standards when engineering and administrative controls are insufficient to do so. Safety glasses have also been proposed for RF protection, but there is no convincing evidence that they are effective. The use of personal protection (protective clothing), though useful under certain circumstances, should be regarded as a last resort to ensure the safety of personnel.

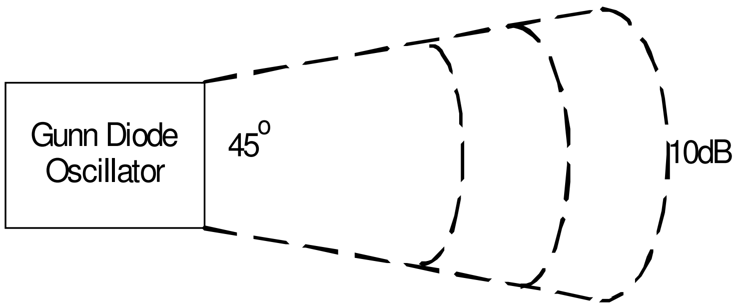


Figure 3.5: Gunn diode RF power output

Wherever possible, priority should be given to engineering and administrative controls.

3.2.3 Safe working distance

The minimum safe distance can be calculated as shown; it refers to figure 3.5 of a Gunn diode oscillator producing an output at 45°at a minimum power of 100 mW. It must be noted that the results are referring to the eye, and under no circumstances should you look directly down any waveguide.

- Assumed worst-case sidelobe level: -10 dB.
- Radiation limit for the eye: 100 mW per 10 g (Kowalczuk & Sienkiewicz 1991).
- Conversion: $100\,\mathrm{mW\,m^{-2}} = 10\,\mathrm{mW\,cm^{-2}}$.

Equations 3.2 to 3.4 on the facing page show how to Calculate the value of absorption ($\mathrm{W\,m^{-2}}$):

$$S = \frac{PG}{4\pi r^2} \tag{3.2}$$

$$10\,\mathrm{mW\,cm^{-2}} = \frac{100\,\mathrm{mW} \times 10}{4\pi r^2} \tag{3.3}$$

$$r = \frac{\sqrt{100}}{\sqrt{4}\sqrt{\pi}}$$

$$= \frac{10}{2\sqrt{\pi}}$$

$$
\begin{aligned}
&= \frac{5}{\sqrt{\pi}} \\
r &= 2.82\,\mathrm{m} \qquad (3.4)
\end{aligned}
$$

Where:

S	Expected value of absorption ($\mathrm{W\,m^{-2}}$).
G	Gain.
P	Receiving output power.
r	Radius distance (m).
PG	ERP (effective radiated power).

Therefore, the minimum safe working distance is 2.82 m when looking directly down the waveguide output, but as stated above, looking down a waveguide is prohibited. Additionally, to summarise this particular risk assessment the actions to be followed are to isolate the supply when making alterations to the system or when the system is not in use. Also, added measures are to allow only authorised personnel around the test bench area and have warning signs indicating a high RF area.

The risk assessment forms drawn up as a result of these health and safety investigations are included as appendix B on page 73.

3.3 Simulation

3.3.1 Introduction

Simulating systems can be a cheap and quick way to test a system's operation without actually making anything. The issue of using simulation software is a controversial one, with many engineers opting for practical tests instead. The issue arises because many question the accuracy of such simulations and whether the time spent setting up a simulation can be justified if the results are not accurate. A simulation can never perfectly describe a physical situation, it has limitations, but it can give the user a good idea of the effects of certain variables. The limitations are due to the fact that the simulation software uses many complex mathematical formulae to simulate physical conditions based on theories and laws.

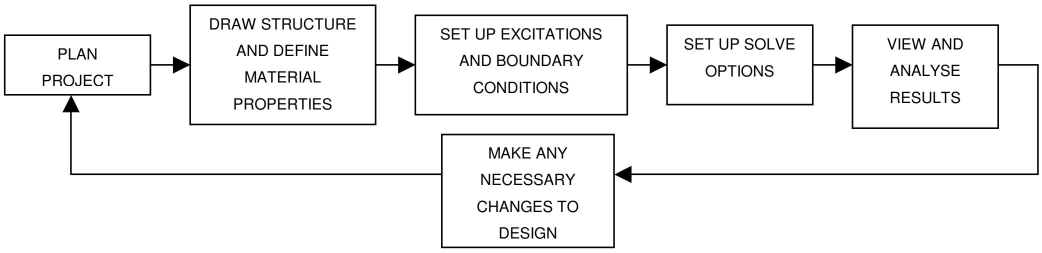


Figure 3.6: Block diagram of simulation steps

After discussions with e2v the team was told that e2v engineers opt for a practical hands-on approach of making Gunn diode oscillators. From his years of experience, Mr P Norton, has concluded that it is quicker to produce a working system this way. In the case of this project it has been decided that using a simulation package will be worthwhile because it can give an insight into the operation of a waveguide oscillator and certain components in the waveguide can be simulated (such as the radial line transformer). The dimensions of the radial line transformer are critical and the effects of changing certain values can be simulated and investigated. This is useful because when it comes to practical tests knowledge will have been gained about changing such variables. There is currently no known software available that can simulate Gunn diodes or negative resistance devices. For this reason it will only be possible for the team to simulate the Gunn diode as an internal port that generates a current. The components that will be simulated are the waveguide and some of its internal components such as the radial line transformer and the adjustable backshort.

3.3.2 High Frequency Structure Simulator (HFSS)

The simulation package that has been recommended to simulate the waveguide is called HFSS (High Frequency Structure Simulator). It is a software package for FEM (finite element method) modelling of electromagnetic fields in 3-dimensional structures (Aglient Technologies 2000). HFSS is an extremely powerful tool and its capabilities stretch far beyond the scope of this project. The simulation tool solves Maxwell's equations to find solutions to problems posed to it. Once a 3D structure is created, HFSS can simulate its response to stimuli defined by the user and display the results in various ways. Figure 3.6 is a block diagram illustrating the typical steps taken when simulating a design.

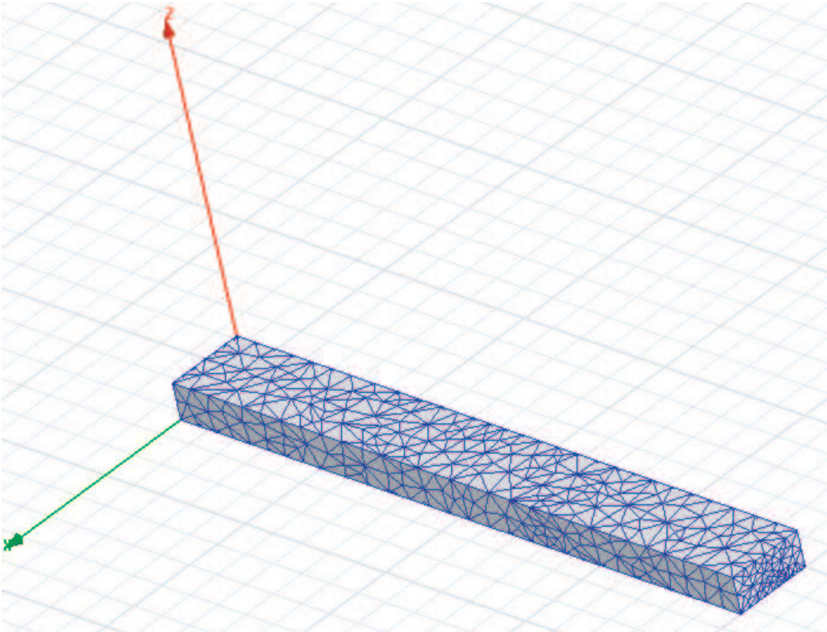


Figure 3.7: Tetrahedron mesh

HFSS is very flexible and a vast array of simple or complex shapes can be created in the drawing editor manually or by using a library of elements. In preparation for the simulation materials must be assigned to each object and then excitation conditions can be applied. The excitations can be ports or voltage sources, ports set field conditions at a specified boundary. To obtain results the frequency must be identified as well as the mesher conditions. HFSS generates a mesh of tetrahedrons and an electric field is approximated over each tetrahedron with a second order polynomial containing unknown coefficients. The matrix is then solved to determine the values for the polynomial coefficients. Figure 3.7 shows the mesh of tetrahedrons over a 3D box.

Once a system has been simulated there are many different ways of analysing the results. S-parameter plots can be generated as well as field plots (of E and H fields), mesh plots, and far field plots.

To begin, the waveguide dimensions need to be entered into HFSS. The graphical user interface is well laid out and is quite easy to use, the model created can be seen in 3D space on the screen. The design was simple at the start, for this reason the waveguide was entered as a 3D block of dimensions 23mm by 200mm by 10mm for x, y and z respectively. The aim of this initial

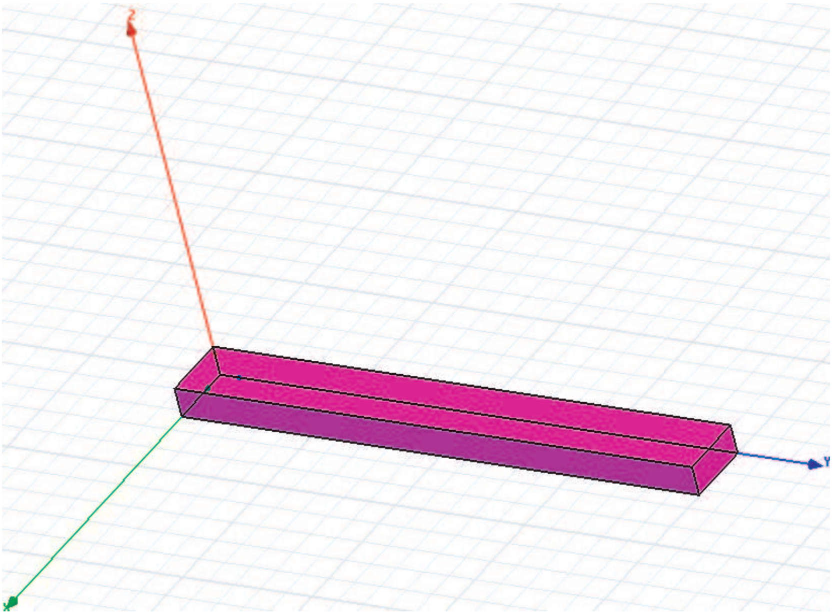


Figure 3.8: 3-dimensional representation of the waveguide

simulation was to gain experience in using the software effectively. At this point the proposed waveguide dimensions were not known. Figure 3.8 shows the 3D box drawn in HFSS.

The material of each of the panels of the box was specified as a perfect conductor and the inside the box was a vacuum. Each end of the waveguide was left open and set as a port, each of these two ports are where the excitation can be applied in the form of an oscillation.

In order to analyse the 3D model, the boundary conditions had to be defined. In this model each of the panels of the waveguide were set as perfect E boundaries. The excitations were the two ports at either end where a 10 GHz signal was propagated. Once the solve options have been set the waveguide can be analysed. Firstly the losses of the waveguide were found to be zero, this was expected because the sides were defined as perfect conductors and there is a perfect E-field. The magnitude of the E-field can be represented in the waveguide. Figure 3.9 on the next page shows the spread of the field at one end, looking down the waveguide.

This clearly supports the theory that the field is strongest in the middle of the waveguide and that it reduces as it gets closer to the sides. At the very edges the E-field is zero.

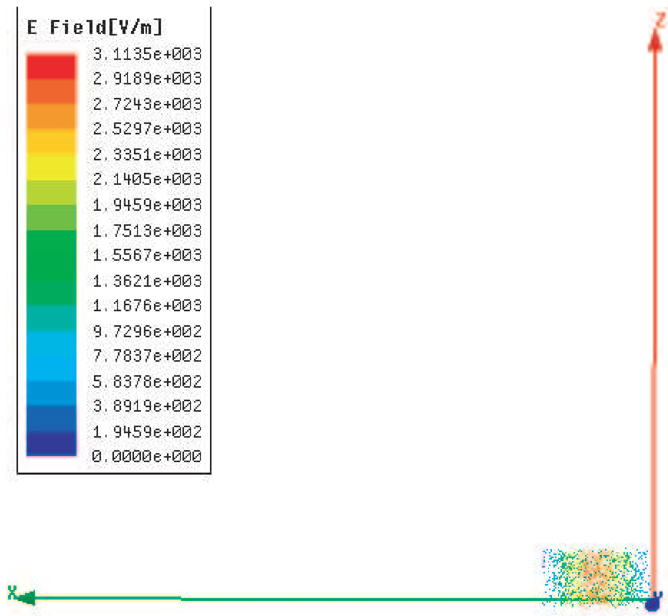


Figure 3.9: Magnitude of the E-field

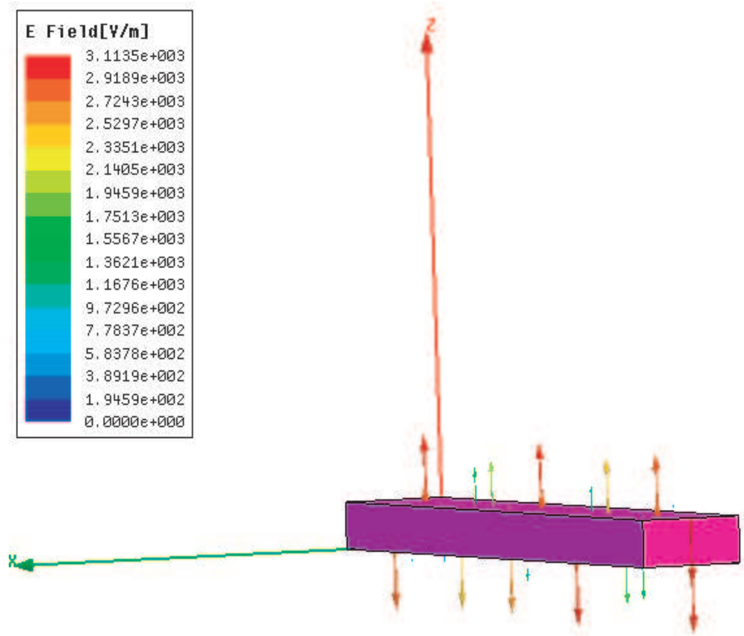


Figure 3.10: Vector plot of the E-field

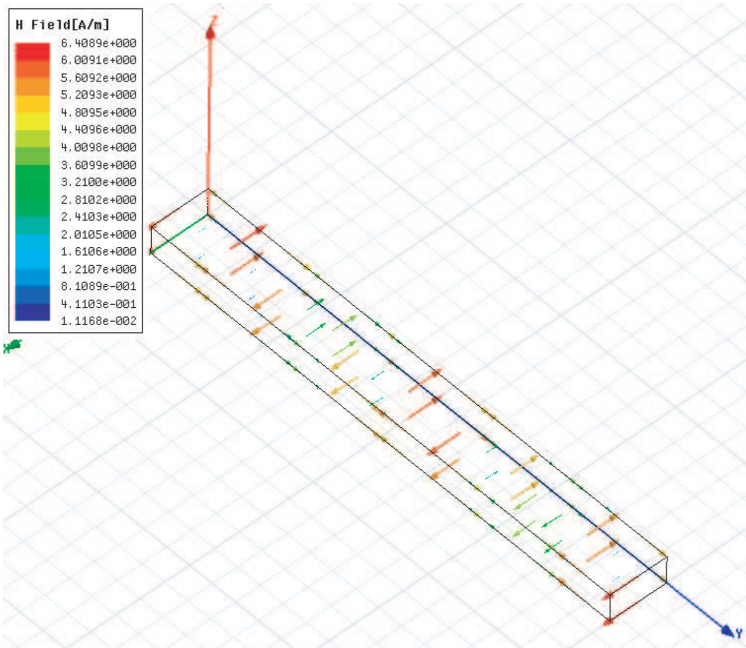


Figure 3.11: Vector plot of H-field

Another plot that can be generated is the vector plot of the E-field. As the wave travels down the waveguide the magnitude of the field will vary. A useful feature of HFSS is that this variation can be illustrated by animating the vector plot. When this animation is performed, the E-field can be seen to increase and decrease at a particular point as the wave propagates down the waveguide. Figure 3.10 on the preceding page is a screenshot of the vector E-field plot.

The vector plot of the H-field (magnetic field) can also be seen in HFSS, Figure 3.11 shows this. This plot can also be better illustrated with the animation feature as the field can be seen changing as the wave propagates horizontally along the waveguide. By comparing figures 3.10 and 3.11, the simulation proves that the E and H-fields are at right angles to each other.

The simulations conducted for this basic waveguide have given an insight into the many features that HFSS offers. The simulations have also clearly illustrated and proven much of the theory known by the team about waveguides and the effects on the wave inside it. This has provided a useful platform in order to simulate more thoroughly the proposed waveguide design.

3.3.3 Proposed simulations

The planned simulations for the project are to simulate the waveguide with the radial line transformer and backshort. The waveguide dimensions are now known but the radial line transformer is yet to be designed, once the design of the radial line transformer is achieved, the simulations can begin, in preparation for the practical tests. Once the 3D representation of the final system has been created it will be possible to investigate the effects of a wave travelling down the waveguide. Also the simulations will reveal whether any of the harmonics are leaking back up the radial line transformer. The most difficult 3D model to be designed will be the radial line transformer because of the succession of discs around the central pin, but this shape is definitely possible to achieve using HFSS. The discs of the radial line transformer occupy a certain amount of space in the waveguide and therefore the speed of the wave will be affected, this can also be simulated and investigated. To confirm that the waveguide is behaving correctly the distance between the guide wavelength and the 1st and 2nd harmonic can be measured. Also the Gunn diode can be partially simulated as an internal port can be added that generates a current, the phase of the wave travelling down the waveguide at both harmonics gives an insight into matching devices together.

Once the single diode oscillator is successfully working the team will move on to designing and making the power combining oscillator. HFSS will be a useful tool in predicting the effects of placing a succession of diodes in a waveguide. Each of the diodes will affect the other and each will have its own radial line transformer. HFSS can be used to analyse each of the waves produced by the diodes and how they interact with one another. It is hoped that the project will benefit from using this simulation software and maximise the efficiency and performance of the oscillator.

3.4 Semiconductor materials

3.4.1 Available materials

An overview of Gunn diodes and the Gunn effect has already been outlined in section 3.1 on page 10. Gunn diodes can be made of various semiconductor materials. In order to progress with this project a choice of the material of the Gunn diodes to be used is necessary.

The materials used to produce Gunn diodes include Gallium Arsenide (GaAs) and Indium Phosphide (InP). Both these semiconductors use elements from

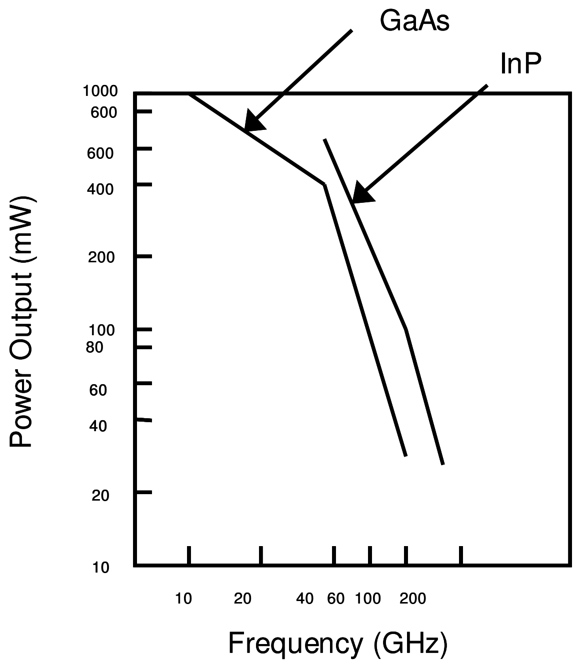


Figure 3.12: Power output of GaAs and InP at operating frequencies

groups III and V of the periodic table and their semiconductor properties are therefore related. Of these types of Gunn diodes, GaAs is by far the most common type being produced and sold on a commercial basis. InP Gunn diodes are only produced by a very small number of manufacturers for specialist use.

3.4.2 Differences

Although GaAs and InP are very similar, there are differences that make the choice of material an important one. Figure 3.12 shows a sketch of the possible power output of both types of diode up to their maximum oscillation frequency.

GaAs Gunn diodes oscillate at a fundamental frequency which is much lower than that of InP Gunn diodes. Therefore to show a comparison of the power outputs over the same frequencies, the power output at the second harmonic of the GaAs diode is shown. The power output of the InP diode is shown operating at its fundamental frequency.

From this graph it can be seen that InP Gunn diodes can operate at a fun-

Table 3.1: Gunn diode life spans: GaAs vs InP

(a) Maximum safe temperature at support

Semiconductor	Maximum Temperature at support
InP	60°C
GaAs	75°C

(b) Mean time to failure when operated above the maximum safe temperature

Semiconductor	Mean time to failure at 85°C
InP	2500 hours
GaAs	6000 hours

damental frequency higher than the second harmonic frequency of the GaAs device. The maximum power output of the InP Gunn diodes is greater than the GaAs devices when operating at the same frequency.

In this project, the designed device will be operated in the W-Band with high power outputs, this graph suggests the use of InP Gunn diodes because of their apparent better performance over GaAs Gunn diodes.

3.4.3 Life span

Tests on Gunn diodes made of the two materials have been performed by Thompson-CSF (Langheim, Francois & Liabeuf 1999). Their research highlights the two important characteristics of the diodes. Table 3.1 shows the maximum safe operating temperature and mean time to failure of Gunn diodes of the two semiconductors.

It can be seen that GaAs Gunn diodes have a much longer life span than InP Gunn diodes. GaAs diodes remain undamaged working up to higher temperatures than InP diodes. It is also noted that InP material is more temperature dependant and brittle than GaAs.

3.4.4 Second harmonic

Extracting the second harmonic from a Gunn diode oscillator, so producing a second harmonic oscillator, is not considered much more difficult than pro-

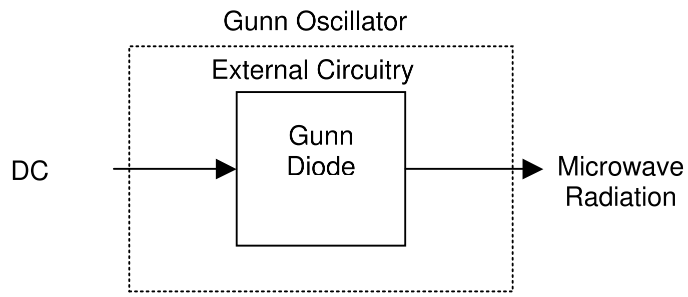


Figure 3.13: Block diagram of the Gunn oscillator

ducing a fundamental frequency oscillator. With this in mind and careful consideration of the arguments presented here, the team have decided that GaAs Gunn diodes should be used because of their high availability and good operating properties.

3.5 Waveguide and planar circuits

3.5.1 Introduction

When a DC bias is applied to the Gunn diode it produces a microwave signal; the input to the Gunn diode is the DC bias and the output is the microwave radiation. There is circuitry around the Gunn diode that enables the diode to produce a stable microwave output signal; this circuitry is known as a Gunn oscillator, as shown in figure 3.13. The Gunn oscillator is usually a sub-system of a larger system, for example an automatic cruise control (ACC) system. The output of the Gunn oscillator sub-system is the input to the next sub-system. The microwave radiation, the output of the Gunn oscillator, needs to be constrained and transferred to this next sub-system. There are two circuit configurations that can be used to transfer the microwave signal from the Gunn oscillator to the next sub-system: a planar circuit or a waveguide circuit. This circuit configuration also houses the Gunn oscillator as well as constraining and transferring the output microwave signal, as shown in figure 3.14 on the facing page, the planar or waveguide circuit is shown shaded.

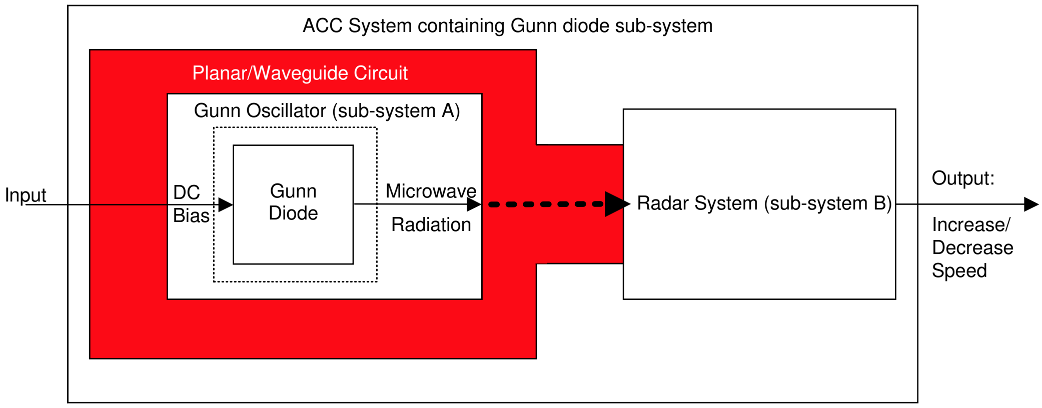


Figure 3.14: Illustrator of planar and waveguide circuits

3.5.2 Introduction to planar

The planar circuit configuration is a 2-dimensional circuit. The microwave device, the Gunn diode is placed on a flat piece of substrate and tuned with microstrip transmission lines and capacitive and inductive elements. The microstrip transmission lines are usually two thin strips of metal placed either side of an insulating surface; they act in the same manner as transmission lines. The microwave signal is transmitted along the microstrip transmission line (Holzman & Robertson 1992).

There are advantages and disadvantages of using the planar circuit configuration. The advantages are that the planar circuit is cheap when mass manufactured, so the configuration is suitable for system of which many are built. The circuit is small and light since it is a printed circuit board (PCB). The circuit is relatively easy to design because the modelling of the circuit is relatively simple.

The disadvantages of the planar circuit are that the quality factor (Q) of the circuit is low; this means that the power losses of the output signal are high and the signal degrades quickly because of attenuation, which is absorption of the signal. Microwave signals are attenuated by many mediums, including air, water and water vapour. The planar circuit is heavily affected by changes in external conditions including temperature changes. The Gunn diode dissipates a huge amount of heat; the planar circuit is a poor heat sink. The planar circuit does not allow any tuning of the frequency of the output signal.

3.5.3 Introduction to waveguide

The waveguide circuit configuration is a 3-dimensional circuit. The Gunn diode sits inside a hollow metal cavity inside of which the microwave signal propagates (Baden Fuller 1979). The circuit is tuned by a number of capacitors and inductors in a configuration known as a radial-line transformer (see section 3.6). The metal walls of the cavity constrain the microwave signal by reflecting it, enabling the signal to propagate freely in the desired direction.

The advantages of the waveguide circuit are that the quality factor (Q) is high; the power losses of the output signal are low since the walls of the waveguide are metal, which is a very low attenuation medium and reflects most of the signal. The waveguide acts as a heat sink and efficiently dissipates most of the heat from the Gunn diode. The waveguide circuit allows some tuning of the frequency of the output signal by altering a number of components, including moving the sliding backshort.

The disadvantages of the waveguide are that the waveguide is costly to manufacture; it is a metal box that is more expensive to purchase and machine than a PCB, though as the desired frequency of the output signal increases the magnitude of the box decreases. Modelling of the waveguide is difficult because modelling the interaction of the electromagnetic fields is complex.

3.5.4 Chosen circuit configuration

The aim of the project is to provide a high power, high frequency output signal. The characteristic of the output that is affected most by the choice of circuit configuration is the power. The planar circuit has a low quality factor so power loss is high, but the waveguide circuit has a high quality factor and power loss is low. Because of this relationship the waveguide circuit configuration has been chosen for the project.

3.5.5 Waveguide circuit

The waveguide is a hollow metal pipe that, under certain conditions, will allow electromagnetic radiation to propagate freely along the inside of it. The metal walls on the inside of the waveguide act as the boundaries for the wave. The boundary condition is that the metal acts as a perfect conductor, this is for simplification, though no metal is a perfect conductor but this is a reasonable approximation (Baden Fuller 1979).

In part (a) of figure 3.15 on the next page, a wave is shown to be incident on a perfect conducting metal wall at an angle of $\theta°$ and the maximum positive and negative peaks of the electric field are shown in red and blue. The electric field peaks are perpendicular to the front of the propagating wave. These peaks are a half wavelength ($\frac{\lambda_0}{2}$) apart, where λ_0 is the wavelength of the wave in free space. No charge can reside on a perfect conductor boundary; so the metal wall has no charge on it. Because no charge can reside on this wall all of the electric field is reflected by the wall, the hashed red and blue lines illustrate this. There are points where the peaks of the electric field intersect, between point A and B it can be seen that the opposite peaks of the field intersect, and the resulting electric field along this line is $0\,\mathrm{V\,m^{-1}}$.

Since the electric field along this line is $0\,\mathrm{V\,m^{-1}}$, a second perfectly conducting metal wall can be place here without affecting the wave pattern. A waveguide has now been produced, as shown in part (b) of figure 3.15. In the middle of the waveguide a standing wave of the electric field is produced, this wave is a sinusoid. The peaks of the wave are a half wavelength ($\frac{\lambda_g}{2}$) apart, where λ_g is the wavelength of the electric field inside the waveguide. The distance between the waveguide walls is b, which is the width of the waveguide (Baden Fuller 1979).

Equations 3.5 to 3.7 express the waveguide:

$$b = \frac{n\lambda_0}{2\sin\theta} \tag{3.5}$$

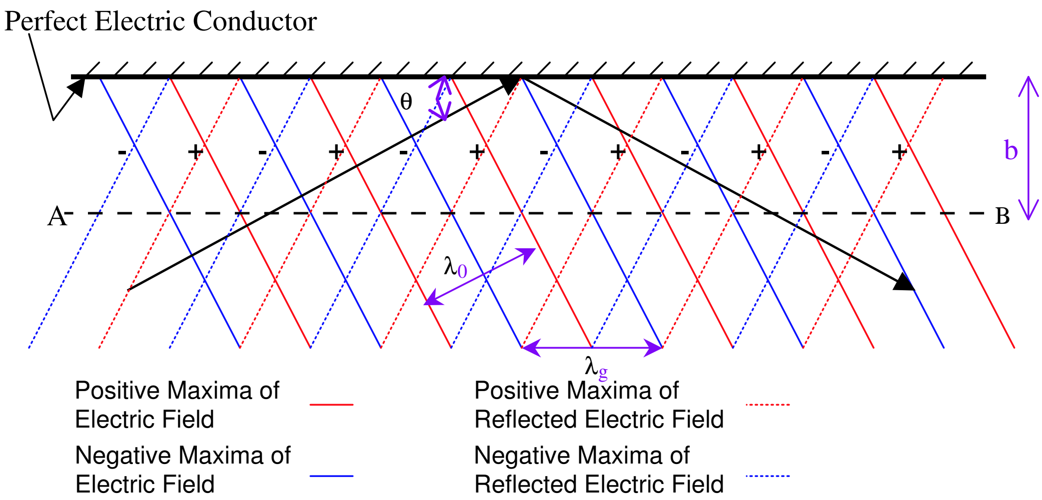
$$\lambda_0 = \lambda_g \cos\theta \tag{3.6}$$

$$\lambda_0 = \frac{c}{f} \tag{3.7}$$

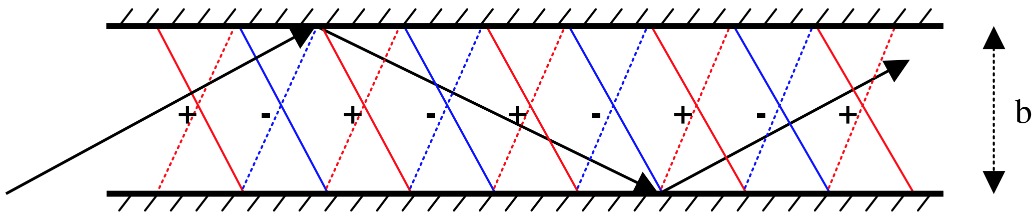
Where:

b	Width of waveguide.
n	An integer ($n \in \mathbf{N}$).
λ_0	Wavelength in free space.
θ	Angle at which wave is incident upon waveguide.
λ_g	Wavelength in waveguide.
f	Frequency.
c	Speed of light.

Using figure 3.15 these equations graphically reasoned.



(a) A propagating wave is incident upon the metal wall at an angle, illustrated by the electric field lines of the wave, which are perpendicular to the wave



(b) Wave propagating inside a metal waveguide

Figure 3.15: Propagating waves

3.5.6 Cut-off Conditions

The dimensions of the waveguide affect which waves can be propagated along the waveguide, dependant upon the frequency of the wave. There is a frequency named the cut-off frequency (f_c), (which corresponds to the cut-off wavelength, λ_c), any wave whose frequency is below this point cannot propagate down the waveguide.

If the width of the waveguide is such that

$$b = \frac{n\lambda_0}{2} \tag{3.8}$$

then $\theta = 90°$ and $\lambda_g = \frac{\lambda_0}{\cos\theta} = \frac{\lambda_0}{0} = \infty$.

From part a of figure 3.15 it can be seen that the wave will not propagate down the waveguide, instead it will be reflected back and forth between the walls of the waveguide. This is known as the cut-off condition and under these conditions the wave is not propagated.

From equations 3.7 and 3.8, the cut-off frequency (f_c) and wavelength (λ_c) can be calculated as in equations 3.9 to 3.11:

$$f_c = \frac{nc}{2b} \tag{3.9}$$

$$\lambda_c = \frac{c}{f_c} \tag{3.10}$$

$$\lambda_c = \frac{2b}{n} \tag{3.11}$$

Equations 3.5 and 3.7 can be combined to eliminate θ:

$$\lambda_g = \frac{\lambda_0}{1 - \left(\frac{n\lambda_0}{2b}\right)^2} \tag{3.12}$$

and substituting in λ_c gives:

$$\lambda_g = \frac{\lambda_0}{1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2} \tag{3.13}$$

Equation 3.13 is often rewritten as equation 3.14 (Baden Fuller 1979):

$$\frac{1}{\lambda_c^2} + \frac{1}{\lambda_g^2} = \frac{1}{\lambda_0^2} \tag{3.14}$$

3.6 Radial line transformers

3.6 Radial line transformer

The radial line transformer is a critical part of the circuit as it provides biasing for the Gunn diode. It can also be called the:

- Resonant cap/disc.
- Coaxial circuit.
- Coaxial bias line.
- Bias pin.

It is a small pin that has a voltage applied to it so that the DC input can be converted into microwave power using the Gunn diode. The radial line transformer consists of a filter circuit and a disc at the lower end of the pin that sits on top of the Gunn diode. The dimensions are extremely critical and are determined by the desired frequency of operation. The radial line transformer is typically fabricated using brass.

Every dimension of the radial line transformer affects the operating frequency and removing even a thin amount of material will result in a change in the frequency. The filter part of the circuit is made up of inductors and capacitors, their values can be calculated. The filter circuit usually remains fixed once fabricated but the resonant disc may require adjustment to its size to optimise the efficiency of the oscillator. This requirement to alter the disc's size may be due to inaccuracies in the fabrication of the pin as a result of its small size. For instance the thickness of one of the discs may be required to be 0.2 mm, but this value of the manufactured pin will not be exact. When the machined pin is placed in the circuit it can be tested and its dimensions may be altered to achieve better performance. For this reason it is better to make the pin's dimensions slightly larger than the specified values so that, if necessary material can be turned off on a lathe.

Figure 3.16 on the facing page (Haydl 1982) illustrates the number of variables that can affect the frequency. Each of these dimensions must be calculated.

The filter circuit comprises of a succession of discs. The discs act as capacitors and the thinner poles, between the discs, act as inductors (because the current is squeezed through a small area). The gap between the discs and the housing

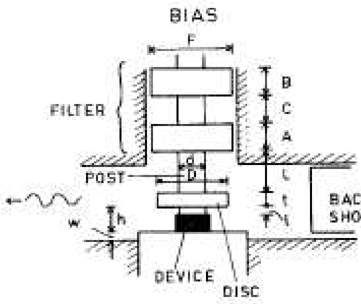


Figure 3.16: Gunn oscillator with radial transformer

of the waveguide (which is grounded) must be minimal without resulting in contact between the disks and waveguide. To ensure there is no contact, an insulator is placed around the radial line transformer; this small gap will act as a good capacitor.

Figure 3.17 (e2v Technologies 2003*c*) shows how the filter circuit looks in terms of components.

The resonant disc diameter and thickness is of great importance as it is situated directly on top of the Gunn diode. The disc diameter, d inches, can be calculated as equation 3.16, by using Equation 3.15, the target fundamental frequency for the project, f_0, is 43.5 GHz (in order to give 87 GHz at the 2nd harmonic). (Ondria 1985):

$$d = \frac{6.922}{f_0} \tag{3.15}$$

$$\begin{aligned} d &= \frac{6.922}{43.5} \\ &= 0.159\,\text{inches} \\ &= 4.04\,\text{mm} \end{aligned} \tag{3.16}$$

This formula gives an approximate idea of a value for the disc diameter. At this stage in the project the necessary theory has not been applied to determine the dimensions of the radial line transformer. Once the values of the capacitors and inductors are decided the dimensions of the filter circuit can be reached by calculating the capacitance per unit length of brass. It was suggested by Engineers at e2v, that the disk diameter should be within the range of 2.15-2.2mm.

Once the values of the radial line transformer have been decided, using theory from books, papers and recommendations from the Project Supervisors and

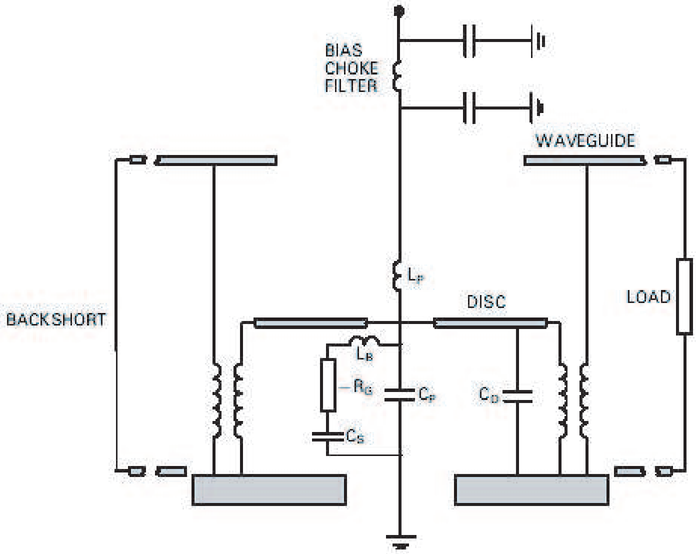


Figure 3.17: Radial transformer circuit

e2v Engineers, the radial line transformer can be simulated using the HFSS software package. This simulation will be useful to observe whether the radial line transformer is behaving properly and whether any energy leaks up the pin during operation.

Once the values have been verified the radial line transformer will be machined and can be tested in the circuit. It is unlikely that the first fabricated radial line transformer will function as desired, so a trial and error approach can be adopted. By measuring the operation of the oscillator the necessary changes can be made to the radial line transformer, a smaller diameter radial disc increases the frequency and a larger diameter radial disc reduces the frequency.

It has been proposed that all of the components of the radial line transformer shall be made slightly larger than the calculated values. The radial line transformer will be fabricated by a machinist in the UMIST workshop, and needs to be ready for testing with the waveguide in mid-January. Early discussions have indicated that this may not be possible so another option is that e2v Technologies could machine the radial line transformer using technical drawings produced by the project team.

3.7 Commercial model testing

Two Gunn diode oscillators have been provided by e2v Technologies for use during this investigation. The first is a 91 GHz oscillator using a single GaAs Gunn diode in a rectangular brass waveguide operating at its second harmonic. The second is a 76 GHz oscillator using a single GaAs Gunn diode in a rectangular aluminium waveguide operating at its second harmonic.

By biasing the radial line transformer of the oscillator above some threshold, the Gunn diode enters its negative differential resistance region of operation3.1. The Gunn effect is described in the overview section 3.1 on page 10. Whilst the Gunn diode is biased in the negative differential resistance region the diode oscillates at a frequency determined by the Gunn diode, the geometry of the waveguide, the radial line transformer and position of the backshort. Provided the bias voltage maintains the diode within this mode of operation, any variations in the bias will also cause variations in the oscillation frequency. As the geometry of the oscillator at these frequencies is very small, inconsistencies in dimensions are almost unavoidable. By varying the bias voltage, fine tuning of the frequency may be achieved without the need for such accurate machining and mechanical adjustments.

3.7.1 Bias voltage vs frequency

The best procedure employed for investigating the voltage vs frequency characteristic is described below:

3.7.1.1 Equipment used

HP8562A Hewlett Packard Spectrum Analyser.

HP11970 Hewlett Packard External W Band 75–110 GHz mixer for spectrum analyser.

LT30-2 Farnell Instruments Linear Power supply 2×0–30 V DC variable. 2 A max.

DVM Digital volt meter.

Oscillator e2v Technologies.

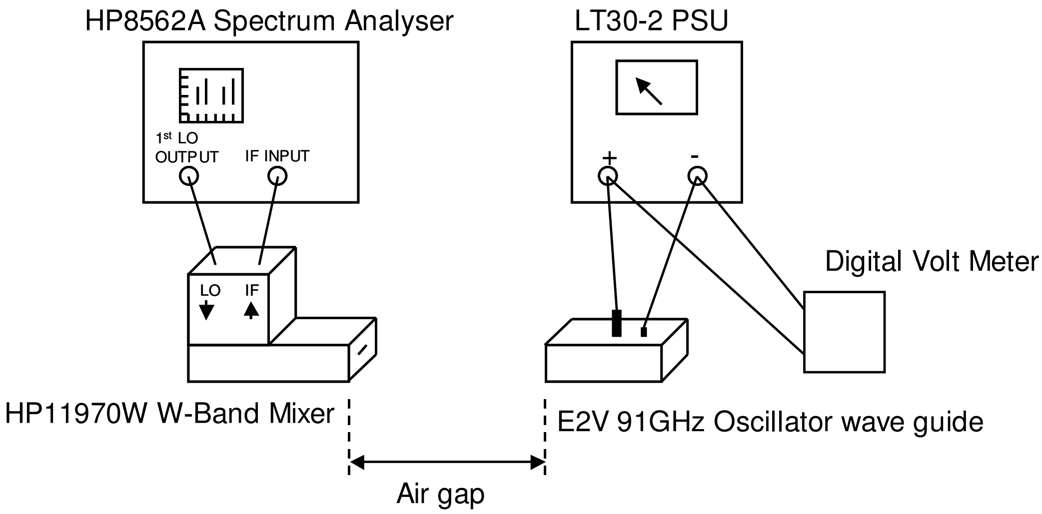


Figure 3.18: Spectrum analyser test setup

3.7.1.2 Test arrangement set up instructions

The general arrangement of the test equipment is shown in Figure 3.18.

3.7.1.3 Oscillator setup

1. Ensure that the oscillator waveguide is pointing away from the body to minimise radiation absorbed by the body. See the risk assessment on microwave testing depicted in figure B.3 on page 79.
2. Ensure that the power supply unit (PSU) is isolated at the main power feed.
3. Set the PSU output to 0 V and the current limit to about 1 A.
4. Connect the positive supply to the radial line transformer.
5. Connect the negative supply to the case pin (body of waveguide).
6. Set the PSU meter to show current output.
7. Connect a digital volt meter across the PSU to measure the bias voltages.
8. Line up visually the output of the oscillator waveguide with the input of the mixer waveguide leaving a gap of approximately 10 cm (which is

filled with air). This is to ensure that the power received by the mixer will not damage it.

3.7.1.4 Spectrum analyser setup

1. Connect the local oscillator (LO) cable between the spectrum analyser and mixer. Secure both ends with spanner.
2. Connect the intermediate frequency (IF) cable between the spectrum analyser and the mixer. Secure both ends with spanner.
3. Turn on the Spectrum Analyser
4. Select Mixer→"Ext" from the analyser front panel to allow operation with the external mixer
5. Select the "Full Band" soft key from the on screen menu and rotate the selection wheel to select W-Band operation.
6. Either the conversion loss calibration curve of the mixer should be entered manually into the spectrum analyser or an average value selected. The instructions for this are detailed in appendix C on page 80.

3.7.1.5 Test procedure

1. Turn on the PSU and ramp up the voltage gently until oscillation is detected by, and displayed on the spectrum analyser as a series of distinct peaks.
2. There is only one peak that corresponds to the exact frequency of oscillation, the other peaks are "images". In order to measure the correct frequency of oscillation, the correct peak must be selected. The peaks on the analyser can be individually selected with the cursor, by selecting "Peak Search" from the front panel. This selects the largest peak displayed. To move on to subsequent peaks the "Next Peak" soft key can be selected.
3. When a peak is selected with the cursor the "signal identity" function of the analyser is used. Select Mixer→"Ext" from the front panel. Then select the "Signal Ident" soft key followed by the "Sig id at mkr" soft key. After a few moments the analyser will display the frequency of the detected oscillation. If the peak selected is an image the analyser will also state this.

4. To get a more accurate reading of the oscillation frequency, provided that the real peak is selected, "Freq Count" may be selected from the front panel. This causes the LO to be re-calibrated against an internal crystal at the frequency indicated by the marker.

5. Record the value of the bias voltage where oscillation commenced together with the frequency of the oscillation.

6. Increase the bias voltage in steps of 0.1 V and record the frequency of oscillation at each bias voltage.

7. When the oscillation frequency stops increasing with the bias voltage the upper end the negative differential resistance region has been reached. Care must be taken because the Gunn diode can easily be destroyed when operated above this region, so the bias voltage must not be increased further.

8. Reduce the bias voltage in steps of 0.1 V and record the frequency until the oscillation ceases.

9. Plot a graph of frequency and bias voltage as the voltage is increased and decreased.

3.7.2 Results

Appendix C on page 80 shows the results of testing using the brass, 91 GHz wave guide assembly. The procedure is as described in section 3.7.1. It shows a positive relationship between bias voltage and the frequency of oscillation. By firstly steadily increasing the bias voltage from zero through the negative differential resistance region, and secondly decreasing the bias until oscillations cease, the frequencies of the oscillations have been recorded. Figure 3.19 on the facing page shows a graph of these results.

3.7.3 Observation and comparison

From the graph in figure 3.19 it can be seen that there is a positive relationship between the voltage and frequency of the oscillator. When the voltage is increased steadily from 0 V the oscillation only starts when the bias voltage reaches 3.8 V. As the voltage is reduced, however, the oscillation continues

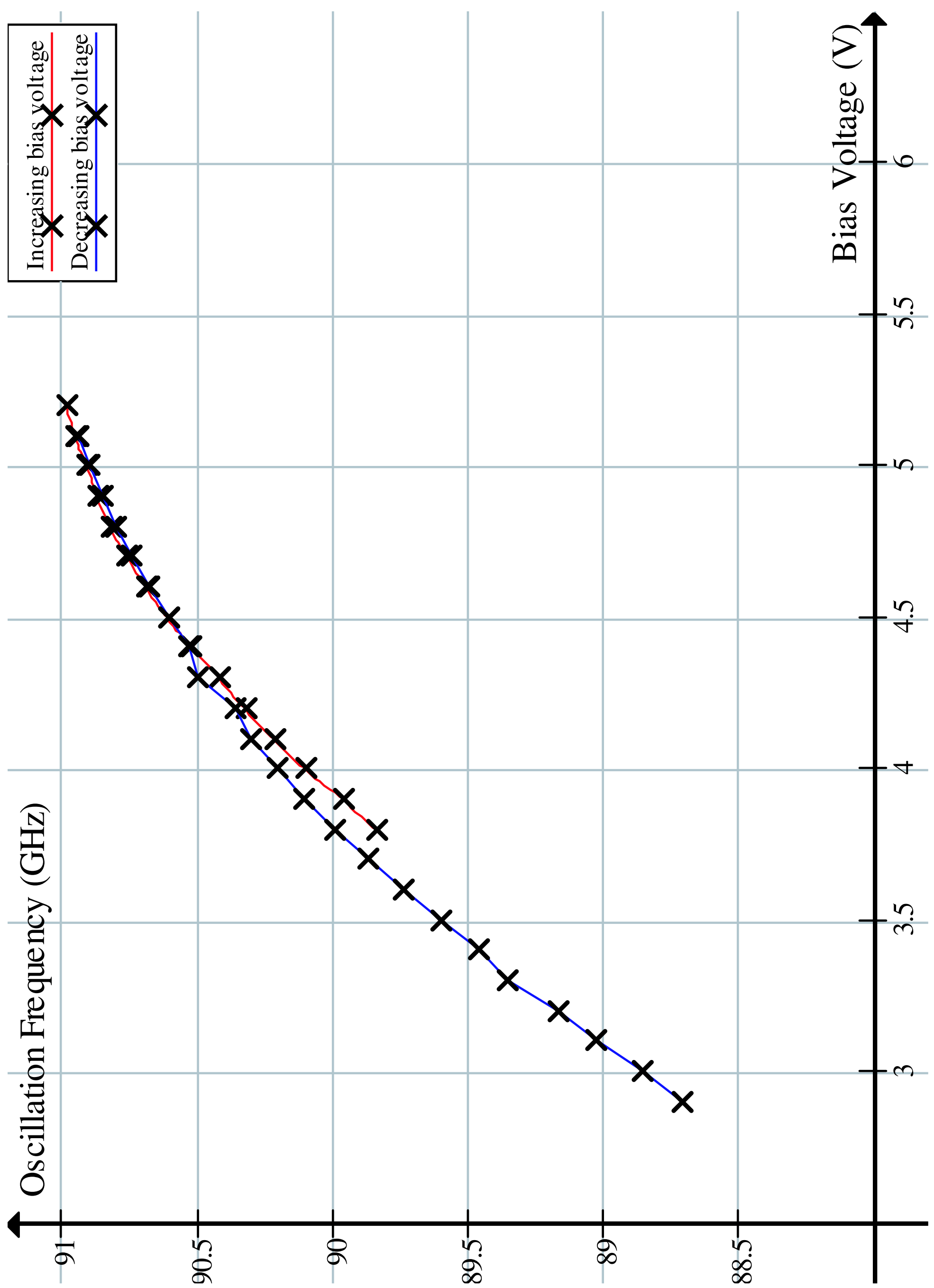


Figure 3.19: Gunn diode oscillator frequency vs voltage characteristics

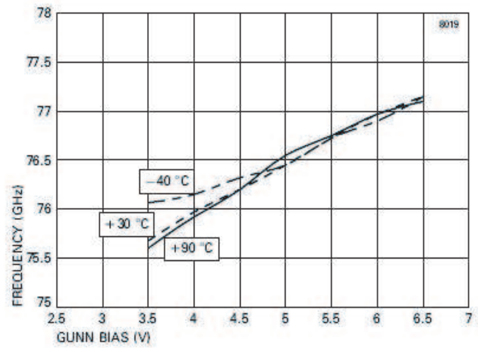


Figure 3.20: Frequency voltage characteristic of an e2v Gunn diode

to be stable until the bias voltage is reduced below 2.8 volts. It will be important to understand this characteristic hysteresis when attempting to bias the diodes in a power combining configuration.

Figure 3.20 shows the frequency voltage characteristic of a W-Band Gunn diode manufactured by e2v Technologies, the diode is set in a waveguide cavity and is operating around a centre frequency of approximately 76.5 GHz (e2v Technologies 2003*b*).

The graph of results in figure 3.19 shows that as the voltage is reducing, the frequency of oscillation is greater at low bias levels compared to when the voltage is being increased. Initial speculation was that this could be due to the temperature that the diode has reached after several minutes of operation. However, the graph provided by e2v Technologies in figure 3.20 shows that the frequency decreases as the temperature increases.

3.8 Harmonic operation

The Gunn diode produces a microwave output signal. The microwave signal is stable and oscillates at one frequency; this frequency is usually between 35 GHz and 70 GHz and is dependant upon a number of variables including the magnitude of the bias voltage and the components of the radial-line transformer. The frequency at which the diode oscillates is known as the fundamental frequency. The aim of the project is to produce an output signal with a frequency of 87 GHz. This required frequency is higher than the achievable range of frequencies with respect to the fundamental frequency of the diode; there is a way of achieving higher frequencies.

The fundamental frequency is the frequency at which the device oscillates, and is composed of higher frequency waves, known as harmonics. The greater the non-linearity of a signal, the more harmonics the signal comprises of, this was shown by the work of Fourier. The fundamental frequency is highly non-linear, and so it can be concluded that the signal is composed of many harmonics. The harmonics are integer multiples of the fundamental frequency. For Gunn diode operation, the fundamental frequency has the highest power; followed by the second harmonic, third harmonic etc. the power of each harmonic is less than the previous harmonic.

The second harmonic is twice the frequency of the fundamental frequency, 70 GHz to 140 GHz, the range we want to work in. This is shown in equation 3.17. The second harmonic can be extracted from the diode, and the other harmonics can be disposed of using filters.

$$f_{(2)0} = 2f_0 \tag{3.17}$$

3.9 Power combining

3.9.1 Reasons for power combining

The aim of the project is to obtain a high frequency, high power RF output signal. As the frequency of oscillation of Gunn oscillators increases, the active area (or transit region, 14) of the diode used within the device must be decreased. Several problems arise because of this. The first is that the active region can become smaller than a Gunn domain (Teoh, Dunn, Priestley & Carr 2002), thereby inhibiting oscillation.

One other side effect of this is that as the device size decreases, the power that can be dissipated by the device falls proportionally. If a device is expected to produce a 30 mW radio frequency power output at 3% efficiency, the device will be dissipating one watt of power, which will be dissipated as heat. With Gunn diode dimensions as low as 10 μm, it is clear that high RF power outputs from a single diode would “cook” the device very quickly.

This suggests that to achieve a high frequency, high power output signal, one Gunn diode may not be sufficient.

3.9.2 Methods

Other methods have to be found to produce high RF power outputs from Gunn diode based oscillators. One popular method for oscillators operating at the fundamental frequency is to combine the RF power of multiple oscillators (Adler 1946, Bae, Uno, Fujii & Mizuno 1998, Mortazawi & Itoh 1990*a*). Very little work has been carried out about power combining oscillators operating in second or higher harmonic modes (Barth 1981).

Various options are available for combining RF power from multiple oscillators. For planar circuits an arrangement such as a Wilkinson power combiner could be employed (Adler 1946). Since it has been decided, as described in section 3.5, that a waveguide circuit should be used, this is not a feasible option. The simplest and most common option is to combine the RF power in free space (Mortazawi & Itoh 1990*b*), or within a waveguide; within the waveguide is our chosen method (Eisele & Haddad 1998).

Various methods can be used for power combining in free space within a waveguide. The simplest method is to place a number of Gunn diodes in a row along the waveguide cavity (Eisele & Haddad 1998). Alternatively, multiple waveguide sections can be bolted together to mix the signals, such as combining at the first harmonic and tapping off the second harmonic power (Barth 1981), or using an overmoded waveguide and an array of other waveguides (Bae et al. 1998).

3.9.3 Oscillation locking

Whatever method of power combining is used, it is important to consider the relationship between the signals being combined.

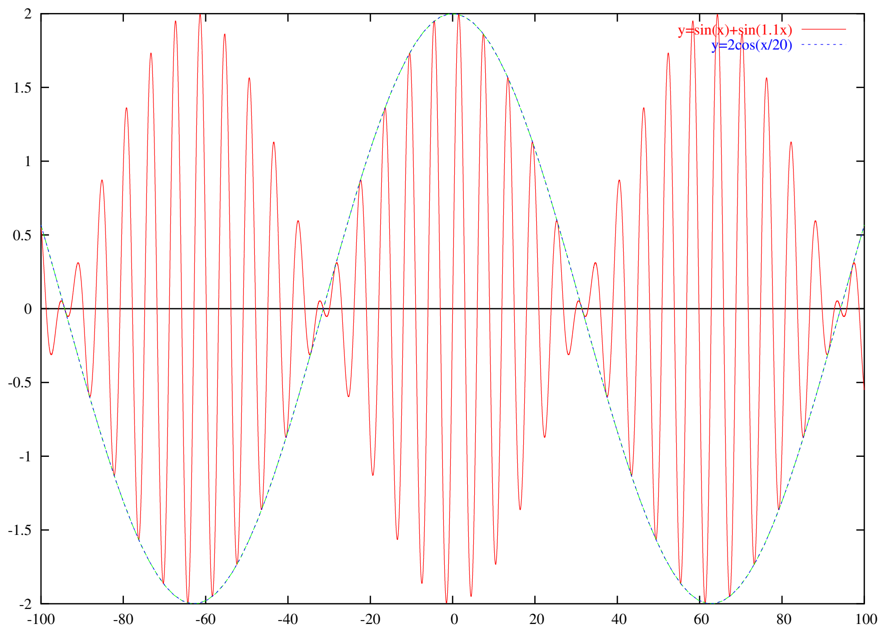
If frequency of the two signals is not completely in phase, a beat frequency is produced. Part (a) of figure 3.21 on the facing page illustrates this: the high frequency waveform shown is given in equation 3.18.

$$y = \sin(x) + \sin(1.1x) \tag{3.18}$$

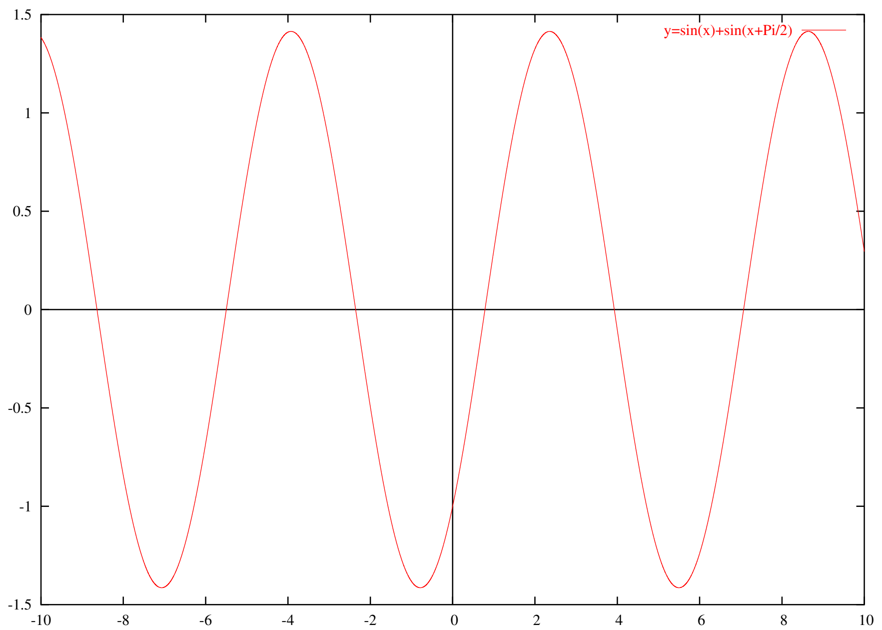
The envelope beat frequency is also shown on the graph. Equation 3.19 describes the envelope of the sinusoid.

$$\begin{aligned} y &= 2\cos\left(x \times \frac{\Delta f}{2}\right) \\ y &= 2\cos\left(\frac{x}{20}\right) \end{aligned} \tag{3.19}$$

If the phase of two signals being combined is not matched, the resulting signal will not have an amplitude equal to the sum of the two individual waveforms, this is illustrated in part (b) of figure 3.21 on the next page. The waveform



(a) Signals with mismatched frequencies



(b) Signals with mismatched phases

Figure 3.21: The results of power combining mismatched signals.

in part (b) has equation 3.20, which is equivalent to the combined waveform described by equation 3.21.

$$y = \sin(x) + \sin\left(x - \frac{\pi}{2}\right) \tag{3.20}$$

$$y = \sqrt{2}\sin\left(x - \frac{\pi}{4}\right) \tag{3.21}$$

This shows clearly that for maximum efficiency in a power combining arrangement:

1. The frequency of the two signals must match exactly.
2. The phase difference between the two signals must be exactly zero.

Our testing has shown that two different Gunn diodes, even from the same batch, placed in the same waveguide will oscillate at different frequencies (see section 3.7 on page 37 for more details). This is caused by slight variations in the fabrication processes for the devices, such as differences in diffusion temperatures or dopant distribution, for example. Even if the frequencies of two oscillators could be controlled very precisely, there could easily be non-zero phase differences between the individual oscillators.

Many current commercial systems requiring frequency and phase matched signals will use a phase locked loop to achieve this. With this arrangement, one reference signal and the signal from a voltage controlled oscillator are fed into a phase detector. The output of the phase detector is fed back to the voltage controlled oscillator (VCO) through a low-pass filter to remove unwanted harmonics. As long as the signals are sufficiently close to each other before locking, the two signals will be quickly drawn together to give zero phase and frequency differences.

3.9.4 Injection locking

Phase detectors cannot be used at the frequencies required for this project. Injection locking is used as an alternative method. Here, a fraction of the power generated by one oscillator is fed into the other oscillator. This causes the frequency and phase of the two oscillators to be pulled together within certain conditions (Adler 1946):

1. The frequencies of the signals are initially similar.

2. Enough power is passed between the oscillators.

3. Too much power is not passed between the oscillators.

The last point is important, as, if a large amount of RF power is incident upon an oscillator (i.e. the second oscillator), multiple solutions to the injection locking become possible, and the oscillators may lock to an unwanted mode.

These two principles of oscillation locking and injection locking can be partially combined. The frequency of oscillation of a Gunn diode is dependant on the bias voltage of the device, as confirmed by our testing (see section 3.7). Once the devices have successfully locked, the bias on the individual diodes can be adjusted to move their natural oscillation frequency towards the locked frequency, thereby increasing the power combination efficiency.

If multiple devices are placed in a waveguide designed to propagate only the second harmonic, the fundamental frequency, f_0, will be heavily attenuated over short propagation distances. The devices could, however, be placed so that enough of the power at f_0 from one diode reaches the other to allow for injection locking. The full power generated at $2f_0$ will be present at the output of the waveguide, as the guide will allow this frequency to propagate as normal.

3.9.5 Summary

Since this project requires more than the possible power output from a single Gunn diode, power combining must be employed. Power will be combined within a section of waveguide with diodes carefully spaced within. Injection locking will ensure the diodes oscillate at a common frequency and phase.

3.10 Thermal considerations

Due to the small size of the Gunn diode and the power that is involved, the device can become very hot. If this heat is not dissipated the diode will overheat causing it to fail. If the oscillator was implemented using planar techniques the heat dissipation would be an even greater issue but in this case the waveguide can act as a heat sink, other methods of removing heat are also required.

During practical tests undertaken in a laboratory it was noted that the brass waveguide becomes very hot and, if left on a bench, can take up to 45 minutes to cool down. This is a problem because after a short time the brass waveguide becomes too hot to touch. The heat must be removed to prevent overheating.

Thermal and electric circuits can be considered in an analogous manner; heat energy can be thought of as behaving like electric current and temperature rise as the equivalent of a voltage drop. The materials through which the heat energy flows have thermal resistance, which can be thought of as electrical resistance. The more heat energy that flows through a material, the greater the temperature rise across it is. Metals such as copper and aluminium have very low thermal resistance where as ceramics, plastics and air have relatively high thermal resistances. Therefore in the case of dissipating heat quickly away from the Gunn diode it is desirable to have a heatsink that has a low thermal resistance so that the heat will be dissipated at a high rate.

There are various methods to achieve this, the ones considered for this project are:

- Metal heatsink.
- Water cooling.
- Air cooling (fan).

3.10.1 Heatsink

The metal heatsink is the most common form of heatsink used for electrical applications. The heatsink is usually a large piece of metal with a large surface area and a series of fins to maximise the amount of heat dispersed. The heatsink must be designed so that the heat can easily travel from the upper part of the heatsink that is in contact with the waveguide, to the fins where the heat dissipation takes place. The part of the heatsink that is in contact with the waveguide must be very flat in order to allow good thermal transfer. Even if the surface appears to be flat, there will still be small air gaps between the heatsink and the waveguide, therefore a thermal compound or a thermoconductive pad must be used. These heatsinks are relatively cheap, easy to buy and there is a large range of different types available offering various sizes and thermal properties.

3.10.2 Water-cooling

To water cool the waveguide it would be necessary to drill a hole in its base in order to pass water through it inside a pipe. Water-cooling is often avoided when electrical equipment is involved but when it is used the water must be de-ionised. Raw water has free ions and many dissolved substances, if there was a leak it could cause a safety risk and damage equipment. De-ionised water also is less corrosive to the brass waveguide. This method of cooling would be relatively easy to implement and would be very effective in dissipating the heat quickly. All the connections between pipes would have to be very carefully checked so that the risk of a leak is minimised. The heat capacity of water is large and due to the fact it is flowing through the waveguide and is re-circulated round the loop the heat can be removed efficiently. The loop would also require a pump to make the water flow.

3.10.3 Air-cooling

To air cool the waveguide would involve using a fan and blowing cool air over the heatsink. This method is used widely in PCs to cool chips and heatsinks. The fan would be implemented in conjunction with a metal heatsink because it is not feasible to blow air directly onto the Gunn diode, because it is encased in the brass waveguide. The fan cooling approach is the least efficient in terms of dissipating the heat because of the large thermal resistance of air.

3.10.4 Chosen method

To solve the heat dissipation problem it has been decided to use a combination of the above proposals. Firstly the waveguide will be mounted onto a metal heatsink with a thermoconductive pad. This solution is cheap and very easy to implement and will also be very effective. It has also been proposed that cooling shall also be achieved by drilling a hole on the bottom of the waveguide and passing de-ionised water through it. This approach will require care and planning in its implementation to ensure safety is upheld. Along with the metal heatsink this solution will provide a very effective heat dissipation system and should ensure the oscillator performs to a higher standard.

3.11 Test plan

This chapter outlines a guide to the tests to be performed on the single diode oscillator to be designed and built by the project team. Its is hoped that the tests carried out on the devices provided by e2v can also be carried out on the single device, to provide comparisons and a target performance.

3.11.1 Voltage Frequency Characteristics

Voltage-frequency measurements are an important part of the tests and an understanding of this relationship is essential for the design of a power combining Gunn diode oscillator. The centre oscillation frequency of a Gunn diode is defined geometrically. Dimensions such as the size of the resonant cavity, radial line transformer and back short affect this centre frequency to the extent that it is impossible to make two identical oscillators. It is therefore accepted, that there will always be minor differences and imperfections between devices.

By varying the DC bias voltage applied to the radial line transformer, it is possible to adjust the frequency of operation around the centre frequency. This avoids the need for mechanical adjustments in the oscillator assembly. No two oscillators will have the same centre frequency; therefore it follows that no two oscillators will have exactly the same voltage frequency relationship, though the relationship will be of the same form.

The test procedure for measuring the frequency-voltage characteristics of the oscillator provided by e2v Technologies is given in section 3.7 on page 37 together with the results of the test. This procedure can be used to take measurements of the single Gunn diode oscillator designed by the project team. The results obtained provide a reference for comparison.

3.11.2 Power measurements

The power output of a Gunn diode oscillator depends on the frequency at which the diode is oscillating. As the frequency is dependant on the bias voltage, it follows that the power output is also dependant on the bias voltage. This project is to design and build a power combining oscillator, so it is important that the output power of oscillators can be measured. In order to measure the power output of an oscillator the setup in figure 3.18 is required but with the addition of a waveguide attenuator connected directly between

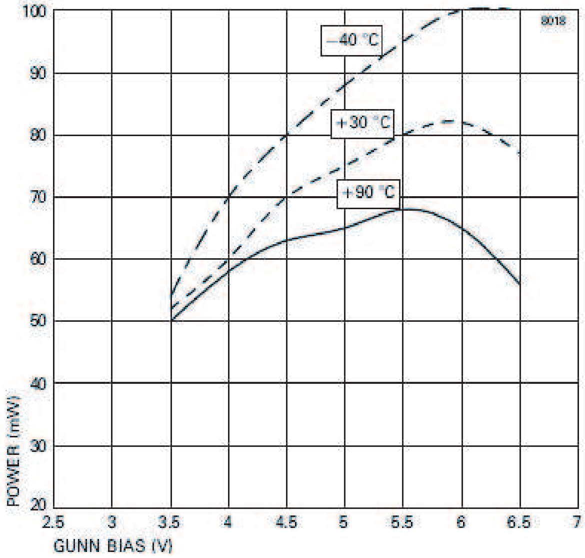


Figure 3.22: Typical power-frequency output of an e2v 76 GHz oscillator

the oscillator and the mixer to prevent damage to the mixer. The attenuation is known so the spectrum analyser can measure the output power of the oscillator. It is proposed that for accurate measurements, a power meter should be used since the spectrum analyser used in chapter 3.7 can have an error margin of up to 4 dBm. At the time of writing this report, an attenuator is not available to the team. Therefore, a method to calculate the approximate power output when the signal is transmitted across an air gap of a known length is being investigated. This method can be used by treating the oscillator as an antenna, the mixer as a receiver and calculating the percentage of the transmitted power that would be received if an attenuator was present.

Figure 3.22 shows the output of a W-Band Gunn diode manufactured by e2v that is set in a cavity operating around a centre frequency of approximately 76.5 GHz (e2v Technologies 2003*b*).

This characteristic shows the second harmonic power output. The use of the second harmonic is explained in chapter 3.8 on page 42. After power testing, a similar characteristic for both the e2v oscillator and the project teams design is sought so that comparisons can be made and if necessary, the design can be changed.

It is proposed that a test procedure for power measurements should be made, at first, the measurements can be taken approximately over an air gap of a known distance. Later, when an attenuator becomes available a more accurate test procedure will be developed. This procedure can then be used to measure the output of a power combining oscillator to prove its performance.

3.11.3 Fundamental frequency

As both, the oscillator provided by e2v Technologies and the oscillator designed by the project group operates at the second harmonic it would be useful to measure and compare the amount of power that is emitted from these devices at their fundamental frequencies. For an efficient second harmonic oscillator, the fundamental frequency power should be much less than the second harmonic frequency power.

The amount of power emitted at the fundamental can be measured in the same way as described in section 3.11.2 except that a U-band mixer would be required.

3.11.4 Phase noise

It has been advised by e2v Technologies that measuring the phase noise of the oscillators is important. e2V suggest that this should be approximately 75–80 dB Hz^{-1} at 100 kHz offset (Applied Radio Labs 2003).

It is proposed that an understanding of phase noise be gained and a test method developed.

3.12 Oscillator fabrication

This chapter deals with the manufacture of a prototype Gunn diode oscillator device. The reason for building this prototype is to learn how these devices are fabricated, using the precision engineering facilities at UMIST, as well for the team to familiarise themselves with the Gunn oscillator. In section 3.5 on page 28, the benefits of using waveguide over planar design were shown. One of the advantages of using waveguide is that it is relatively simple to design and easily tunable. An additional benefit is that the waveguide acts as a heatsink, so temperature problems can be reduced. In this chapter, an in-depth explanation of how the device was assembled is given.

3.12.1 Research

The inspiration for the initial design came from a journal paper (Barth 1981). The paper suggests that it is possible for a W-band (75–110 GHz) Gunn oscillator to be built containing three Gunn diodes which oscillate at the second harmonic frequency in the waveguide. It became apparent that high frequency Gunn oscillators are mostly built as second harmonic oscillators. At the start of this paper a design for a single Gunn diode was outlined. This single diode design three main components; W-band waveguide, Gunn diode housing and variable backshort.

The first waveguide is W-band which ignores the fundamental frequency and allows only the second harmonic to pass through. The Gunn diode housing has a waveguide output for the fundamental frequency in addition it incorporates a resonant biasing circuit which allows the frequency to be altered by changing the bias. The third part of the design is the backshort waveguide in the Q-band (30–50 GHz) which influences the magnitude of the fundamental frequency. The performance of this backshort is found to alter the oscillator performance between 15 GHz.

The paper also describes coalescing three Gunn diodes "in line" using a design based on the first design, the single diode oscillator. The results looked exceptionally promising giving a frequency of 90 GHz with a power output of 60 mW. This method of design will be investigated for future designs.

3.12.2 Aims

The reasoning for building a single device oscillator was because it appeared to be the most logical step to begin this project. The main aims were:

- To learn how these devices are manufactured.
- Use precision engineering for waveguide construction.
- To gain an understanding of how these devices operated.
- Make use of this device for a variety of tests.
- Verify the second harmonic design works.
- Have it as a pre-development model before combining four Gunn diodes.

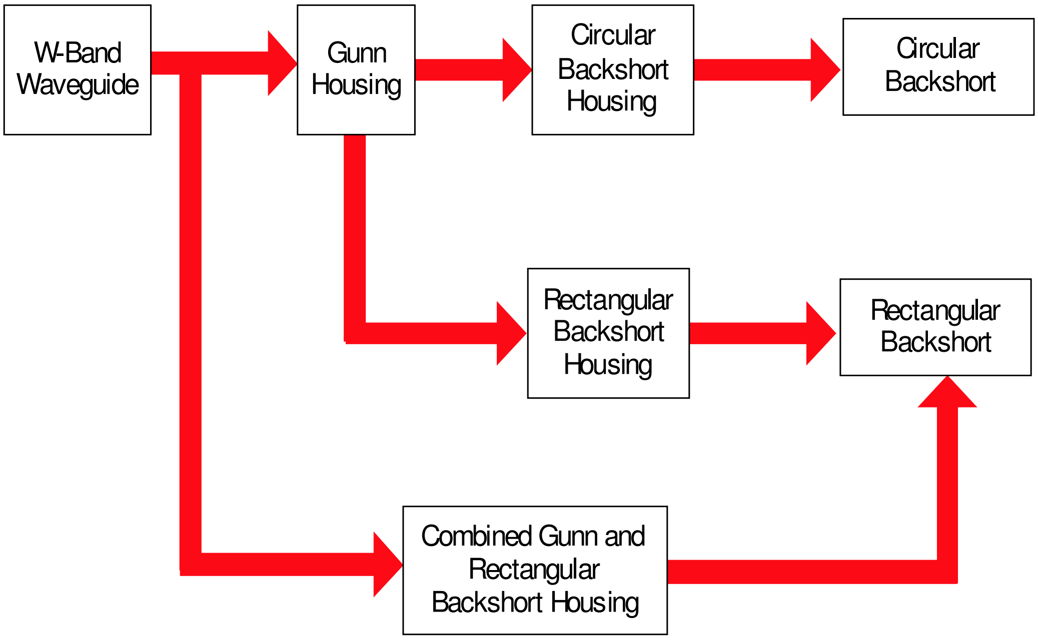


Figure 3.23: Various combinations of building a single Gunn device

3.12.3 Design

The pre-development model is made up from three major parts; W-Band waveguide output, Gunn diode housing and the variable backshort both set at the Q-Band. The device can be made by one of three different approaches as shown in figure 3.23.

Copies of the various mechanical diagrams of how each device can be constructed are included as appendix D on page 84. All the systems comprise of a W-band waveguide. From this the design can be split into either having the Gunn diode mounted alone or combined with the backshort. The remaining choice is to use either rectangular or circular waveguide. The rectangular type of waveguide will probably the best choice due to its simplicity. Alternatively the Gunn diode housing can be combined with the rectangular backshort, this will reduce any coupling losses and be relatively easy to machine.

The combined Gunn and backshort device was chosen, which is discussed in detail below.

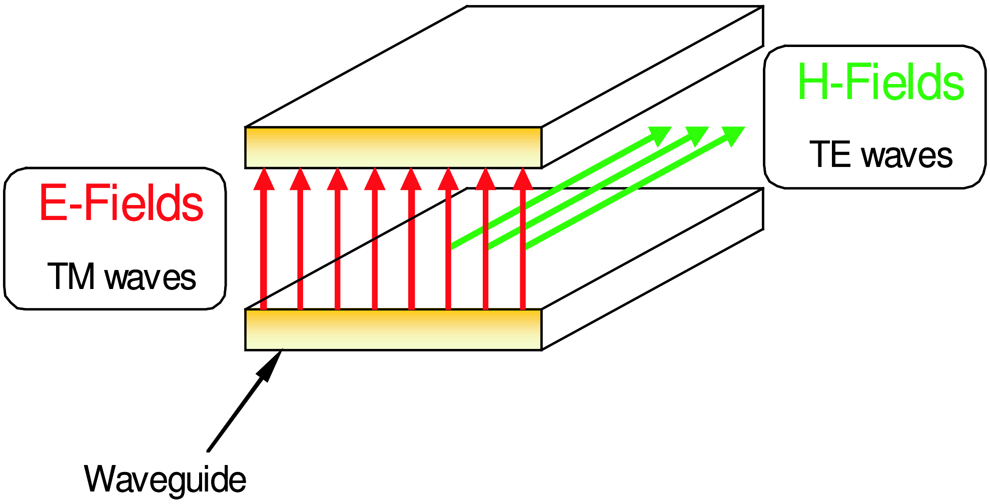


Figure 3.24: E and H field boundary conditions

3.12.4 W-Band waveguide output

A waveguide for a 1 MHz would be about 300 metres wide since the waveguide width is inversely proportional to the frequency of the wave which the guide propagates. This makes the use of waveguides at frequencies below 1000 MHz increasingly impractical. Fortunately the specification for this design is a frequency of 87 GHz making the physical dimensions of the waveguide minute but realistic to fabricate. The hollow rectangular waveguide can propagate TE waves but it has a cut-off frequency, below this propagation is not possible. The energy travelling down a waveguide is similar, but not identical, to electromagnetic waves travelling in free space.

The difference is that the energy in a waveguide is confined to the physical limits of the waveguide. A condition, known as the boundary conditions, must be satisfied for energy to travel through a waveguide. For an electric field to exist at the surface of a conductor, the electric field must be perpendicular to the conductor, this is called the E-fields boundary condition which are the traverse magnetic (TM) waves. The H-fields boundary conditions are the traverse electric (TE) waves. These form a closed loop perpendicular and parallel with the conductor, both types of waves TM and TE are shown in figure 3.24.

Both E and H fields must exist at the same time within the waveguide for the boundary conditions to be satisfied. The E and H fields are perpendicular

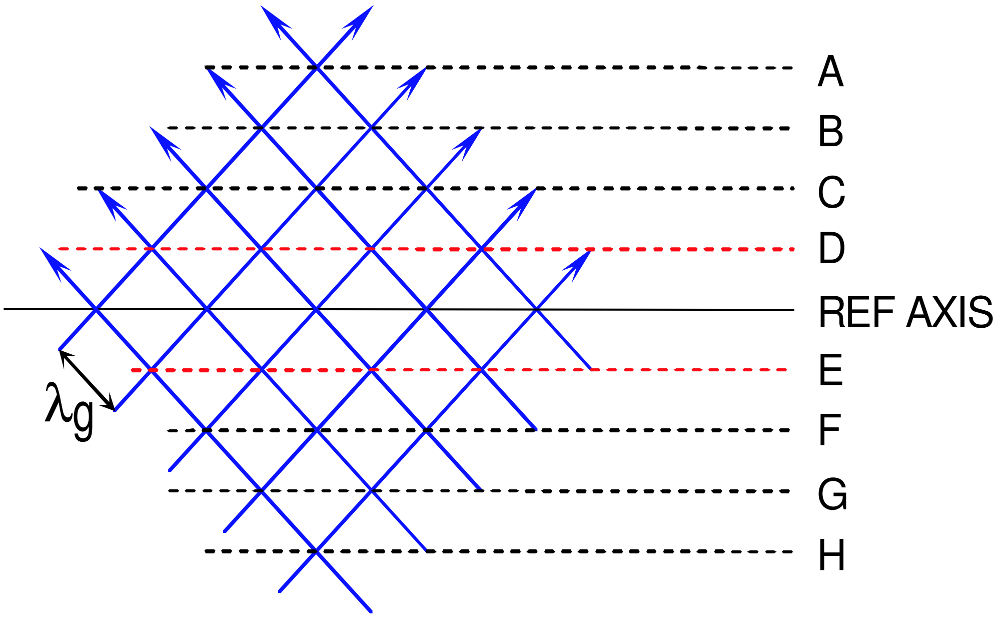


Figure 3.25: Wave-fronts combined

to each other, a simple analogy to establish this relationship is to use the right-hand rule for electromagnetic energy.

The combined E and H fields form a "wave-front" along the axis of the alternate negative and positive peaks at half-wavelength intervals. The angle is the direction of travel of the wave with respect to some reference axis.

If a second wave-front differing from the first only in the direction of travel is also present at the same time, a wave resulting from the two wave-fronts is formed. Both wave-fronts add at all points on the reference axis and cancel at half-wavelength intervals from the reference axis. Therefore, alternate additions and cancellations of the two wave-fronts occur at the reference axis shown in figure 3.25.

Two conductive plates are put at point D and E in figure 3.25, this will create the E field boundary condition, the H field boundary condition are also satisfied by the plates. The dimensions of the plates are given by a and b in figure 3.26.

Figure 3.26 on the next page demonstrates the waveguide operating in TE_{10} mode of operation which is the easiest mode to produce. It is called the dominant mode. Operation in the dominant mode will have dimension a set at a minimum of the wavelength of the transmitted wave. The dominant

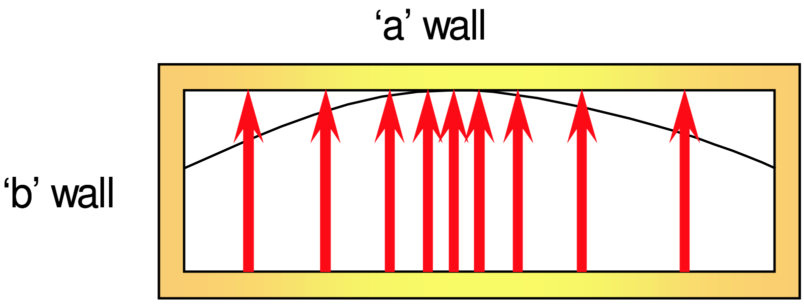


Figure 3.26: Dimensions of waveguide, TE_{10} mode

mode is selected is because it has the lowest cut-off frequency compared to the other modes.

Applying this theory to our construction, the waveguide needs to propagate the second harmonic frequency of 87 GHz. This frequency lies in the W-Band region, using standard rectangular waveguide data indicates that the required inside diameter should be 2.54×1.27 mm (Pozar 1998). These measurements refer to a standard type of waveguide WR-10 or WG-27 (UK equivalent). With this information the cut-off wavelength can be calculated as shown in equations 3.22 to 3.25:

$$\lambda_c = \frac{1}{\sqrt{\left(\frac{m}{2a}\right)^2 + \left(\frac{n}{2b}\right)^2}} \tag{3.22}$$

$$\lambda_c = \frac{1}{\sqrt{\left(\frac{1}{2\times0.00254}\right)^2 + \left(\frac{0}{2\times0.00127}\right)^2}}$$

$$= 5.08\,\mathrm{mm} \tag{3.23}$$

$$f_c = \frac{c}{\lambda_c} \tag{3.24}$$

$$f_c = \frac{3 \times 10^8}{5.08 \times 10^{13}}$$

$$= 59.1\,\mathrm{GHz} \tag{3.25}$$

Where:

c Velocity of light in free space ($m\,s^{-1}$).

m, n Mode of operation.

These calculations show that below the frequency of 59.1 GHz the wave will not propagate. The length d of the waveguide can now be calculated as shown in equations 3.26 to 3.31:

$$\lambda_0 = \frac{c}{2f_0} \tag{3.26}$$

$$\lambda_0 = \frac{3 \times 10^8}{87 \times 10^9}$$

$$= 3.45\,\text{mm} \tag{3.27}$$

$$\frac{1}{\lambda_0^2} = \frac{1}{\lambda_g^2} + \frac{1}{\lambda_c^2} \tag{3.28}$$

$$\frac{1}{\lambda_g^2} = \frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2} \tag{3.29}$$

$$\frac{1}{\lambda_g^2} = \frac{1}{3.45^2} - \frac{1}{5.08^2}$$

$$= 22.05 \times 10^{-6} \tag{3.30}$$

$$\lambda_g = 4.70\,\text{mm} \tag{3.31}$$

Therefore the length of the first waveguide flange must be 4.70 mm. With this information a waveguide flange can be manufactured. The type being designed is called the cover-to-cover flange which can be bolted together with other flanges to form the contacting joint. A second alternative is a choke-to-choke flange which basically incorporates a radial transmission line between the two flanges, this configuration will help in returning any leakages back into the device. Due to time limitations the cover-to-cover flange was preferred, if any losses are a problem the next design could incorporate the choke-to-choke design instead.

Having a smooth plane with a surface finish of 3 μm, reduces reflections and resistive losses at the joints between the waveguides. Also holes which are intended for alignment purposes shall be precision drilled. The magnitude and spacing of these alignment holes are defined by a British Standard (BS60154-2 1997). The flange being made will conform to these measurements with a tolerance of ± 0.05 mm. Having all components manufactured to these dimension should make testing easier since other device can be easily attached to this uniform flange. Figure 3.27 on the facing page shows a drawing of the waveguide with the dimensions calculated.

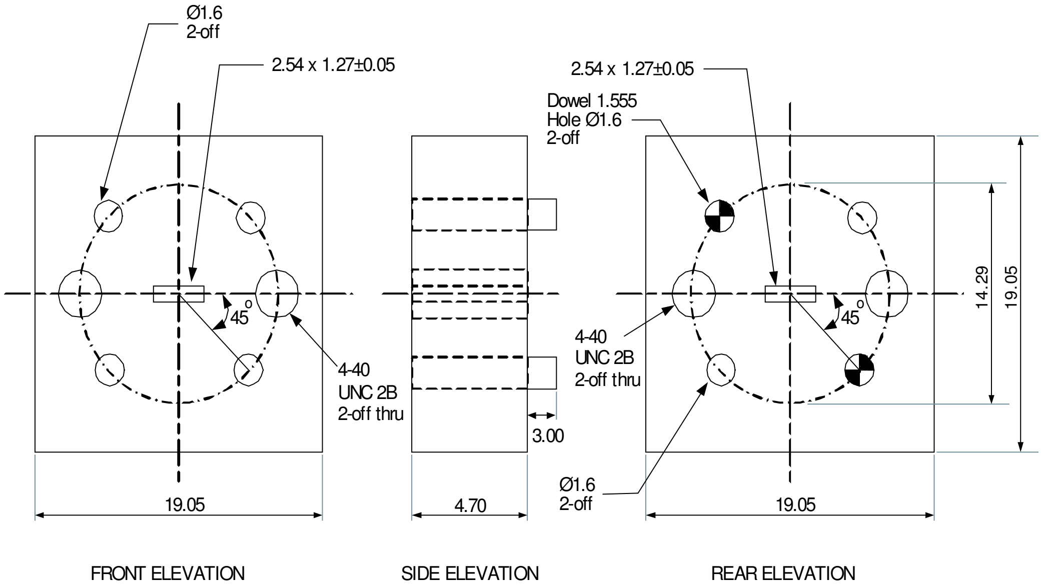


Figure 3.27: W-Band Waveguide Flange

3.12.5 Gunn Diode Housing

The second piece of the system to be manufactured is the Gunn diode housing. This will contain two main components the Gunn diode and the radial line transformer. The Gunn diode is in a cavity which can be tuned to alter its frequency, this can be done mechanical or by capacitive/inductive tuning.

Capacitive and inductive tuning of the cavity is achieved buy using the radial line transformer. This transformer is accurately manufactured to give the correct frequency for resonance. An increase in capacitance causes a decrease in the resonant frequency, alternatively increasing the inductance decreases the resonant frequency. In is necessary to find the right balance of inductance and capacitance for the operating frequency.

The radial line transformer is situated above the Gunn diode. The RF output from the Gunn diode radiates out of a third waveguide. This RF output will be at the fundamental frequency of 43.5 GHz. So the dimensions of this waveguide will slightly larger to the previous waveguide. It is suggested that the guide wavelength needs to three times the magnitude of the second harmonic guide wavelength (Barth 1981), as shown in equation 3.32.

$$\begin{aligned}\lambda_{gf_0} &= 3\lambda_{g2f_0} \\ &= 3 \times 4.70\end{aligned}$$

$$
\begin{aligned}
&= 14.90\,\text{mm} && (3.32)\\
\frac{1}{\lambda_c^2} &= \frac{1}{\lambda_0^2} - \frac{1}{\lambda_g^2} && (3.33)\\
\lambda_0 &= \frac{3 \times 10^8}{43.5 \times 10^9} \\
&= 6.90\,\text{mm} && (3.34)\\
\frac{1}{\lambda_c^2} &= \frac{1}{6.90^2} - \frac{1}{14.90^2} && (3.35)\\
\lambda_c &= 7.91\,\text{mm} && (3.36)\\
f_c &= 37.9\,\text{GHz} && (3.37)
\end{aligned}
$$

Equations 3.33 to 3.37 combined with the knowledge that $\lambda_c = 2a$ shows that the third waveguide dimensions are:

a	3.95 mm
b	1.98 mm

The cut off frequency is 37.9 GHz. The wave must be above this frequency otherwise it will not propagate. The reference design (Barth 1981) suggests that dimension b should be the same as the W-band. The reasoning behind this is that it should allow only the second harmonic frequency output and reflects the fundamental frequency. Figure 3.28 on the next page is a mechanical diagram which illustrates the Gunn diode housing combined with the variable backshort.

3.12.6 Variable Backshort

The final component to the design is a variable backshort, this makes the oscillator easily tunable. The paper suggests that design can provide a variable performance of more than 15 GHz (Barth 1981).

The frequency in the cavity is determined by two variables which are the size and the shape of the cavity. In essence having a smaller the cavity gives a higher frequency.

The variable backshort is energised in the same manner as the waveguide and has a similar field distribution. Having the backshort in the correct position causes the electromagnetic wave to reflect back and forth along the

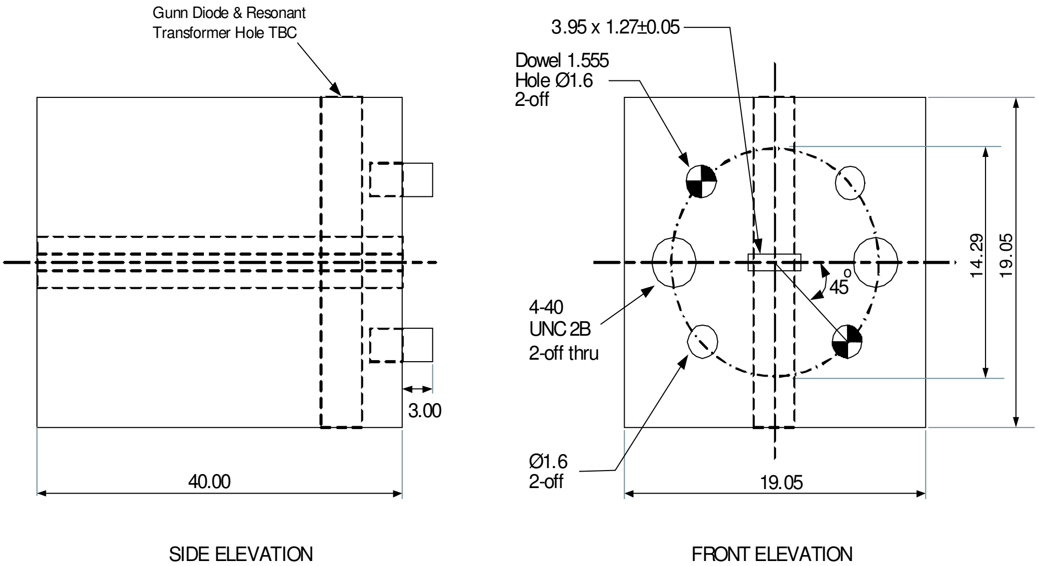


Figure 3.28: Gunn diode housing combined with backshort

backshort cavity and form standing waves. The standing waves will form a field condition within the cavity and satisfy the boundary conditions.

Changing the cavity volume can vary the frequency of the RF output from the cavity. This mechanical method of tuning a cavity is by means of altering the backshort distance. Varying the distance will result in a new frequency because the inductance and the capacitance of the cavity are changed by different amounts. If the volume is decreased, the frequency will be higher; this method of variation will be used to calibrate the device.

As shown in figure 3.28, the backshort housing has been combined with the Gunn diode housing. The reason for this is because it uses the same size waveguide and reduces any coupling errors that may occur. It can be seen that our design is rectangular rather than circular, making the manufacturing easier because there are fewer alignment issues, reducing the machining time.

The backshort component is vital to the operation of the device. The backshort is a brass bar which fits down the rectangular slot.

3.12.7 Building

All the components will be manufactured in high grade brass; this is because brass has high-quality strength, and an excellent conductivity both electrical

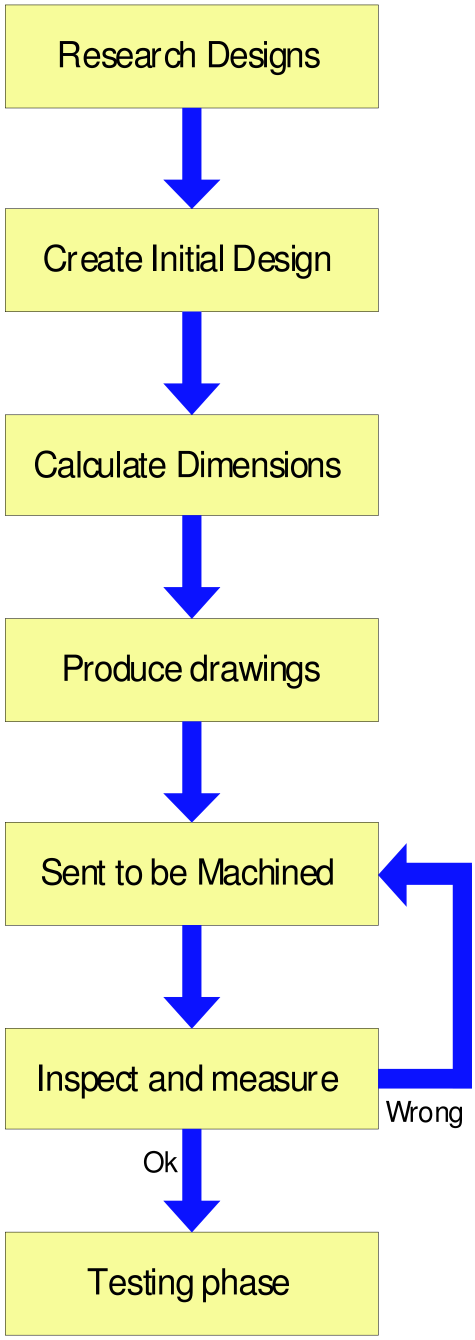


Figure 3.29: Block Diagram of the building stages

and thermally. Also brass is very easy to machine requiring small amounts of lubrication causing minimal wear on the cutting and machine tools. Brass components can be easily joined using soldering, brazing or even adhesive bonding. Furthermore, brass will be the most suitable for this project because it can be machined to a close tolerance giving near-net shapes which are critical for the accurate measurements requested.

Figure 3.29 on the facing page gives an indication of the various stages to building the single device oscillator. At this stage in the project the drawings were handed to UMIST's workshop machinist to review, with the intention of having it manufactured for mid-January. The initial time plan indicated to have it ready before the end of the year, although due to the lack of skilled machinists this seemed unfeasible. If the waveguide is ready for January, there will be enough for it to be tested and any results can be given at the presentation in early February.

3.13 Web site

3.13.1 Content

A web site has been set up for the purpose of sharing information about the project, both internally between team members and to any interested third parties. The web site contains information on a variety of topics, including:

- Information about team members.
- Minutes and agendas for the team meetings.
- Health and safety information.
- Related links.
- An interface to the project mailing lists.

3.13.2 Server

The server is currently running the Apache web server, version 1.3.27. The team has experience operating such a server, allowing easy creation of a web site based around it. A virtual named server was set up purely for the project. Public access is available to the site at `http://gunn.winterwolf.co.uk/`.

Content negotiation is enabled on the server, allowing multiple equivalent files to be present on the server. When a file is requested, the server selects the file best matched to the client's preferences based on a prioritised list sent by the client to the server. This is used to present more compressed graphics to clients able to use them, whilst allowing clients that do not support such formats to use larger but more established graphics formats, for example. It is also used in places to select spreadsheet formats or static PDF versions depending on applications available on the client machine.

3.13.3 Document markup

A great advantage of running an Internet web site is that it is accessible from many platforms in locations all around the world. The W3C maintain the standards on hypertext markup language (HTML), which is a standard for describing the structure of a document for web publication. Originally, HTML was designed purely as a structural markup language, and recently moves have been made to remove all stylistic information form the markup to simply parsing by clients (W3C 2002).

It was decided that the web site should comply fully with recent HTML guidelines. This should allow the site to be viewed in a sensible fashion on any client able to read standard code, rather than limiting proper display to a subset of web browsers.

XHTML version 1.0 strict was chosen as the markup language for pages of the project web site. This format mandates that no stylistic information is present in the document markup, forcing pages to be properly structured. There is also a rich pool of structural objects available, which should be suitable to describe all information required in the project.

3.13.4 Rendering style

Once a structured document has been received by a client, it must be rendered into a suitable form for presentation to the user. Different clients will be able to render documents in completely different ways, depending on the needs of the user and the facilities available. Because the document structure is defined rather than a strict layout, many renditions of a page are possible. Most people will view the page in graphical browsers, but some users will be using text browsers, braille readers or even aural clients.

Since presentation as well as content is important to the perception of a document, provision has been made to provide hints to clients on how to present information contained within the documents. Cascading style sheets (CSS) version 2.0 has been chosen for this, as it is supported by most current browsers, and along with well structured XHTML will allow browsers without or with partial CSS support to sensibly render the document based purely on its structure and their internal styles (W3C 1998).

CSS is also a W3C standard, which should allow any compliant client to use the stylistic hints provided to alter the rendition of elements within a structured document, in this case an XHTML page. Hints can be provided on how to render text, where to position an object, where to emphasise words, sizes of objects any a large array of other aesthetic properties. A client should use as many hints as possible under its current constraints. For example, clients rendering a page aurally will ignore layout information, but should honour emphasis styles.

3.13.5 Scripting

In order to create a consistent feel for the web site, it was decided that a menu bar and certain branding items should be present on all pages within the site. In order to simplify this, a scripting system was introduced to allow functions to be created to generate page headers and footers. This method is preferred over using structures such as static frames, as such methods are geared purely to graphical clients, and do not easily have an analogue in non-visual or limited visual clients.

PHP version 4 was chosen as the scripting language for the project web site. The group already had knowledge of the language, and the web server was already set up to server pages parsed by PHP.

Once the decision to use PHP was made, it was used as a parsing engine for data files, allowing easy updates of frequently changing information, such as records from the project meetings. Similarly, PHP was used to automatically keep parts of the site up-to-date, for example information on archived versions of various papers on the links page. The source code for the PHP used on the web site is available on the attached CD.

3.14 Summary

3.14.1 Completed work

Firstly the project needed to be researched thoroughly, it was not decided that a waveguide system would be implemented at the beginning so it was necessary to investigate all the possible routes to finding a solution. Research was conducted into waveguide and planar Gunn diode oscillators, much of the useful information came from journals by using the search facility on the IEEE Xplore website. Other information was obtained from textbooks and Internet searches. The team collated the information and gained an understanding into the operation and fabrication of Gunn diode oscillators.

A visit to e2v Technologies proved extremely useful with much valuable advice given. The information was useful in many areas of the project and it was strongly recommended that the system should be a waveguide system. The engineers at e2v have years of experience in the field of Gunn diodes. Advice was offered in other areas such as design, fabrication, simulation and testing. The project group delivered a presentation to e2v introducing the team and stating the information that had been obtained from research. The engineers also gave practical demonstrations of oscillators and a tour of the site was given.

After the visit to e2v Technologies the team were able to make some decisions and the proposed solution was reached. It was decided that a single oscillator device would be designed, built and tested before attempting to construct the power-combing oscillator. The waveguide dimensions have been designed and technical drawings have been produced so that the waveguide can be machined. The radial line transformer design has been researched but the dimensions have not yet been produced. The team have been given several commercial devices which have been partially tested in order to gain experience of Gunn diode test procedures. Work has also begun on the simulation software with a simple waveguide being simulated.

3.14.2 Future targets

The first aim is to successfully produce a single diode oscillator. The designs for waveguide have been made and have been sent to the machinist. The radial line transformer dimensions must be decided and technical drawings produced. Once the waveguide and radial line transformer are machined the single oscillator device can be constructed and testing will begin. A range of tests will be conducted in order to achieve the highest possible efficiency of the oscillator, including spectrum analysis at both the second harmonic and fundamental frequencies,as well as power measurements against a variety of bias voltages. The cooling system will be designed and put into operation.

A full simulation of both the single diode oscillator and the power combining oscillator will be completed and the results will be used to optimise the effectiveness of the designs. The power combining system consists of several sections; each section will be designed and machined. A number of radial line transformers will also be produced for the system. An investigation into power supplies will be conducted, as each of the bias circuits for the diodes needs a separate adjustable DC voltage applied to it.

3.14.3 Future uses

Once the power combining system has successfully been produced at the target specification there are several uses for it that span beyond the scope of the fourth Year project. The specification was originally decided because the oscillator has an application for research currently being carried out at UMIST. The research involves generating and detecting terahertz waves for investigating a wide variety of problems in the physical, biological and medical sciences. A reasonable amount of power is considered to be 1 mW, the aim is to achieve 1 mW at 1 THz (1000 GHz).

The power combining oscillator will also be used by e2v Technologies and will have commercial applications. In order to achieve high power at high frequencies InP Gunn diodes are used but they have limitations and it is not an attractive material to use. If the same high power at a high frequency can be achieved using GaAs devices then there would be no need to use InP diodes. The design would be taken by e2v Technologies and developed further.

Chapter 4

Summary

4.1 Progress against time plan

Week Beginning	Progress
13 October	Ongoing research carried out and findings reported to members of the group. Benefits of both planar and waveguide designs were weighed up. A microwave simulation lab was arranged for the following week. The format of the e2v presentation was also briefly discussed. All tasks have been carried out according to plan.
20 October	Further research carried out as planned, with each member of group researching a different area and reporting the findings to other team members. The e2v presentation was split up into a number of sections, and PowerPoint slides produced.
27 October	PowerPoint slides were combined into one presentation, and the styles of the slides adjusted to make it look coherent. Notes were produced to assist in the presentation. Further research work took place. A safety report was produced allowing measurement and testing work to take place in the lab. Little to no simulation work was carried out as initially planned due to the additional work carried out for the e2v presentation.

10 November — Discussion of the points made by e2v were discussed leading to a change in the tasks to be completed. More research was carried out due to the subtleties of second harmonic power combining. A draft task split for the interim report was presented.

Simulation was not carried out as on the time plan due to ADS not being very useful form simulating waveguides.

17 November — Minor changes to the interim report task split were made, and each task was assigned to a member of the team. The team deadline for completing individual sections was discussed and set for 8/12/03 — later than scheduled on time plan due to coursework in other modules. Initial waveguide designs produced. Simulation work on radial-line transformers using HFSS proposed. Testing work on a commercial model carried out, a week later than initially planned.

24 November — Heat sinking and power supply requirements discussed, but decided that no final designs would be made yet. Further work on waveguide designs took place. Additional testing work on the commercial oscillators took place. Different parameters were measured. Measurements for the waveguide sections were finalised. Work continued on interim report.

01 December — Additional simulation work using HFSS was carried out. Waveguide technical drawings completed with tolerances and finish stated, but unlikely to be manufactured until the end of January. Work on the interim report continued.

4.2 Changes to the plan

The time plan was set out quite early on in the project, the individual tasks were only a rough outline and the times were just an estimate. Up until the time at which the e2v presentation took place, all tasks were carried out as initially planned, with relatively no deviation from the time plan. Only simulation work was put back as more time was spent finalising the presentation slides and content.

After the presentation tasks, a lot of time was spent on discussing and digesting the points raised by e2v. This had not been anticipated when the time plan was first produced, ultimately leading to tasks not being completed as scheduled. The information given by e2v provided more direction and focus to the focus to the project. Additional research work needed to be carried out on areas which had previously not been covered. There was a small delay in receiving the commercial Gunn oscillator models from e2v, which meant testing had to be put back. The testing took longer than originally specified in the time plan, this was because it was not known what parameters needed to be measured when creating the time plan and time not being allocated to learning how to use the measuring equipment. Building a single device oscillator again involved more work than first thought and not enough time was correctly allocated. It was thought that the design and manufacture would be relatively simple and only a short time span was given to this. However, this is not the case as the fine detail in each element of the design is crucial in creating a device that would work as planned, and the manufacture of this would not be simple. Tasks involved in the power supply and heat sinking were not strictly completed. When testing on the commercial models were being carried out aspects of these tasks were mentioned and discussed. It was found that these were not critically important, and work could not really be done on these until our design had been built and tested. Due to the extra work required on the research and design, work on the interim report started later than planned.

The time plan is due to be reviewed in the new year and changes will need to be made to address these issues. The waveguide sections are not due to be completed before the end of January, so any building and testing work involving this will need to be pushed back. This should be carried out as soon as possible, so any changes that are required can be made quickly to avoid any future problems. The manufacture of the waveguide is critical and anything delaying this can have severe consequences on the project. The power supply and heat sinking requirements can be specified as a result of the testing and a suitable solution developed. Simulation work is still ongoing to help design the radial-line transformers. This will also need to be applied to the time plan. The date at which the team will start writing the final report may be slightly optimistic and may need to be pushed back as other tasks need to be carried out which weren't initially accounted for. This should not present too much of a problem as the work can easily be done in parallel.

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 records for the project is available on the attached CD.

A.4 Presentation slides

A presentation was organised to allow us to demonstrate to e2v Technologies our current level of understanding of 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.

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 section 3.13 on page 63.

A.6 Main report

A copy of this report is also included on the attached CD for reference.

Appendix B

Risk assessments

Risk assessments created and used for project work are included for reference in this section.

B.1 Completion guidelines

A list of guidelines for completing risk assessments was compiled and distributed to the group. The guidelines are reproduced here for reference.

B.1.1 Works

- This will always be UMIST, any work outside should be altered accordingly.

B.1.2 Area

- This is the particular building in the UMIST grounds, for example Main Building.

B.1.3 Department

- This is the where the work is involved, Department of Electrical and Electronic Engineering.

B.1.4 Location

- This the particular room number where the activity is taking place.

B.1.5 Table

B.1.5.1 What Could Cause a Hazard

- By looking at the place of work, identify all the hazards possible, whether major or minor and list in the table, eg. slips, falling objects, electric-shock.

- You should be aware that accidents frequently occur outside normal operation eg. during maintenance, cleaning, unusual (but known) sequences etc.

- Consider in this section what particular risks there may be to each of the different groups of people who may be involved (or exposed) to the hazards identified and how this will affect the level of risk.

B.1.5.2 Existing Control Measure(s)

- Give details of control measures (what has been done to protect people from the harm) that are already in place to reduce the likelihood and/or severity of the harm occurring.

B.1.5.3 Probability

- By looking at each hazard and control measure(s) the risk has to be given a score from 1-5, where 1 is extremely unlikely and 5 is extremely likely depending on the probability whether the event will occur.

B.1.5.4 Severity

- By looking at each hazard and control measure(s) the risk has to be given a score from 1-5, where 1 is minimal loss and 5 is a fatality, depending on the severity of the risk if it occurs.

B.1.5.5 Total

- The total is the value of the probability and severity multiplied together.

B.1.5.6 Risk Band

- The total score will be a value from 1-25, if the value is 0-4 then the risk band will be low, if its 5-9 then the risk band will be medium, and if its 10-25 then the risk will be high and action will be needed.

B.1.5.7 Proposed Control Measure

- If the risk band, as indicated from the table is medium or high then as a guiding principal you should consider that additional control measures will be needed to reduce the risk to low.

- Even if the existing risk is found to be low consider if there are any other simple and effective actions which could be taken to reduce the risks even further.

- If you believe that the existing control measures are adequate (and that the risks are low) then state this on the assessment form.

B.1.6 Declaration

B.1.6.1 Date

- It is important to date the risk assessment form.

B.1.6.2 Who is Responsible

- Once the Risk Assessment has been completed the form should be signed by the Students and then passed to the Supervisors, who will decide whether the level of risk is acceptable or if the activity(ies) must be prohibited.

B.2 Completed assessments

The following risk assessments are attached:

- B.1 on the facing page: Working on personal computers.
- B.2 on page 78: University out-of-hours working.
- B.3 on page 79: Testing microwave devices.

For a discussion on the risks involved and how these tables were drawn up, see section 3.2 on page 15.

RiskAssessment - High Power Gunn Diode Oscillator

Works: UMIST

Area: Main Building

Department: Electrical & Electronic Engineering

Location: A19 Computer Laboratory

Task: Working on Computer

Personnel Involved: Staff, Students, Visitors, Operator

Probability
5 = Extremely Likely
4 = Very Likely
3 = Likely
2 = Unlikely
1 = Extremely Unlikely

Severity
5 = Fatality or major incident
4 = Serious Injury or significant loss
3 = Lost Time Accident
2 = Minor Injury
1 = Minimal Loss

RiskBand
0-4 LOW
5-9 MED
10-25 HIGH

HAZARD	Existing Control Measure(s)	Assessment		Total	Risk Band	Proposed Control Measures
		Probability	Severity			
1. Slips/Trips/Falls	Equipment stored neatly	2	2	4	Low	
2. Excessive VDUuse	Suitable distance away from monitor	4	2	8	Med	Take a break at regular intervals.
3. Sat in the same position	Chair is correctly setup for individual user	4	2	8	Med	Take a break at regular intervals to stretch muscles.
4						
5						
6						
7						

Date: ________________

Student Signature(s): ________________

Supervisor Signature: ________________

Figure B.1: Risk assessment: Computer working

RiskAssessment - High Power Gunn Diode Oscillator

Works:	UMIST	Personnel Involved:	Staff Students Visitors Operator
Area:	Main Building		
Department:	Electrical & Electronic Engineering		
Location:	AllComputer Laboratorie s		
Task:	Out of Hours Computer Work		

Probability	Severity	RiskBand
5 = Extremely Likely	5 = Fatality or major incident	0-4 LOW
4 = Very Likely	4 = Serious Injury or significant loss	5-9 MED
3 = Likely	3 = Lost Time Accident	10-25 HIGH
2 = Unlikely	2 = Minor Injury	
1 = Extremely Unlikely	1 = Minimal Loss	

HAZARD	Existing Control Measure(s)	Assessment		Total	Risk Band	Proposed Control Measures
		Probability	Severity			
1. Slips/Trips/Falls	Equipment stored neatly	2	2	4	Low	
2. Excessive VDUuse	Suitable distance away from monitor	2	2	4	Low	Take a break at regular intervals.
3. Sat in the same position	Chair is correctly setup for individual user	2	2	4	Low	Take a break at regular intervals to stretch muscles.
4. Confrontation with third parties	Security monitoring	2	3	6	Med	Keep mobile phones at all times. Note security number (back of swipe card)
5. Accident whilst unattended (special case of hazard 1)	Security monitoring	1	2	2	Low	Security: 200 4999, Nightline: 275 2983/4 There is an internal phone in A19b
6						
7						

Date: 27 November 2003

Student Signature(s): ____________________

Supervisor Signature: ____________________

Figure B.2: Risk assessment: Out-of-hours work

RiskAssessment - High Power Gunn Diode Oscillator

Works: UMIST

Area: Main Building

Department: Electrical & Electronic Engineering

Location: D-Floor Laboratory

Task: Build & Testing of Microwave device

Personnel Involved: Staff, Students, Visitors, Operator

Probability
5 = Extremely Likely
4 = Very Likely
3 = Likely
2 = Unlikely
1 = Extremely Unlikely

Severity
5 = Fatality or major incident
4 = Serious Injury or significant loss
3 = Lost Time Accident
2 = Minor Injury
1 = Minimal Loss

RiskBand
0-4 LOW
5-9 MED
10-25 HIGH

HAZARD	Existing Control Measure's	Assessment		Total	Risk Band	Proposed Control Measures
		Probability	Severity			
1. Biological effects of RFradiation	Care taken around the waveguide output	3	4	12	High	See additional control measures attached
2. Electric shock	Any exposed live connections are insulated	2	4	8	Med	
3. High temperatures associated with Power equipment	Components allowed to cool down before handling	3	3	9	Med	
4. Slips/Trips/Falls	Equipment stored neatly in laboratory	2	2	4	Low	
5						
6						
7						

Date: ____________________

Student Signature's: ____________________

Supervisor Signature: ____________________

Figure B.3: Risk assessment: Testing microwave devices

Appendix C

Experimental results

C.1 Spectrum analyser calibration

Manually entering the conversion loss calibration curve of the W-Band mixer into the spectrum analyser.

These instructions assume the use of the HP8562A spectrum analyser and HP11970W harmonic mixer.

1. Select mixer→"Ext" from the front panel of the spectrum analyser.
2. Ensure that W Band is selected by rotating the selection wheel.
3. Press the "Ampd Correct" soft key from the on screen menu.
4. Press the "cnv loss vs freq" soft key from the resulting menu.
5. For 75 GHz enter 42.0 (dB) and press Enter.
6. Press the ↑ key.
7. Enter the value for 80 GHz from the table C.1 on the facing page .
8. Repeat until all values are entered.

Frequency (GHz)	Attenuation (dB)
75	-42.0
80	-41.6
85	-41.8
90	-42.2
95	-42.8
100	-42.8
105	-43.5
110	-44.1

Table C.1: W band mixer calibration details

C.2 Test results

The raw results obtained during testing the oscillators are tabulated here. The devices show a certain amount of hysteresis when looking at the relationship between bias voltage and frequency, so two tables have been produced to demonstrate this.

Table C.2 on the next page shows the relationship between bias voltage and second harmonic oscillation frequency as the bias voltage is being increased. Table C.3 on page 83 shows the same information as the bias voltage is decreased. Each table shows a full set of results from the start of oscillation at 3.80 V, through to the maximum safe bias voltage at 5.20 V then back to the point where oscillations collapse at 2.80 V.

The analysis for these results is discussed in section 3.7 on page 37.

Table C.2: Increasing bias voltage vs. frequency

Bias Voltage (V)	Oscillation Frequency (GHz)
3.80	89.832
3.90	89.960
4.00	90.095
4.10	90.207
4.20	90.315
4.30	90.418
4.40	90.521
4.50	90.605
4.60	90.689
4.70	90.755
4.80	90.819
4.90	90.861
5.00	90.908
5.10	90.944
5.20	90.976

Table C.3: Decreasing bias voltage vs. frequency

Bias Voltage (V)	Oscillation Frequency (GHz)
5.10	90.939
5.00	90.898
4.90	90.851
4.80	90.798
4.70	90.739
4.60	90.678
4.50	90.606
4.40	90.532
4.30	90.500
4.20	90.360
4.10	90.303
4.00	90.201
3.90	90.106
3.80	89.987
3.70	89.865
3.60	89.740
3.50	89.595
3.40	89.460
3.30	89.350
3.20	89.163
3.10	89.027
3.00	88.851
2.90	88.709
2.80	Lost oscillations

Appendix D

Waveguide construction

Mechanical drawings for various methods of waveguide construction are provided in this section. Some dimensions have been omitted due time constraints when this report went to print.

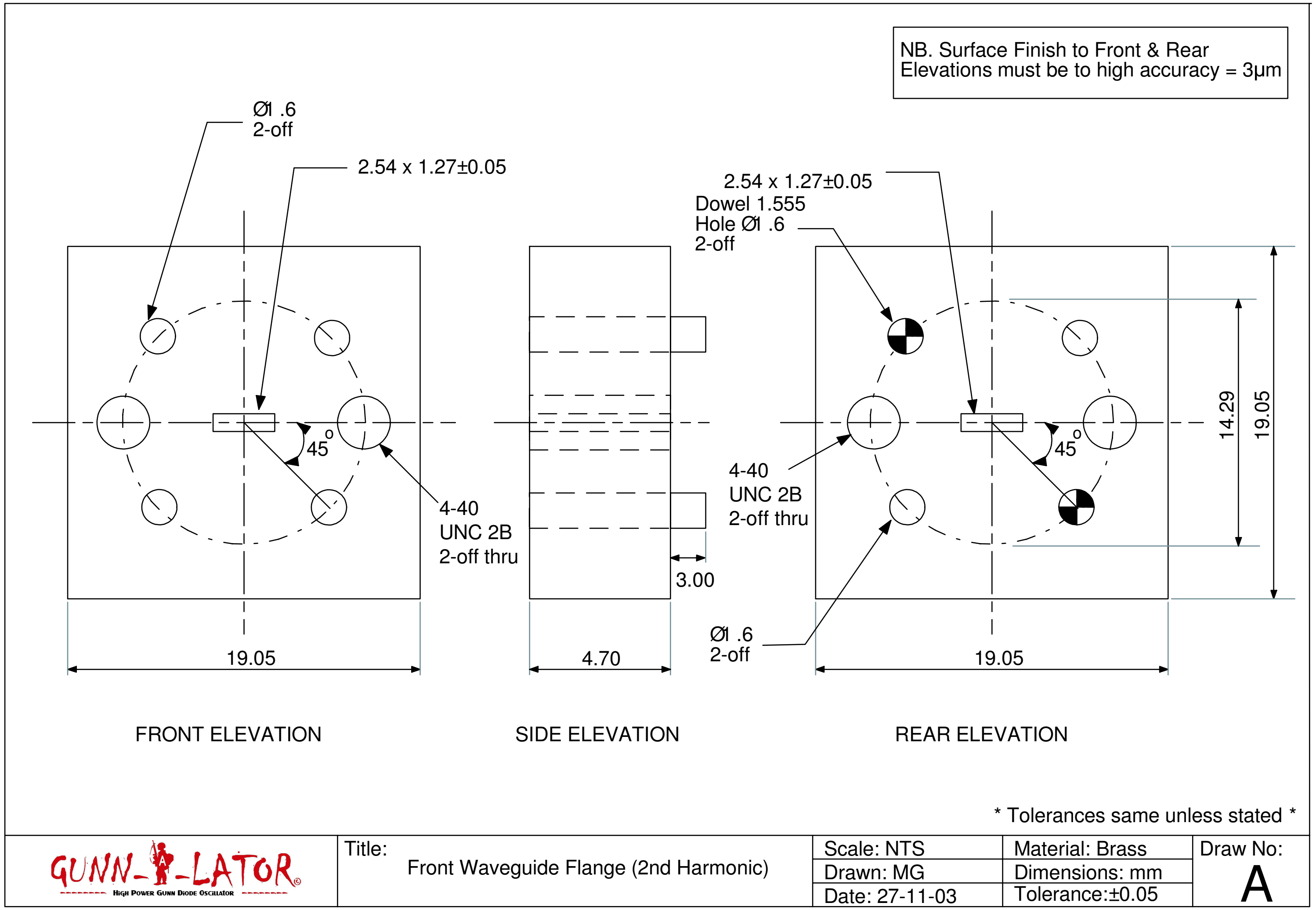


Figure D.1: Front waveguide flange

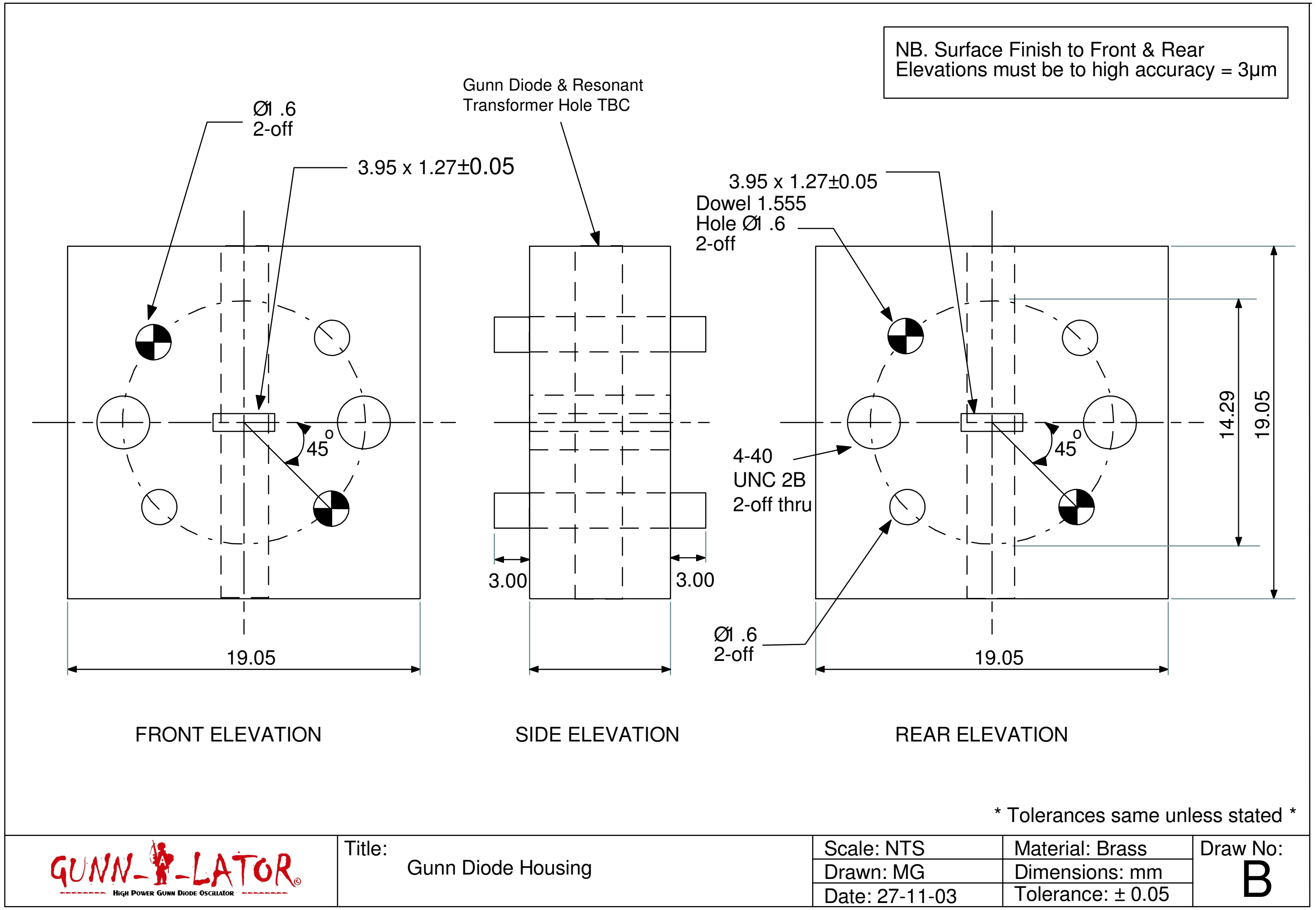


Figure D.2: Gunn diode housing

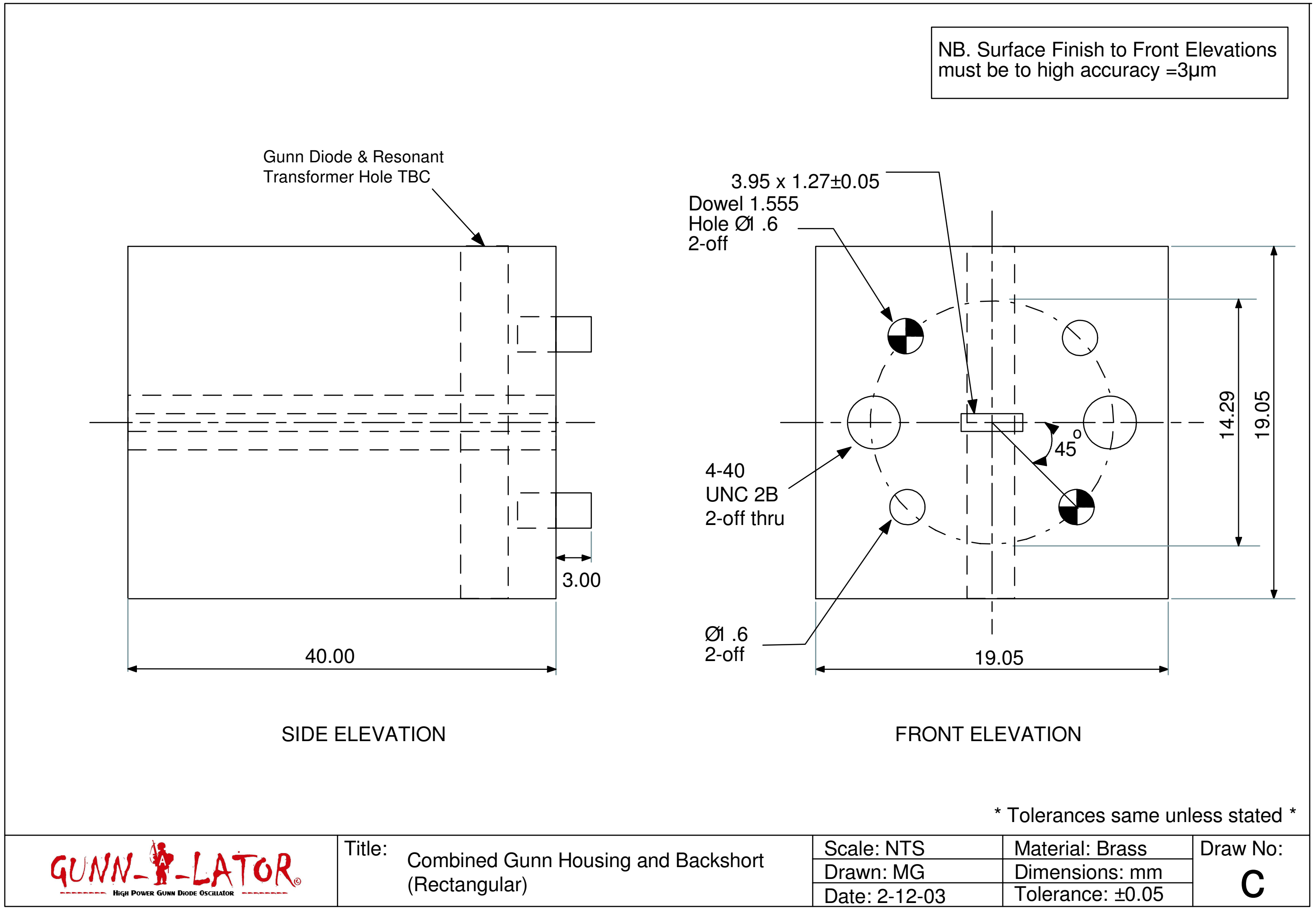


Figure D.3: Combined Gunn housing and backshort

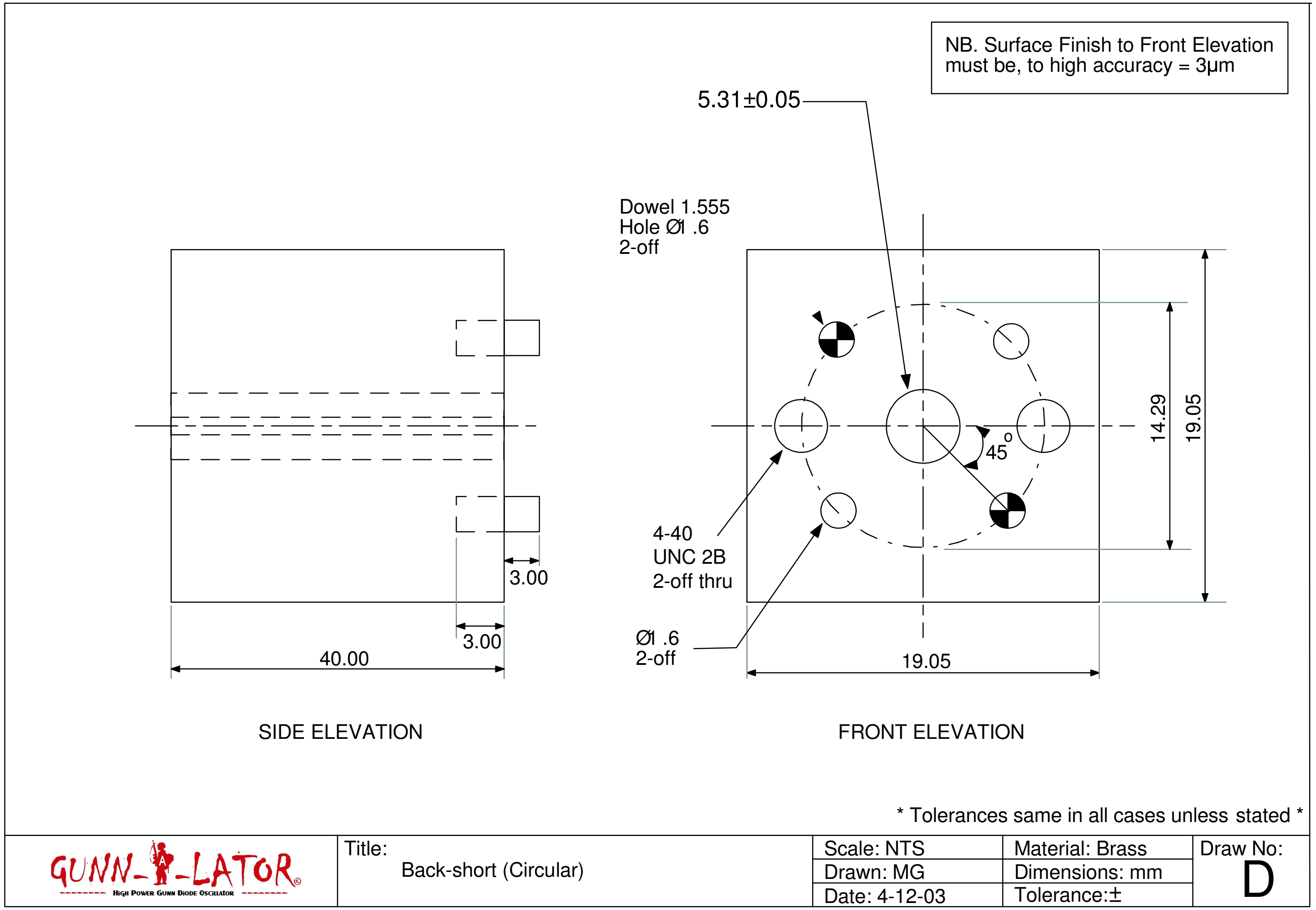


Figure D.4: Circular backshort housing

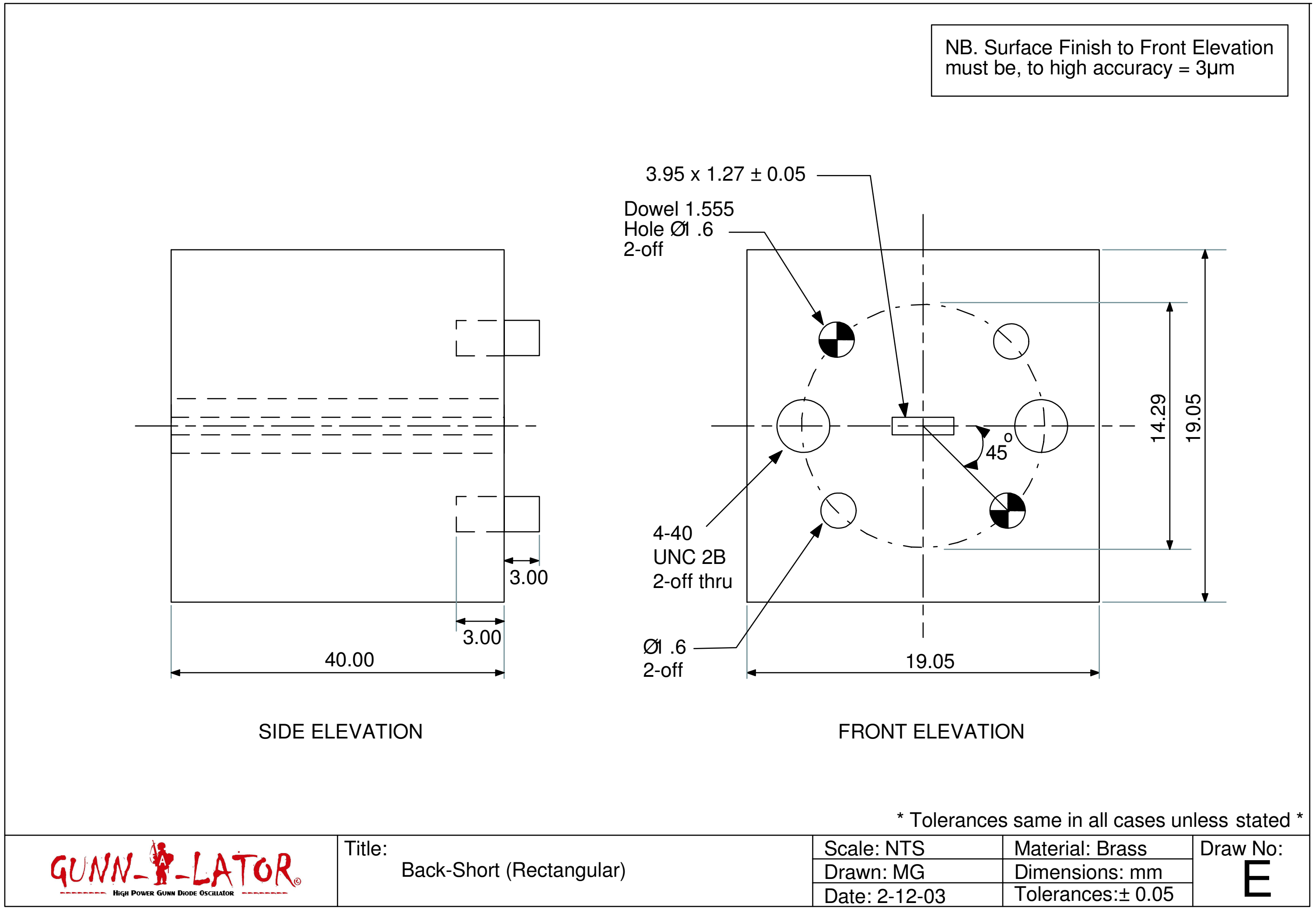


Figure D.5: Rectangular backshort housing

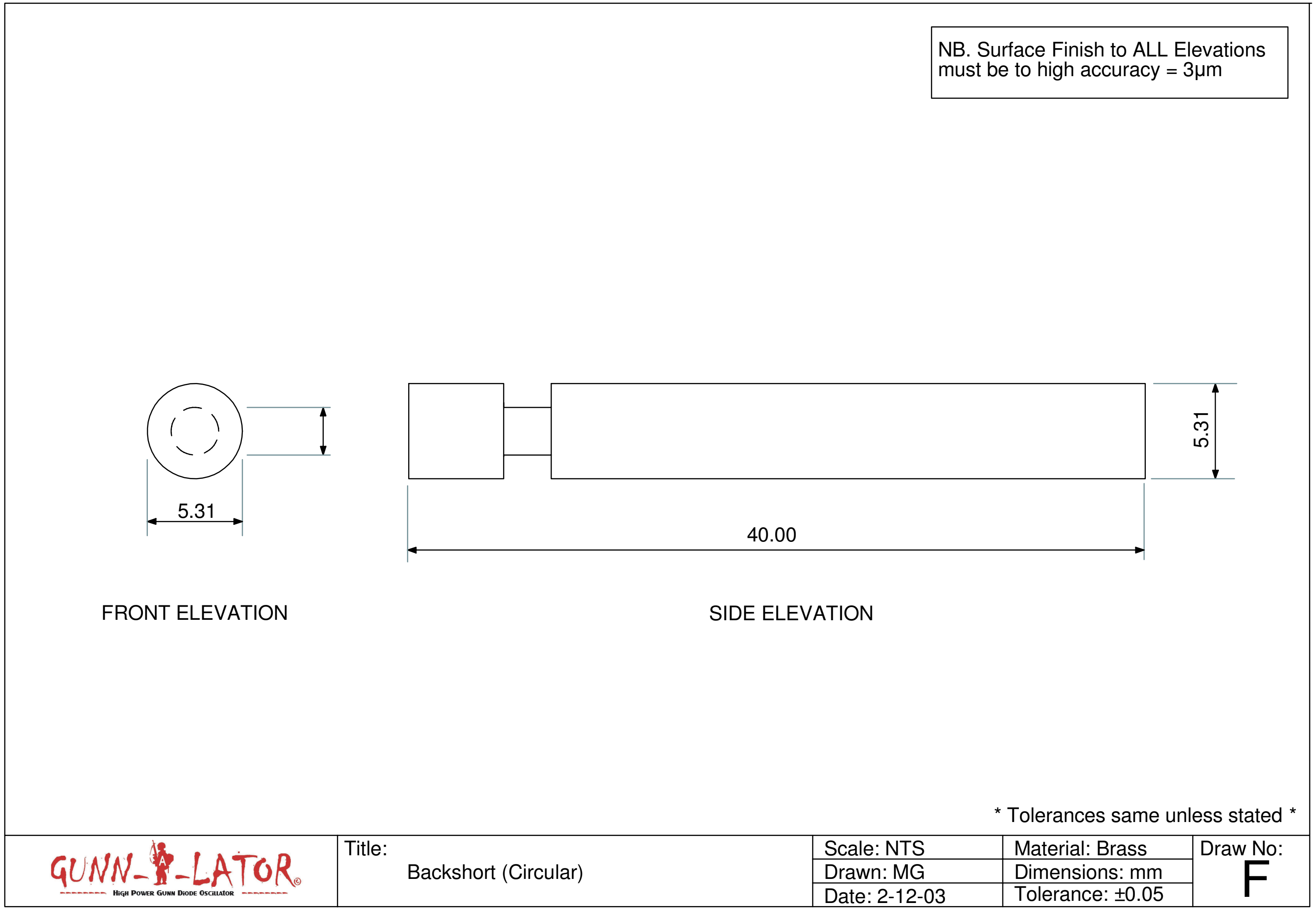


Figure D.6: Circular backshort

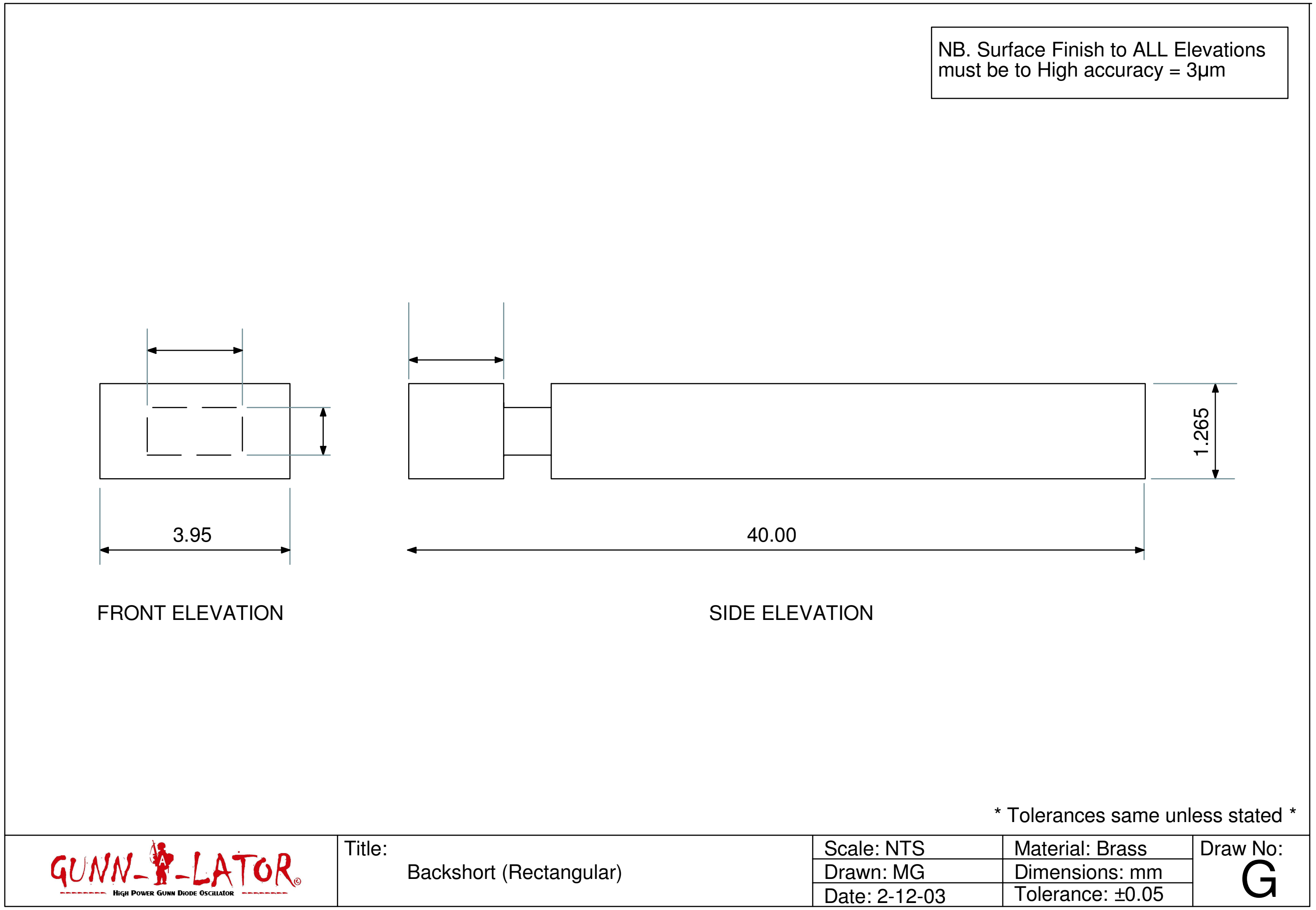


Figure D.7: Rectangular backshort

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