DESIGN AND IMPLEMENTATION OF EXPERIMENTS INVOLVING THE VECTOR NETWORK ANALYSER

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A thesis is submitted as partial fulfilment of the requirements

for the degree of Electrical Engineering at the University of Cape Town

ACKNOWLEDGEMENTS

DECLARATION

I, Irene Catherine Cruywagen declare that the work contained in this thesis is my own work unless otherwise stated. This project is being submitted as partial fulfilment of the degree of Bachelor of Science in Electrical Engineering at the University of Cape Town. It has not been submitted before for any degree at any other university.

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Irene Catherine Cruywagen

Cape Town

17 October 2005

TERMS OF REFERENCE

This thesis was carried out by Irene Cruywagen under the supervision of Prof. M. Inggs. The terms of reference as drawn up by Irene Cruywagen and her supervisor were as follows:

The broad aim of this thesis was to develop experiments for the EEE 486F course, RF and Microwave Fundamentals, to provide comprehensive tutoring information on the HP 8410 Vector Network Analyser (VNA).

These tutorials and experiments should include the following:

1. Introduction to the VNA and s-parameters: functions of the VNA, applications of the VNA.

2. Introduction to connector types and other microwave hardware.

3. Block diagrams of the various components of the VNA and how they are interconnected.

4. Tutorial on the calibration of the VNA.

5. Basic introductory experiments to become familiar with the VNA (short circuits, transmission lines etc) where the user will observe the s-parameters (amplitude and phase) using both the rectangular and polar display.

6. Smith Chart applications – utilising a stub to tune a impedance mismatch

7. Creating two port "black boxes" to be tested analysed and then identified by the user by means of observing the S-parameters for example a Low-Pass Filter (LPF).

A report detailing the thesis is to be submitted on the 18th of October 2005.

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GLOSSARY AND ACRONYMS

RF   - Radio Frequency

VNA   - Vector Network Analyser

DUT   - Device under Test

S-Parameter   - Scattering Parameter

VSWR   - Voltage Standing Wave Ratio

UCT   - University of Cape Town

SYMBOLS AND DEFINITIONS

S_{11} = reflection parameter when port 2 is terminated in a matched load

S_{22} = reflection parameter when port 1 is terminated in a matched load

S_{21} = forward transmission gain

S_{12} = Reverse transmission gain

Γ = reflection coefficient

LPF = Low-Pass Filter

1 INTRODUCTION

1.1 Subject of the Research

This research report contains the design and implementation of Vector Network Analyser (VNA) experiment test sets for a fourth year Electrical Engineering undergraduate RF and Microwaves course.

1.2 Background to the research project

The Electrical Engineering Department at the University of Cape Town (UCT) offers a Radio Frequency (RF) and Microwave course (EEE 486F) to fourth year undergraduate students. It is essentially a higher level course covering fundamental wireless system design concepts. Being quite an intense course that covers a vast amount of material, students often get caught up in the theory without acquiring a proper solid understanding of the physical meaning behind the theory. Microwave theory in particular is often difficult to understand and electromagnetic concepts are sometimes tricky to visualise. It is also a course that attempts to achieve a balance between the '*coverage of the broad fundamentals and exposure to the details in specialized areas or topics'* [1]. The theory presented in lectures covers broad fundamentals, while the laboratory experiments expose students to details in specialised areas.

'*McIntosh has pointed out that there is a strong need to have the theory presented in a lecture to be supplemented with laboratory demonstrations and exercises timed to support classroom work and that such exercises should avoid "cookbook" procedures and encourage the student to use his theoretical understanding of microwaves in the laboratory.*' [2]

'Recent studies of engineering education emphasize the importance of strong laboratory experience for engineering graduates' [1] especially for those entering the work environment, where practical experience is particularly useful.

Therefore it is important that students get as much exposure to practical experiments as possible. Currently the EEE 486F course offers some practical work but this involves mostly computer-based simulations and lacks hands on practical experiments with real equipment.

Practical work also allows the student to gain a better intuitive, "gut feeling" for the work, rather than reciting verbatim the theory that they've learnt.

One of the subjects covered in the course is the Vector Network Analyser and the Scattering parameters (S-parameters). The VNA is sometimes referred to as the 'oscilloscope' of high frequency signals [3] and is the primary instrument for characterising RF and Microwave components. Network analysis is one of the most important topics taught in the RF and Microwave course because *'it enables the transition from electromagnetic analysis to transmission line and circuit theory [4]'*.

Therefore the VNA is the ideal measurement tool to illustrate the fundamental concepts of RF and Microwaves to students of EEE 486F.

1.3 Objectives of this project

This thesis will involve designing fourth year experiments using the VNA and the S-parameter test set.

1.4 Limitations of development

Time was the main limitation. This thesis project had to be completed in three months and thus time was the central limitation imposed upon the work. .The experiments developed were therefore rather simple and did not involve complex test sets which would require more time to design and implement. Many RF concepts are easy to study in theory but difficult in practice to design and implement. The amount of time to implement RF components was underestimated and hence not all the proposed ideas were implemented. The first experiment was fully implemented but due to time constraints the second experiment was only designed and not implemented. The implementation could be completed after the submission of the project.

The next section outlines each chapter of this thesis project.

1.5 Structure of the Report

The following section briefly describes the outline of each chapter:

Chapter 2 consists of two sections namely:

- Theoretical Background
- Literature Study

The theoretical background section summarises the fundamental concepts that are necessary to understand this thesis project. It discusses the following: S-parameters, the VNA and the Smith Chart.

The literature review discusses the various possible applications of the network analyser.

Chapter 3 presents a design and implementation of the first practical which involves the use of the rectangular display. This practical includes the following fundamental concepts, namely:

- Block diagrams of both the VNA and the setup of the VNA with the sweep oscillator and S-parameter test set

- Connector types and the importance of making correct connections

- Calibration of the VNA which involves short circuit tests and open circuit tests

- Observing the effect of adding a transmission line on the phase

- Characterising certain devices such as antennas and filters

Chapter 4 discusses the second experiment which uses the polar display of the VNA. It also outlines the use of the Smith Chart.

This experiment entails measuring impedance and using matching circuits to avoid a mismatched circuit.

Chapter 5 discusses future possible experiments.

Conclusions are then drawn in **Chapter 6** followed by the recommendations of experiments, which are presented in **Chapter 7.**

2 LITERATURE REVIEW

Equation Section 2

The fundamental concepts of the Vector Network Analyser are summarised in this chapter. A short literature study is presented, summarising the research undertaken.

2.1 Vector Network Analysis Fundamental Concepts

This section covers the following fundamental concepts:

- S-parameters and 2-port networks
- Vector Network Analysers
- Smith Charts

These concepts need to be emphasised in order to understand the rest of this project.

2.1.1 S-parameters and two-port networks:

'Engineers have devised many (perhaps too many) ways to describe systems' [5, page 66]. One way of looking at a system is to see it as a two-port device considering only the inputs and the outputs, without regarding the internals of the system [5 , page 67].

Typically, at low frequencies a model is used where voltages and currents are the inputs and outputs to the network. However, when the operating frequency is increased, the voltage and current two-port model is no longer accurate. This is because the impedances of the reactive components are frequency dependant and hence the system can no longer be describes by linear equations in terms of voltage and current.

The set of two-port parameters used for high frequency signals are known as Scattering parameters (S-parameters). The S-parameters will be explained using the following figure. The inputs and outputs in the case of the S-parameters are known as incident voltages and reflected voltages or waves respectively.

Consider the two-port device in Figure 1. The network being examined is often referred to as the Device Under Test (DUT).

Figure 1: Two Port Devices [6]

Where a_1 and a_2 are the incident waves and b_1 and b_2 are the reflected waves [6]. The linear equations used to describe the S-parameters are as follows:

The following equations are taken from [6]:

$$b_1 = S_{11}a_1 + S_{12}a_2 \qquad\qquad (2.1)$$

$$b_2 = S_{21}a_1 + S_{22}a_2 \qquad\qquad (2.2)$$

Where:

   a_1 is the normalised incident voltage at port 1

   a_2 is the normalised incident voltage at port 2

   b_1 is the normalised reflected voltage at port 1

   b_2 is the normalised reflected voltage at port 2

A normalised voltage is one that has been normalised or scaled to the characteristic impedance of the system (typically 50Ω).

The S parameters are then as follows:

$$S_{11} = \frac{b_1}{a_1}\bigg|_{a_2=0} \tag{2.3}$$

(Input reflection coefficient when port 2 is terminated in a matched load)

$$S_{22} = \frac{b_2}{a_2}\bigg|_{a_1=0} \tag{2.4}$$

(Output reflection coefficient when port 1 is terminated in a matched load)

$$S_{21} = \frac{b_2}{a_1}\bigg|_{a_2=0} \tag{2.5}$$

(Forward transmission gain with port 2 terminated in a matched load)

$$S_{12} = \frac{b_1}{a_2}\bigg|_{a_1=0} \tag{2.6}$$

(Reverse transmission gain with port 1 terminated in a matched load)

The s-parameters can also be illustrated as follows in Figure 2:
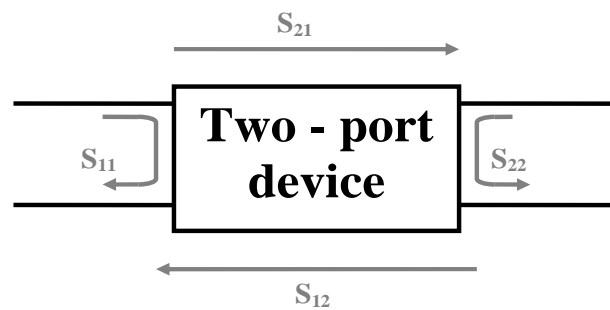
Figure 2: 2-Port device illustrating S-parameters

In Figure 2:

S_{11} can be regarded as the reflected wave from port 1.

S_{22} can be regarded as the reflected wave from port 2.

S_{21} can be regarded as the forward transmission gain and S_{12} can be seen as the reverse transmission gain.

2.1.2 Vector Network Analyser

There are two types of network analysers namely Scalar Network Analysers (SNA) and Vector Network Analysers (VNA). As their names suggest, the SNA can only display the magnitude of some property (transmission coefficient or reflection coefficient magnitude) whereas the VNA can display both magnitude and phase of some property [7].

The vector network analyser is often referred to as the 'oscilloscope' of RF and Microwave signals [3 as it enables one to visualise the relationships between high frequency signals]. '*Although absolute measurement of signal magnitudes and phases at VHF and at higher frequencies are very difficult to make, comparative measurements are relatively simple* [8, page 57]. Its main function is to measure the relative magnitude and phase of two RF input signals [9].

It is particularly useful in measuring the transmission and reflection characteristics of two-port devices over a range of frequencies. These transmission and reflection characteristics are known as the S-parameters, as discussed in the previous section.

The Vector Network Analyser model used in this practical is the HP8410C model. It can utilise two types of display either rectangular or polar. The rectangular display shows either the magnitude or the phase of the selected S-parameter and the polar display shows the selected s-parameter as a vector (that is with both phase and magnitude information).

The HP 8410 model is a relatively old model (circa 1983) and more modern and advanced models are available. This model is ideal for introductory applications. This will be discussed in more detail in section 2.2.

The HP8410C mainframe and its controls is shown in Figure 3.
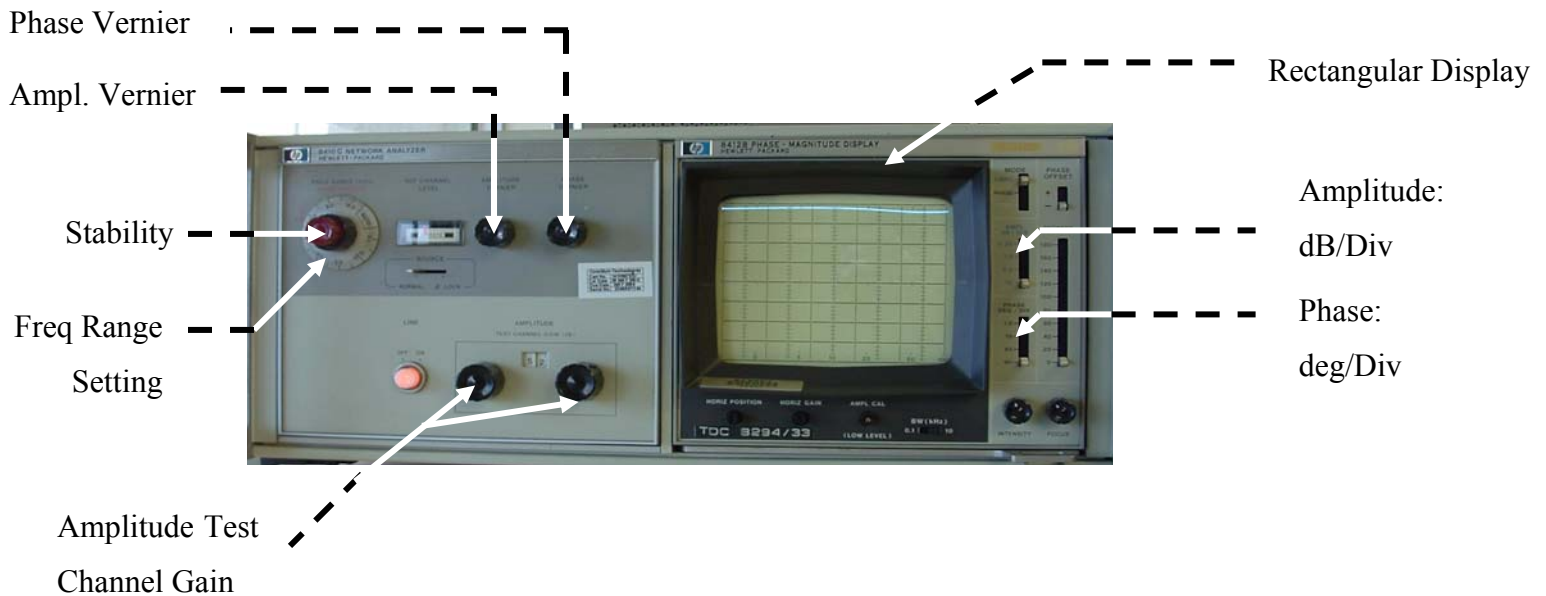
Figure 3: HP 8410C VNA Mainframe

The VNA consists of a mainframe section and a display section. There are a few settings that can be adjusted. These are as follows:

Mainframe settings:

Frequency Range Setting

This control sets the range of the automatic tuning to the selected frequency range. The selected range must include the frequencies at which measurements are to be made.[9]

Sweep Stability

The sweep stability control is used for fine tuning of the frequency range [9]. If the displayed signal is not very stable (with respect to frequency) and oscillatory then by adjusting the sweep stability control, the signal should become less oscillatory.

Amplitude Test Channel Gain

This control adjusts the amplitude of the test channel by up to 69dB. The left control adjusts the magnitude by up to 60dB in steps of 10dB. The right control adjusts the magnitude by up to 9dB in step of 1dB [9].

Amplitude Vernier

This control is used to adjust the amplitude of the reference signal by up to 2dB during calibration [9].

Phase Vernier

This control is used to adjust the relative phase of the reference and test channel signals. It has a range of 90º [9].

Display Settings:

Amplitude/Division

This control can be adjusted to set the desired amplitude per division depending on the amplitude of the signal. The magnitude can be displayed at 0.25, 1, 2.5 or 10dB per screen division.

Phase/Division

As in the case of the Amplitude/Division control, the Phase/Division control can adjust the scale of the displayed phase difference. The scaling factor can be set to 1, 10, 45 or 90 degrees per screen division

2.1.3 The Smith chart:

The Smith chart is a graphical tool used to design certain microwave circuits and systems. The main application of a Smith chart is for impedance matching and it can also be used to represent complex impedances. This section concentrates on explaining the construction of the Smith chart.

Although the Smith chart appears to be an old fashioned tool, when used properly it can provide insight into the operation of a circuit that could have been bypassed by simply reading data produced by a computer simulation [10]. When illustrating fundamental concepts the Smith chart is the ideal tool, especially at the level where concepts are being explained to students and when they are exposed to these concepts for the first time. '*The Smith chart provides an extremely useful way of visualizing transmission line phenomenon, and so is also important for pedagogical reasons. Microwave and RF engineers can develop intuition about transmission line impedance matching problems by learning to think in terms of the Smith chart*' [11]. Therefore, at a beginner's level, using the Smith chart is ideal, as it will assist in developing intuition regarding microwave concepts.

The Smith chart is a polar plot of the voltage reflection coefficient (Γ). The reflection coefficient can be calculated as follows:

$$\Gamma = \frac{Z_{nL} - 1}{Z_{nL} + 1} \quad (2.7)$$

Where Z_{nL} is the normalised load impedance:

$$Z_{nL} = \frac{Z_L}{Z_0} \quad (2.8)$$

Where Z_0 is the characteristic impedance, usually 50Ω.

The Smith Chart consists of contours of constant reactance and resistance. This is shown in

Figure 4. The blue circle represents one of many fixed resistance contours. The resistance contours extend radially outwards as shown by the dotted blue line. The red arcs represent one of many fixed reactance contours. The reactance arcs also extend radially outward, illustrated by the dotted red lines.
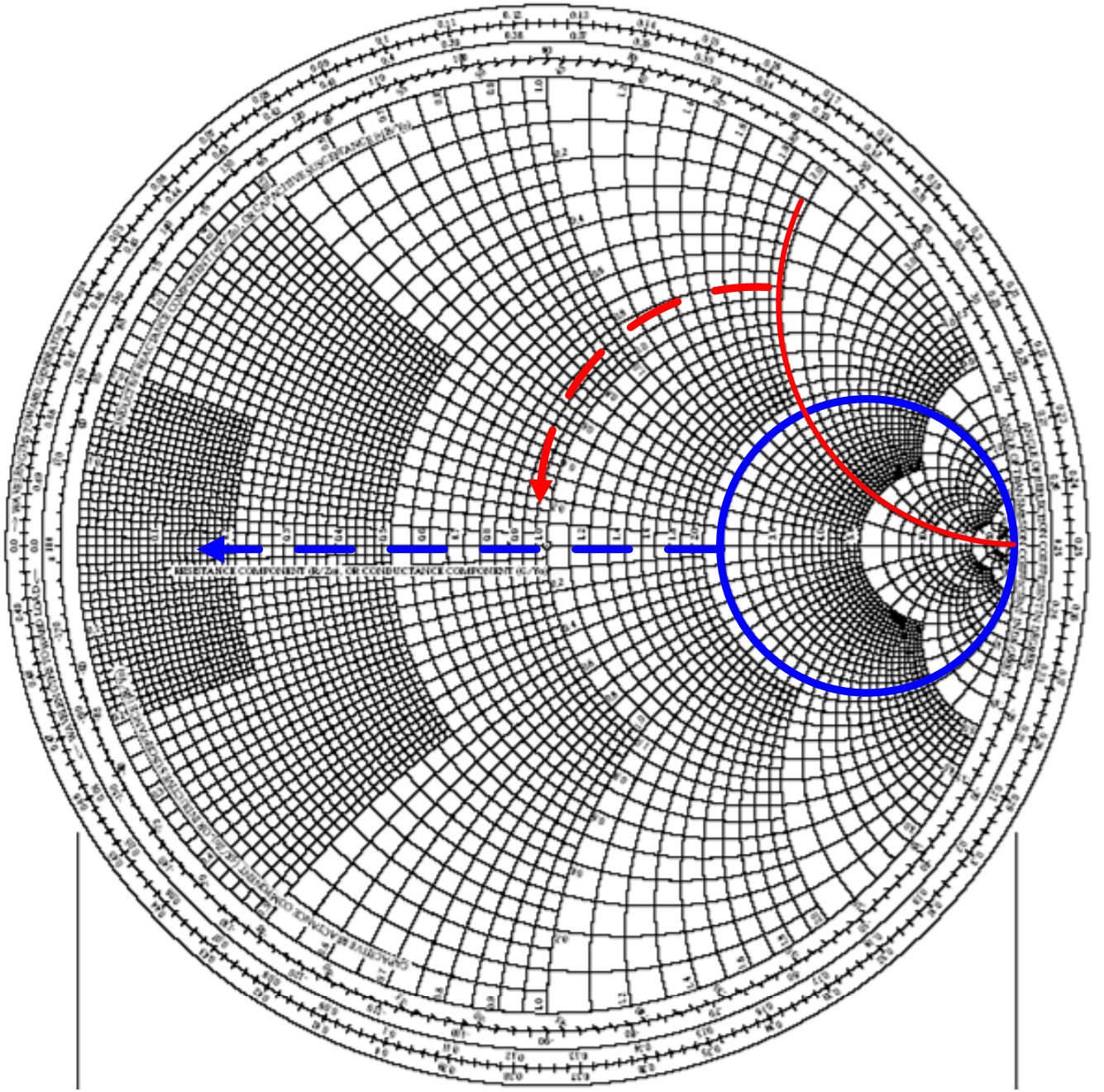
Figure 4: Smith Chart

2.2 Literature Review – looking at various options

Most thesis projects have the following sequence of events/sections to execute (see Figure 5). Specific instructions are given, after which the various options for solving the problem are reviewed by researching previous attempts to the problem. The best option is then chosen, based on the literature review, implemented, tested and then compared to the theory. This section aims to review the various options based on the research done.
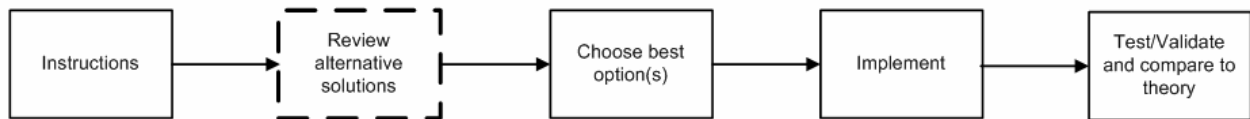
Figure 5: Project flow chart including literature review

There are various applications for the microwave range of frequencies, '*such as radar, communications, electronic warfare, weapons guidance, surveillance, navigation and a variety of commercial applications*' [2]. Wireless technology is growing at a rapid pace in South Africa and as well as globally and '*there is sufficient evidence to indicate that reasonable growth will continue into the foreseeable future*' [2].

Students interested in these applications, should therefore try and get as much exposure to these areas as possible. One way of allowing for this is to offer more courses covering these topics. However, theory needs to be balanced with sufficient laboratory experience [1]. This need for laboratory experience has been discussed in great detail in section 1.2.

Laboratory experience is very important as it allows the students '*to develop their physical intuition about microwave phenomenon*' [4]. It is also important that students at a graduate level have enough practical experience and have been exposed to microwave equipment [1].

The vector network analyser, together with the spectrum analyser, is a primary measurement instrument used in RF and Microwaves [3]. In order for students to get as much practical experience in the RF and Microwave field it would be essential to introduce them to this important measuring instrument.

'*Probably the biggest problem with a microwave instructional laboratory is in equipping it, as microwave test equipment is very expensive.*' [4]. It is for this reason that the equipment in the Microwave lab at UCT is not the most modern of instruments.

'*The HP8410A Network Analyzer is not a state-of-the-art instrument* [1].' More modern analysers feature '*integrated packaging, more versatile displays and graphical output capability, built-in computational power for data analysis and error correction, built in synthesized swept signal sources, and even some tutorial slant to their operating software [1].*' As briefly discussed in section 2.1.2 this less modern system is preferred as the analyser on which to give students their first introduction to this kind of equipment. A separate sweep oscillator and S-parameter test set is used, therefore students should get a good idea of the signal paths [1]. Most modern instruments have automatic tuning and calibration. The older model of the VNA requires manual adjustments and calibration '*which reinforce the students' understanding of how the system produces the desired data [1].*' The main disadvantage of the older model is that many of the processes have to be done manually for example calibration and taking readings, whereas with more modern models these processes are carried out automatically. This can become tedious if the VNA is used to acquire many readings and may lead to inaccurate readings.

There are various applications and applicable procedures for the VNA. There are various experiments available that have been designed for senior undergraduate microwaves courses. This section will be based mostly on these experiments. This section aims to review the various options available. The following sections will be discussed:

- Calibration
- Measuring Impedance
- Impedance Matching

- Applications/Experiments

- Microstrip circuit design

2.2.1 Calibration

Calibration is necessary to ensure accurate measurements [3]. In some cases calibration can improve measurements by up to 20dB [3]! Calibration is an important part in using the VNA and cannot be bypassed. Calibration compensates for mismatches caused by coaxial cables between the various components (VNA, Sweep Oscillator and the S-parameter test set) and also between the S-parameter test set and the DUT [7]. When using a cable to connect the DUT to the S-parameter test set calibration needs to be done at the end of the cable, effectively this moves the reference plane to the end of the cable [7]. It is also very important to note that calibration can only occur after the frequency range has been set and is only valid for that frequency range [7]. Calibration consists of 4 basic tests namely a short circuit test, an open circuit test, a thru test and a load test. The calibration process will be discussed in more detail in section 3.3.5.

2.2.2 Time-domain measurements

Most modern VNAs have an additional useful feature, which is to transform the measured frequency domain response of a device to the time domain [3]. This is particularly useful when the imperfections of connectors and cables are not clearly distinguishable from the measured response in the frequency domain. When transforming to the time domain these imperfections are clearly visible. These imperfections can then be gated out in the time domain and the remaining 'true' signal can be transformed back to the frequency domain [3]. This transformed signal is then a more accurate measurement of the device under test. The HP 8410 model doesn't offer this useful feature.

2.2.3 Measuring Impedance

The VNA can be used to measure impedances of certain components and track their frequency changes.

2.2.4 Impedance Matching

'Impedance matching and tuning is a topic that naturally follows the interconnection of components and transmission lines. [4]'

Impedance matching is desired in wireless systems for the following reasons:

- Maximum power is delivered to the load when it is matched.
- It improves the signal-to-noise ration of the system resulting in maximum data rate.
- In a transmitting system, impedance matching minimises the required RF power thus maximising battery life and reduces the risk of radiation hazard. [11, page 56]

Given a source resistance of R_S and a load resistance of R_L (See Figure 6), a perfectly matched condition will only be met when $R_S = R_L$ [12]. Matched conditions are desirable as they allow for maximum power transfer.
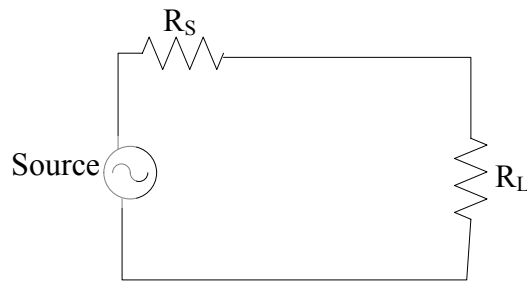

Figure 6: Load connected to a source

When the source impedance (Z_S) is not purely resistive but complex, maximum power transfer occurs when the load impedance (Z_L) is the complex conjugate of the source impedance [12].

Let:

$$Z_s = A + jB \qquad (2.9)$$

Then:

$$Z_L = Z_s{}^* = A - jB \qquad (2.10)$$

If a transmission line with characteristic impedance of Z_0 is terminated in a load of Z_0 then maximum power is transferred to the load and there is no reflected power as all the incident power is absorbed by the load. This maximum power transfer is valid for all lengths of transmission lines and is valid for any wavelength [13, page 881].

If the load is not equal to the characteristic impedance then part of the signal sent to the load is reflected back to the source [12]. This condition is undesirable because some of the transmitted data is sent back to the source and therefore not all the data is received. When a mismatch occurs it is interesting to observer the effect in the frequency domain [13, page 881]. There are 2 reasons for this, firstly any reflected waveform would have some extra phase relative to the incident waveform and this phase is frequency dependant [13, page 881]. Secondly, the input impedance depends on the mismatch and the electrical length of the line (in wavelengths) [13, page 881].

If the load impedance Z_L has a positive real part a matching network can be found [11, page 56]. A matching network can be inserted between the transmission line and the load, and is designed in such a way that the input impedance looking into the network is Z_0 [11, page 55] (see

Figure 7).
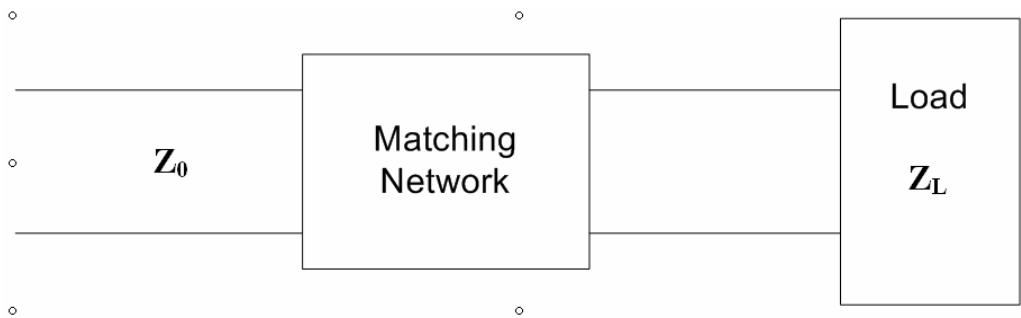
Figure 7: A lossless network matching a load to a transmission line [11, page 55]

There are 3 basic types of impedance matching networks [11, page 56] namely:

- The Quarter Wave Transformer
- Matching L-Sections
- Single-Stub Tuning

These methods will be briefly discussed:

1. **The Quarter Wave Transformer**

   The quarter wave transformer is a matching circuit used to match real loads to a transmission line. The circuit is shown in Figure 8.
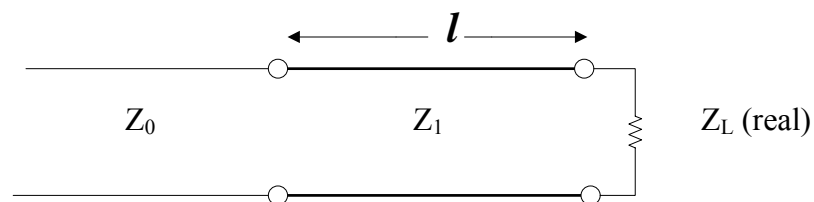
Figure 8: A quarter-wave matching transformer [11, page 56].

The characteristic impedance of the matching network is:

$$Z_1 = \sqrt{Z_0 Z_L} \qquad (2.12)$$

The impedance of the matching section must be chosen in such a way that it matches the Z0 (characteristic impedance of feed line) and ZL (impedance of the load) [13, page 881].

2. Matching Using L-Sections

L-section impedance matching networks make use of two reactive elements to match a load to a transmission line [11, page 58]. The main differences between this technique and the quarter wave transformer, is that L-sections are used in lower frequency designs and that the load can be a complex value [11, page 58]. This method is not suitable for high frequency signals, as it would be difficult to implement lumped element capacitors and inductors [11, page 59]. There are two possible configurations for this method depending where the normalised load is situated on the Smith chart. If the normalised load is inside the 1+jx circle then the configuration illustrated in   Figure 9 is used.
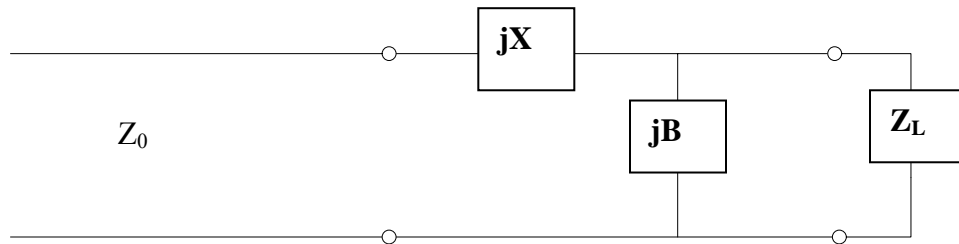
Figure 9: L-section matching network for Z_L in the 1+jx circle [11, page 59]

If the normalised load is outside the 1+jx circle then the configuration illustrated in Figure 10 is used.
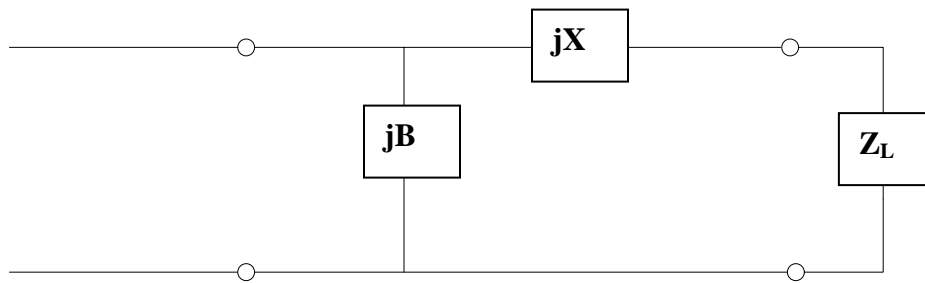
Figure 10: L-Section matching network for Z_L outside the 1+jx circle [11, page 59]

jB and jX are calculated using the Smith Chart. These methods are described in [11, page 59].

3. Single-Stub Tuning

In this technique a short length of transmission line, connected either in series or parallel with the transmission feed line at a certain distance from the load [11, page 61], is used to tune a mismatch [13, page 881]. The advantage of this method is that lumped elements are not necessary and the transmission lines can be in the form of a microstrip circuit [11, page 61]. Examples of single-stub tuning circuits are illustrated in Figure 11 and Figure 12.

$Y = \frac{1}{Z}$
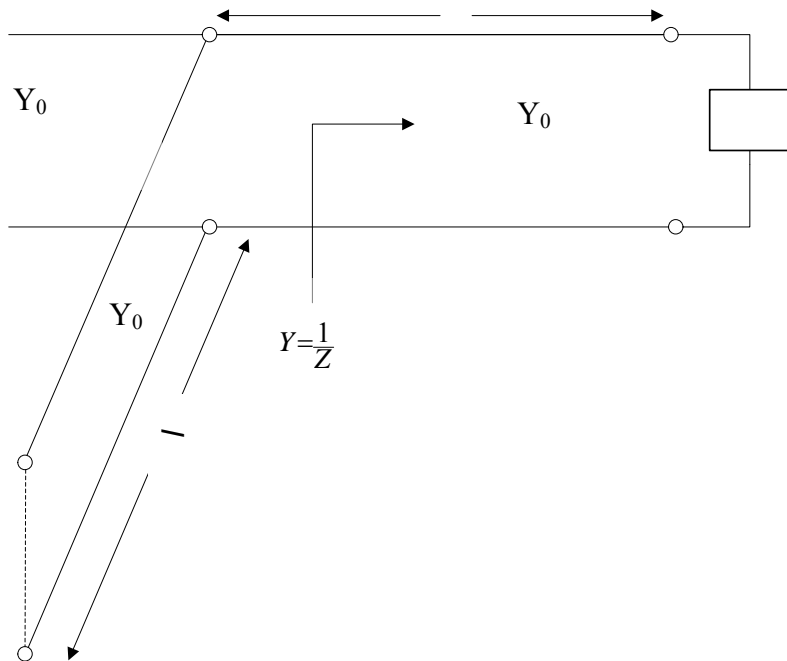
Figure 11: Shunt single-stub tuning circuit [11, page 62]

$Z = \frac{1}{Y}$
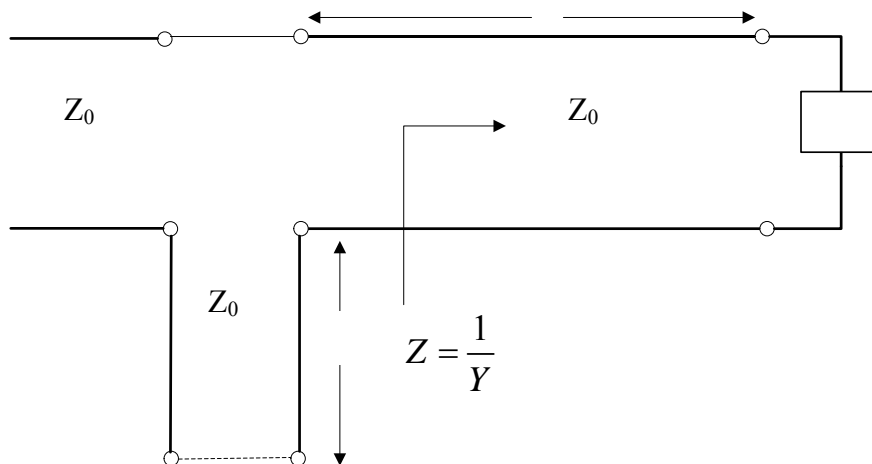
Figure 12: Series single stub tuning circuit [11, page 62]

This method is described extensively in [11, page 61-64]. The Shunt-stub impedance matching method will also be described in Experiment 2.

2.2.5 Characterising components

One of the useful applications of a VNA is to characterise RF and Microwave components. Their S-parameters are tested across a range of frequencies to test their characteristics. Amongst many components, the VNA is commonly used to characterise the following components:

- Filters [3]
- Antennas [14, chapter 4]
- RF Cavities [7,3]
- Amplifiers [7]
- Directional couplers [7]

2.2.6 Microstrip circuit design

The VNA can be used to test microstrip circuits.

3 DESIGN OF EXPERIMENT 1: USING THE NETWORK ANALYSER

This chapter begins by describing the design process of the first experiment, that is the use of the rectangular display. The aims of Experiment 1 are then stated, followed by the main elements of the experiment and then finally the actual design will be presented.

This practical consists of 3 stages namely:

1. **Pre-lab preparation:** Students will be required to prepare for the laboratory session. Any preparation will be specified in the sections below. They will not be allowed to attempt the experiments without presenting their preparations.

2. **Experiments:** Once the students have presented their pre-laboratory preparations, they will be required to carry out the experiments.

3. **Report:** The students will be required to submit a report, summarising the experiment and their findings.

3.1 Design Process

The design process used for Experiment 1 can be illustrated as follows:
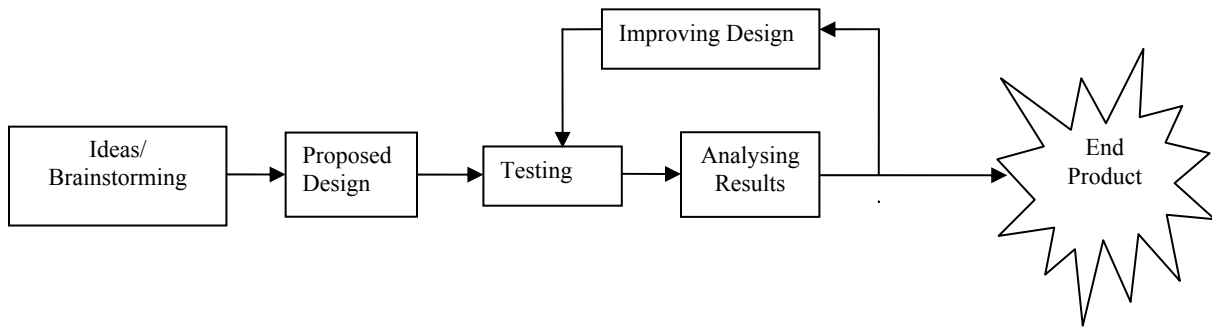
Figure 13: Design process used for Experiment 1

Firstly brainstorming and idea making are undergone, gathering thoughts and ideas on the various possible solutions (see literature review). A design then is proposed, tested and the results are analysed. Depending on the outcomes, the design may need to be improved, retested and results analysed again. This chapter will describe the design part of this process.

The next section will discuss the aims of Experiment 1.

3.2 Aims of Experiment 1

Experiment 1 will utilise the rectangular display of the network analyser.

The aim of this experiment is for students to develop a solid understanding of the vector network analyser and its basic applications. Experiment 1 will consist of basic measurements, allowing the student to become familiar with the network analyser and also to master the fundamental concepts. It aims to allow students to acquire more of an intuitive feeling for RF and microwave signals, to complement/reinforce their existing theoretical knowledge.

Once equipped with these basic skills and concepts the student should then be able to perform any advanced ("complex") measurement. This experiment would be useful to any first time user including Masters students needing to use the VNA for measuring their RF designs.

The following section will discuss the main elements of this experiment.

3.3 Main elements of Experiment 1

Not all the possible applications were chosen for these experiments. The reason is two fold. Firstly, not all of the applications (e.g RF cavities, microstrip circuits) were covered in the EEE486F course and students will not be familiar with the components. The second reason is the time constraint. Some of the applications would require a lot of implementation time, where time was the main constraint in this project.

Before an experiment can be designed, the fundamental theories behind the VNA need to be defined.

The main elements and fundamental theories of this experiment are thus as follows:

- General functions of a Network Analyser
- Block diagram of Network Analyser and setup
- S – parameters and the concept of reflection and transmission
- Connector types and the importance of making proper connections
- Calibration
- Adding a transmission line
- Using the network analyser to characterise certain RF and Microwave devices

3.3.1 General Functions of the Network Analyser

Before attempting to use the VNA, the students need to understand the functions of the VNA and its various applications. It will be required and expected of each student to do some research on the VNA and its various applications as part of their pre-lab preparation.

3.3.2 Block Diagram of Network Analyser and Setup

Block diagrams are useful in gaining an overview of systems. The students are asked to provide two block diagrams namely:

- A block diagram of the VNA

- A block diagram of the set up between the VNA, Sweep Oscillator and the S-parameter test set.

Block Diagram of the VNA

To ensure that students obtain a good understanding of the operation of the VNA, they are asked to provide a block diagram of the VNA, illustrating the process that a signal undergoes. By studying this process they should gain a better comprehension of the signals measured.
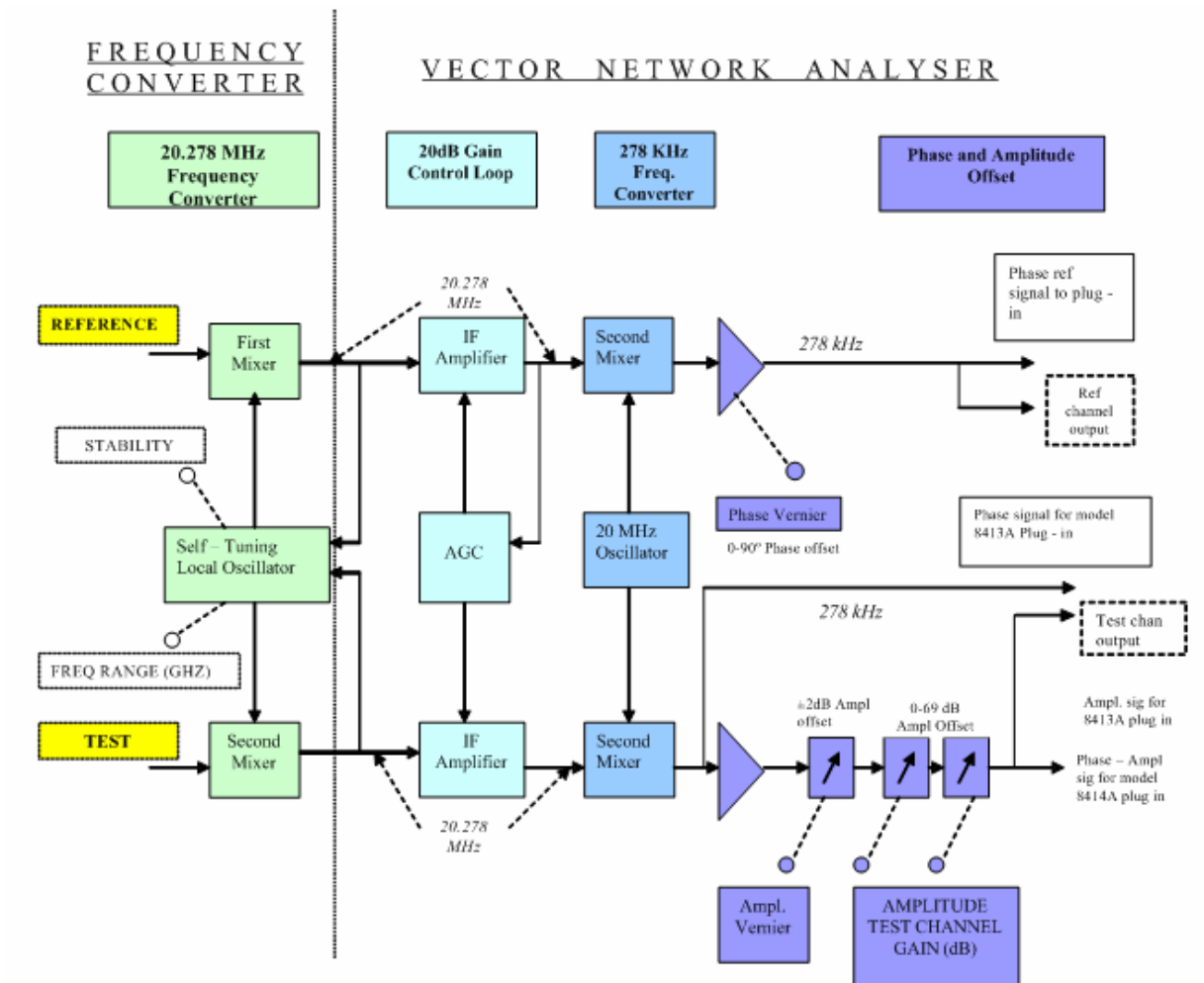
The block diagram of the VNA is shown in Figure 14.

Figure 14: Block Diagram of VNA [9]

There are two input signals to the VNA, the test signal and the reference signal. The reference signal comes from the sweep oscillator. Both signals are modulated down and converted to an intermediate frequency (IF) centred on 20.278 MHz by a self tuning local oscillator. This oscillator can be adjusted by the frequency range tuner and the stability tuner (on the VNA). Note that the magnitudes of these 20.278 MHz IF are unchanged and remain exactly the same as the magnitudes of the input signals. Each of the converted signals is then amplified by an automatic gain controller (AGC). The AGC maintains the output of the down-converted reference signal at a constant level. The same gain is applied to the down-converted test signal so that the ratio of their magnitudes remains identical. Both these signals are then down-converted again to a much lower IF frequency of 278 kHz. These two 278 kHz signals have the same phase properties and amplitude ration as the input signals. [9] The reason for this two-stage down conversion is that it relaxes the requirements of the filters in the IF bands because image rejection becomes much simpler.

The phase of the reference signal can be adjusted during calibration and then the position of this reference signal will be used as the reference signal. In the case of the test signal the amplitude can be adjusted during calibration.

The two main components of the VNA main frame are the HP 8411A frequency converter and the HP 8410 VNA.

Although complete, the block diagram above (Figure 14: Block Diagram of VNA [9]) may be too detailed for the students and can be simplified as follows:

Figure 14: Block Diagram of VNA [9] can be divided into two main sections namely:

- **Frequency Modulation** – where the original signals are mixed to a lower frequency.
- **Amplitude and Phase adjustments.**

These two sections are illustrated in a more simplified Figure 15
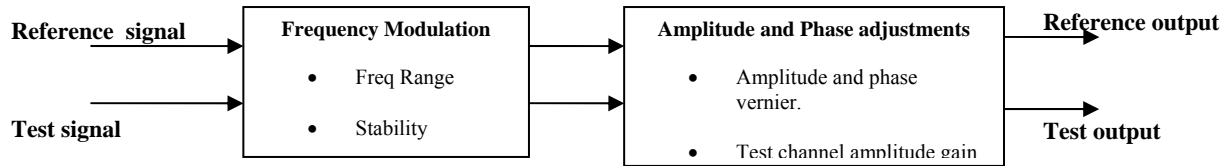
Figure 15: Simplified block diagram of the VNA

Block diagram of setup between VNA, S-parameter test set and Sweep Oscillator

It is important that students understand how the 3 main components (VNA, Sweep Oscillator and S – parameter test set) are connected. This will allow the student to get an idea of the physical meaning of the output signal.

This set is illustrated in Figure 16.
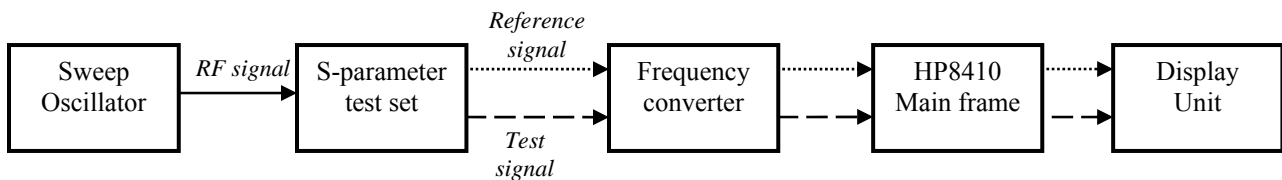
Figure 16: Setup of components: VNA, Test Set and Sweep Oscillator [15]

The sweep oscillator generates a RF signal which is output to the S-parameter test set. This RF signal is then divided into the reference and test signals. These two signals are then applied to the frequency converter where they undergo frequency modulation and are first translated to 20.278 MHz and then eventually down to 278 kHz. Phase and amplitude adjustments are made at the HP8410 mainframe and then the two 278 kHz

signals are output to the display unit [15]. This set up should be explained by the demonstrator at the beginning of the practical. Detailed connections are shown in Appendix A.1.

3.3.3 S – parameters and concept of reflection and transmission

Before attempting the practical, students should have a firm understanding of S-parameters and the concept of transmission and reflection. Without this understanding they will not be able to benefit from the practical. These concepts will briefly be discussed by the demonstrator at the beginning of the practical, but students are expected to revise these concepts before attempting the practical.

3.3.4 Connector types and the importance of making proper connections

There are various connector types used for RF and Microwave components. The students need to be introduced to the various connector types and understand their significance. As part of the preparation for the practical the students are asked to research the various types of connectors, namely BNC, SMA and N-type connectors. They are also asked to compare the various types of connectors and also to note their frequency limitations. The main reason that Microwave connectors are emphasised is that they are used to *"make low VSWR coaxial connections"* [16] and the students need to understand the difference between using normal DC connectors (such as crocodile clips) and RF and Microwave connectors. The various connector types and proper usage will be discussed and demonstrated at the beginning of the practical by the demonstrator. The following connectors are of importance:

Figure 17: Various connector types [16, 17, 18]

The SMA Male and Female pictures are taken from [16]. The BNC connector picture is taken from [17] and the N-type connector picture is taken from [18]

SMA – Sub Miniature Type A

These connector types are widely used in the laboratory and are *"perhaps the most widely-used microwave connector system in the universe"* [16]. They are often used to make connections between the S-parameter test ports and test equipment. SMA connectors have a frequency limit of 12 GHz [16]. Examples of SMA connectors are shown in Figure 9.

BNC – Bayonet Neill Concelman

BNC connectors are suitable for miniature or sub miniature cable terminations (RG – 59) [19]. BNC connectors are handy in the sense that they do not need to use a torque wrench to be attached and can be connected or disconnected rather quickly [19]. Some of the antennas used in the practical have BNC type connectors. BNC connectors have a frequency limit of 4 GHz [16]. An example of a BNC connector is shown in Figure 9.

N-type

These connectors are inexpensive and rugged [16]. They are used during the calibration process as the calibration kit has N-type connectors. N-Type connectors have a frequency limit of 11 GHz [16]. An example of an N-type connector is shown in Figure 9.

Adapters

Adapters are used to connect components of different genders and also of different connector types e.g. BNC to SMA. There are 3 types of adapters namely:

- Male to Male or "Barrel"
- Female to Female or "Bullet"
- Male to Male/Female to Female or "Connector Saver"

The importance of making proper connections

Students also need to be aware of making the correct connections. When attaching a connector it is advisable to keep the test equipment connector stationary and then turn the adapter. The reason for is this is that if a connector is damaged or broken, it is far cheaper to replace a connector than an expensive piece of equipment [16]. If the connections are not made properly then the signals measured may be inaccurate. To test whether proper connections have been made, the displayed signal should not vary or fluctuate at all when the cables/connectors are moved slightly. If the signal varied then the connections need to be reconnected and retested.

3.3.5 Calibration

Calibration is the first step in using a VNA. Accurate measurements cannot be taken without a calibrated instrument. There are four basic tests done during calibration namely

- Short Circuit Test
- Open Circuit test
- Thru Test
- Load Test (50Ω)

The calibration process will be demonstrated using the HP calibration kit (Type – N). These tests will be demonstrated at the beginning of the practical by the demonstrator. It is important to note that calibration needs to be done from the point at which devices are being tested. For example, if a cable is used to connect a device to one of the ports then the losses due to the cable need to be compensated for by means of calibration. In other words calibration will be done at the end of the cable. Not at the beginning of the port. The same applies for adapters or any component that links the DUT to the S-parameter test set.

The students should be able to predict the outcomes during calibration. They should be able to predict the significance of a short circuit test, open circuit test, thru test and load test by calculating the reflection coefficient of each of the scenarios. For example the reflection coefficient of a short circuit is 1 therefore the signal measured is $20 \log |1| = 0$ dB and the line measured should be noted as the reference line. The same applies to an open circuit test, load test and thru test. When calibrating the VNA students should intuitively predict the outcomes and meaning of the measurements.

Due to oscillations and imperfections of the signals at high frequencies, the reference "line" could be oscillatory (not a perfect straight line). This reference line needs to be recorded carefully and the measurements at different frequencies will be relative to the reference line at that frequency.

3.3.6   Adding a transmission line

Transmission lines could have an insertion loss an affect the measurements taken. It is very important to note that if a transmission line is used to connect a DUT to the test set, then calibration needs to be done at the end of the transmission line (the point where the DUT is connected).

Adding a transmission line can add extra phase to the signal.

3.3.7   Characterising RF and Microwave devices using a VNA

One of the main applications of the VNA is to characterise RF components and measure their S-parameters. This is a very useful application as designers are able to test their components and test their performance over a range of frequencies.

In this part of the practical students will characterise two different types of components namely:

- Various antennas
- A Filter

The students will be required to connect these components and then characterise them by looking at the various S-parameters across a range of frequencies. They will not be told what the components are and will be expected to figure out what the component is by looking at the S-parameters. This can be done as follows:

Antennas

There are several antennas available in the Microwaves Laboratory and the students will be required to characterise these antennas by looking at their S-parameters. In the case of the antenna it is a one-port device and will have to be connected to port 1 of the S-parameter test set. The reflection coefficient (S_{11}) will be measured and the resonant frequency should be determined by looking at S_{11}.

There are two antennas available for use for this experiment. The will be named antenna A and antenna B.

The following graphs are examples of S_{11} vs. Frequency.
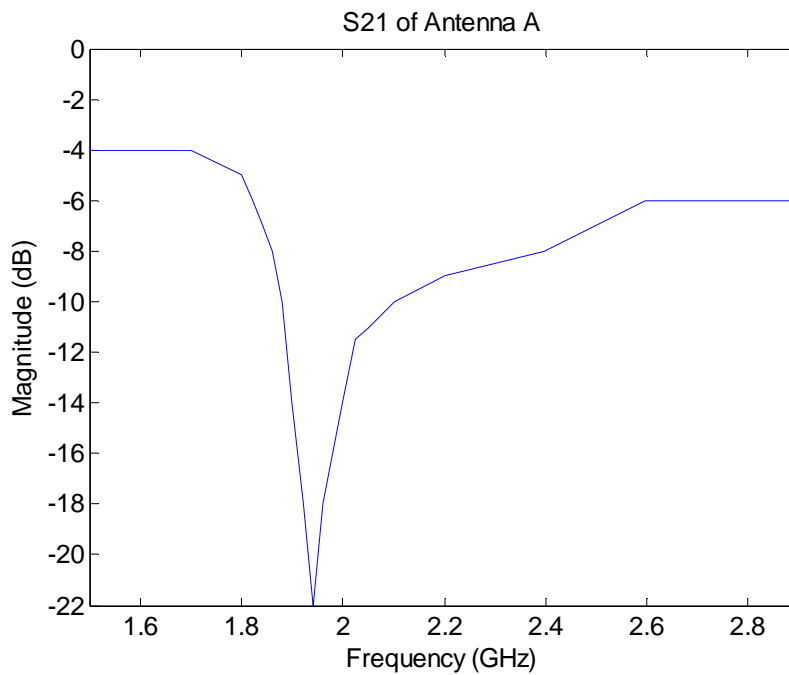
Antenna A:

Figure 18:S_{21} transmission characteristic of Antenna A

By looking at this graph students should be able to gather that the resonant frequency of antenna A is 1.94 GHz.
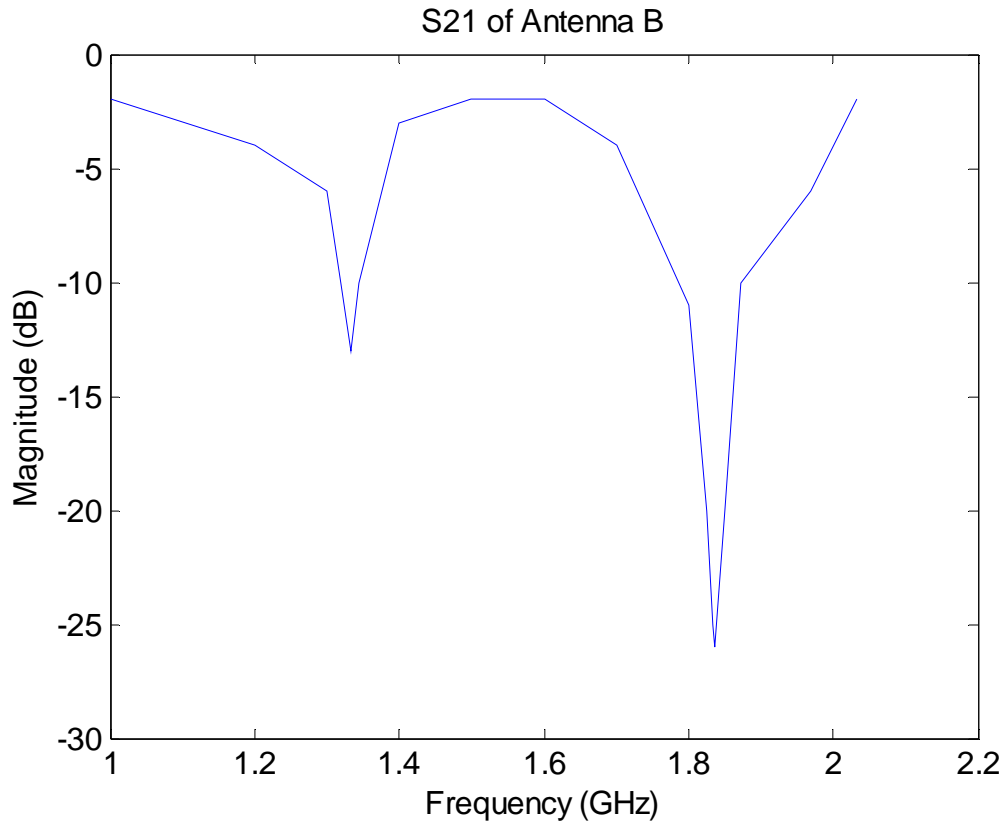
Antenna B:

Figure 19: S$_{21}$ transmission characteristic of Antenna B

The resonant frequency of antenna B is 1.84 GHz

Low Pass Filter

The characteristics of filters can also be determined by looking at its S-parameters.

In the case of a filter, which has two ports, S_{21} will be used to characterise the filter properties as S_{21} is the transmission characteristic and will determine which frequencies are allowed through the filter.

Filters can be categorised by the frequencies which are passed with no or little loss and the frequencies which are blocked.   This can be determined by examining the transmission characteristic, S21. (For example a low pass filter will have a high S21 at low frequencies and a low S21 at high frequencies)

The department of Electrical Engineering at UCT has 1 filter available in the Microwave Laboratory. It is a Low Pass filter with a cut-off frequency of 2.05 GHz. Its specifications are as follows:

Manufacturer	Lark Engineering
Serial Number	LSF2050-9AA-0960-0085
Type	Low Pass Filter
Cut-off Frequency	2.05 GHz
Insertion Loss	1.4dB

Table 1: Specifications of Low Pass Filter
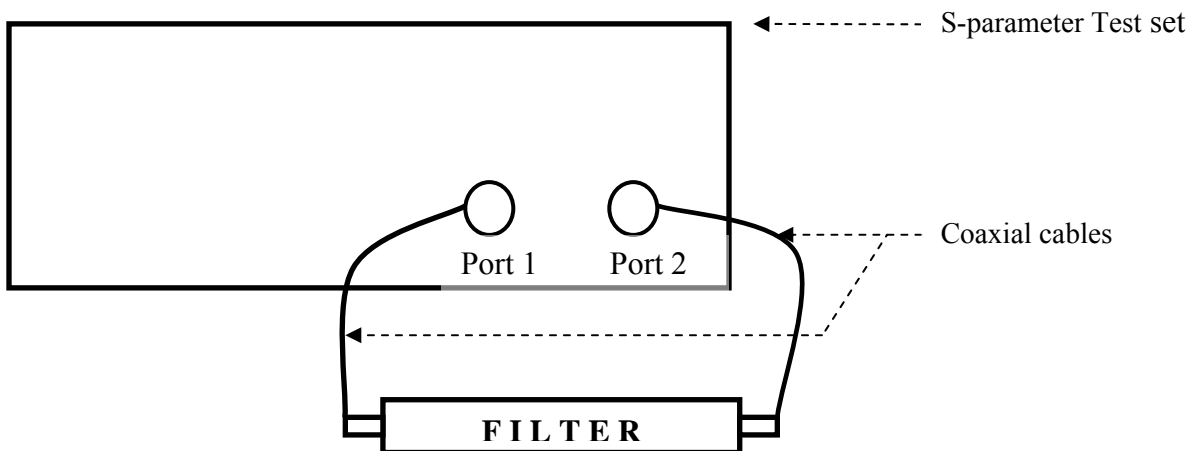
The filter will be connected as follows:

Figure 20: Set up showing connection of Filter

The parameter S_{21} is plotted against frequency, by acquiring measurements of the parameter at various frequencies across the range. (The measurement of S_{21} for the Lark Engineering filter can be found in the Appendix B.2). It should be noted that obtaining measurements from the VNA is tedious as they have to be done manually rather than having a computer output.

For the LPF, the measured S_{21} should resemble Figure 21.
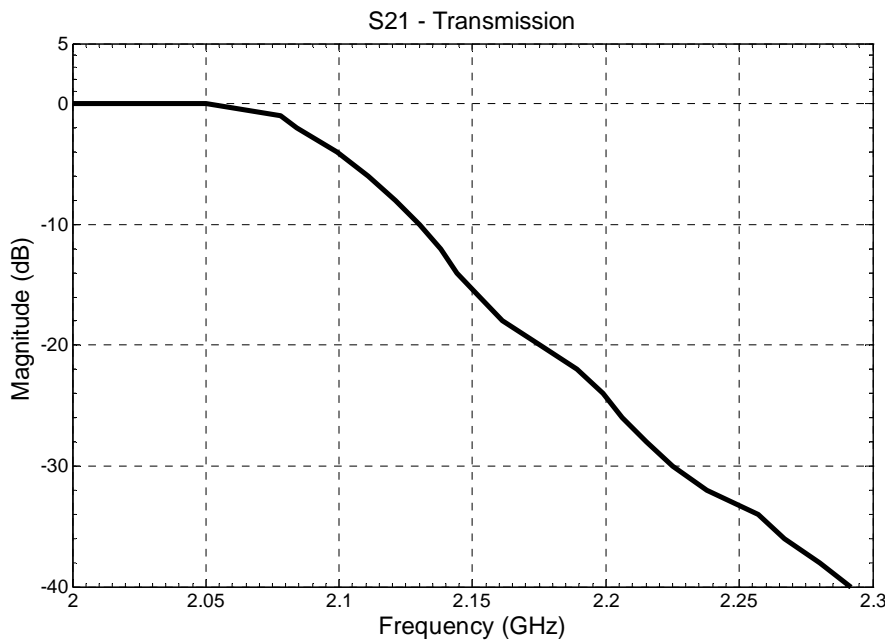
Figure 21: Low Pass Filter: S_{21} measurement

By looking at the S_{21} transmission characteristic the students should figure out that the device is indeed a low pass filter with a cut off frequency of 2.05 GHz.

Once the measurements have been made and readings have been taken the students will be asked to research this specific filter and find out the specifications and the properties of this filter and then use this information to verify the measurements made in the laboratory.

3.4 Design

The actual practical sheet to be given to the students can be found in the appendix B.1.
The model solution can be found in appendix B.2.

4 EXPERIMENT 2

Experiment 2 will utilise the polar display of the VNA illustrating the use of a Smith Chart for impedance matching. As in the case of Experiment 1, it will consist of 3 phases namely:

- A pre-lab preparations
- Experiments
- A report

Each of these phases has been described in section 3.

4.1 Introduction

As mentioned in section 2.2.4, impedance matching should naturally follow the interconnection of transmission lines and components [4]. This experiment aims to illustrate the importance of impedance matching by designing a laboratory experiment using a matching network.

As illustrated in Figure 22, if a load impedance (Z_L) attached to a transmission line does not match the characteristic impedance (Z_0) of the transmission line then a matching circuit can be connected between the load and the transmission line. This matching circuit compensates for the mismatch and the resultant circuit would be a matching circuit.
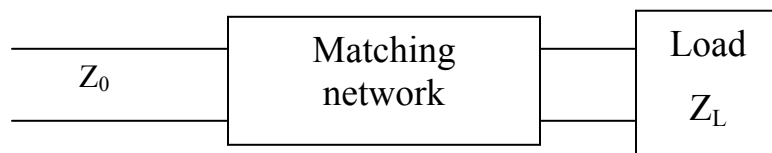

Figure 22: A lossless network matching a load impedance to a transmission line. [11, page 55]

Ideally, the matching network should be lossless to avoid loss of power and is designed in such a way that the impedance when looking into the matching network is Z_0 [11, page 55].

Impedance matching allows for maximum power transfer to the load [11, page 56].

There are 3 basic types of impedance matching namely:

- Quarter-wave transformers
- Matching L-sections
- Single-Stub Tuning circuits

These types of matching networks have been described in section 2.2.4.

Experiment 2 will only deal with single-stub tuning as it is more convenient for microwave fabrication, since lumped elements are not required [11, page 61].

Note that this is a very short practical and can be added to experiment 1. The two experiments have been presented separately as they utilise different displays.

4.2 Aim

The aim of this experiment is to match a complex load to a transmission line, to allow maximum power transfer.

4.3 Pre-lab preparation

As preparation for the practical, students will be required to do example 2.6 in the prescribed course text book [11]

4.4 Experiment

Students will be presented with 3 complex loads and 3 matching networks and will be required to figure out which network matches which load.

The experiment will consist of the following steps:

4.4.1 Measuring the reflection coefficient of an unmatched load

A 25Ω load will be attached to port 1 and the reflection coeffiecient of this load will then be measured. This aims to illustrated to students that if a perfectly matched load (50Ω) is not attached to a transmission line then not all of the power is transferred. A 50Ω load will then be attached to port 1 and the reflection coefficient of this perfectly matched load will then be measured and compared to that of the unmatched load.

Note that a 25Ω load can be constructed by connecting two 50Ω loads in parallel.

4.4.2 Measuring an unknown load

A complex load is of the form

$$Z_L = R + jX$$

Where R is the real resistive part and X is the imaginary reactive part of the load

To measure the refection coefficient of an unknown load, the load is attached to Port 1 of the S-parameter test set and S_{11} is then measured as a display on the Smith Chart. This value will then be the normalised complex load. So if the characteristic of a transmission line is 50Ω, then the actual impedance of the device is z_L * 50Ω.

Students will be given 3 complex loads and asked to measure their impedance.

4.4.3 Calculating the shunt stub matching circuit

This method is taken from [11]
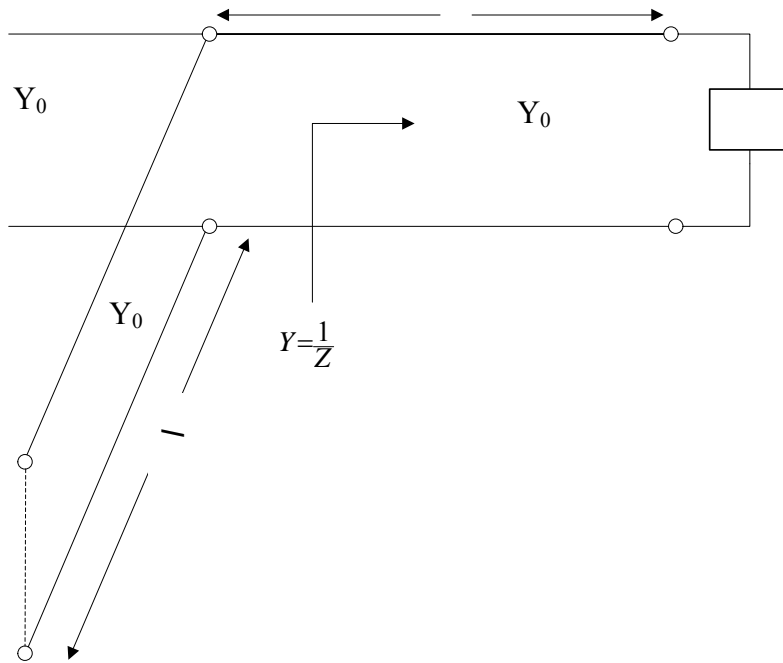
The students will then be asked to calculate the 2 lengths for each of their 3 loads:

- the distance from the load to the shunt stub (d)
- the length of the shunt stub (l)

They will also be asked to calculate the susceptance of the stub.

4.4.4 Matching Networks

They will then be required to match the loads to the various matching networks and measure the effect of having a matching load.

4.5 Report

The students will then be required to write a very short report on their findings and draw conclusions.

4.6 Implementation

Please note that this is merely a design for Experiment 2. Due to time constraints, this experiment has not been implemented yet and could be implemented after the submission of this project.

5 RESULTS

5.1 Results

The practical was tested by 4 Masters students. Some of these students are familiar with the VNA, while others are first time users. Their feedback was positive and they added a few suggestions.

They were asked the following questions:

Questions:

1. Would you say that the practical is useful to first time users?

2. Is it too simple/too complicated?

3. Was anything in the practical sheet unclear?

4. Do you have any suggestions as to how this practical could be improved?

The response from the students was as follows:

Student 1:

1. Yes, very useful and simplistic.
2. No, it is neither too simple nor too complex; I think the approach you've used is just right.
3. The calibration – the reference line doesn't have to be at the top of the screen.
4. No, you've used the best approach.

Student 2:

1. Very useful
2. No, not too simple
3. Very clear and not cryptic at all
4. Perhaps demonstrate the practical first and then allow students to do the practical themselves.

Student 3:

1. Yes, very useful.
2. No, it uses the right approach
3. Yes, very clear.
4. When the doing research on the connectors, students should compare the different connectors based on their dimensions and operating frequencies. You should also incorporate measuring the reflection properties of many different coaxial cables of different dimensions and lengths and then compare the results.

5.2 Discussion of results

The results indicate that most of the students agree that the practical is a good introductory practical for first time users; this indicates that the design was successful and thorough. The practical is neither too basic nor too complicated. The suggestions given by Student 3 were added to the practical.

6 CONCLUSIONS

Initially the aim of this thesis was to design and implement experiments involving the Vector Network Analyser (VNA) for 4th year RF and Microwave students.

Research was then done on the various applications of the VNA and possible experiments were studied. The EEE 486F course is a system level course and only covered a few of the applications studied.

The proposed practicals were therefore as follows:

Experiment 1 – A basic introductory practical for first time users, using only the rectangular display of the VNA. It consists of calibration methods, transmission line effects, characterising antennas and characterising unknown two-port devices.

Experiment 2 - A more advanced practical illustrating impedance matching using a single-stub matching network.

 The conclusions drawn are thus as follows:

- Experiment 1 was tested and it was found that most of the students were able to understand the basic network analysis theory by doing the practical. They also said that the experiment was very thorough and that it covered all the main elements of the VNA.

- It is concluded that the HP 8410 model is a relatively old model (circa 1983) and more modern models are available.

- Although there are many microwave applications and designs available, the practical implementation of the designs can be rather tedious as microwave circuits do not behave as normal low frequency circuits.

- It is evident that students need to be exposed to more laboratory experiments. Microwave theory is introduced to students at a 3rd year level and they are not exposed to any practical experiments. The 4th year RF and Microwaves course offers mostly computer based simulations as practicals and not enough experimentation with real equipment.

7 RECOMMENDATIONS

Based on the conclusions the following recommendations are made:

- Experiment 1 should be presented as a practical to 4th year students

- Experiment 2 needs to be implemented and more time should be taken to implement more components to be used for practicals. I propose that the implementation of experiment 2 is assigned as a thesis project for 2006.

- I would suggest that the department purchases at leas one more modern VNA as the available one is not computerised at all and obtaining results from the VNA involves tedious manual readings. The older model can still be used for educational purposes, but a modern VNA is necessary to make accurate readings.

- I suggest that students are exposed to the design and implementation of microstrip circuits.

- Practicals and experiments for Microwave courses should be developed and introduced at a 3rd year level to develop intuitive practical skills amongst the students.

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Appendices are a separated document.