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DEPARTMENT OF TECHNOLOGY AND BUILT ENVIRONMENT

LARGE SIGNAL RF MEASUREMENT METHODS AND IMPLEMENTATION OF A TUNED RECEIVER SYSTEM

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September 2008

Master's Thesis in Electronics/Telecommunications

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ABSTRACT

This report shows a survey of sate of the art different large signal RF measurement systems. Such measurement systems are discussed in detail with respect to their architecture, method of measurement, calibration, accuracy, dynamic range and bandwidth. Finally, a RF measurement system for large signal was designed and implemented. This measurement system was based on a tuned receiver. Harmonic distortion type measurements were taken by this system and time domain waveforms were reconstructed using external software.

ACKNOWLEDGMENTS

I would like to thank my supervisor Mr. Olof Bengtsson for guiding me throughout my thesis work. His experience and deep knowledge of the subject has helped me a lot in understanding the problem and in learning how to solve problems in a professional way. I would like to congratulate him for completing his Ph.D.

I would also like to thank all my friends for sharing countless enjoyable moments with me. Per Landin, Efrain Zenteno, Hibah Al Tahir and Edith Graciela Company during thesis work was really worthy. Sharing knowledge with them was fun and specially those lunch time discussions helped me in broadening the vision.

Finally to my beloved family for always encouraging me in my life to go ahead and helping me in every sense. All credit goes to my parents for always providing me a good environment and for teaching me all the good things in life.

Never Let the Knowledge to Limit Your Vision …..

Some Wise Person

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List of Abbreviations

ACPR : Adjacent Channel Power Ratio
ADC : Analogue to Digital Converter
AM : Amplitude Modulation
DUT : Device Under Test
DSO : Digital Sampling Oscilloscope
CW : Continuous Wave
GPIB : General Purpose Interface Bus
HPR : Harmonic Phase Reference
IF : Intermediate Frequency
NIST : National Institute of Standards and Technology
PM : Phase Modulation
RF : Radio Frequency
S-parameters : Scattering Parameters
SOLT : Short Open Load Through
TRL : Through Reflect Line
TRM : Through Reflect Match
VNA : Vector Network Analyzer

1 INTRODUCTION

Characterization of microwave devices has always been important in microwave field. It is needed to check that whether designed devices are really complying with the specifications. Linear devices can be completely characterized by using S-parameters. Such linear devices can include cables, attenuators, couplers, dividers and filters. Their behavior is linear and hence, superposition principle can be applied on S-parameters. A typical VNA (Vector Network Analyzer) is capable to measure the S-parameter for such devices very accurately. Semiconductor devices like diodes, amplifiers and mixers introduce nonlinearities in the system. If the input signal is small, their behavior is still linear and S-parameters (Scattering parameters) theory is still valid there. This can be checked by measuring S-parameters at two different power levels but same frequency and then comparing the results. For linear behavior, results must be same.

However as needs for power efficiency is increasing, systems like amplifiers need to be operated in compression region. RF power amplifier engineers need to make a tradeoff between linearity and power added efficiency. This means system must be operated in nonlinear region where a lot of harmonics and intermodulation products are generated. In this region, S-parameters are no more valid, because other frequency components are also present at output.

To analyze a system in this region is referred to as large signal analysis, means that input signal to a system is large enough to push it into nonlinear region. In linear region, S-parameters are calculated by taking ratios of incident and reflected waves. While in large signal analysis, individual incident and reflected waves present at each port are measured and then analyzed. Which means a good knowledge of the amplitude and the phase of each component present at input and output is needed. Or in other words, real time domain analysis is of more interest. By getting large signal behavior information, accurate models for non linear devices and systems can be built. Different phenomenon happening in nonlinear region like breakdown voltages and currents, am-am and am-pm conversion, ACPR, harmonics generation and compression can be studied in much more detail.

1.1 Previous Work Done

Different approaches for large signal analyses had been proposed and tested earlier. These methods vary in complexity in architecture and the method they measure. Earlier, sampling oscilloscopes were used to obtain the voltage and current waveforms [1]. Later, concept of receiver mode of VNA for data acquisition in the measurement system was implemented [2]. Some load pull setup was also introduced in such a system [3].

Modern systems have included Vector Signal Generators along with broad band acquisition system [4]. This system is called Large Signal Network Analyzer (LSNA). Another system has been introduced named as VNA+ which turns a normal VNA into receiver mode. By adding an additional signal source for reference and dedicated software, large signal measurements are performed [5].

1.2 Objective

The aim of the thesis was to study different measurement techniques to characterize nonlinear devices. Several measuring techniques like using sampling oscilloscopes, source-load pull setup, VNA in receiver mode, and a LSNA (Large Signal Network Analyzer) etc are used by engineers for large signal analysis. These measurement systems can be differentiated on basis of their stimuli signal, data acquisition systems and what they measure. Aim was to study such measurement systems and to analyze them with respect to their architecture, method of measurement, calibration etc.

A part of project was to design and implement a large signal RF measurement system using a tuned receiver. This measurement system was supposed to do harmonic distortion type measurements. Anritsu 37169A VNA in receiver mode was to be used in this measurement system. Aim was to measure the amplitude and phase of harmonics generated by a nonlinear DUT and then to recreate their time domain waveforms using external software.

1.3 Outline of Report

Chapter 1 is a brief introduction about the large signal analyses, objective and contents of this report. Also, a view of previous done work done in the same field is mentioned. A clear problem statement is mentioned. Also.

Some theory related to S-parameters and types of errors in a measurement system is mentioned in Chapter 2. It was felt necessary to refresh the basic concepts about S-parameters and nonlinear S-parameters. Different types of error in measurement system are also discussed in detail.

Chapter 3 deals about the different measurement techniques for large signal analyses. Results of these techniques are more or less the same. They differ mostly in excitation signal types and data acquisition. Measured data is represented in different ways as there are several ways to represent nonlinearity. A small conclusion is also mentioned in the end of this chapter.

A large signal RF measurement system was designed to measure harmonics generated by an amplifier. Anritsu 37169A VNA in receiver mode was used for data acquisition in this system. Chapter 4 discusses the architecture, calibration and measurement method of this system in detail. Different parts of the measurement system and their specifications are focused. Also the calibration procedure is mentioned. External software was used to measure and display the time domain wave form. Algorithm of this software is presented in this chapter.

Some measurements were taken by the designed system. Chapter 5 deals about the measurement results. Results are analyzed in this chapter and different sources of error are also mentioned. A final conclusion of the work is also presented along with future work.

Finally in chapter 6, a list of references is presented that were used during the project work. These references are very useful in understanding the project.

2 THEORY

2.1 S-parameters

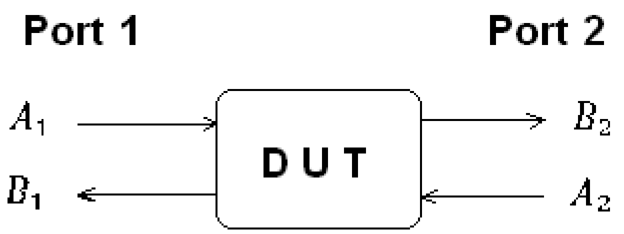

Figure 1 : Waves at Port 1 and Port 2 of a DUT (Device under Test).

If some voltage wave is applied on a 2port DUT (Device Under Test), some of the wave is transmitted through the device and some of it is reflected back due to mismatch. Figure [1] represents such waves, where A represents incident wave and B represents the reflected wave. Subscripts 1 or 2 represent the port 1 or port 2. The voltage and current present at each port can be calculated by using Equations [1] and [2].

$$V_n = \sqrt{Z_o}\,(A_n + B_n) \qquad [1]$$

$$I_n = \frac{1}{\sqrt{Z_o}}(A_n - B_n) \qquad [2]$$

Where subscript n shows the port 1 or port 2 and Z_o is the characteristic impedance of the network. At microwave frequencies, all parts of a system must be matched to each other. Otherwise a lot power would be lost as reflections. Solution to this problem is to choose a fixed characteristic impedance for all parts of the system. Most systems use 50 ohm characteristic impedance and all components of system are normalized to 50 ohms. Some systems are normalized to 75 ohms also.

S-parameters define a relation between incident and reflected voltage waves by taking ratios ofA_n and B_n. For a 2 port device, S-parameters can be found out by Equations [3], [4], [5] and [6].

$$S_{11} = \frac{B_1}{A_1} \; given \; A_2 = \; 0 \qquad [3]$$

$$S_{21} = \frac{B_2}{A_1} \; given \; A_2 = 0 \qquad [4]$$

$$S_{22} = \frac{B_2}{A_2} \; given \; A_1 = 0 \qquad [5]$$

$$S_{12} = \frac{B_1}{A_2} \; given \; A_1 = 0 \qquad [6]$$

In matrix form S-parameters can be found out according to Equation [7].

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} \qquad [7]$$

.

2.1.1 S-parameters for nonlinear region

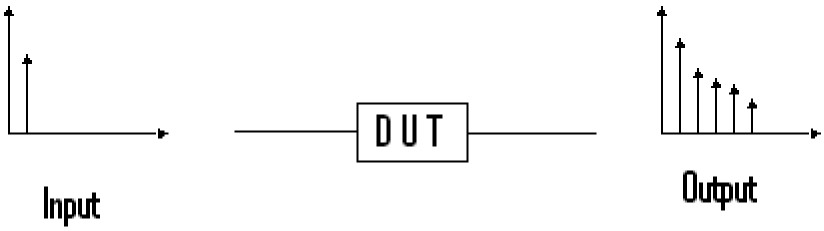

Figure 2 : DUT under large signal

By large signal, it is meant that input signal is strong enough to turn the nonlinear device into compression region. In this region, many spectral components are present at the output like IM products and harmonics as shown in Figure [2]. The superposition principle of S parameters cannot be applied here. Absolute amplitude and phase of each wave present at input and output of a device are needed for large signal analysis.

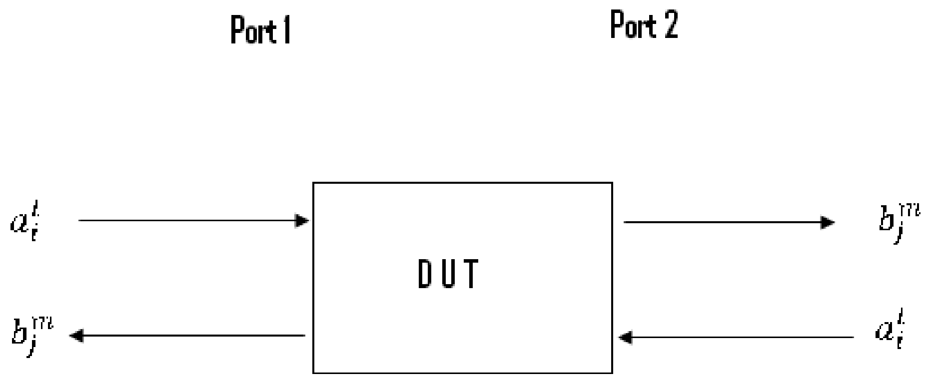

Figure 3 : Two port nonlinear network.

Consider the Figure [3]. It shows a 2 port nonlinear device. A signal containing a harmonic (for simplicity) is fed to each port. This signal is denoted bya_i^l. The reflected signals from DUT are denoted by b_j^m. In both notations, subscripts i and j denotes the port 1 or port 2 and the superscripts l and m shows the order of harmonic. 1 is for fundamental (f_o), 2 for 1st harmonic ($2*f_o$). Nonlinear s-parameters should not only give relation between the incident and reflected (or transmitted) wave but also should give relation between each harmonic. Nonlinear s-parameters for such a case would be defined by S_{ji}^{ml}. It is the ratio of mth harmonic present at jth port to the lth harmonic present at ith port, mathematically shown by Equation [8].

$$S_{ji}^{ml} = \frac{b_j^m}{a_i^l} \qquad [8]$$

In matrix form, nonlinear s-parameters of this system can be shows as in Equation [9].

$$\begin{bmatrix} b_1^1 \\ b_1^2 \\ b_2^1 \\ b_2^2 \end{bmatrix} = \begin{bmatrix} S_{11}^{11} & S_{11}^{12} & S_{12}^{11} & S_{12}^{12} \\ S_{11}^{21} & S_{11}^{22} & S_{12}^{21} & S_{12}^{22} \\ S_{21}^{11} & S_{21}^{12} & S_{22}^{11} & S_{22}^{12} \\ S_{21}^{21} & S_{21}^{22} & S_{22}^{21} & S_{22}^{22} \end{bmatrix} \begin{bmatrix} a_1^1 \\ a_1^2 \\ a_2^1 \\ a_2^2 \end{bmatrix} \qquad [9]$$

2.2 Types of Error

One should be fully aware of what we are measuring. Otherwise erroneous data can be perceived as corrected one. There are generally three types of error that effect measurements.

Stochastic Errors
Drift Errors
Systematic Errors

2.2.1 Stochastic Errors

These are random errors and they change by time. As it is difficult to predict them, they cannot be corrected mathematically. Main sources of stochastic errors are switch and connector repeatability, noise by mixers and local oscillators. Stochastic errors can be reduced by increasing the power of input signal, reducing IF bandwidth and averaging.

2.2.2 Drift Errors

Drift errors are mainly due to temperature changes. Even after a calibration is performed, system can deviate from calibrated behavior because of change of temperature. This in turn determines how often one should perform calibrations. By maintaining the temperature of equipment, they can be reduced.

2.2.3 Systematic errors

These are due to imperfections in measurement system. Systematic errors are reproduce able and hence can be corrected mathematically. Such a correction is commonly known as calibration.

2.3 Calibration

Calibration is an important part of any measurement system. In this section, calibration for a VNA is in focus. Different correction models are available for calibration. They differ in complexity and accuracy. 12 term, 16 term, 6 term and response calibration are mostly used. Simple models are less complex and take less time to perform, but in turn accuracy is also less. Choosing a correct model solely depends on the requirement of the system. After selecting a suitable model, calibration type must be chosen. For 12 term correction TOSM (Through Open Short Match) is employed. Other popular types are TRL (Through Reflect Line) and TRM (Through Reflect Match). Selecting a calibration type involves the selection of calibration kit to be used.

2.3.1 6- Term Error Model

6 term correction model or one path two port calibration is shown in Figure [4]. The letter 'F' in Error terms represents forward path which is from Port 1 to Port 2. By using the same error model in reverse path, we can obtain the full 2 Port error model or 12- Term error model. Here one thing is notable that the term ETF (Transmission Tracking Error) is defined for the whole path and not only for port 2.

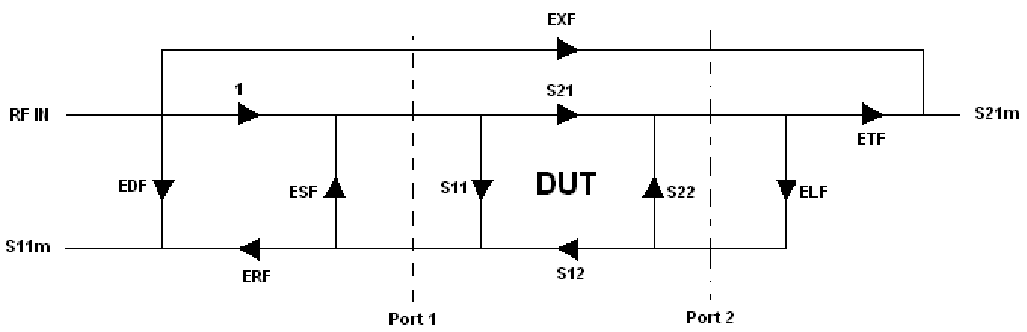

Figure 4 : 6 -Term Error Model (One path Two Port Calibration).

Where,

EDF = Error due to directivity of couplers

ESF = Error due to source mismatch (reflection)

ERF = Error due to reflection tracking,

ELF = Error due to load mismatch (reflection)

ETF = Error due to transmission tracking

EXF = Error due to cross talk

By using SOLT (Short Open Load Through, also known as TOSM) type calibration, these error terms can be corrected. These error terms are complex and they correct for both amplitude and phase of signals.

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3 DIFFERENT MEASUREMENT TECHNIQUES

For large signal analysis a new measurement system is needed to be design. So far different techniques have been proposed and tested. This chapter discusses such techniques.

These techniques are different from each other with respect to stimuli signal and acquisition systems [6]. Typical stimuli signals are CW or mutlitone CW (modulated signals). Acquisition systems are the crucial part of such measurement systems. It may contain a combination of sampling oscilloscopes, VNA, tuners, RF couplers and samplers etc.

3.1 Measurement System Using a Sampling Oscilloscope

3.1.1 Sampling Oscilloscopes

Oscilloscopes are used for time domain analysis. It measures the amplitude and phase of the input waves to oscilloscope. Oscilloscopes can be dived into two categories; real-time oscilloscopes and sampling oscilloscopes. Main difference in these categories is due to their internal operation. Real-time oscilloscopes repetitively sample a wave form at a high rate. Their input impedance is quite high and operating bandwidth is limited to about 500MHz.

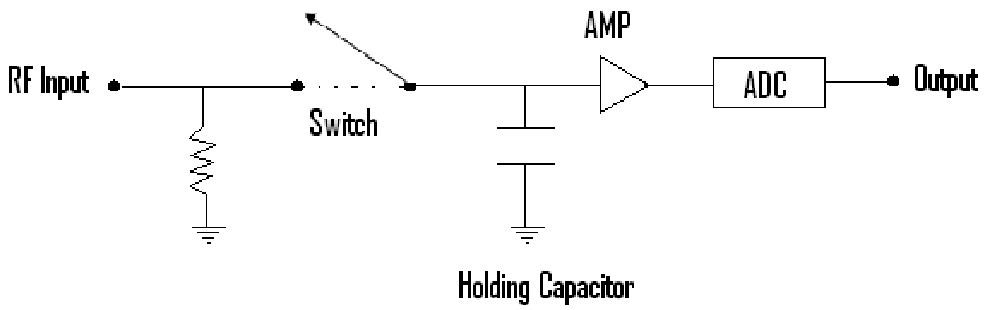

Figure 5 : Sampler Circuitry for sampling oscilloscope.

Sampling oscilloscopes use equivalent time sampling. It means that they sub sample the input waveform and then reconstruct it. This makes them slower devices and only repetitive signals can be measured. Figure [5] shows a typical circuit of the sampling head of a sampling oscilloscope. A programmable delay generator closes the switch momentarily after being triggered. The charge achieved by the holding capacitor during closed switch is proportional to the voltage at the input of oscilloscope. An amplifier followed by an ADC is used to measure this charge. Hence, the input voltage when the switch was closed is measured.

Errors offered by time base of oscilloscopes are of three types. Jitter; random error in time at which the oscilloscope samples, Drift; a slow drift in sampling time between successive sweeps and Time base Distortion or Phase Distortion; a systematic error in time base.

Other errors are due to mismatch (due to mismatches between source and load) and impulse response (due to sampling heads). VNA is used to encounter mismatch errors. Impulse response error is a fundamental and challenging aspect of the calibration of high speed oscilloscopes. NIST has developed a system to calibrated oscilloscopes. It uses a calibrated power meter for amplitude correction and a photo diode (calibrated on NIST's electro-optic sampling system) for the phase correction. Detailed study of calibration of oscilloscopes is in [7].

3.1.2 Nose-to-Nose Calibration

Like all other microwave instruments, calibration of oscilloscopes is necessary to measure accurately. For low frequency waves, calibration can be neglected as the wavelength is big enough. But for high frequency waves like microwaves, oscilloscopes must be calibrated up to the input terminal or probe. So called nose-to-nose calibration is used for calibrating the oscilloscopes and corrects for impulse response. In this process, two oscilloscopes input are connected directly to each other. Then, one oscilloscope measures the impulse response of input channel of other oscilloscope. In this procedure, it is assumed that both oscilloscopes are identical. By using three different oscilloscopes, assumption for both oscilloscopes to be identical is no more needed. A detailed study of such a calibration is given in [8]. NIST is investigating about the validation of such calibration.

3.1.3 Measurement System using a two channel Sampling Oscilloscope

A measurement system was implemented by using a two channel broadband sampling oscilloscope for measurement of waves at input and output of DUT [1]. Figure [6] shows a simple schematic of such a system.

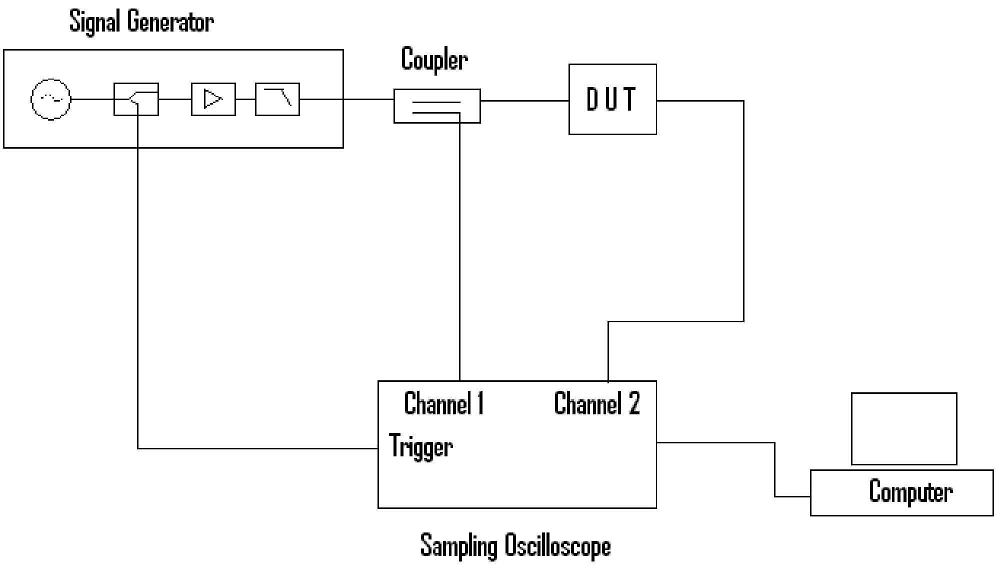

Figure 6 : Measurement system using sampling oscilloscope.

The signal generator consisted of a synthesized signal source (sinusoidal), a power divider (to divide signal in two paths; one for input to DUT and one for triggering oscilloscope), a linear power amplifier (to make signal strong enough to put DUT in nonlinear region) and a low pass filter (to cut all harmonic contents in the input signal to DUT). One channel of oscilloscope was connected to a coupler at input of DUT to measure the reflected signal.

Input signal can be measured by replacing DUT by a short. The second channel was connected to output of DUT. In this way, wave at input and output of DUT were measured by the sampling oscilloscope. Bias tees were used to give bias to DUT. A separate computer was attached to this system and an algorithm was made to compute the waveform in time domain.

The system was calibrated by knowing the S parameters of the input and output modules using a VNA. Also an attenuator was used at source output to improve matching between the source and DUT.

Main advantage of such a system is simplicity. Excitation is possible on input port and it can measure the harmonic contents at output port only. That is, only harmonic distortion type measurements are possible. It was also assumed that no phase distortion is offered by the sampling heads. Data acquisition system normally determines the overall dynamic range of the system. Dynamic range of such system can be low due to sampling oscilloscopes. Also some problems regarding trigger stability of the oscilloscope were faced which made it difficult to use fundamental frequency component higher than 5 GHz. Measuring speed would also be slow because sampling oscilloscopes are rather slow instruments. Replacing the DUT by a short for incident wave measurement is also a factor for reducing speed. This connecting and disconnecting of DUT give arise to connector repeatability problem.

A modified version of such a system was introduced by G. Kompa et al. [9], where a VNA was added to system to totally and accurately characterize the test setup. A schematic of such a system is shown in Figure [7].

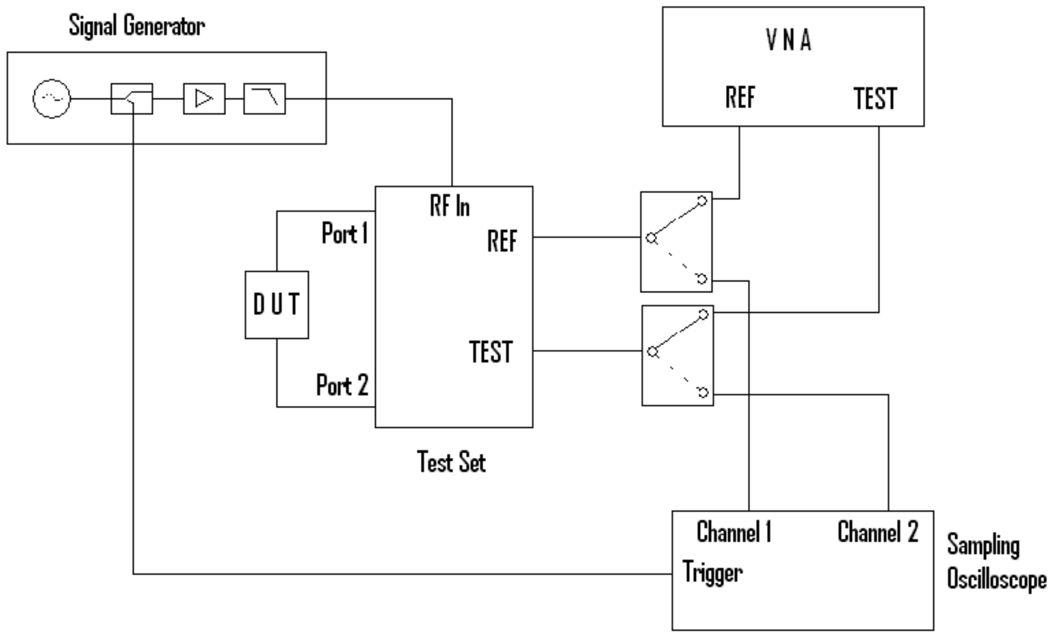

Figure 7 : Measurement system using sampling oscilloscope and a VNA.

Signal coming from source is again divided, one for triggering and one as stimuli to DUT. A test set was introduced to detect the incident, reflected and transmitted waves. REF output of test set is the incident wave (coming from port 1) and TEST output of test set is either transmitted wave (collected at port 2) or reflected wave (collected at port 1). For this purpose a switch was introduced in test set to select between transmitted wave or reflected wave. Two more switches were introduced to select whether the REF and TEST signal of test set are detected by broadband sampling oscilloscope or by the VNA. Sampling oscilloscope (triggered by fundamental) was used to measure harmonics and VNA was used to measure fundamental and calibrate the whole system accurately. A power meter was used on channel 2 of oscilloscope during calibration for absolute amplitude.

This setup improves the accuracy of the system as VNA was used to accurately characterize the whole test set up . The bandwidth of the system was also improved to 20 GHz. Also the triggering drift problems occurred in setup by Sipilä et al. [1] was also removed because of coherent measurement of incident wave and reflected or transmitted wave.

3.2 Measurement System Using a VNA

3.2.1 Vector Network Analyzer

A vector network analyzer or VNA is an instrument which basically measures the s parameters of a network. It has four receivers to measure the incident and reflected waves on each port. By taking the ratios of theses waves, S parameter set of a DUT is determined. The basic parts of a network analyzer are:

The Signal Source
The Signal Separation Unit
The receiver

3.2.1.1 Signal Source

Main function is to supply the stimuli signal to the DUT. Signal source should be a good one as VNA always takes some reference signal for the phase lock and measurements. Modern VNA uses synthesizers as source. The source can also be supplied externally if one found it better than the internal one. The VNA used in the project can sweep from 40 MHz to 40 GHz.

3.2.1.2 The Signal Separation Unit

Its function is to separate the incident and the reflected signals. It also measures strength of incident signal. This can be done inside a VNA. Mostly a dedicated set is made to attach it with VNA externally, commonly known as a test set. It mostly uses directional couplers of good directivity. This in turn determines the dynamic range of the system. The directivity of couplers in VNA used for the project, with K type connectors, is greater than 42 dB and isolation is greater than 110. A typical setup of signal source and separation unit is presented in Figure [8]. The switch shown in Figure [2] is for making either port 1 or port 2 active.

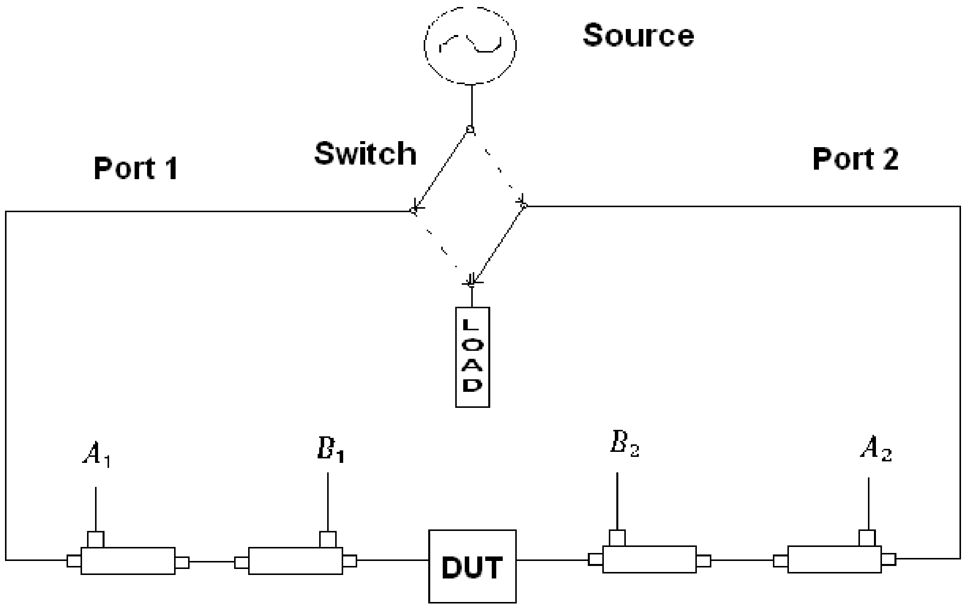

Figure 8 : Source and Signal separation unit in a typical VNA.

3.2.1.3 The Receiver

The narrow band receivers are used for signal detection and generally they are mixer based. They are also known as Heterodyne Receivers. Some modern VNA uses samplers for detection. All receivers are tuned. It means they are locked to some local oscillator frequency. The local oscillator frequency of the VNA used in project is 10MHz. Frequency multipliers are used to translate this frequency to higher frequencies. A typical mixer based tuned receiver is shown in Figure [9].

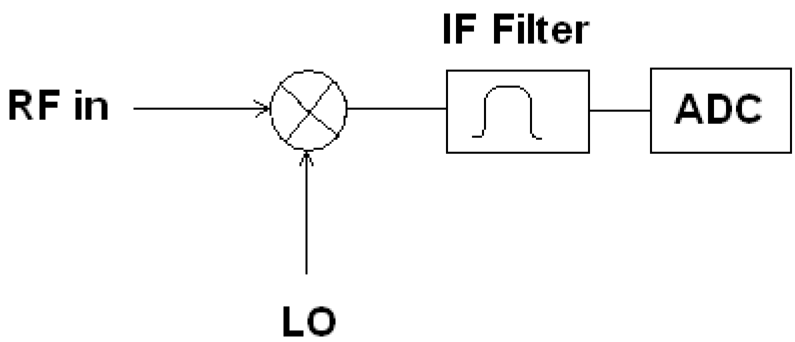

Figure 9 : A Heterodyne Receiver.

Enhancements in measurements can be made by carefully selecting the span, number of data points, I.F bandwidth and averaging.

3.2.2 Receiver Mode

A conventional VNA only measures the ratio of the waves. Also the source and receiver are synchronized to same frequency. In modern VNA, it is often possible to operate the analyzer in what is called the receiver mode. It basically turns a VNA into a tuned receiver. Reference signals are no longer necessary for the system. Or in other words it can be driven on one frequency and analyze on other. It is often used for measurement of frequency translating devices like mixers. It can be used to measure harmonics also. This project aim was also to use this feature of VNA for the large signal analysis

3.2.3 Measurement System using a VNA

A measurement system using a VNA for measuring the absolute amplitude and phase of harmonics at DUT output was implemented [2]. A simple schematic of such a system is shown in Figure [10].

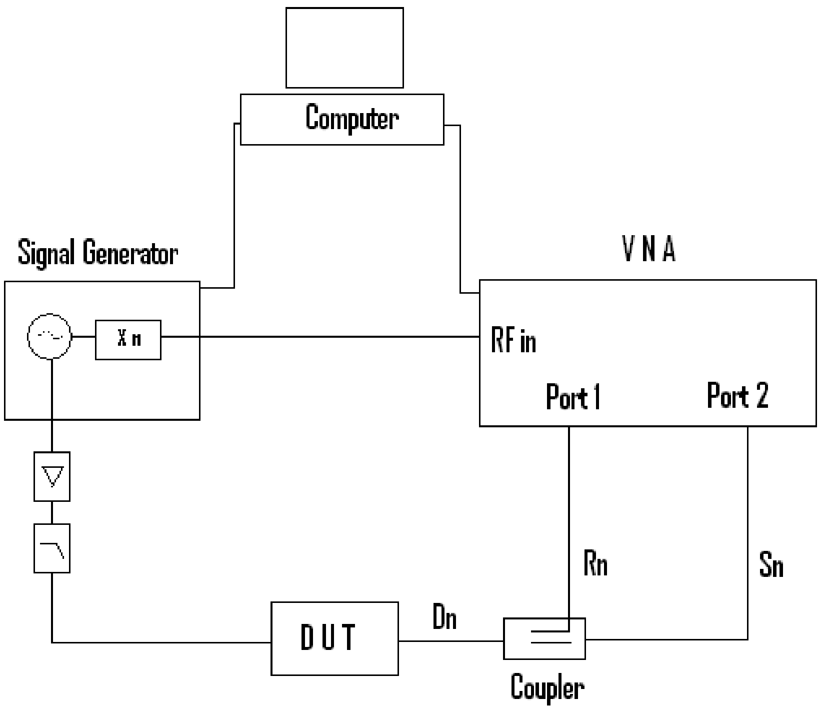

Figure 10 : Measurement System a VNA.

The signal generator consisted of a source (sinusoidal) and a frequency multiplier to increase output frequency. Fundamental and multiplied signal are present at the two RF output ports of the generator. Fundamental signal is amplified and filtered through a low pass filter and then it is applied to the DUT input.

Multiplied signal is fed as RF input to VNA and is present on port 1 of VNA. This signal is mixed to the output signal from DUT through a coupler. During forward response calibration of VNA, DUT is replaced by two matched loads. This will make the signal coming from port 1 as reference R_n with magnitude 1.0. The net signal S_n (output from DUT and signal from port 1 of VNA) is fed to port 2 of VNA for detection.

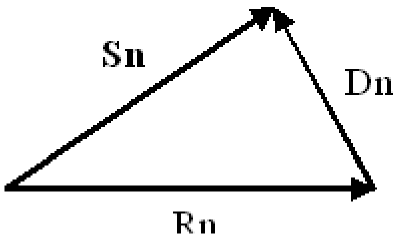

Figure 11 : Vector diagram for measured signal by VNA.

Figure [11] shows the vector diagram for signal measured by VNA at port 2. Here,

S_n = Net signal measured by VNA at port 2
R_n = Reference signal from port 1
D_n = Output signal from DUT

The signal detected by VNA is sum of R_n and D_n . Mathematically it will be

$$S_n = R_n + D_n \qquad [8]$$

Now, D_n can be calculated by using Equation [9].

$$D_n = S_n - R_n \qquad [9]$$

And after calibration

$$D_n = S_n - 1.0 \qquad [10]$$

This signal D_n is still referenced to R_n. For absolute amplitude, calibration is done by disconnecting the DUT and replacing port 2 of VNA by a power meter. For absolute phase, calibration is done by replacing the DUT by a diode. The phase information of harmonics generated by such a diode can be deducted mathematically. The measured phase information of the harmonics by diode is corrected according to this mathematical model. It means that this diode was used as harmonic phase reference for the system. A separate computer was connected to system for the final computation of time domain representation of input and output waves.

The use of VNA makes the dynamic range of the system more as compared to one by oscilloscopes. Dynamic range of VNA can reach to 100db with IF bandwidth at 10 Hz. Also the measurements are faster as VNA is a narrow band instrument. Such a system gave a new idea about the receiver mode for VNA. By using a reference diode for harmonic phase reference, error between mathematical model and measured data was found to be less then 10^0 at 15 GHz with fundamental at 5 GHz.

3.2.4 Measurement System Using a VNA in Receiver Mode

A time domain measurement system using VNA in receiver mode along with load pull system was introduced [3]. A schematic of such a system is shown in Figure [12].

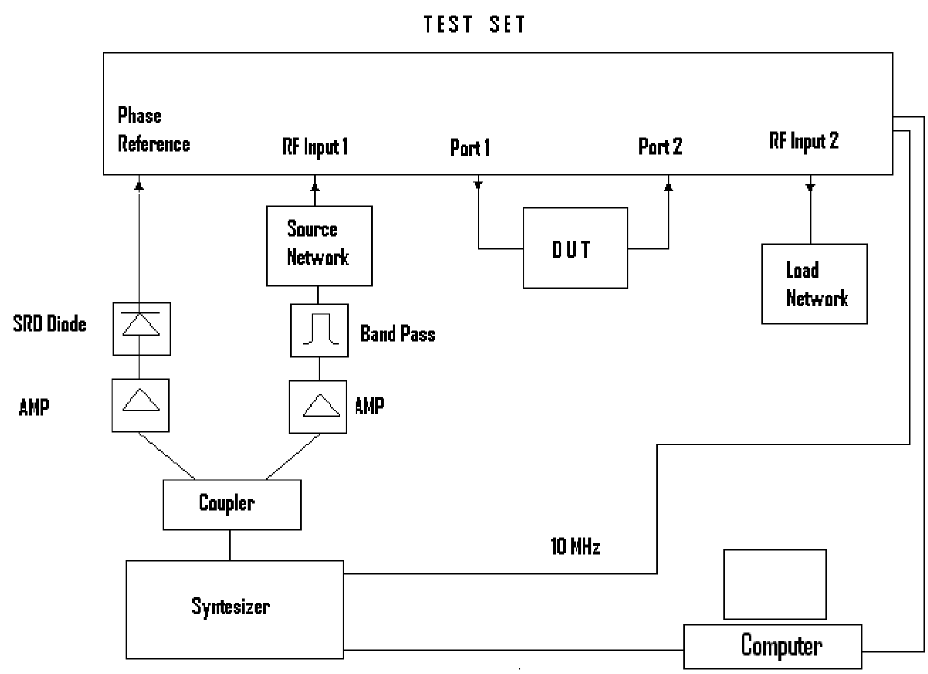

Figure 12 : Block Diagram of measurement system using VNA in receiver mode.

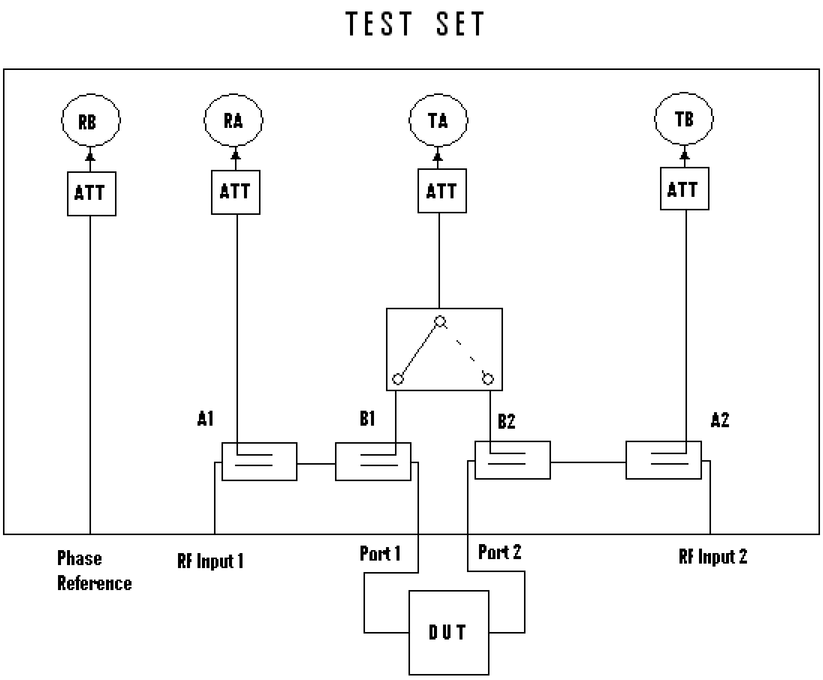

Figure 13 : Modified test set configuration.

A four receiver VNA in receiver mode was used. One of the receivers was used as a harmonic phase reference. Hence, a programmable switch was introduced in the test set to select between B_1 and B_2. The modified test set is shown in Figure [13]. Separate synthesizer (sinusoidal source) was used as input to VNA. Both VNA and synthesizer were synchronized to 10 MHz signal. Some signal conditioning was also applied to get a strong and harmonic free signal as input to VNA. A separate computer was used to finally determine the time domain waveforms.

Calibration of such a system is a little time consuming. Four steps were needed to have accurate calibration for each frequency of interest.

1) As on wafer measurements were taken, a TRL calibration and principle of reciprocity [10] were applied. Hence, error terms between VNA port 1 - DUT and VNA port 2 – DUT were corrected.
2) SOL calibration was done on RF Input 1 with the probes connected to TRL line and generator connected to RF input 2. It corrects for the error terms between RF Input 1 and VNA port 1. In other words it gives a relation between the power waves at probes tips and the waves at RF Input 1. Same procedure was done on RF Input 2, with generator connected at RF Input 1 and probes still connected to a TRL line.
3) For absolute amplitude, a power meter was connected at the RF input 1 and generator was connected at RF input 2 and calibrated. Same procedure was done on RF input 2.
4) For absolute phase, a Step Recovery Diode (SRD) was used as a phase reference. This diode worked as a comb generator and it was made sure that it is generating all the frequencies of interest. For this purpose a preamplifier was also used to able the highest

harmonic be detected by the receiver. For measuring the phase of harmonics generated by this diode and taking them as a reference, a sampling oscilloscope was used which was calibrated by using nose to nose calibration procedure (mentioned in section 3.1.2).

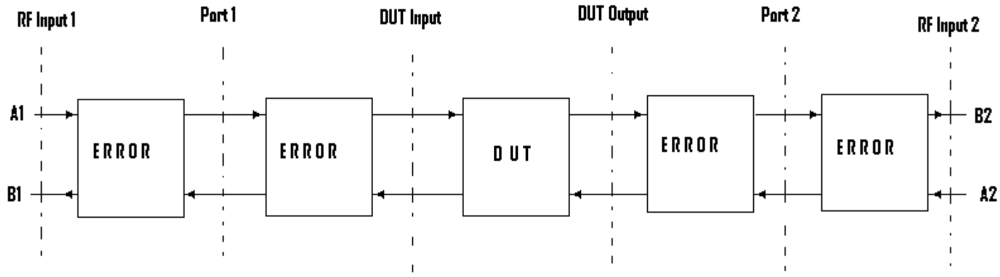

Figure 14 : Error model for calibration.

Source pull and load pull systems were connected at RF input 1 and RF input 2 respectively. This was used to get the optimum performance of amplifiers and frequency multipliers. System shows good dynamic range, again as narrowband VNA is used for data acquisition.

3.3 *Measurement System Using a Microwave Transition Analyzer*

3.3.1 Microwave Transition Analyzer

Microwave Transition Analyzer was introduced in 1991 [11]. It is a broad band 2 channel device and is based on harmonic mixing principle and both channels are synchronized. In harmonic mixing process, whole spectrum is down converted to lower frequencies by mixing several harmonics of LO frequency to the input spectrum. A detailed study of such process is given in section 3.3.4. This allows the measurement of amplitudes and phases of fundamental and harmonics present at its both input channels.

3.3.2 Measurement System Using a MTA

A measurement system was implemented in which Microwave Transition Analyzer was used for data acquisition [12]. A schematic of such a system is shown in Figure [15].

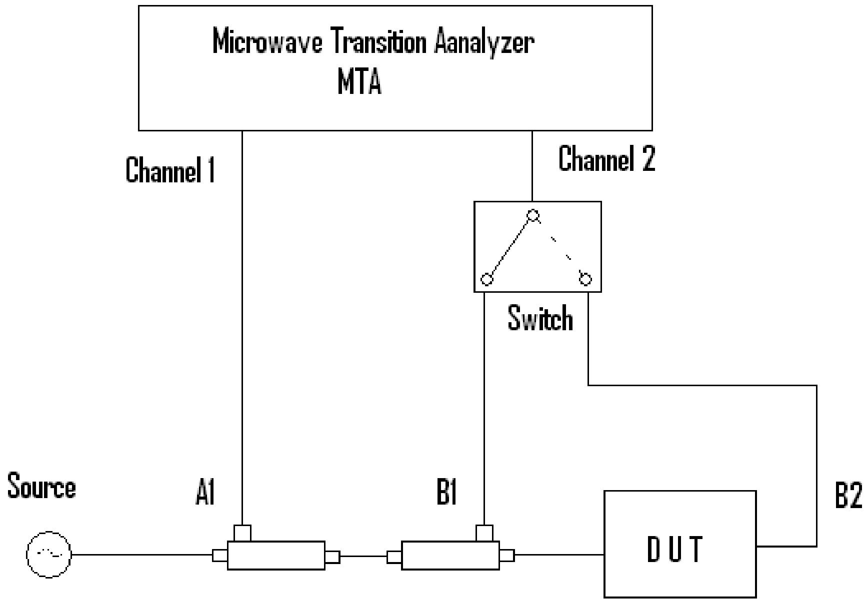

Figure 15 : Measurement system using MTA.

A sinusoidal signal source was used to excite the DUT. Signal from source is detected by a coupler and send to channel 1 of MTA. Reflected signal from DUT is detected by another coupler. A switch was used to select between transmitted signal through DUT or the reflected signal by DUT and is send to channel 2 of MTA.

The main advantage of such system is use of MTA for data acquisition instead of sampling oscilloscope. As it is using harmonic mixing principle rather equivalent time sampling, it is about 100 times faster than sampling oscilloscopes. Also dynamic range is better than sampling oscilloscopes (better than 50 dB). Another advantage is, it is not needed to attach a separate VNA for calibration. MTA itself was used to do network analyzer measurements in order to calibrate the test set up. It was also assumed that no phase distortion is offered by the MTA while measuring harmonics.

3.3.3 Measurement System by Hewlett Packard NMDG

A measurement system has been designed by Hewlett-Packard NMDG, named as LSNA (Large Signal Network Analyzer) [4]. Architecture of a LSNA is shown in Figure [16].

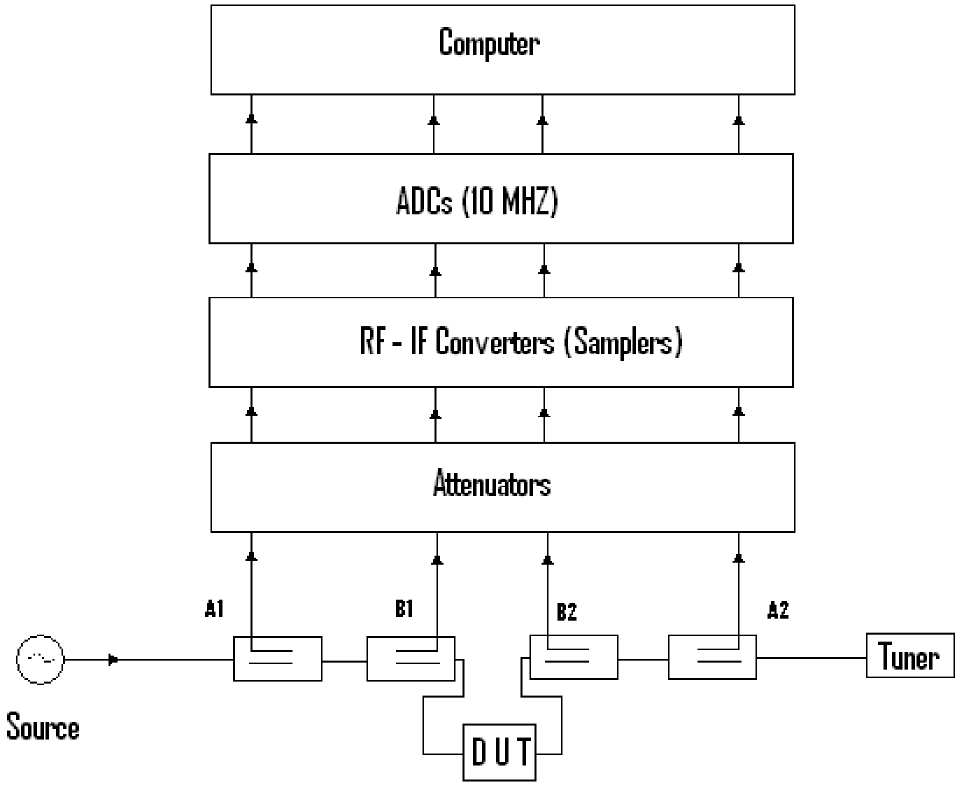

Figure 16 : Architecture of LSNA.

Signal from source is fed to DUT. Four couplers were used to detect the incident and the reflected waves on each port of DUT. The measured signals are sent to attenuators and then fed to four RF-IF converters, one for each wave. These RF-IF converters are broadband samplers based on harmonic mixing principle, and down converts the input spectrum as was in MTA. Then the down converted spectrum is converted to digital form by using 10 MHz ADCs. Finally a computer is attached to system for calculating and representing the final results. A tuner was also connected to system to make load pull measurements possible.

3.3.4 Harmonic Mixing Process

RF-IF converters used in LSNA are based on harmonic mixing principle and is considered as a core of the instrument. One digital synthesizer gives a local oscillator frequency to all four converters at close to 20MHz. LO frequencies is high rich in harmonics and it is meant to mix these harmonics by LO to the input spectrum.

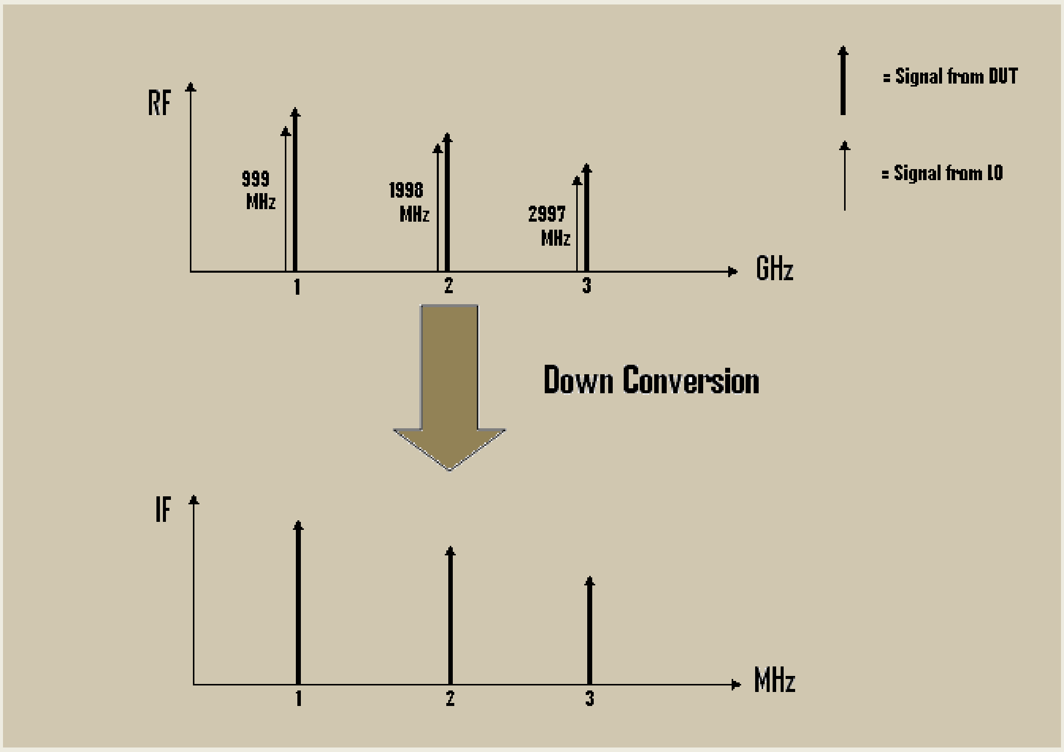

Figure 17 : Harmonic mixing of LO with input Spectrum.

Figure [17] shows the process of harmonic mixing. For example we need to measure 1 GHz fundamental and its second and third harmonic; the local oscillator frequency is set to 19.98MHz. Now, the 50th harmonic of this LO will be at 999MHz. After mixing this LO with the fundamental at 1GHz, we will get component at 1MHz. Similarly, LO 100th harmonic will be at 1998MHz. After mixing this LO frequency with 2nd harmonic of input i.e. at 2 GHz, we will get a frequency component at 2MHz. In this way the whole input spectrum can be translated to lower spectrum. In LSNA, its down converted to below 10MHz.

Calibration of LSNA is somewhat similar to one presented in section 3.2.4 and is done in three steps.

1) First a classical SOLT calibration was done for relative calibration. It is similar to one done by a VNA. Stimuli signal was set on each frequency of interest. For example if requirement is to characterize a transistor on 1 GHz with 20 harmonics, stimuli signal is set to 1GHz, 2GHz… 20GHz. As on wafer measurements are also made possible on LSNA, a classical TRL calibration was employed and also a SOL calibration with TRL line connected.

2) For absolute amplitude, a power meter is connected on Port 1 of LSNA and the source is stepped on the whole frequency grid. For each step, power is measured by power meter and also by the LSNA acquisition system and hence correction is made.
3) For absolute phase, a HPR was used as reference. The main components of HPR are a power amplifier, a SRD diode and a pulse sharpening nonlinear transmission line. It is a pulse generator with a repetition of 1GHz for all frequencies of interest. HPR was characterized by using broadband sampling oscilloscope, which were calibrated by using nose-2-nose calibration procedure. During phase calibration. DUT was replaced by HPR and phase of each frequency were measured by the LSNA acquisition system and corrected for phase.

For on wafer measurements, as both power meter and HPR have a coaxial output, reciprocity principle [12] were applied between the probe tip and generator input connector of test set. Power meter and HPR are connected to this coaxial input and calibration is done while TRL line is connected between the probes.

It seems that LSNA is mixture of a measurement system using VNA in receiver mode (section 3.2.4) and measurements system using MTA (section 3.3). As it used four broadband down converters, one for each measured wave and working coherently, speed of LSNA measurements is very high. Typically requires few seconds per measurement and it includes all computer calculations needed to convert data from time to frequency domain and calculations needed to correct raw data. RF bandwidth is also very good, up to 40 GHz. Dynamic range is about 60 dB and is better than sampling oscilloscopes. Use of four couplers and four data acquisition systems, allows to excite DUT on both port simultaneously. Multi sine wave excitation (broad band CDMA signal) is also applied for testing DUT and nonlinear quantities like ACPR can be measured effectively on LSNA.

3.4 Conclusion

In this chapter, different measurement systems for large signal analysis were discussed with respect to their architecture, calibration, dynamic range and bandwidth. These systems differ from each other mostly on data acquisition and stimuli signal type. This in turn determines what kind of nonlinear quantities they can measure and in which form they represent it [8].

Systems based on sampling oscilloscopes show simplicity in architecture, but dynamic range of such systems is rather less, nearly 50 dB. Also measurements speed will be low because of equivalent time sampling. Calibration of oscilloscopes is also a crucial part. Phase distortion offered by sampling heads is common in sampling oscilloscopes. Improvement in accuracy of system was shown by using VNA for characterizing the test setup [9].

Systems based on VNA shows a good dynamic range as it is a narrow band instrument. Noise floor goes down to 110 dB for 10 Hz IF filter bandwidth. Also, by using VNA for characterizing the test setup, accuracy of the system is also improved. Only sinusoidal type signals could be used to excite the DUT. Using two sources in VNA, one for each port, can allow to excite DUT on both ports simultaneously. Speed of such systems is better than the one by sampling oscilloscopes. Bandwidth of system can go to 40 GHz.

Some systems based on true down conversion of spectrum were also discussed like a system using MTA and LSNA. The broadband acquisition of signal and coherently down converting of spectrum makes the measurement speed of such systems incredibly high. Specially in LSNA, by using four synchronized receivers, measurements can be taken in few seconds. This also allows to use multi tone signals as stimuli and non linear quantities like ACPR can be measured. As samplers in MTA and LSNA are based on harmonic mixing process, only periodic signals can be used. They also show very good bandwidth. LSNA bandwidth goes up to 40 GHz. Good thing is whole spectrum is converted to below 10 MHz frequencies. Dynamic range is although not better than VNA because of broad band acquisition. But it is better than sampling oscilloscopes. Calibration process is traceable and correction for both absolute amplitude and absolute phase for each harmonic is made.

4 MEASUREMENT SYSTEM USING A TUNED RECIVER

A part of project was to design and implement a harmonic distortion type measurement system using Anritsu 37169A VNA in receiver mode. In this chapter, architecture, functionality and calibration of such a system is discussed.

4.1 Architecture

A block diagram of the designed measurement system is shown in Figure [18].

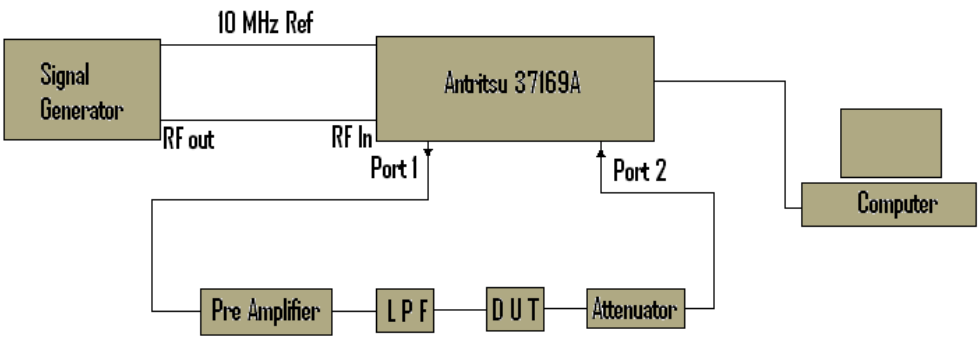

Figure 18 : Architecture of designed measurement system.

Explanation of each block in Figure 18 is as following:

4.1.1 Signal Generator

Rhodes Schwarz SME 03 signal generator was used as signal source to DUT and as a RF In to the VNA. Signal generator was locked to VNA local oscillator frequency i.e. 10MHz. Maximum output of generator was 16dBM and signals up to 3GHz could be generated.

4.1.2 Anritsu 37169A

Wiltron Anritsu 37169A (Figure []) was used for data acquisition. It is a two port VNA having four receivers and with a Receiver Mode option. Dynamic range of receivers is about 104 dB at 22.5 MHz and about 91 dB at 20 GHz (with 10Hz IF bandwidth). This determines the overall dynamic range of the system. Measurement frequency range, after the test set is from 40MHz to 40 GHz.

A special feature of Multiple Source Control is present in this VNA. In this mode of operation, receiver of VNA can be controlled to sweep in one band (can be a CW also) and source can be controlled to sweep in some other band (can be a CW also). This allows to measure waves present on each port irrespective of synchronization between source and receiver. It also gives direct access to its all four receivers to user. So it was now possible to measure individuallyA_1,B_1, A_2 and B_2. A picture of Anirtsu 37169A used in implemented tuned reciever measurement system is shown in Figure [19].

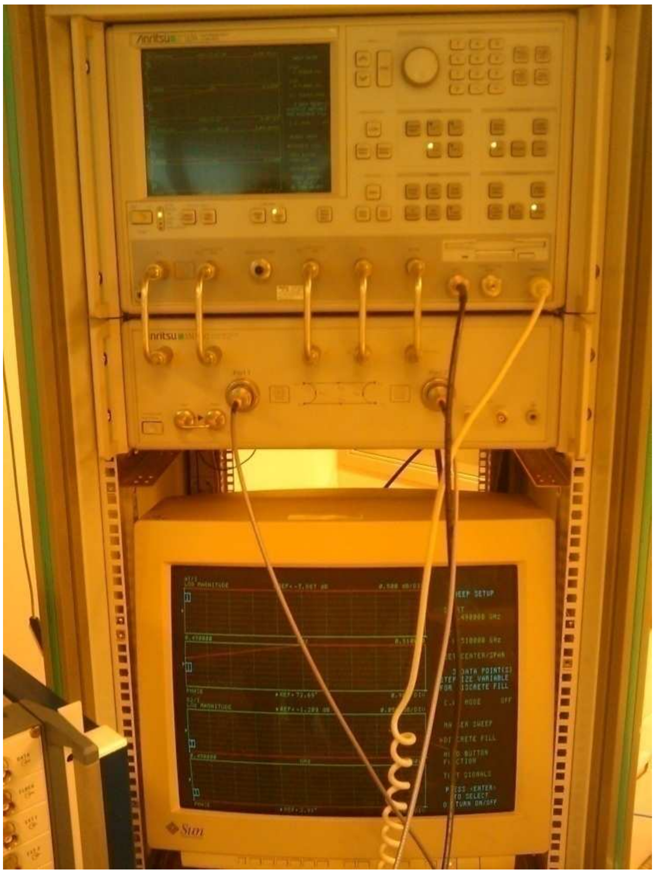

Figure 19 : Anritsu 37169A that was used as a tuned receiver

4.1.3 Low Distortion Amplifier

A pre amplifier was introduced to the signal coming from port 1 of VNA. The purpose was to make signal strong enough to turn DUT into non linear region. Gain of this amplifier was 14.4 dB and operation bandwidth was about 20 – 300MHz.

4.1.4 Low Pass Filter

A low pass filter was used to purify the signal being fed to DUT. Step impedance filter with a cutoff at 500 MHz and 1GHz were introduced. Another filter was later used for low frequency measurements having a cutoff at 111MHz.

4.1.5 D U T

Two DUT were tested. Both were broadband amplifiers. DUT 1 (ZHL-42) operating range was from 700 MHz to 4200MHz. DUT 2 (ZHL-2-8) has and operating range from 10MHz to 1000MHz.

4.1.6 Attenuators

Attenuation of 23 dB was introduced after the DUT to make sure a safe level for the test set ports. Maximum of 25dBm power is allowed as input to all ports of VNA and test set.

4.1.7 Computer

A separate computer was attached to the VNA through GPIB (IEEE- 488.2) interface. Main purpose of this computer was to collect raw data from the VNA and correct it and finally display it in time domain. For this purpose, HP VEE software was used to program GPIB and make all calculation. Also an algorithm was implemented to make calibration and measurement automatic and to make user interface easy to operate.

4.2 Calibration

Different error models were studied and tried to calibrate the system. Idea was to move measured raw B_2 up to the output of DUT. Some difficulties were faced in finding the correction term for port 2 or port 1 only. Error term ETF calculated in 6 term or 12 term error models is defined over the whole path and not for port 2 or port 1 only. Finally, it was assumed that a linear relationship exists between raw measured quantities and corrected ones for each frequency component. This relationship is complex and it corrects for both amplitude and phase of raw quantities. The correction coefficient for port 1 was named as CP1 and for port 2 was named as CP2.

During calibration, source and receiver were set to same frequency. First one path two port calibrations was applied using SOLT (Wiltron Calibration Kit No. 3652). Then with through connected, corrected A_1 was measured along with non-corrected A_1 and non-corrected B_2. This data was send to computer and CP1 and CP2 were calculated according to Equations [11] and [12] respectively.

$$CP1 = \frac{A_1\,(corrected)}{A_1\,(raw)} \quad [11]$$

$$CP2 = \frac{B_2\,(\,raw\,)}{A_1\,(corrected\,)} \quad [12]$$

This procedure was done for each frequency of interest. The coefficients CP1 and CP2 were stored in computer.

4.3 Measurement Method

Initially the feasibility of such a system was tested. Without calibration, several raw measurements were taken to make sure that we can phase lock the harmonics in Multiple Source Control mode. It was noted that internal source of VNA was not much accurate. Hence, a separate signal generator was used to replace internal source. The spectrum analyzer available in the lab could measure up to 2.9 GHz, so it was decided to keep our input signal to 500MHz and 1GHz so that we could see at least four harmonics in spectrum analyzer. A link budget was also made to make sure that DUT is turned into compression and also to be able to phase lock all harmonics of interest without damaging the input ports and receivers. Figure [20] shows a picture of the implemented tuned reciever measurement system.

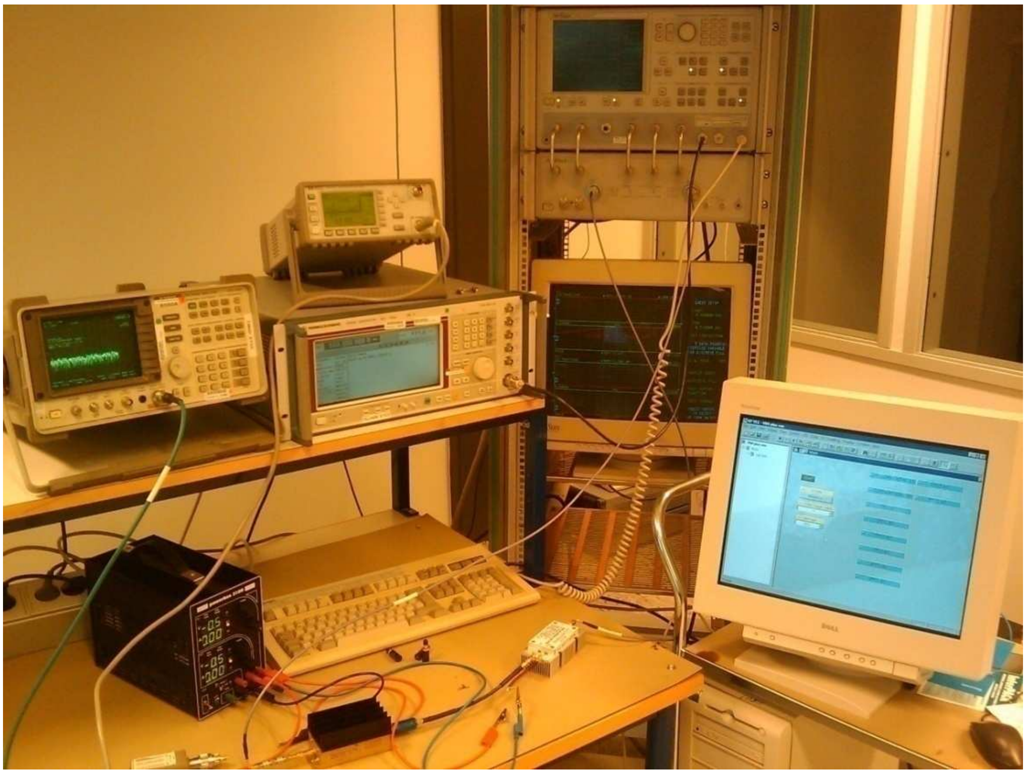

Figure 20 : Implemented Large Signal RF Measurment System using a tuned reciever

Measurements of fundamental and harmonics were taken one at a time. Only port 1 was used for excitation and port 2 was used to measure harmonic content along with fundamental of the First the generator was set to fundamental frequency f_o (CW) and the receiver was also set at f_o (CW). Non-calibrated A_1 and B_2 were measured by the VNA, making sure that receiver can phase lock them. This data was stored in computer. Then generator was remained at f_o and receiver was set at $2f_o$. Again non-calibrated A_1 and B_2 were measured by VNA and were stored in computer. The procedure was repeated till the last harmonic of interest was measured. For each measurement five harmonics were measured.

Once all the measurements were taken, correction on all stored raw data was applied in computer. Correction data was stored in computer during calibration. Finally a time domain waveform for B_2 was calculated and displayed.

4.4 Computer Algorithm

HP VEE program was used to interface computer and VNA through GPIB (IEEE-488.2). Algorithm was written in computer to make measurements and calibration automated. Initially calibration data was saved in computer. Then system was made non-calibrated and raw measurements of fundamental and harmonic were taken. This data was sent to computer also. Finally a program was written that corrects the data and determines the final time domain waveform on the output of DUT .A brief flow diagram of it is presented in Appendix A. Some snap shots of HP VEE program are in Appendix B

5 RESULTS AND CONCLUSION

5.1 Results

Some measurements were taken by the designed system. Two DUT's were tested as mentioned in section 4.1.5. Early a broad band amplifier ZHL-42 was tested at 500MHz with the internal source. Input power to DUT was set to 3dBm. Figure [21] shows the voltage waveform calculated at the output of amplifier.

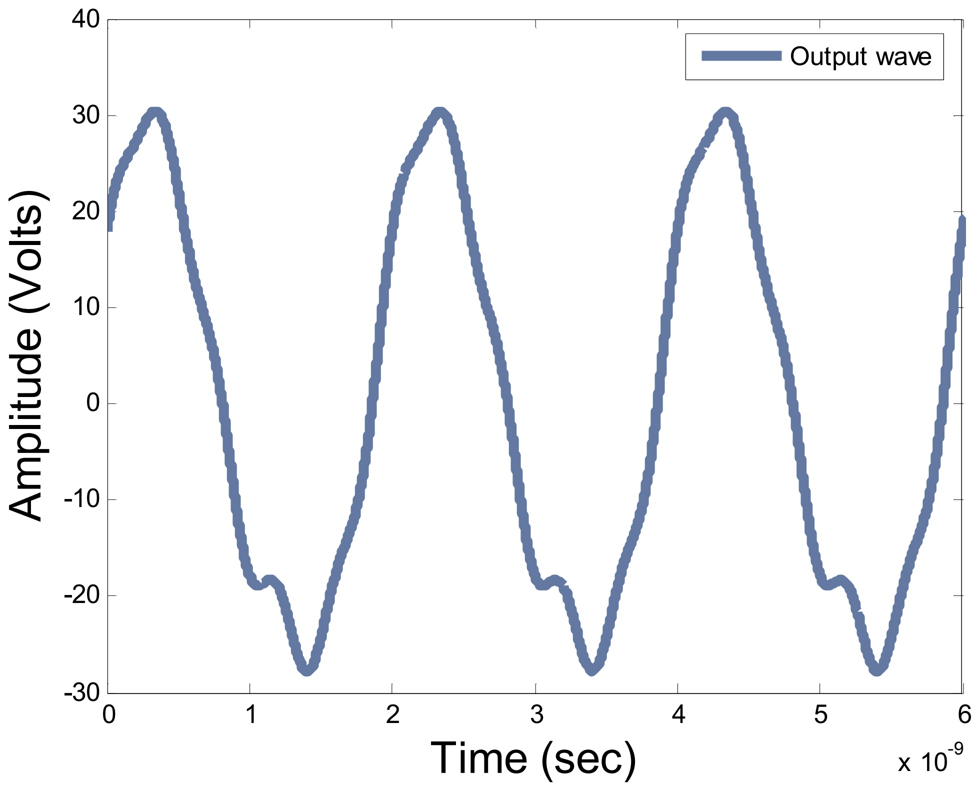

Figure 21 : Measured output wave for 3dBm input by internal source to ZHL-42 (DUT 1)

With the internal source as stimuli, another broad band amplifier (ZHL-2-8) at lower frequency 100MHz was tested. Power level of source was 3 dBm. Figure [22] shows the output voltage waveform of this amplifier.

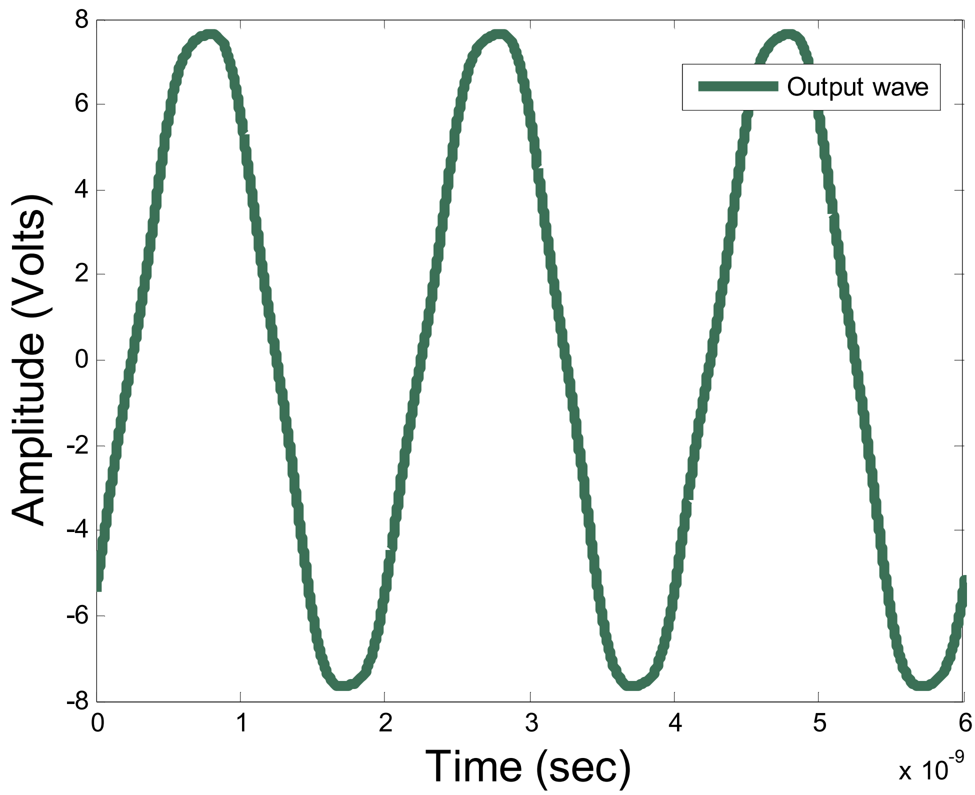

Figure 22 : Measured output wave for 3dBm input by internal source to ZHL-2-8 (DUT 2)

The source itself was tested for its own harmonics and Figure [23] shows the time domain measurement of signal coming from internal source. It can be seen clearly, that the source was not clean.

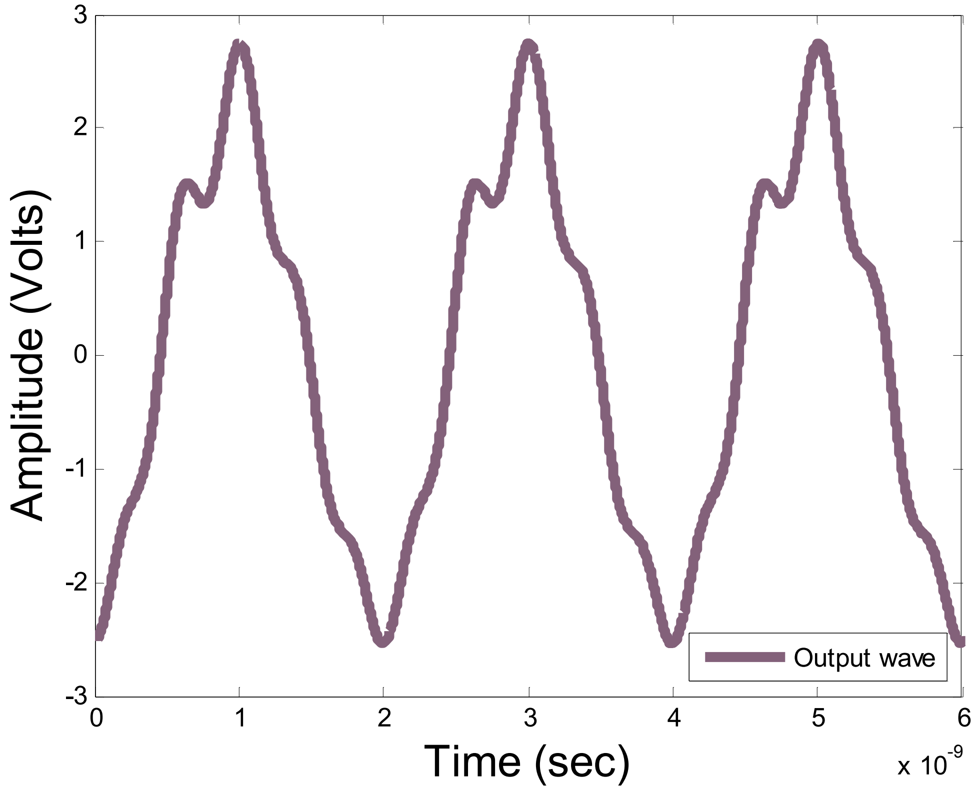

Figure 23 : Measured time domain waveform of 3dBm signal by internal source

Hence it was decided to replace the internal source by an external generator and the DUT 2 was tested at 100MHz. Figure [24] shows the output voltage waveform of DUT.

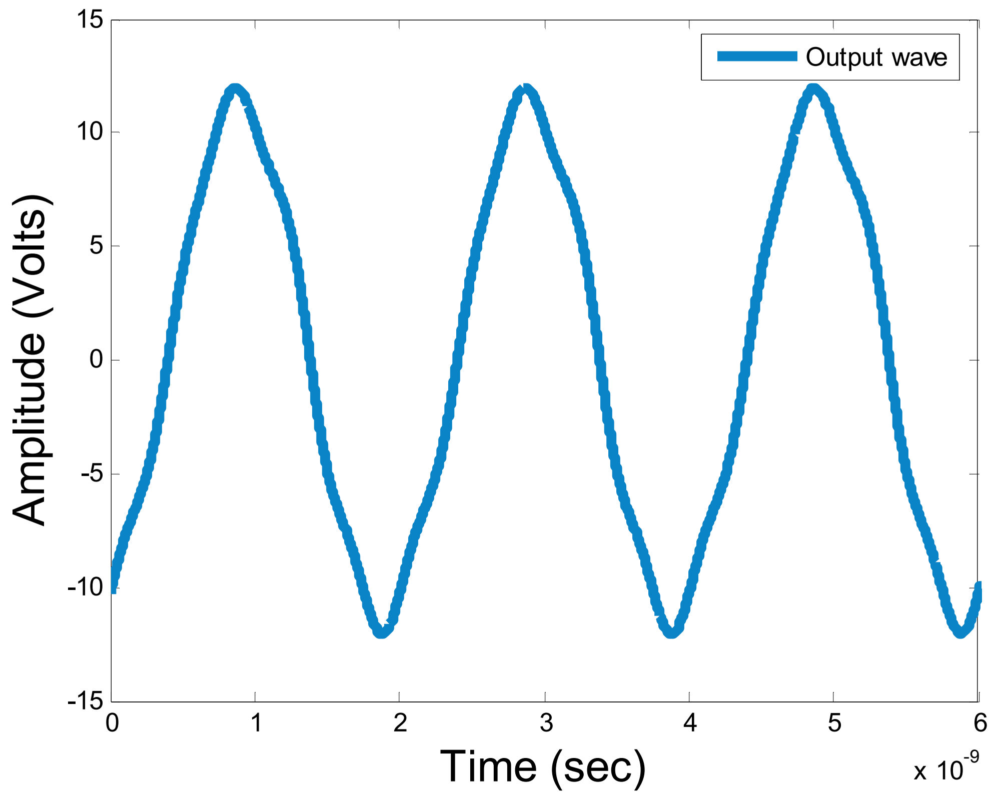

Figure 24 : Measured output wave for 3dBm input by external source to ZHL-2-8 (DUT 2)

5.1.1 Sources of Error

- The coefficients CP1 and CP2 were deducted from a simple model. Although efforts were made to use a better model. Inaccuracy of these terms will affect the results a lot.
- Unavailability of a HPR can cause error in phase measurement of harmonics. Also when testing the output waveform by an oscilloscope, phase distortion inside the oscilloscope must be cared.
- Availability of a pure source is necessary; a bad source also affects the dynamic range of the system. Also if harmonic content of the generator are not filtered to a good value, they will be amplified by the DUT and erroneous data would be collected.
- DUT must be kept at constant temperature, drift errors could result due to heating of DUT.
- In receiver mode of VNA, its receivers are operating on its full dynamic range. Hence they are more sensitive to noise. Averaging can be used to minimize such error.
- Imperfection in the IF filter of VNA can cause error in both amplitude and phase information.

5.2 Conclusion and Future Work

A comprehensive study of state of state of art large signal RF measurement systems was done. Different systems were studied and analyzed on basis of architecture, calibration, measurement method, dynamic range, bandwidth, type of excitation signals and what nonlinear quantities can be measured. Some basic functionality of conventional RF measurement instruments like sampling oscilloscopes and VNA was also made in order to utilize them in a better way. Basically, such measurement systems can be divided in two categories; time domain measurement systems and frequency domain measurement systems. This difference is based on what type of instrument they use for data acquisition. It was noted that instrument used for collecting data determines the overall system specifications like dynamic range, bandwidth etc.

Time domain measurement systems use sampling oscilloscopes and the system architecture is simple. Also not much work is required for the waveform calculation as it measures directly in time domain. However, sampling oscilloscopes must be calibrated for their impulse response distortion. Use of sampling oscilloscopes makes measurement systems dynamic range low, typically about 50 dB. Also measurement speeds are relatively slow as they are based on equivalent time sampling. Cost of sampling oscilloscopes is also high as compared to other conventional microwave instruments. Only CW type signals can be used to excite DUT.

Frequency domain measurement systems include VNA in receiver mode and LSNA (MTA based systems). Such systems show good dynamic range. For system using VNA in receiver mode, at 10 HZ of IF bandwidth, dynamic range can go above 90 dB. Also VNA is good in characterizing the test setup and hence more accurate data can be collected without disturbing the set up. VNA having two sources can be used both DUT ports at a time. As it can measure one harmonic at a time, measuring speed is rather less than LSNA. CW type signals can be used for excitation of DUT. Bandwidth of system is also good and can reach to 40 GHz. LSNA and systems using MTA shows very high measuring speeds. In LSNA, use of four coherent down converters makes one measurement in few seconds. Dynamic range is also better than sampling oscilloscopes. Modulated signals can be used for excitation of DUT and non linear quantities like ACPR can be measured. However, LSNA is an expensive instrument. Need of a harmonic phase reference is also necessary for frequency domain systems. Usually a SRD diode is used for reference. Recently Agilent Technologies has issued a comb generator that can be used as HPR [13].

Implementation of a tuned receiver measurement system was helpful in understanding the frequency domain measuring problems. Bandwidth of this system was up to 40 GHz. However, due to limitations offered by other convention microwave instruments like DSO and spectrum analyzer, measurements were taken up to 3 GHz maximum. Measurements were taken up to 5 harmonics. Such a system could measure harmonic distortion type measurements and CW signals can be used for exciting DUT on port 1 only.

Choice of correct measurement system depends solely on what type of measurements are needed and what nonlinear quantities are needed to be measured. Turning a VNA in receiver mode and utilizing it for large signal RF measurements is relatively cheap. But modulated type signals cannot be used for analyzing the DUT as VNA is a narrow band device. LSNA is there for such measurements but it is rather expensive.

Future work for the implemented system can be to find more accurate model for correction. Correction should be available for all four incident and reflected waves. And system should be able to excite and measure on both ports simultaneously. This can be done by using a VNA having two sources. A HPR should be used for correction of phase. Measurement speed of system can be increased by implementing a more effective algorithm. Measurement should be taken for higher harmonics, as under high compression, higher harmonics become more significant. Different techniques could be tested for the feasibility of using modulated signal as stimuli to DUT. Different DUT should be tested and nonlinear phenomenon should be studied.

6 REFERENCES

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APPENDIX A

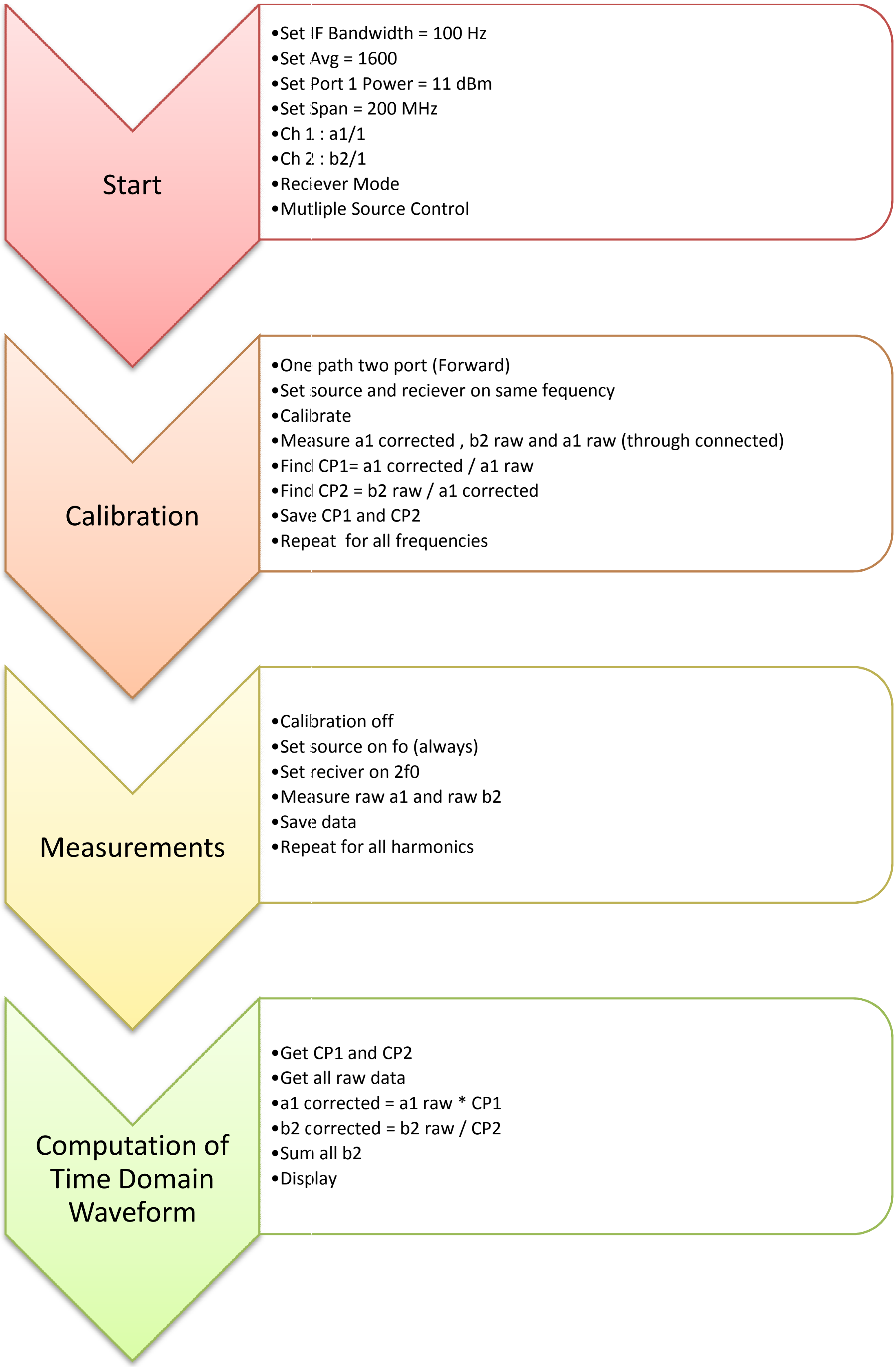

Figure 25 : Flow diagram for measurement system using a tuned receiver

APPENDIX B

Some snapshots of HP VEE program modules:

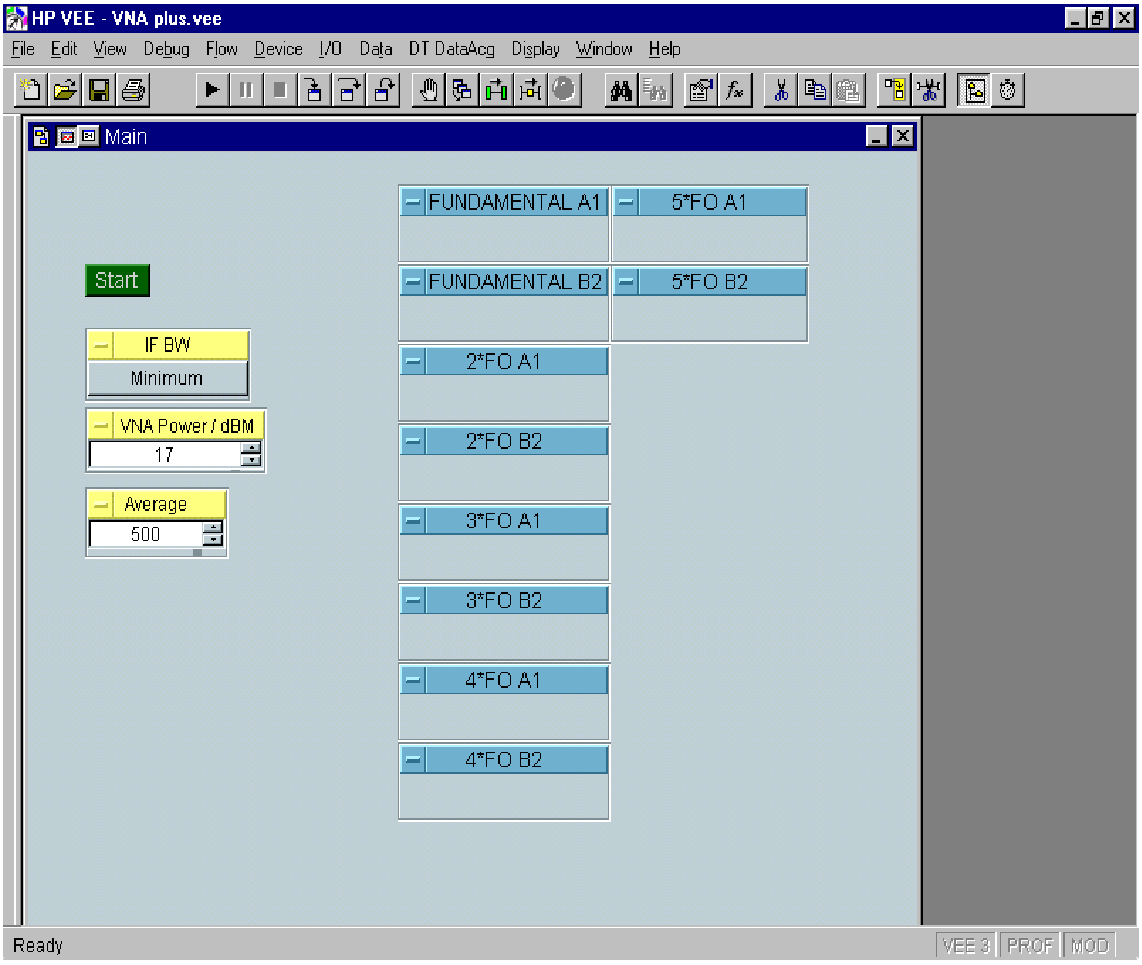

Figure 26 : User interface for the designed measurement system in HP VEE

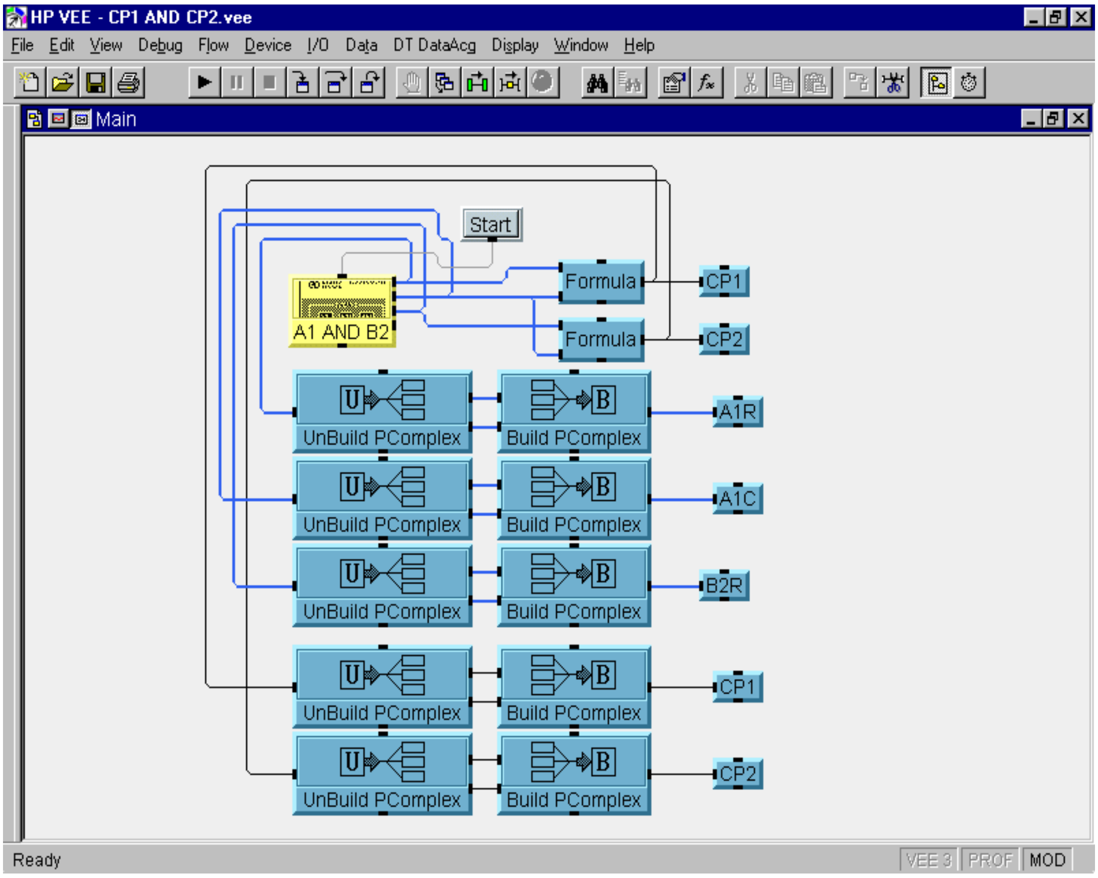

Figure 28 : Programming module for computing CP1 and CP2

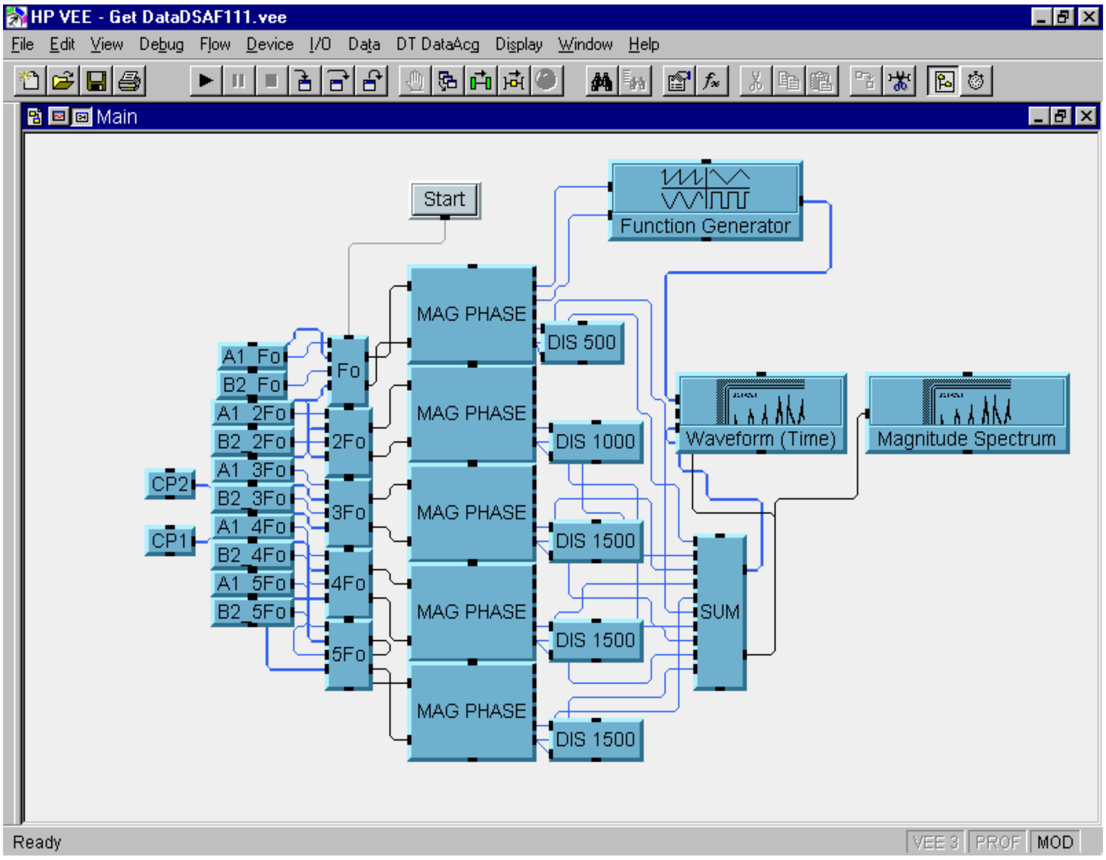

Figure 27 : Programming module for final computation of time domain waveform