Design Document

Low Cost RF Power Meter

Team: DEC14-14

TEAM MEMBERS: Silu Feng, Yijia Huang, Yusi Xie

Xiaoshuo Li, Boyang Hu, Cong Han

Client/Advisor: **Mr. Dan Stieler, Dr. Nathan Neihart**

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Revision History

Version	Date	Description	Author
1.0	03/14/2014	First Draft	Xiaoshuo Li & Boyang Hu
2.0	04/20/2014	Second Draft	Silu Feng & Yijia Huang
3.0	04/24/2014	Third Draft	Yijia Huang & Xiaoshuo Li & Yusi Xie
4.0	11/23/2014	Final	Xiaoshuo Li & Silu Feng

Table 1: Revision History

1   Introduction

1.1 Project Statement:

Radio frequency ("RF") power measurement has its own significance to modern communication technology. Large number of systems and components are required accurate and efficient RF power detection. The reason in choosing power detection over voltage is because a waveguide setup is very difficult in measuring.

Our client, PowerFilm. Inc, needs us to build a low cost RF power meter which can successfully measure his RF source. PowerFilm. Inc is a solar cell fabrication industry, and there are hundreds of power generation machines. Our goal is to design a power meter for their measurement, however the price has to be low in order for massive production. So the ultimate mission for us is to construct a low cost RF power meter and test the product to ensure its compatibility and accuracy.

1.2 Specifications:
- RF pickup
- Capable of measuring forward and reflected power
- Capable of measuring sinusoidal RF input
- Capable of measuring sinusoidal modulated pulse RF input
- Power range: 100-250W
- Frequency level: 13.5MHz and 40Mhz
- Output voltage within 5V
- Attenuation up to 60dB for output voltage
- Be able to connect to RF transmission line using Type N connector
- Total error within 5%
- Under 100 dollars
- A plan for power measurement up to 1200W
- Safe and easy to use

1.3 Deliverables:

First semester:
- Wired directional coupler
- Detector simulations
- Project plan and design document

Second semester:
- PCB board
- Aluminum closure with all components

2   Design Overview

2.1 Definitions

Watt
Watt (W) is one of the International System of Units which is usually used for power and energy. Watt can also be defined as one joule per second.

dB
The decibel is a unit of power ratio.
$$L_{dB} = 10log_{10}(\frac{P_1}{P_2})$$
So, 10 dB means 10 power ratio
       20 dB means 100 power ratio
       30 dB means 1000 power ratio

dBm
dBm is also a unit of power ratio. The difference between dB and dBm is:
$$x = 10log_{10}(\frac{P}{1mW})$$

DC
Direct current means in the circuit there is only one direction for current. It is usually produced by batteries.

AC
Alternating current means in the circuit the current reverses its direction in period time.

Impedance
Impedance (Z) is the resistance reference to AC circuits.
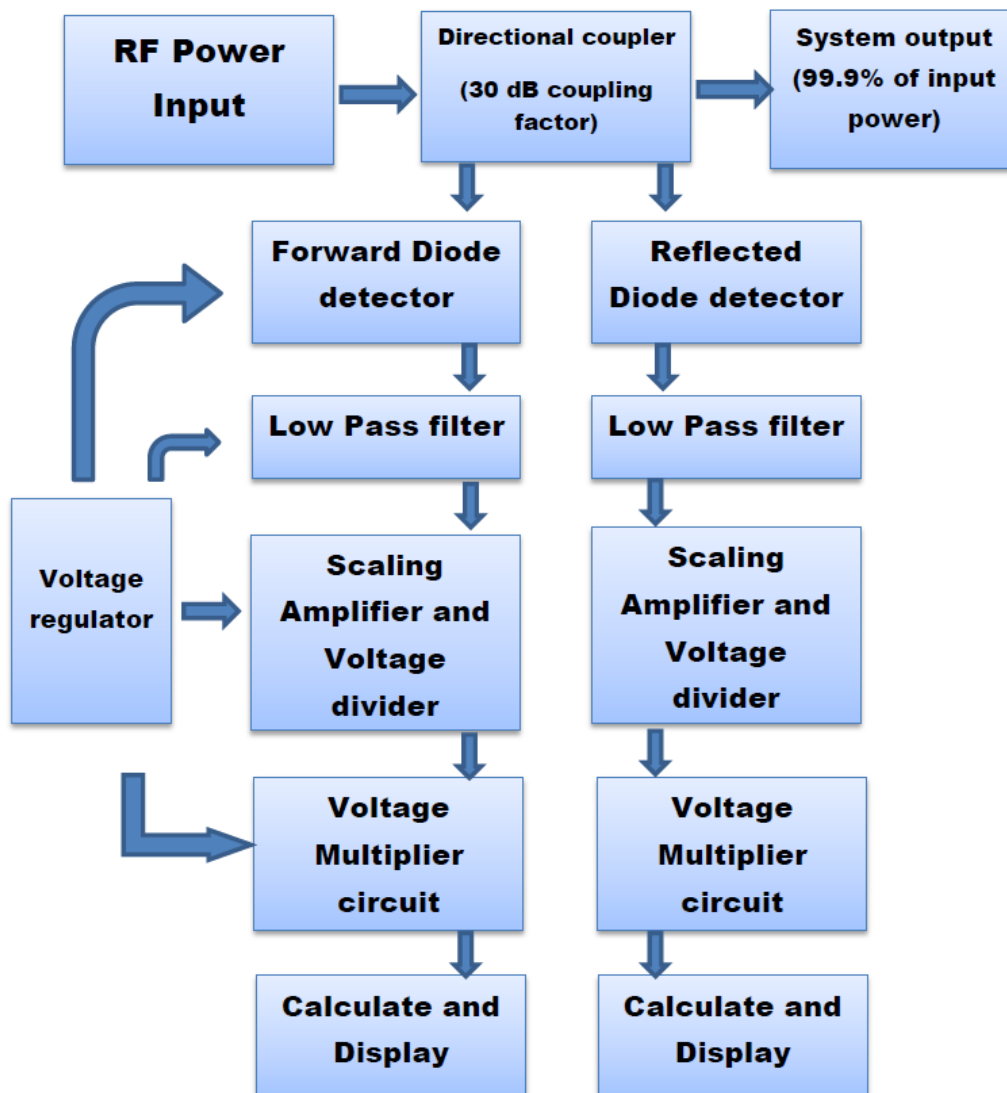Z = R + jX, where R is resistance, and X is reactance

Rectifier
Device converts AC to DC.

Power
Electric power (P) is defined how much work/energy will be done in period time.
$$P = work\ done\ per\ unit\ time = VI = \frac{V^2}{R}$$

2.2 Block Diagram

System Block Diagram

3   Design Decomposition

3.1 Transmission Line

A transmission line is a cable which is designed to carry radio frequency. It will be used to connect the generator to a 50Ω load. According to the requirements of our client: power ranges from 20 to 60 dBm with 13.5 or 40MHz, we choose RG-8A/U to be our transmission line. The datasheet is below:

General Specifications			
Outer Diameter	0.45inches	**Center Conductor**	Stranded copper
Impedance	50 Ohm	**Outer Conductor**	Braid
Velocity of Prop.	66%	**Jacket**	Black
Max Frequency	1000MHz	**Shielding**	Braid bare copper

Attenuation (dB per 100 feet)								
MHz:		1	10	50	400	700	900	1000
#2247	**RF-8X**	0.2	0.6	1.3	4.1	6.5	7.6	8

Table 2: RG-8A/U Data Sheet [1]

3.2 Directional Coupler

The directional coupler can help us to split a measurable power that can be used in another circuit (detector). In this project, we try to build a directional coupler at -30 dB coupling factor with 100-250W power rangers, and capability is from 0-1000W.

In order to understand how our directional coupler works some concepts must be made clear. (Fig. 1) For our directional coupler, there is an input port from generator, an output port to load and two coupled ports below to our diode detector circuit. RF power can be consider a standing wave which consists of two traveling waves, one moving from generator to the load (the forward wave) and another one (the reflected wave) moving in the opposite direction. These waves moving through transmission line in the directional coupler gives a forward power (Pf) and a reflected power (Pr). $P_{load} = P_f - P_r$ If the load is 50Ω, then the forward wave is terminated in this resistor and the forward power will be the power to send to the load resistor. Since the characteristic impedance of our transmission line is 50Ω which is matched by 50Ω loads, so the reflected power is zero.
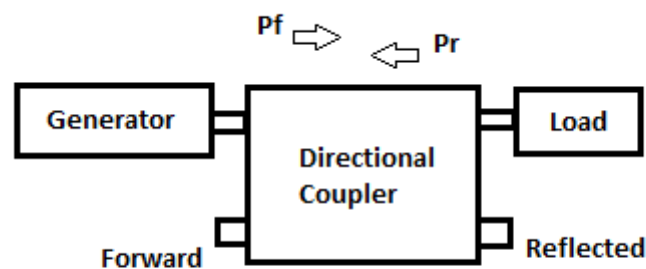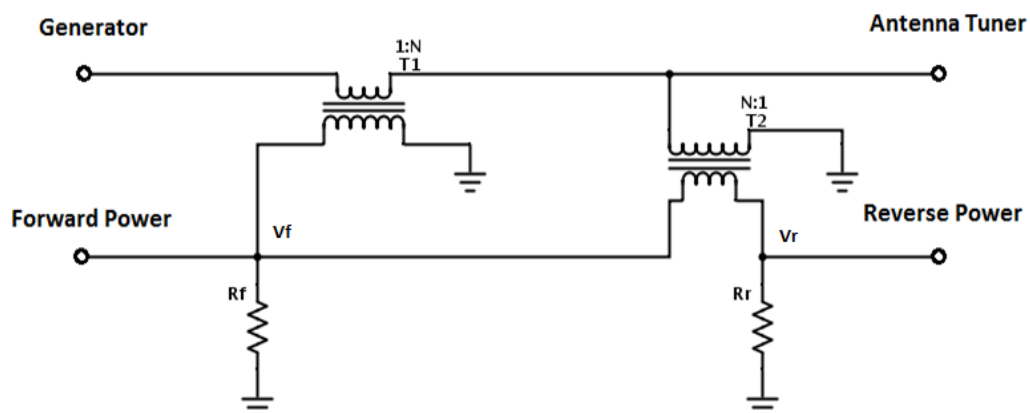

Figure 1: Directional Coupler Block Diagram

Figure 2: Directional Coupler Schematics

The directional coupler comprises of a pair of toroid transformers. T1 is a current source transformer and T2 is a voltage source transformer. (Fig. 2) Since we use a -30 dB coupling factor, the value of N should be 32 turns. (32^2=1024) To better understand how this circuit works, let us separately the forward and reflected wave.
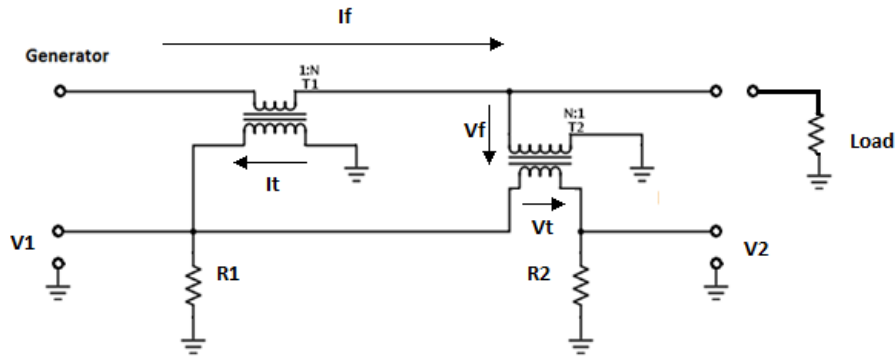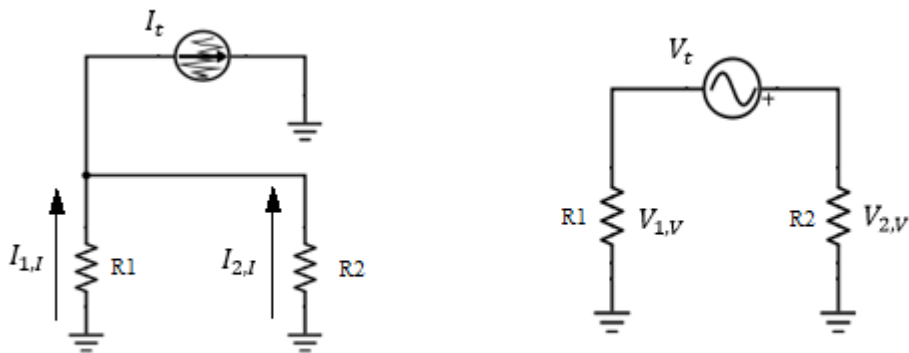

Figure 3: Current Source Circuit

Figure 4: Circuit of Current and Voltage Source Transformer

This is the directional coupler with forward power. (Fig. 3) With superposition, we can regard this circuit to two circuits above. (Fig. 4) Z is the characteristic impedance of the transmission line.

$$I_t = \frac{I_f}{N} = \frac{V_f}{N \times Z}$$

(1.1)

Set the value of R1 and R2 to 50Ω. In the current source transformer, we will have:

$$I_{1,I} = -\frac{I_f}{2N} = -\frac{V_f}{2N \times Z}$$

(1.2)

$$I_{2,I} = -\frac{I_f}{2N} = -\frac{V_f}{2N \times Z}$$

(1.3)

Current changes to voltage, it gives:

$$V_{1,I} = -\frac{V_f}{2N}$$

(1.4)

$$V_{2,I} = -\frac{V_f}{2N}$$

(1.5)

In the voltage source transformer, we will have:

$$V_{1,V} = -\frac{V_f}{2N}$$

(1.6)

$$V_{2,V} = \frac{V_f}{2N}$$

(1.7)

Then we can calculate for V_1 and V_2:

$$V_1 = V_{1,V} + V_{1,I} = -\frac{V_f}{N}$$
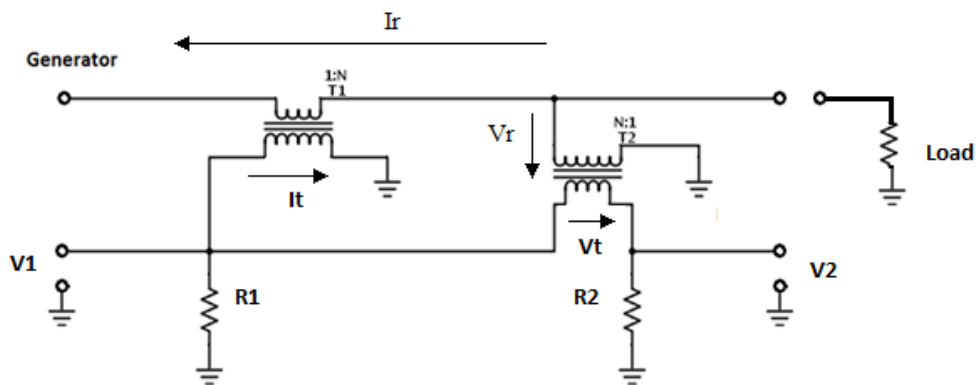$$V_2 = V_{2,V} + V_{2,I} = 0$$

(1.8)

Figure 5: Circuit Diagram of The Directional Coupler with
Reflected Power

This is the directional coupler with forward power. (Fig. 5) We can find that only the current flow changes direction and voltage remains the same sign. So there is no changes for voltage source transformer. But current flows in the opposite direction.
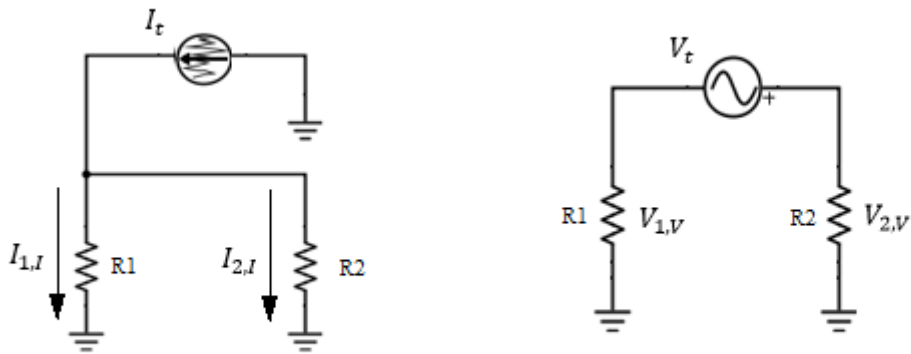
(Fig. 6)

Figure 6: Circuit of current And Voltage Source Transformer

For V_1 and V_2, we will have:

$V_1 = V_{1,V} + V_{1,I} = 0$

$V_2 = V_{2,V} + V_{2,I} = -\dfrac{V_r}{N}$

(1.9)

If we combine the forward power and reflected power. It gives:

$$\begin{cases} V_1 = -\dfrac{V_f}{N} \\ V_2 = \dfrac{V_r}{N} \end{cases}$$

(1.10)

So we find out V_1 can be stand for forward power and V_2 can be stand for reflected power. If the value of the load is 50Ω, there will be no reflected power. That means:

$$\begin{cases} V_1 = -\dfrac{V_f}{N} \\ V_2 = 0 \end{cases}$$

(1.11)

3.3 Toroid Transformer

To build transformer, the first thing is to choose the correct iron core. Since the transmission line will be our primary wind. For our secondary wind, the inductive reactance should be greater than 150Ω to avoid excessive insertion loss. $X \gg Z0$ We set $X = 150\Omega = \omega L$. Due to $N = 100\sqrt{\dfrac{L}{A_L}}$, we can calculate the range is

$A_L = 117.118\ \mu\dfrac{h}{100}\ to\ 39.062\ \mu h/100$. According to the table below, T-44-6, T-50-6, T-68-6, T-80-6, T-94-6 and T-106-6 can be our options.

MATERIAL 6-- Permeability 8, Freq. Range 10 MHz to 50 MHz, Color - Yellow

Core Number	O.D. (inches)	I.D. (inches)	Hgt (inches)	I_e (cm)	A_e (cm)^2	V_e (cm)^3	A_L Value µh/100 Turns
T-12-6	.125	.062	.050	.74	.010	.007	17
T-16-6	.160	.078	.060	.95	.016	.015	19
T-20-6	.200	.088	.070	1.15	.025	.029	22
T-25-6	.255	.120	.096	1.50	.042	.063	27
T-30-6	.307	.151	.128	.183	.065	.119	36
T-37-6	.375	.205	.128	2.32	.070	.162	30
T-44-6	.440	.229	.159	2.67	.107	.286	42
T-50-6	.500	.303	.190	3.03	.121	.367	46
T-68-6	.690	.370	.190	4.24	.196	.831	47
T-80-6	.795	.495	.250	5.15	.242	1.246	45
T-94-6	.942	.560	.312	6.00	.385	2.310	70
T-106-6	1.060	.570	.437	6.50	.690	4.485	116
T-130-6	1.300	.780	.437	8.29	.730	6.052	96
T-157-6	1.570	.950	.570	10.05	1.140	11.457	115
T-184-6	1.840	.950	.710	11.12	2.040	22.685	195
T-200-6	2.000	1.250	.550	12.97	1.330	17.250	100
T-200A-6	2.000	1.250	1.000	12.97	2.240	29.050	180
T-225-6	2.250	1.405	.550	14.56	1.508	21.956	100

Table 3: Amidon Iron Power Toroidal Cores

In order to avoid burning our iron coils, we need to calculate the maximum flux density by using the equation: $Bmax = \dfrac{V_{rms}}{4.44fNA_e}$. T-94-6 can be our appropriate choice with $Bmax = 29.6$ Gauss < 42 Gauss in 14MHz.

Frequency:	100 KHz	1 MHz	7 MHz	14 MHz	21 MHz	28 MHz
AC Flux Den.	500 gauss	150 gauss	57 gauss	42 gauss	36 gauss	30 gauss

Table 4: Maximum Flux Density Table

Since we have the toroid T-80-6 with I.D. 0.495 inches and the transmission line with O.D. 0.405 inches. (0.495-0.405)/2=0.045 inches. We choose 26 AWG for our copper wire gauge.

3.4 Directional Coupler Building

According to the outer diameter of toroid we select $4 \times 4 \times 2$ inches aluminum enclosure. After decided the size of enclosure, we measure that the length of transmission line which connects the BNC connector is 7cm and connect the N-type connector is 9.3cm. In order to improve the coupler directivity, we need to use the PC board. The length and width are 9.9cm and 4.6cm.

Figure 7: Schematic for directional coupler
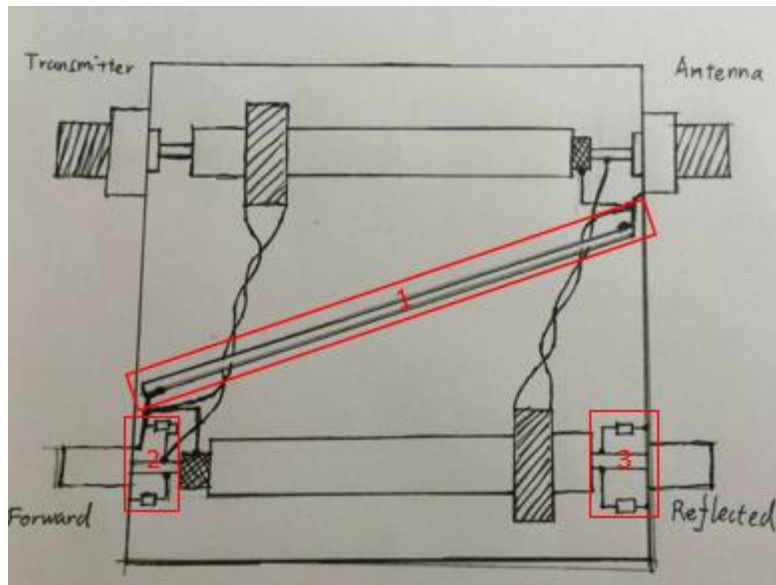
In our enclosure, we will have two N-type connectors from generator to 50Ω load and two BNC connectors to Forward and Reflected. (Fig. 7) In the block 1, it is on our PC board across the enclosure. The center conductor of the coaxial cable is soldered on the center pin of the connectors.

The coaxial-cable shield is connected only at one end and the other end is open. For our registers R1 and R2, (block 2&3) we use 4 paralleled 200Ω registers at each side.

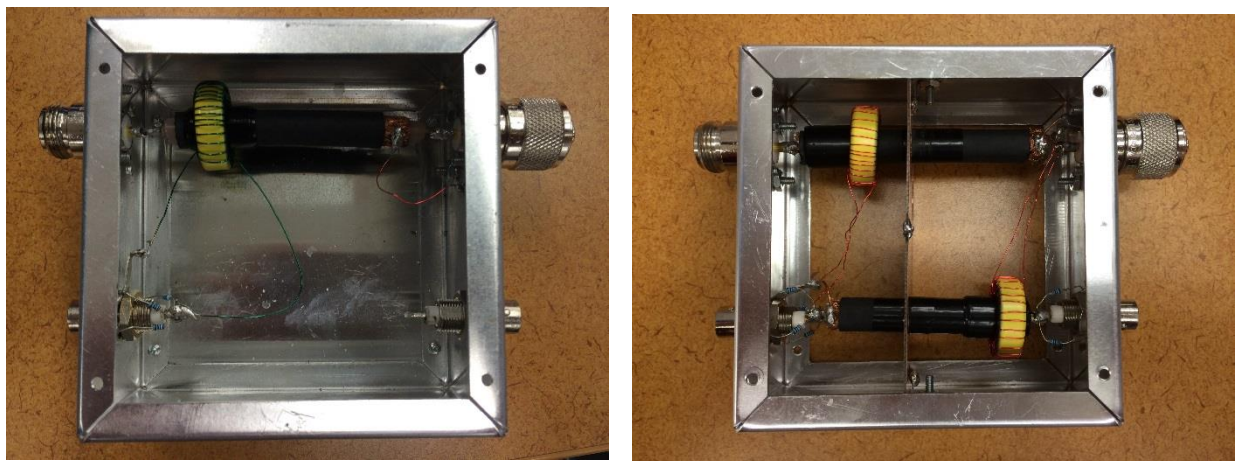Those are our single transformer and directional coupler.

Figure 8: Single transformer (left) and Directional Coupler (right)

3.5 Directional Coupler Test
i)   Single Transformer Test

According to our design, the ratio of input voltage by forward voltage should be 32. We need to test the single transformer to check.

We test single transformer in school's signal generator. We used 50Ω loads when we set up the function generator. Since the function generator twice the programmed voltage at 50Ω loads, which mean that the value of "V" equals the twice of the voltage in measured. In this case $V_{measure} = V_{display}$
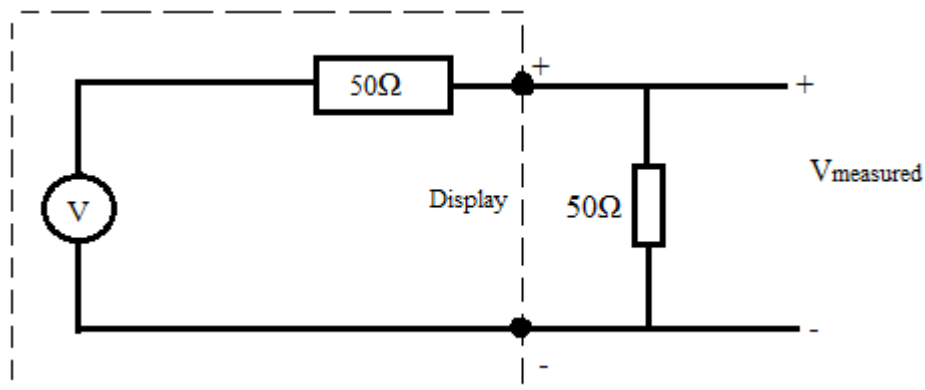

Figure 9: Signal Generator Function

In Figure 10, the input port connects to the signal generator. The output port connects to the 50Ω load.   Then we use of oscilloscope to connect forward port.
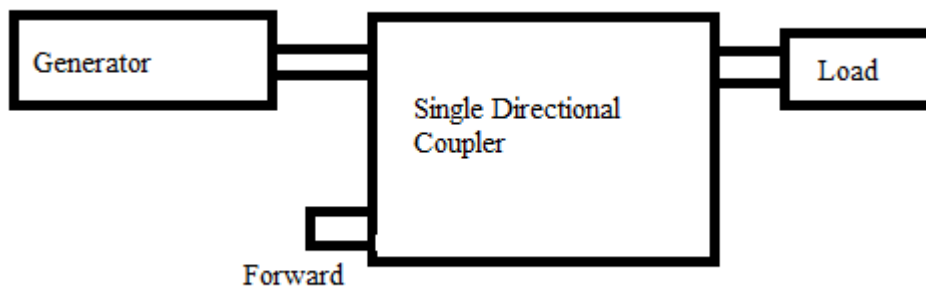

Figure 10: Single Transformer Test Approach

The reason why should connect 50Ω loads is because the impedance of the transmission line is 50Ω, we set the signal generator is also 50Ω load. We use a 50Ω load to connect the output port to match the whole system. That's also the reason why there would have no reflected power ideally.

If we use the power supply to test a single transformer. We connect an input port on the power supply. Other connection is as same as the Figure 2.

ii)   Single Transformer Result
- School Test

The first result we test in school. Since the limit frequency in the signal generator is 25MHZ, we only test the frequency in 13.5MHz. We increase the input voltage from 1V to 10 V. Then we evaluate the realistic input voltage. We also measure the forward voltage. Both values we measured using the same oscilloscope. Then we calculate the Ratio $= \frac{V_{in}}{V_{forward}}$.   The result analysis is in Figure 11.

According to analysis, the average ratio is 32.568624, median is 32.6128. Both values are close to the 32. All the 10 point is close to the diagonal line, which means normal distribution condition maybe met.

Due to the equipment limit, we cannot measure the ratio when the frequency of 40MHz. In order to test our directional coupler, we went to PowerFilm Inc. Using the power supplies to test our single transformer.
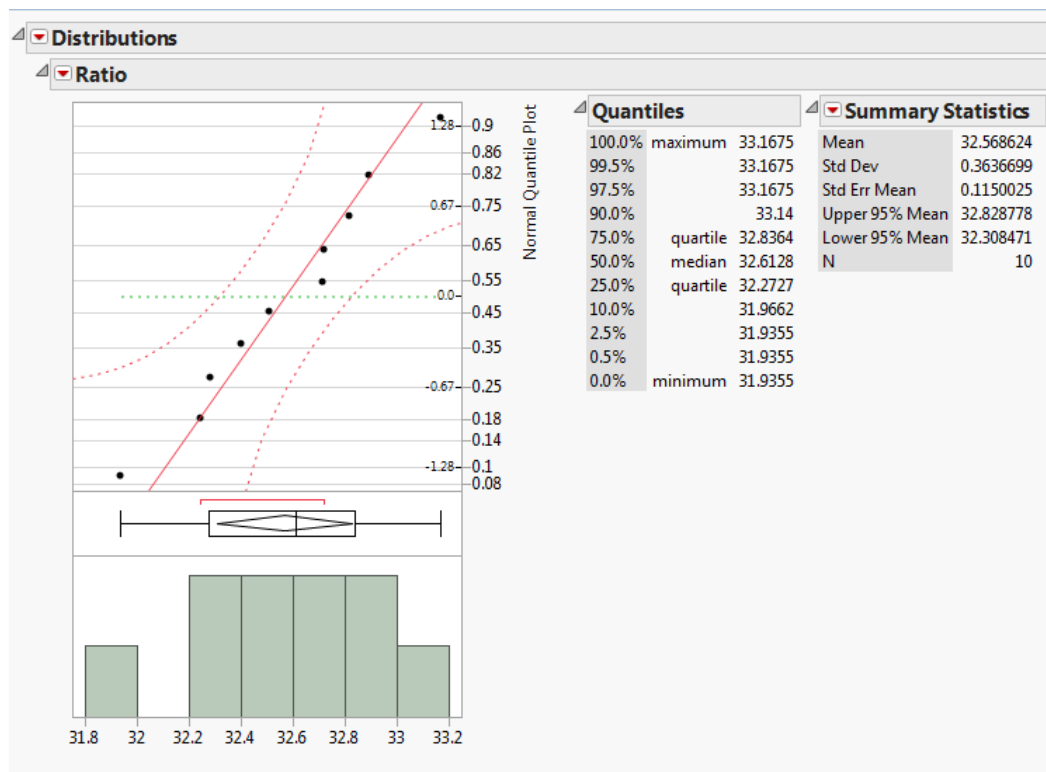

Figure 11: Single Transformer Test Result

- Test In PowerFilm
  - 13.5 MHz single transformer test

In this test, we went to PowerFilm Inc, using power supply to test our single

transformer. The power range we used is from 20W to 90W by 10W.   We utilize the oscilloscope to measure the forward voltage.   Since the forward voltage we measured is the peak to peak. We need to transfer it to forward power by 50Ω resistor. $P_{forward} = (\frac{\frac{V_{p-p}}{2}}{\sqrt{2}})^2/50$. Then we calculate the ratio $= \frac{P_{in}}{P_f}$. Finally we need calculate the coupling factor.   Coupling factor $= 10*\log_{10} ratio$.

In Figure 12, the average coupling factor is 29.987915. Median is 30.0025. Both value very close to our ideally coupling factor 30dB. According to the histogram, it's bimodal. For box-plot, the spread of distribution is skewed left. For the normal quantile plot, the point is close to the diagonal line. It can be seen from a normal distribution.

In Figure 13, we can see, as the input power increase, the coupling factor remain a line. The relationship between the input power and the coupling factor is: Coupling Factor(dB)=29.908048+0.001563*Input Power(W). According to this equation, when the input power is 0w, the coupling factor would be 29.908048. As the input power increase 100W, the coupling factor increases 0.15, on average. Due to the client request, we need to test the main input power is from 100w to 250w. Then we can calculate the coupling factor range from 100w to 250w is between 30.064dB and 30.2988. The error from this input power range is from 0.2% to 0.99%.
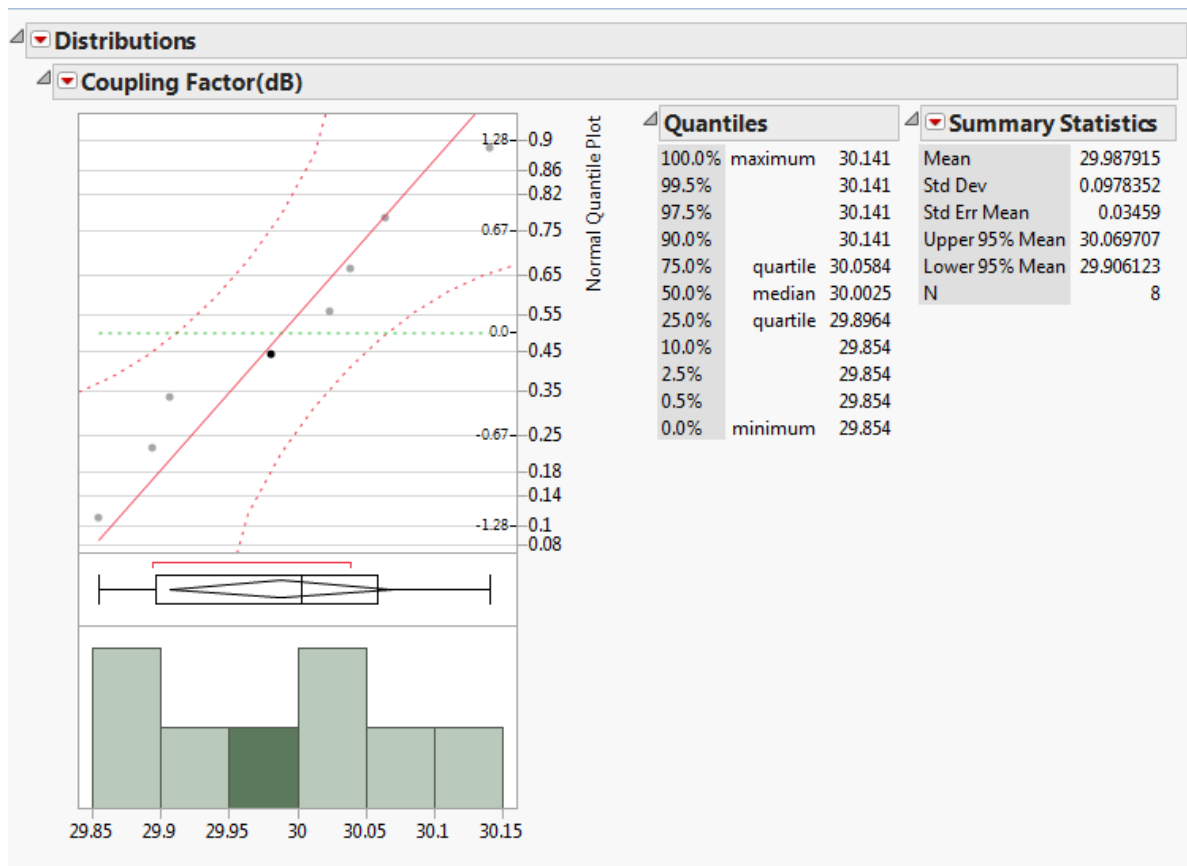

Distributions

Coupling Factor(dB)

Quantiles		
100.0%	maximum	30.141
99.5%		30.141
97.5%		30.141
90.0%		30.141
75.0%	quartile	30.0584
50.0%	median	30.0025
25.0%	quartile	29.8964
10.0%		29.854
2.5%		29.854
0.5%		29.854
0.0%	minimum	29.854

Summary Statistics	
Mean	29.987915
Std Dev	0.0978352
Std Err Mean	0.03459
Upper 95% Mean	30.069707
Lower 95% Mean	29.906123
N	8

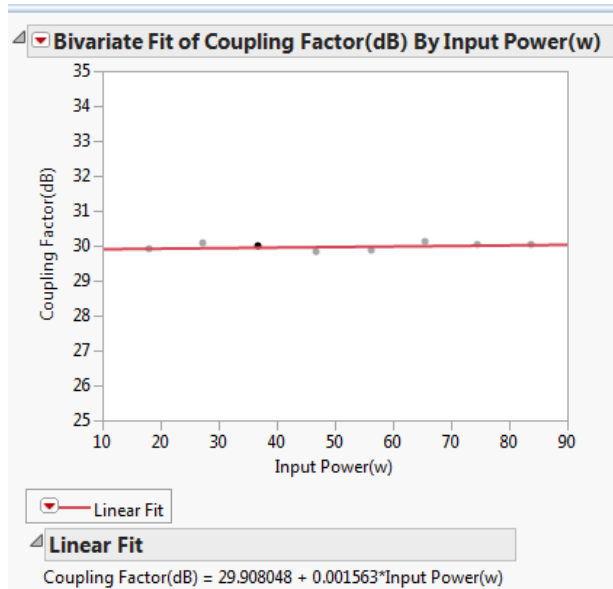Figure 12: 13.5MHz Single Transformer Result

Figure 13: 13.5MHz Single Transformer Plot

● 40MHz single transformer test.

We use the same method to test single transformer when frequency is 40MHz.   The result in Figure 14.
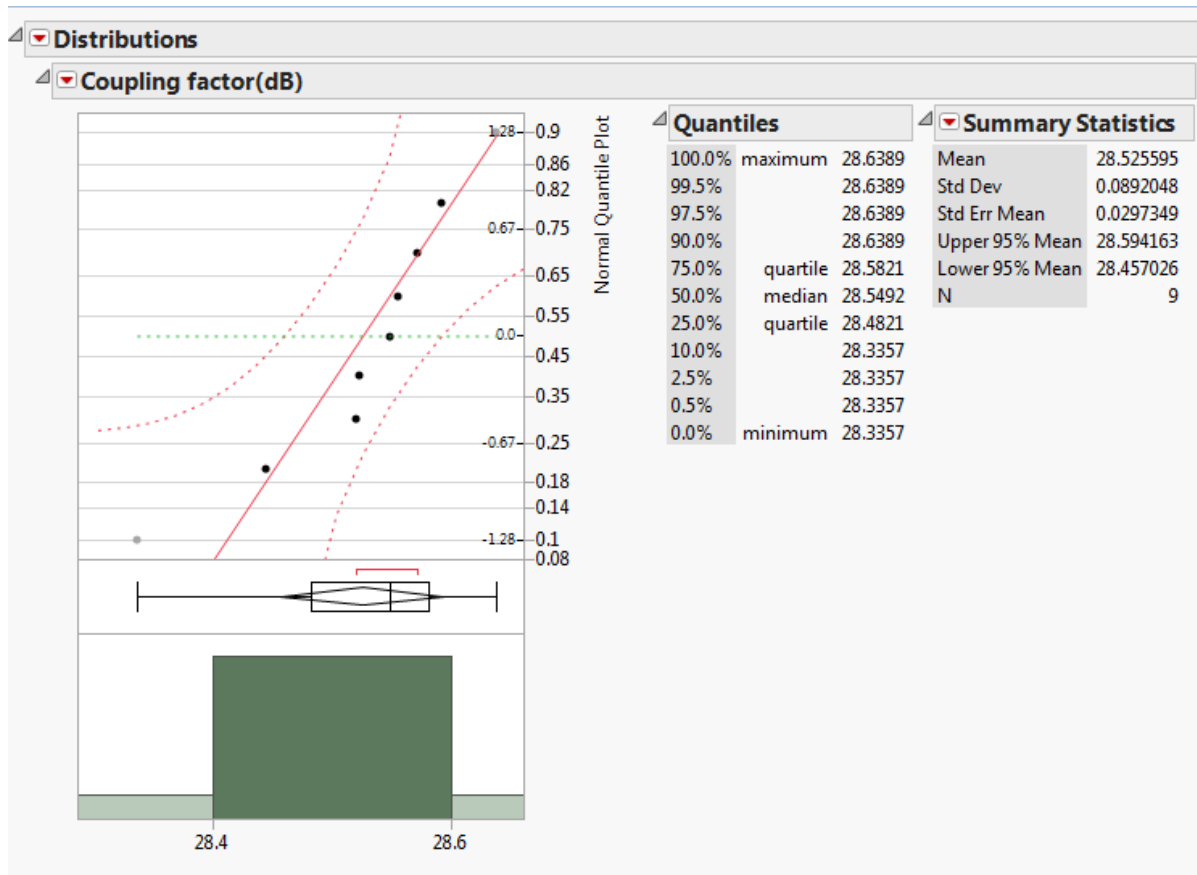

Figure 14: 40MHz Single Transformer Result

The average of the coupling factor is 28.525595, the median is 28.5492. For the histogram, is unimodal and little bit skewed left. However, due to the x-axis range, we can assume it's a symmetric distribution. For the Normal Quantile plot, the point is close to the diagonal line. The normal distribution maybe met.

We also increase the input power from 20w to 90w by 10w. The relationship between the input power and the coupling factor is:
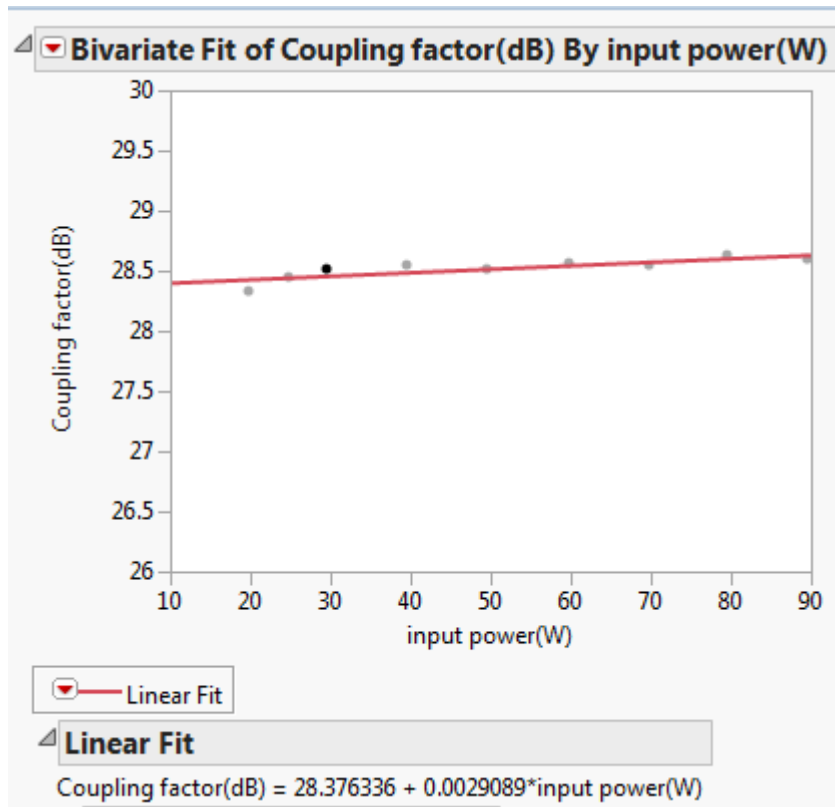

Figure 15: 40MHz Single Transformer Plot

According to the Figure 15,   we can find the relationship between coupling factor and input power in 40MHz is:

Coupling Factor(dB)= 28.376336+0.0029089*Input power(W). Analyzing this equation, we know that when the input power equal 0w, the coupling factor would be 28.376336dB. As the input power increase 100W, the coupling factor increases 0.29089, on average. Due to the client request, the main input power is between 100w and 250w. We can obtain the coupling factor in this range is from 28.6672 to 29.1036.

iii)   **Directional coupler test**

The method we tests directional coupler as same as we test a single transformer. The only difference is we connect reflected port to oscillscope to measure the reflected power. The schematic diagram is in Figure 16.
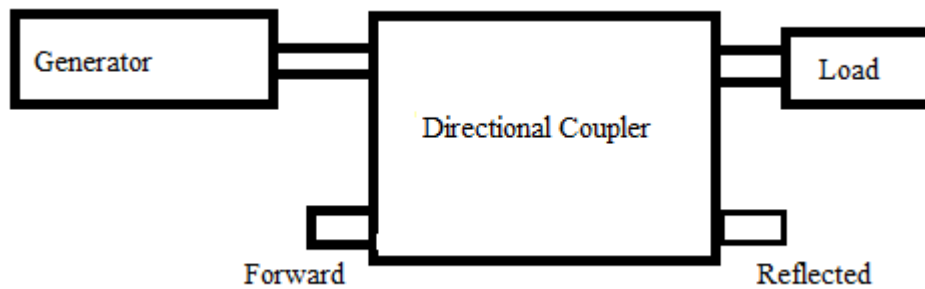
Figure 16: Directional Coupler test method

● 13.5 MHz directional coupler test

We use our school signal generator to test directional coupler in 13.5MHz. The result is in Figure 17.

Frequency(MHz)	Input Voltage (V pk-pk Display)	Forward (mV)	Reflected (mV)	Ratio(Vin/Vf)
13.5	1	34	14	29.41176471
13.5	2	64	16	31.25
13.5	3	96	16	31.25
13.5	4	127	18	31.49606299
13.5	5	159	20	31.44654088
13.5	6	189	20	31.74603175
13.5	7	219	26	31.96347032
13.5	8	249	28	32.12851406
13.5	9	281	30	32.02846975
13.5	10	312	32	32.05128205
			Average ratio	31.47721365
			AVG Powr ratio	990.8149792
			dB	29.95992564

Figure 17: Excel Data for 13.5MHz Directional Coupler at School

Then
we went to PowerFilm.Inc to test. The result is in Figure 18.

Frequency (MHz)	Input Power(Forward)	Input Power(Reflected)	Forward voltage(Vf pk-pk)	Reflected Voltage(Vf pk-pk)	Coupling Factor	Directivity
13.5	20.1	0.2	2.98	1.08	29.56823521	8.815850172
13.5	30.5	0.3	3.5	1.32	29.98223742	8.469882263
13.5	39.9	0.5	3.98	1.4	30.03266743	9.075100728
13.5	49.9	0.6	4.4	1.64	30.13255184	8.572176569
13.5	59.9	0.7	5	1.76	29.81546805	9.06914673
13.5	69.8	0.8	5.32	1.96	29.94092149	8.673111219
13.5	79.8	1	5.76	2	29.83217916	9.187849755
13.5	90.3	1.1	6.12	2.2	29.84244897	8.886574826

Figure 18: Excel Data for 13.5MHz Directional Coupler at PowerFilm Inc.

In Figure 19, we can see that it is the unimodal and the mean of the coupling factor is 29.893339, the median of coupling factor is 29.8917. The error in the mean of the coupling factor to ideal coupling factor is0.35%. We can say we design in coupling factor is almost correct.
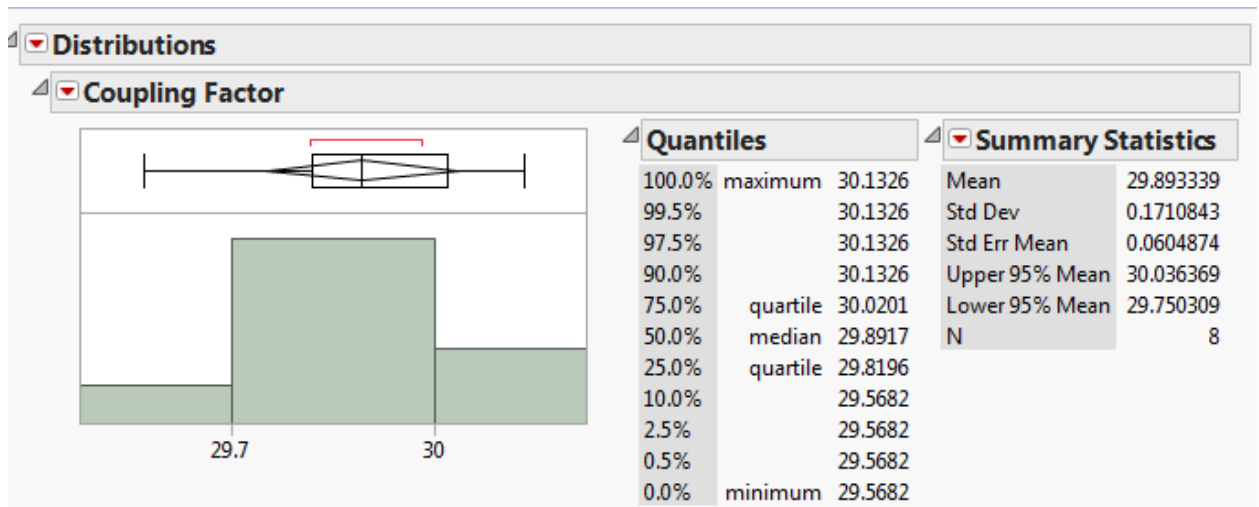

Figure 19: Data Analysis

After we calculate the mean and average of the coupling factor. We need to know the relationship between the input power and coupling factor.
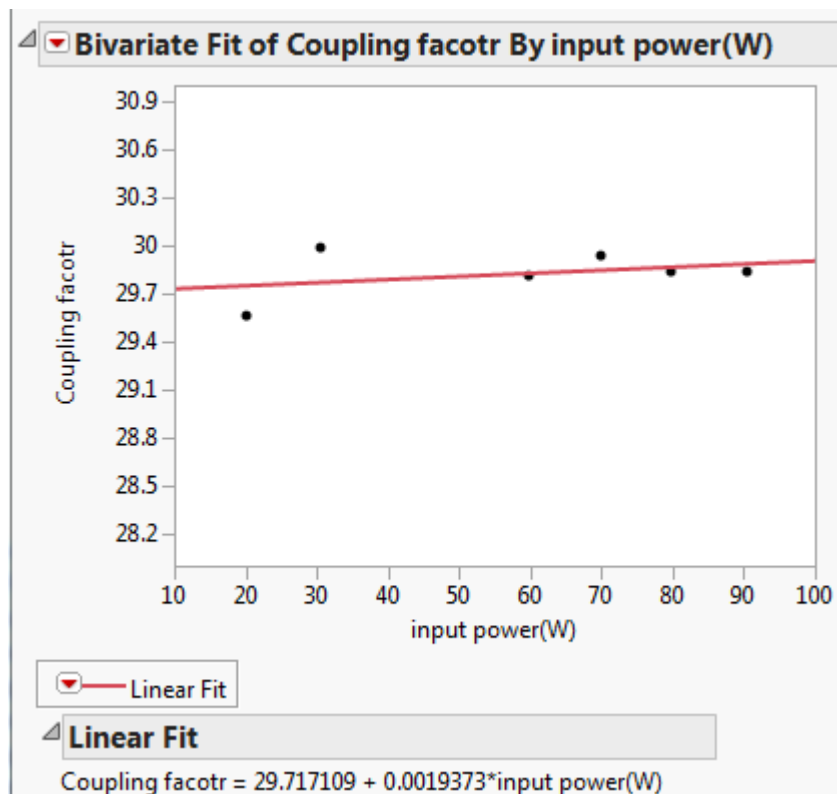

Figure 20: Data Analysis

In Figure 20, we can use fit line to get a equation about input power and coupling factor.

Coupling Factor = 29.717109+0.0019373*Input Power. It does mean that, as input power increase 100 watts, the coupling factor increase 0.19373dBm, on average. According to our client's requirement, the principle measure power range is from 100w to 250w. We can say, coupling factor would not have any significant change in this range.

- 40 MHz coupling factor test
  We did the test in PowerFilm Inc. The result is in Figure 21.

Frequency (MHz)	Input Power(Forward	Input Power(Reflected)	Forward Voltage(Vf pk-pk)	Reflected Voltage(Vf pk-pk)	Power ratio	Coupling Factor
40	19.2	0	3.12	1.68	788.9546351	28.97052303
40	29	0	3.76	1.92	820.5070167	29.14082299
40	38.8	0	4.32	2.24	831.6186557	29.19924223
40	48.6	0	4.88	2.32	816.3128191	29.11856617
40	58.4	0	5.28	2.64	837.9247016	29.23204993
40	68.2	0	5.68	2.88	845.5663559	29.27147695
40	78.1	0	6.28	2.88	792.1213842	28.98791738
40	87.9	0	6.48	3.12	837.3342478	29.22898855

Figure 21: Excel Data for 40MHz Directional Coupler in PoweFilm Inc.

In Figure 22, the distribution is biomodel for coupling factor. According to the data analyze, the mean of coupling factor is 29.143698, the error is 2.85%. The median is 29.17.
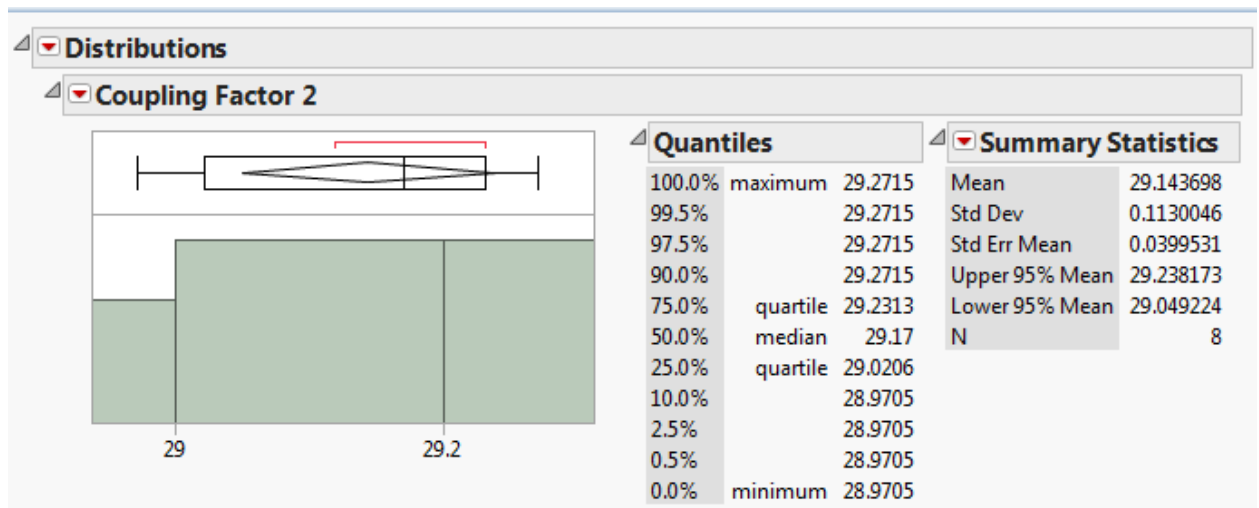

Figure 22: Data Analysis

After we calculate the mean and average of the coupling factor. We need to know the relationship between the input power and coupling factor.
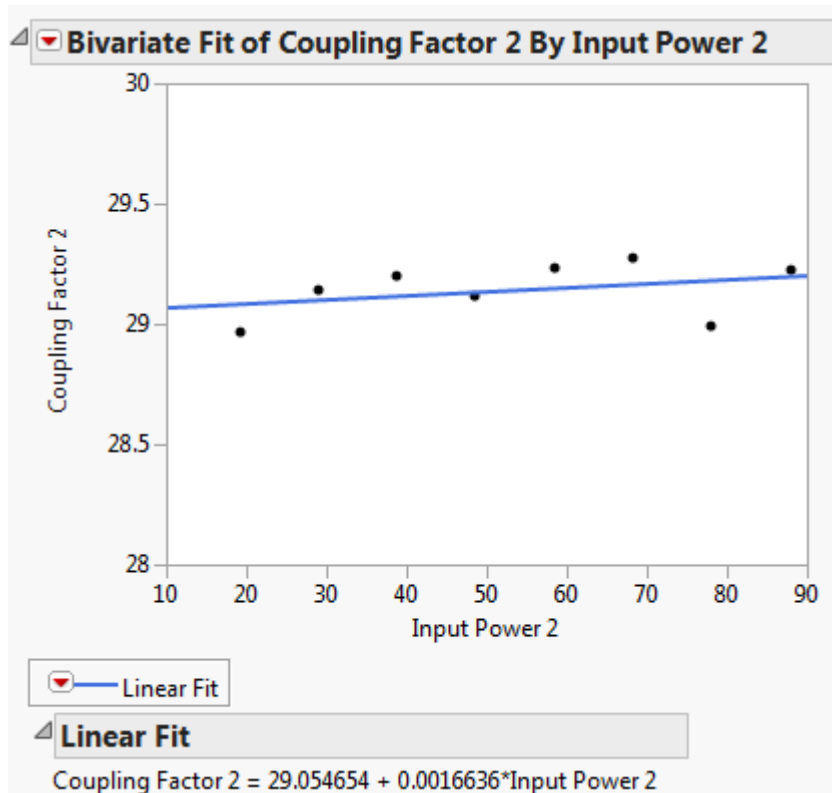
Bivariate Fit of Coupling Factor 2 By Input Power 2

Linear Fit

Coupling Factor 2 = 29.054654 + 0.0016636*Input Power 2

Figure 23: Data Analysis

In Figure 23, the equation is Coupling Factor = 29.054654+0.0016636*Input Power. It means that, as input power increases 1000 watts, the coupling factor increases 1.6636dBm, on average. According to our client's requirement, the principle measure power range is from 100w to 250w. In this power range, the coupling factor is from 29.221 to 29.4706. The error comes from 2.597% to1.76%.

Depending to the data, the reflected voltage is not exactly 0. There are for two reasons make this phenomenon. According to our design circuit, we set up the R1 and R2 equal 0. However, in our real products, we used four of 200 Ω resistor parallels to get a 50Ω resistor. The valid value for this is 50.1 and 50.04. In this case, the reflected voltage cannot be cancelled clear. That's lead to reflecting voltage not 0. The second reason is, during our working process, it exists some tiny error like soldering, etc. That's also generate reflected voltage.

3.6 Directivity & Isolation

As with any component, there are several specifications associated with RF directional couplers. After we test coupling factor, we still need to test directivity and isolation.

Directivity means power level difference between the forward port and reflected port. This is a measure of how independent the coupled and isolated ports are. Because our directional coupler cannot build perfect, there will always be some amount of unintended coupling between all the signal paths. The equation is:

Directivity= $10*\log_{10}\frac{P_f}{P_r}$. Ideally this is infinite, because reflected power should close

to 0W, that means the higher directivity, the better.

Isolation means power level difference between input port and reflected port. It also related to directivity. The equation is:

Isolation= $10*\log_{10}\frac{P_{in}}{P_r}$.   Ideally, reflected power should be close to 0w, so the higher

the isolation, the better.

- **Directivity result**

In Figure 24. We can see the mean of directivity is 8.8437115 and median of directivity is 8.85121. This is a unimodal and little bit skewed left. However, we still can say that the distribution for directivity is normally.
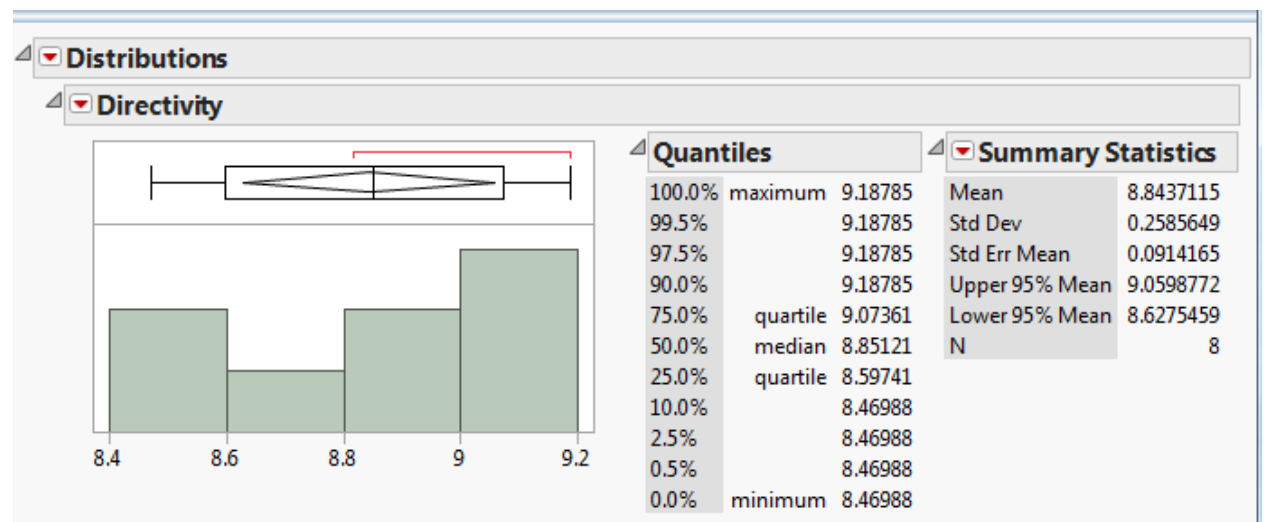

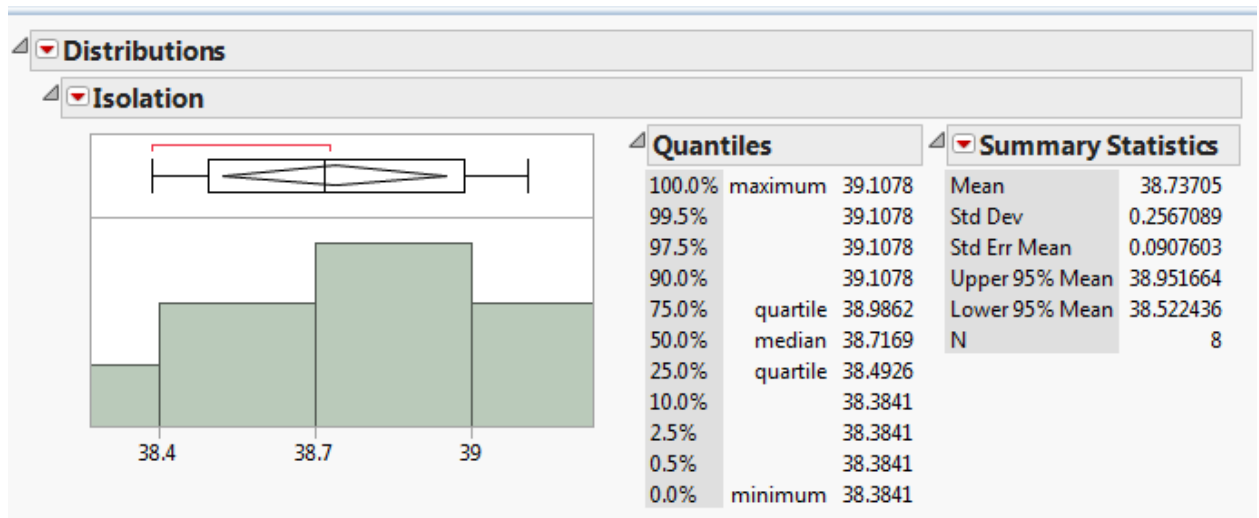Figure 24: Directivity Data Analysis

- **Isolation test result**

Figure 25: Isolation Data Analysis

According to Figure 25, the mean of isolation is 38.73705 and the median of isolation is 38.7169. This is a unimodel and little bit skewed left. But is still a normal distribution.

- **The relation of isolation, coupling factor, and directivity**
  Note that isolation, directivity and coupling factor are not independent values. The relationship for this three values is:

  Isolation (dB) =Coupling Factor (dB) +Directivity (dB)
  We use JMP-fit model to find the relationship for this three values. The analysis of result is in Figure 26.

  According to this data analysis, we can write the relationship for this 3 variables.
  Predict Isolation = $-1.649*10^{-7}$+1*Coupling factor+1*Directivity.
  In this equation, we can find that in our directional coupler, isolation is almost equally the sum of coupling factor and directivity. This result is reasonable.

Figure 26

3.7 Diode Detection

Diode detector is the circuit that converts the high frequency AC voltage to DC. We chose diode peak detector over thermocouple and thermistor as our sensor is because of its fast transient response. Client's input source is the pulsed RF signals in addition to continuous wave signals, so the faster response sensor is needed to achieve better amplitude tracking. Schottky diode results in fast switching and low forward voltage drop.   HSMS-282K is a good choice among all schottky diodes. It has very small inner capacitance, so the time constant is relatively small (fast transient response).

According to diode I-V characteristic curve, two operation regions can act as a rectifier, square-law region and linear region. In the square-law region, the input power is proportional to the square of the peak output voltage. It has good sensitivity in detecting voltage, but the dynamic range is limited. Our project requires wide power range, so in this case, the linear region detector is a better option. Within the linear region, the input power is proportional to the peak output voltage ($Pin = \frac{V_{OUT_{peak}}^2}{2*R_{source}}$).
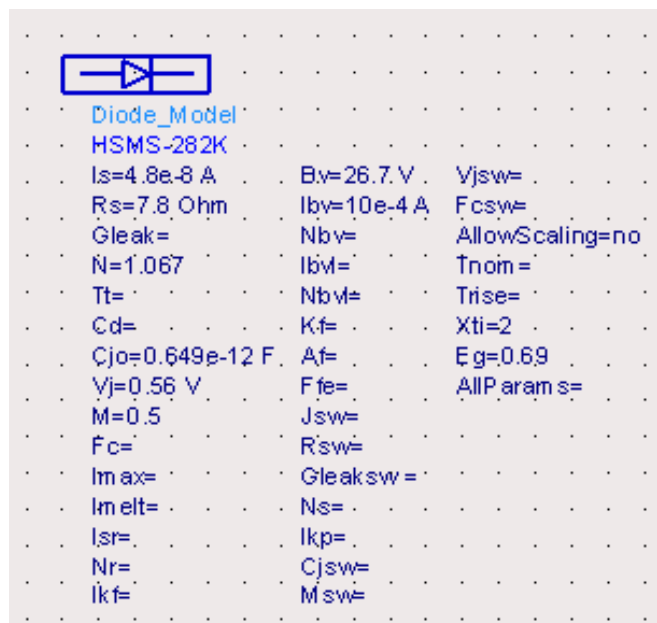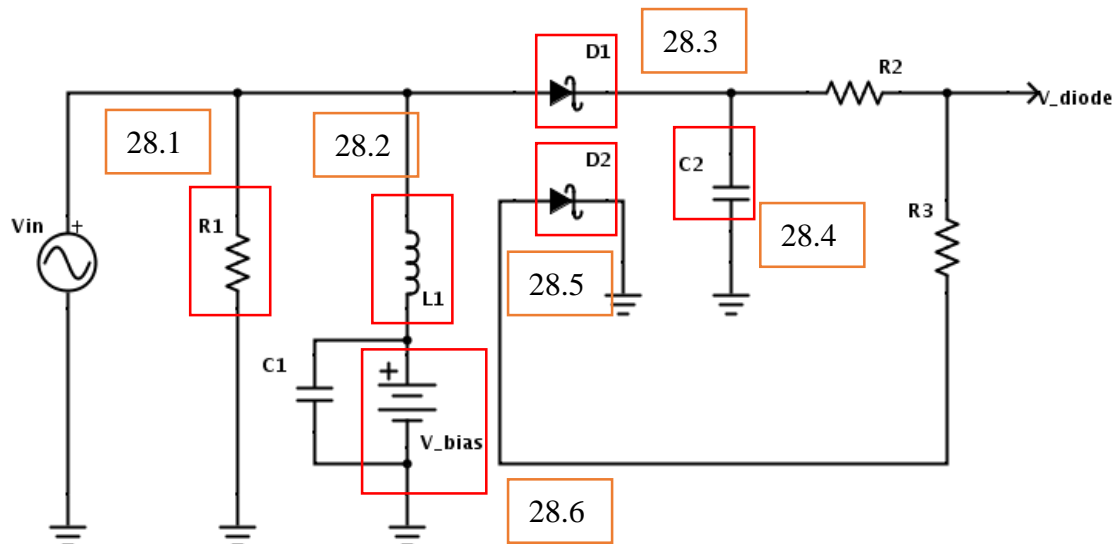

Figure 27: HSMS-282K Diode Model

Figure 28: Diode Detector Schematics

- Matching Circuit (see Figure 28.1):

  Matching circuit is to maximize the forward power transfer (or minimize the reflected power) when load impedance is equal to complex conjugate of source impedance. In our design, source impedance is merely the resistance, so the matching component is a pure resistor which should be identical to our source resistance in theory. So during the transient simulation of the diode detector, when $V_{load} = 0.5V_{in}$, the power transfer is maximum.

- Choke Circuit (see Figure 28.2):

  Choke circuit is a simple inductor. The purpose of adding this component is to block higher frequency currents. It will be used to pass the DC current and suppress any noise and RF from the circuit. However the value should be cautiously selected in case of causing self-resonant.

- Rectifier (see Figure 28.3):

  Rectifier is the key of the detector. It has the ability to convert AC voltage to DC. Our diode will convert the AC voltage to its peak value known as envelope detection.

- Smoothing Capacitor(see Figure 28.4):

  Smoothing circuit is to use a capacitor to reduce the ripple of rectified DC voltage. The principle of smoothing is based on the charging and discharging of capacitor. As voltage increases, the capacitor charges, and as the output starts to fall, it will release its stored charge. So for a large value of capacitance will result better DC output since the capacitor will take more time in discharging, and will charge up for little voltage drop.

- Temperature Compensation (see Figure 28.5):

According to the junction resistor equation $R_j = \dfrac{n\frac{kT}{q}}{I_{bias}+I\_saturation}$, the resistance depends on the temperature T which makes it as a variable resistor. This is a huge value under zero biasing due to the small saturation current. So adding a load diode which is identical to the rectifier will prevent the voltage drop in the middle of the line.

- Biasing (see Figure 28.6):

    As problem mentioned before, the junction resistance of diode is too large. Under zero bias and at room temperature, the diode's saturation current is 48pA, so the junction resistance is about $\dfrac{0.0259}{48*10^{-9}} = 0.54 M\Omega$. This will result a huge voltage loss to the load. One way to reduce the voltage loss is adding a small bias current. When reasonable bias current is injected, both diodes will have less resistance, and the load voltage will depend on two fixed resistances that will improve the linearity of the curve. For example if 1 μA biased current is into the circuit, the junction resistance will become $\dfrac{0.0259}{1*10^{-6}+48*10^{-9}} = 0.0247 M\Omega$, and the voltage on the load will be increased.

The simulation out of the diode detection:
- All simulations are using frequency of 13.5MHz.
- The first type of the simulation is Harmonic Balance (HB) simulation. This simulation directly shows and calculates the steady state response immediately. From HB simulation, we can sweep the power range in order to compare the ideal voltage output and the simulated voltage output.

  ➢ HB simulation of power range from 0.05 to 1 Watts (or 17dBm to 30dBm) (this is the power range after the directional coupler)
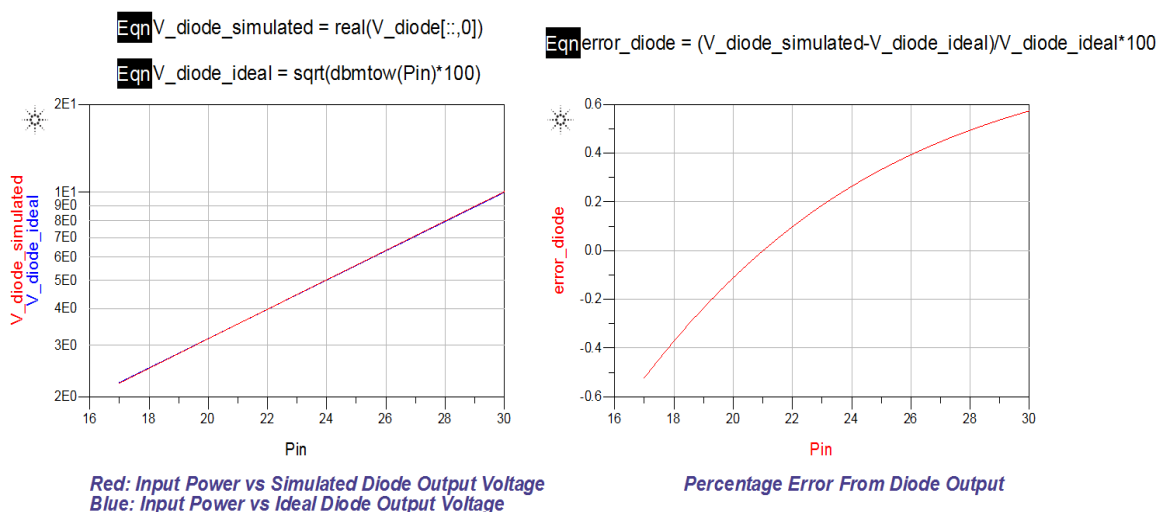

Figure 29: Diode Detector HB Simulation

Figure 29 is the simulation of ideal and simulated output plus the error within the power range. The error is in between -0.5% to 0.6%. However, the error tends to increase when input voltage becomes very small (approximately less than 0.01W after directional coupler). This is due to the missing of the bias voltage/current in our design, which we failed to design it. The power range our client focused on is 100 to 250W (before the directional coupler), and within this range, error due to bias voltage/current is neglected.

➢ Transient simulation of pure sinusoidal input with amplitude of 4 Volts.

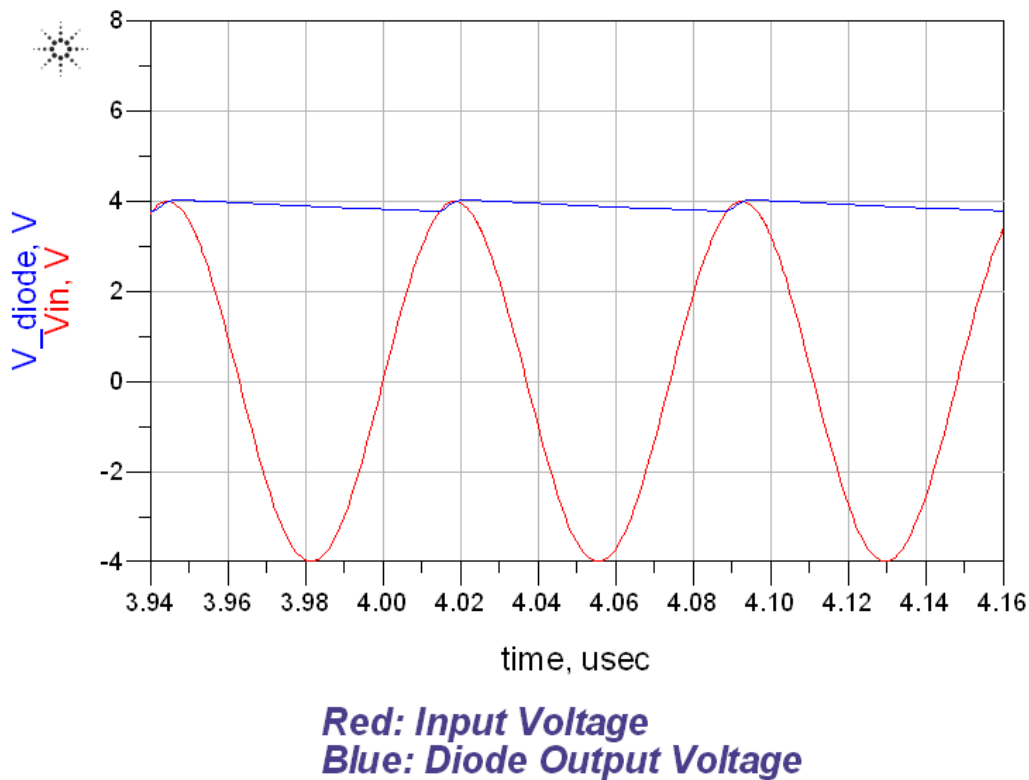**Red: Input Voltage**
Blue: Diode Output Voltage

Figure 30: Diode Detector Transient Simulation with Pure Sine Input Wave

➢   Transient simulation of pulse modulated sine wave, with sine wave amplitude of 4 Volts, and pulse signal with 30 kHz frequency of 50% duty cycle (Client's pulse frequency is from 1 kHz to 30 kHz, so we used worst case scenario to ensure bandwidth is sufficient).
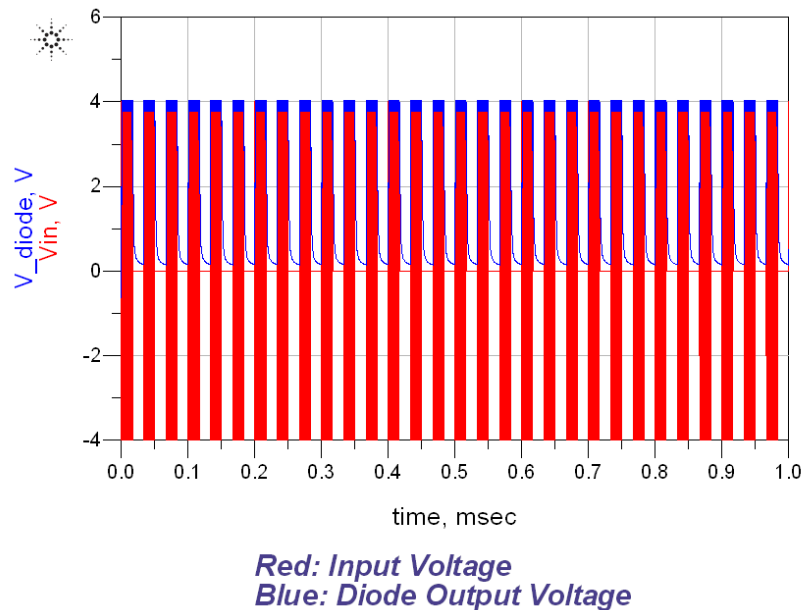

Red: Input Voltage
Blue: Diode Output Voltage

Figure 31: Diode Detector Transient Simulation with Pulse Modulated Sine Input Wave

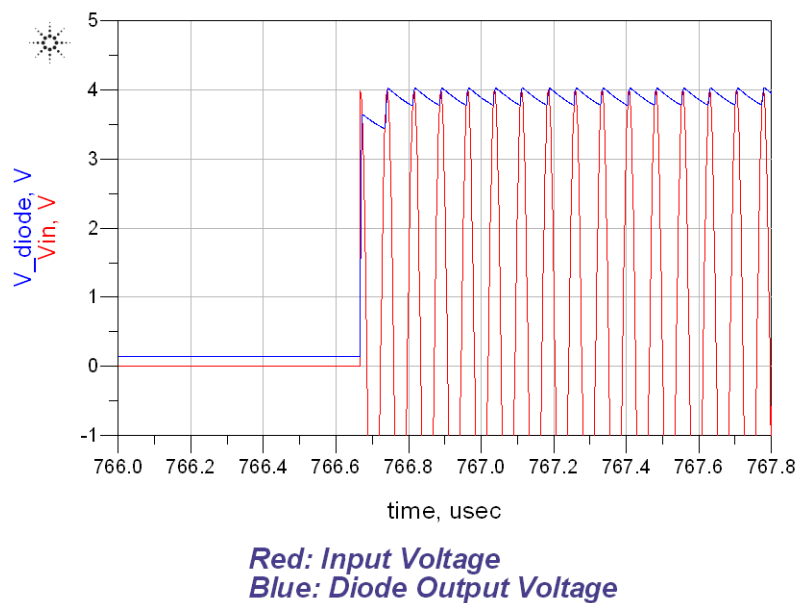Red: Input Voltage
Blue: Diode Output Voltage

Figure 32: Zoom In

The transient simulation shows the diode detector tracks the amplitude of the AC input. However, there still exists some ripple signals that needs low-pass filter to filter them out. As for modulated signal input simulation, the falling time is a little long, so it might produce some errors. This is because the smoothing capacitor is large, so it takes longer time to discharge.

3.8 Low-Pass Filter

The role of low-pass filter is to remove the high frequency signal in order to get DC signals with less ripple. Any signals with frequency higher than cutoff frequency will be attenuated in a certain amount per decade. The operational amplifier is a good active low-pass filter.
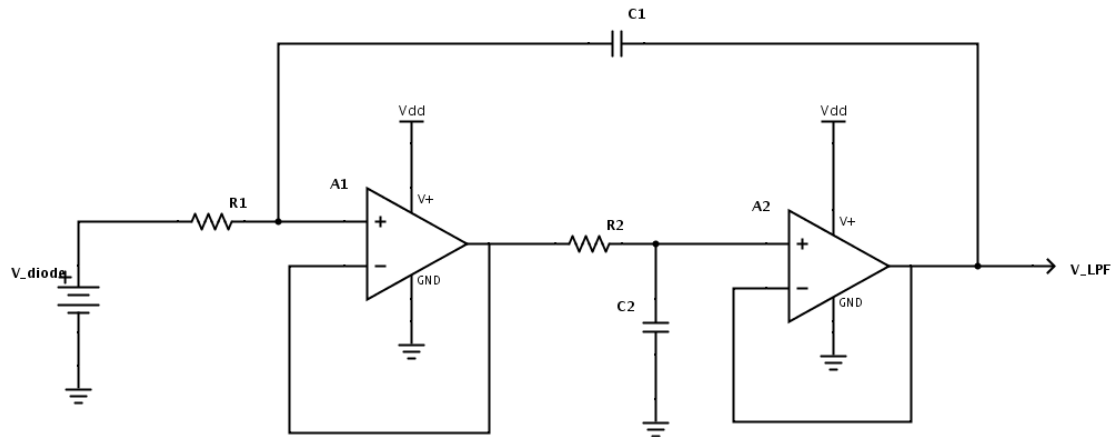

Figure 33: Low-Pass Filter Schematics

Figure 33 shows a low-pass filter with two amplifiers in series. The op-amps used in this schematics are both LMC6492, because it has ultra-low input current (200pA). This bias current is in pico level and such small value of current won't affect significantly to the diode detector.

In our design, when input voltage is a pulse modulation of a sine wave, the low-pass filter will take the average of the pulse because of 50% duty cycle. Then we are allowed to figure out the average power level.

The simulation out of the low-pass filer:

> ➢ AC simulation. The input peak voltage is set to be 1, and 0 in phase. So the output value is exactly the gain value. The frequency range is from 10 times less than wave frequency (13.5 MHz), to 10 times greater than wave frequency.
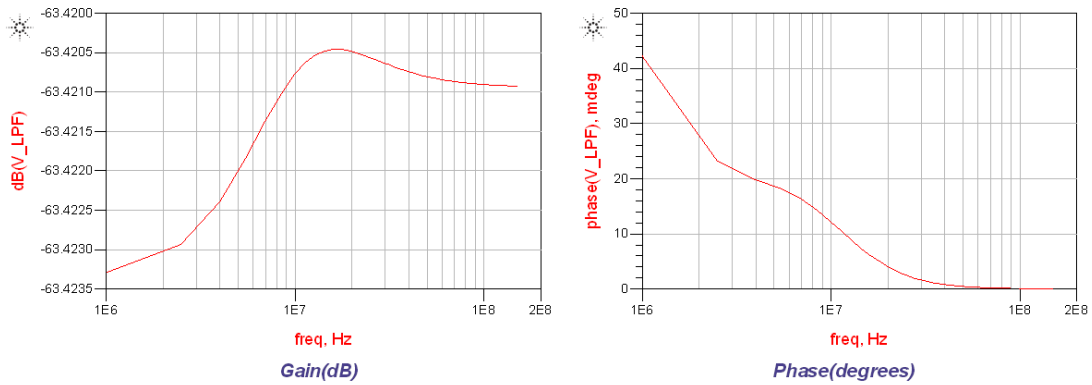

Figure 34: Low-pass Filter AC Simulation

The plot shows the attention is around -63.4db, and phase is approximately zero.

> ➢ Transient simulation. The input voltage is a 50% duty cycle pulse signal with 4 V peak voltage, plus frequency of 30 kHz. The ideal output voltage should be the half of the peak voltage which is 2V. The simulation shows after the steady state, the error out of low-pass filter is very small.
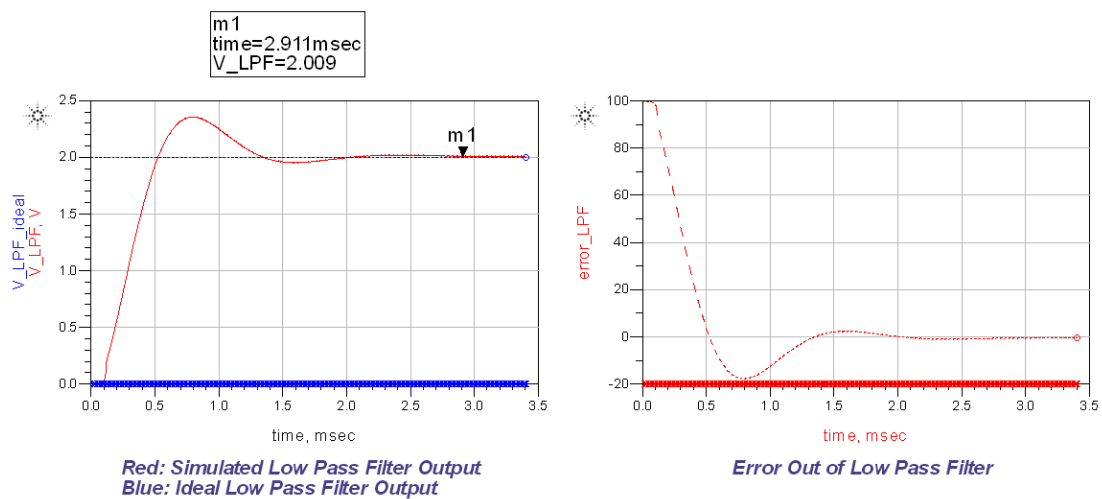

Figure 35: Low-pass Filter Transient Simulation

3.9 Scaling Amplifier

As client request, the output voltage has to be within 0-5V. The traditional way is to distribute this voltage across the whole power range. However in this way, the error will be very large because of the wide dynamic range. The scaling amplifier uses different gains in different ranges but result 0-5V output voltage in each range. Using this approach, the output voltage will be more accurate.
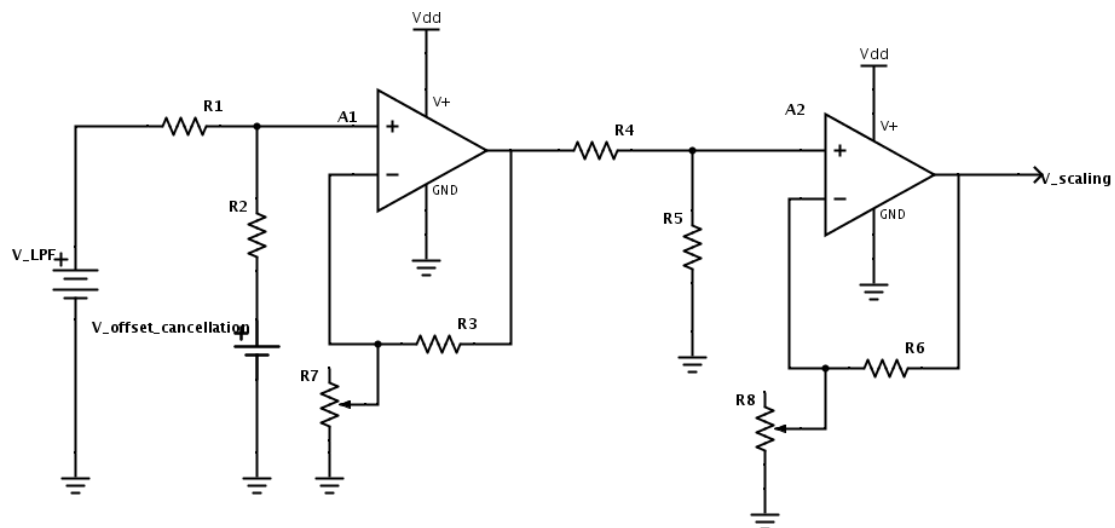

Figure 36: Schematics of Scaling Amplifier

Figure 36 is the schematics of scaling amplifier. This is a non-inverting amplifier configuration to generate a positive gain. The gain is $A_v = (1+\frac{R_3}{R_7})$.

There're two $\frac{1}{\sqrt{10}}$ voltage dividers before and after the scaling amplifier. The main reason to add these voltage dividers is to guarantee the gain of amplifier is greater than 1 for each scaling amplifier range. The worst case is when the input voltage is minimum (gain is maximum), then voltage divider's value needs to be tuned until reaching the scaling amplifier's gain over unity. At the end of the scaling amplifier, we add another identical voltage divider, which makes the total gain of the whole scaling amplifier is $A_v = (1+\frac{R_3}{R_7}) * \frac{1}{10}$. After going through the voltage square circuit (discuss in next step), we will have the output voltage which is under 5V. Using this approach, the error can be minimized due to multiple ranges.

The range and gain selection:
(Starting power is 25W)

Power(w)	Vout(v)	Vin(v)	Gain(v/v)	Feedback Resistance(kΩ)
50	7.071	0.3536	20	5.3
100	7.071	0.5	14.142	7.6
200	7.071	0.707	10	11.1
350	7.071	0.9354	7.559	15.2
500	7.071	1.118	6.325	18.8
1000	7.071	1.581	4.472	28.8

Table 5: Scales When Input Is Pulse Modulated Since Wave

Power(w)	Vout(v)	Vin(v)	Gain(v/v)	Feedback Resistance(kΩ)
50	7.071	0.707	10	11.1
100	7.071	1	7.071	16.5
200	7.071	1.414	5	25
350	7.071	1.871	3.78	36
500	7.071	2.236	3.162	46.2
1000	7.071	3.162	2.236	81

Table 6: Scales When Input Is Pure Since Wave

However, after calculating the errors among all scaling ranges, the lowest power range shows a massive error. The reason of this issue is because of the offset voltage from the amplifier. This value is cannot be ignored regarding to small input voltage. So a voltage cancellation source is in addition to the input.

The same reason we as diode bias voltage, we failed to complete the offset cancellation design, so we chose the starting power level from 20W instead of 1W.

The simulation out of the scaling amplifier:

➢ DC Simulation

Red: Simulated Scaling Amplifier Output Voltage
Blue: Ideal Scaling Amplifier Output Voltage
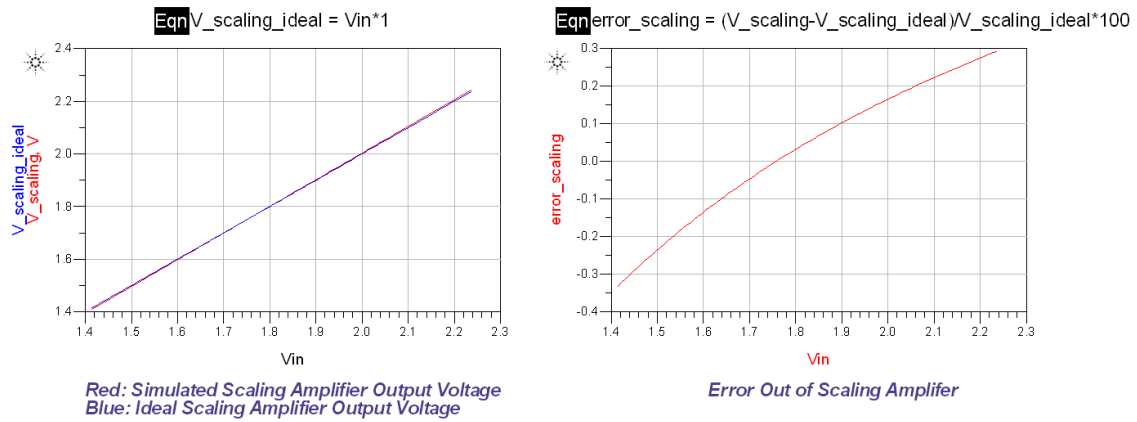
Error Out of Scaling Amplifer

Figure 37: DC simulation Out of Scaling Amplifier

This simulation is the power level from 20W to 50W (before the directional coupler), and this is the lowest power range, which is the worst case (largest gain). However the error is only from -0.4% to 0.3%.

3.10 Voltage Multiplier

According to the equation $P = \dfrac{Vpeak^2}{2*50} = \dfrac{Vpeak^2}{100}$, plus we've obtained the expression

of $\dfrac{Vpeak}{100}$*gain, the next step is to square this expression which will be laying in 0 to

5 V range. AD633 is a simple 4-quadrant multiplication device, and if we take the product of two identical input, the output will be the squared number.
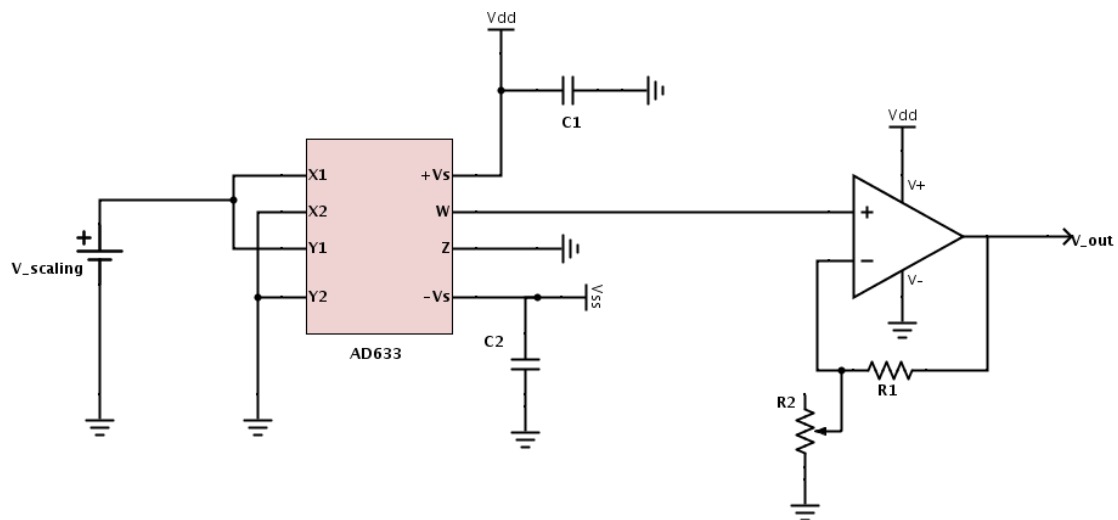

Figure 38: Schematics of Analog Multiplier

The transfer function provided from data sheet is $W = \dfrac{(X1-X2)(Y1-Y2)}{10} + Z$

Set X2, Y2, and Z to be zero (grounded), the transfer function became $W = (X1*X2)/10$. Hence, an additional amplifier is used to eliminate the factor of 1/10.

The simulation out of the multiplier:

➢ DC Simulation.

m1
Vin=1.562
delta=1.011

Eqn V_squarer_ideal = Vin*Vin

Eqn delta=(V_squarer-V_squarer_ideal)/V_squarer_ideal*100

Red: Simulated Squarer Output Voltage
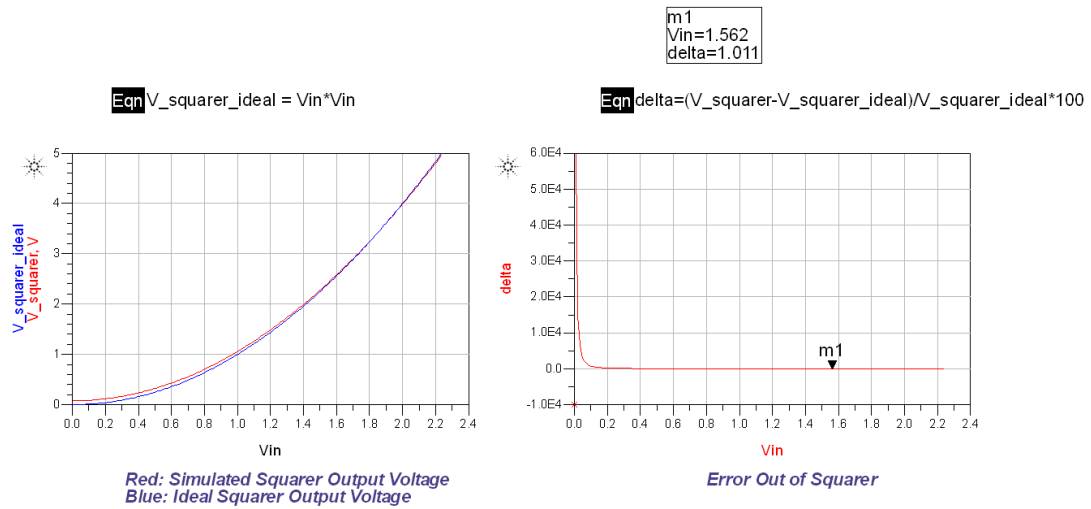Blue: Ideal Squarer Output Voltage

Error Out of Squarer

Figure 39: Multiplier DC Simulation

The simulation above shows when Vin is greater than 1.562 V, the error is less than 1%. In such case, the voltage output from multiplier should be greater than 1.562^2 = 2.44 V. So the ratio of $\frac{Vout}{5}$ should be greater than 0.488. This number reminds us that the ratio between lower and upper scales in scaling amplifier should be greater than 0.488.

3.11 Voltage Regulator

The voltage regulator is to maintain positive and negative 10 Volts DC voltage for power supply.
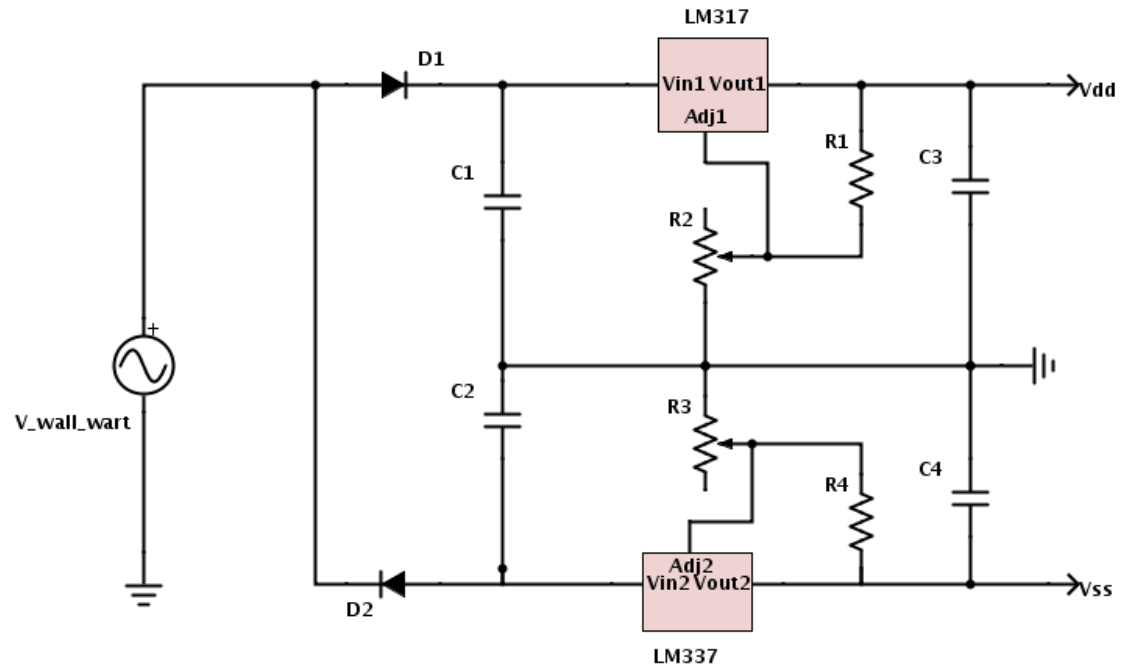
Figure 40: Schematics of Voltage Regulators

The voltage out of wall wart is a 24 V 60 Hz AC signal, and D1, D2 will convert the AC signal into DC, and smoothed by C1, C2. LM317 is a positive adjustable voltage regulator, and LM337 is a negative adjustable voltage regulator. The output voltage depends mainly on the ratio of $\frac{R1}{R2}$, and $\frac{R4}{R3}$. In our design, Vdd is going to be +10 V, and Vss is going to be -10 V.

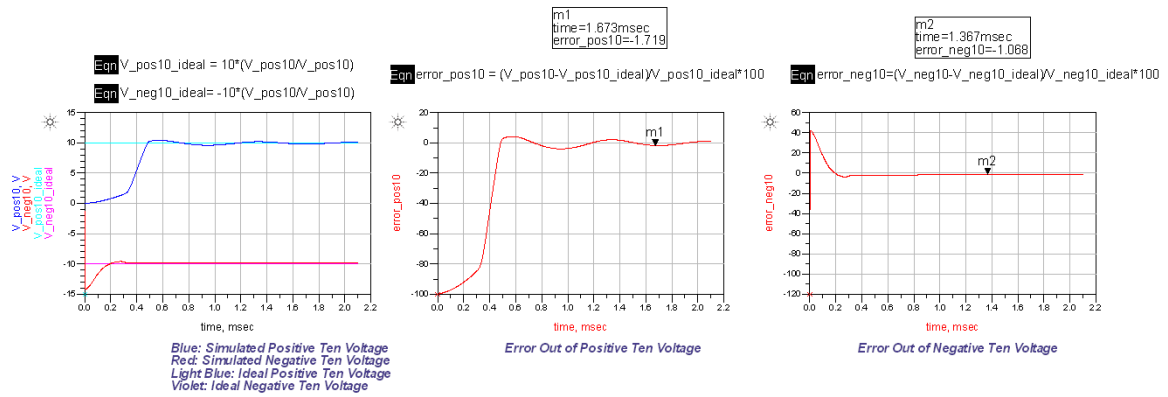The simulation out of the regulator:

➤ Transient Simulation

Figure 41: Regulator Transient Simulation

Although the simulation shows about 1% to 2% error, the power supply to amplifier or multiplier actually doesn't require too much accuracy. So this is a tolerable range of error.

3.12 Overall Simulation

At last, we integrated all circuits together and run several simulations.

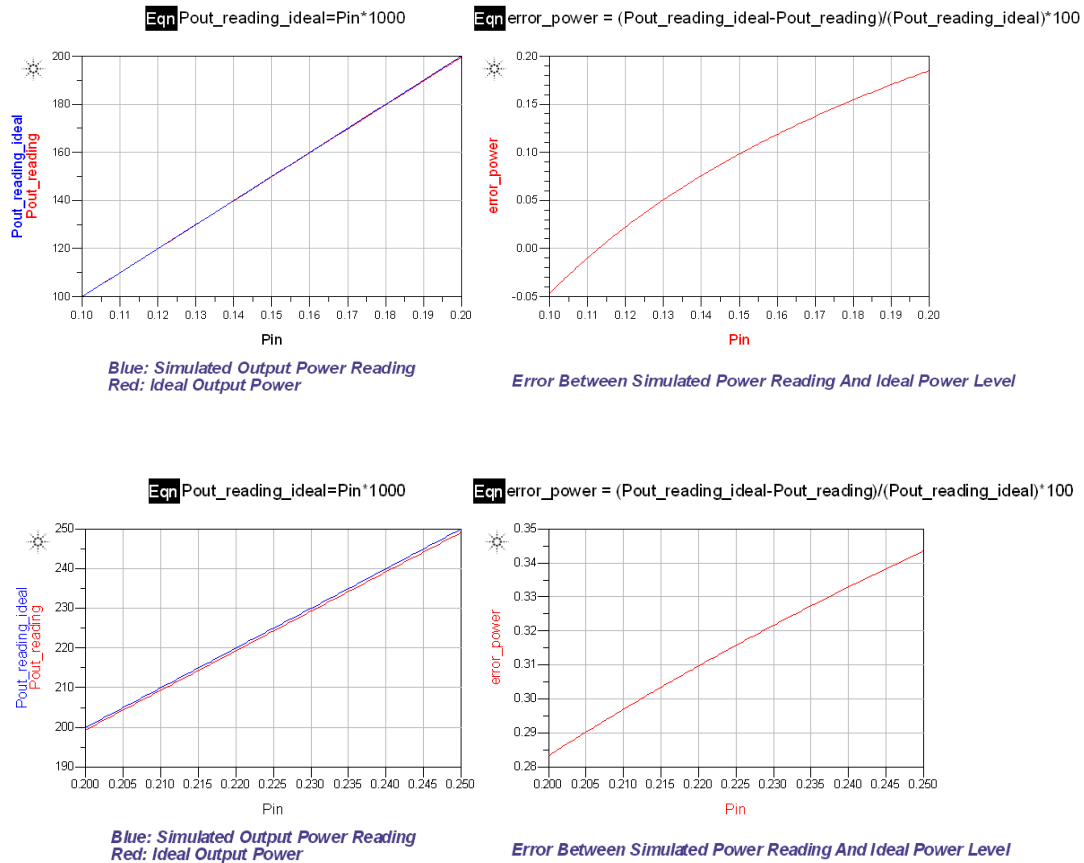➢ Harmonic Balance Simulation for Power range of 100W to 250W (before the directional coupler)

Figure 42: Overall Harmonic Balance Simulation

Simulation above shows the total power reading error is from -0.05% to 0.35% when input power is from 0.1W to 0.25W (after directional coupler). Ideally this is a good result.

➢ Transient Simulation
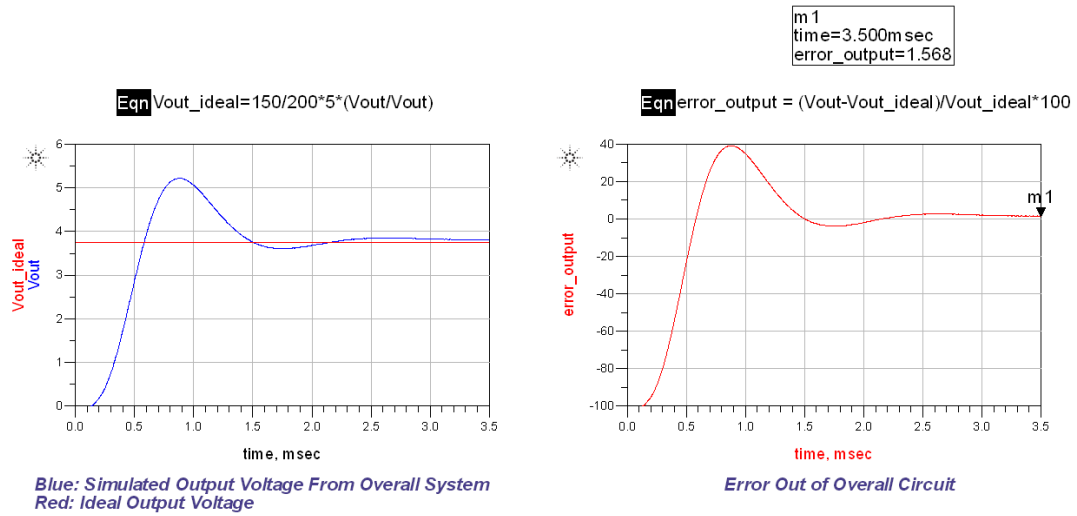
Figure 43: Transient Simulation

This is an example of pulse modulated sine input signal with 150W (before the directional coupler) average power. The input peak voltage should be $\sqrt{\frac{150}{1000}} * 100$ = 3.873V.

The ideal output voltage should be, according to table provided by scaling amplifier, 150/200*5 = 3.75 V.

3.13 PCB Design

Figure 44: Eagle PCB Design

This is Eagle CAD layout that we designed.
This a two layers board with dimension of 100*80 mm^2.

3.14 Detection Device Test

Figure 45: The PCB Board after Assembly

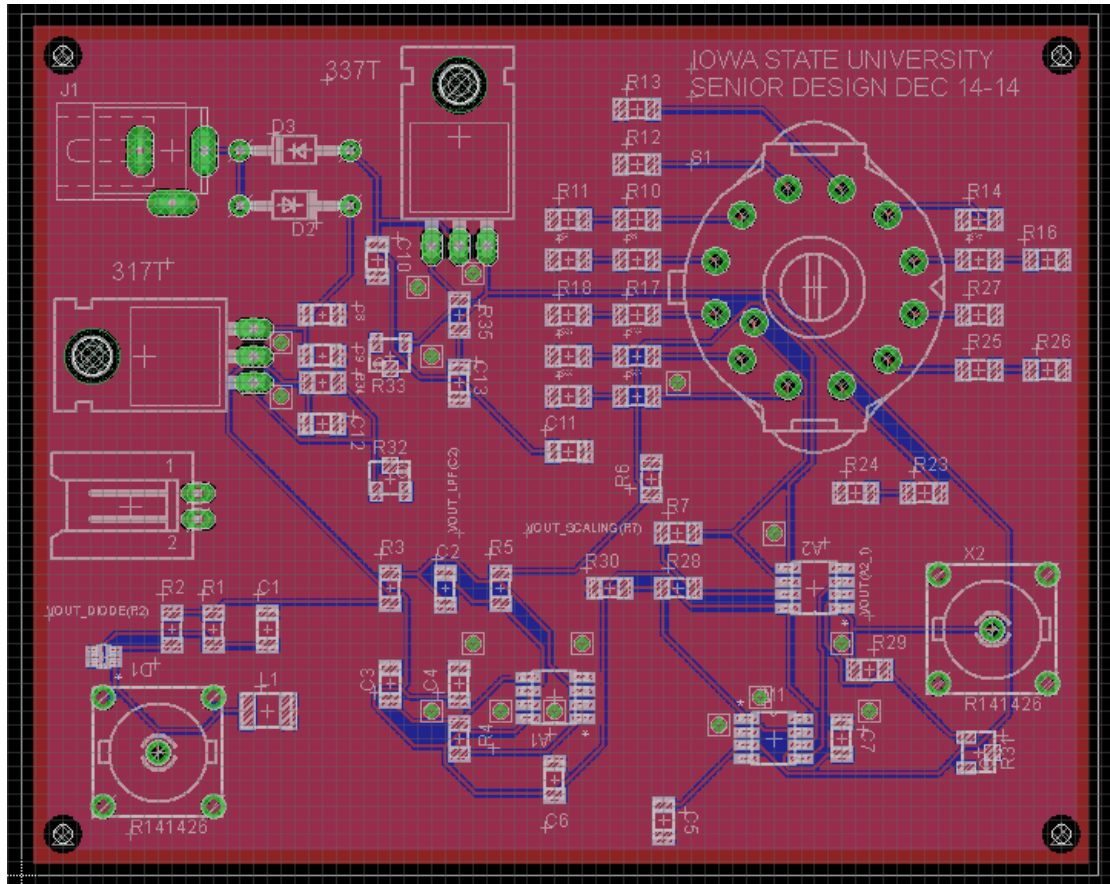We used the function generator in school's lab to generate the pure sinusoid wave. However the maximum voltage provided by generator is 10 Volts peak to peak, which means the maximum input power before the directional coupler is $\frac{5^2}{100} * 1000 = 250$ Watts. Fortunately, this is the maximum power level that client needs to measure.

Figure 46 is the data collection after the test. Input power (Pin) is calculated from measured input peak voltage (Vin), by equation of $Pin = \frac{Vin^2}{100}$.

Output power (P_measured) is calculated from measured output voltage (Vout), by equation of P_measured =

Pin (W)	P measured (W)	Power error (%)
15	14.2	5.333333333
30	29.6	1.333333333
35	34.8	0.571428571
40	40	0
45	45.2	0.444444444
50	50.5	1
55	53.6	2.545454545
60	58.8	2
70	69	1.428571429
80	79.6	0.5
90	90	0
100	100.4	0.4
120	118.4	1.333333333
140	138.8	0.857142857
150	149.2	0.533333333
160	159.6	0.25
180	180.4	0.222222222
200	200.8	0.4
210	204.4	2.666666667
220	214.2	2.636363636
230	224	2.608695652
240	233.8	2.583333333
250	243.6	2.56

Figure 46: Test Data

$\frac{Vout}{5} * P_{upper\ boundary}$, where $P_{upper\ boundary}$ is the maximum limit in your power

range, for example if measured power is 150W, according to the scaling amplifier range table from page 33, the $P_{upper\ boundary}$ is 200 W. The maximum error occurred
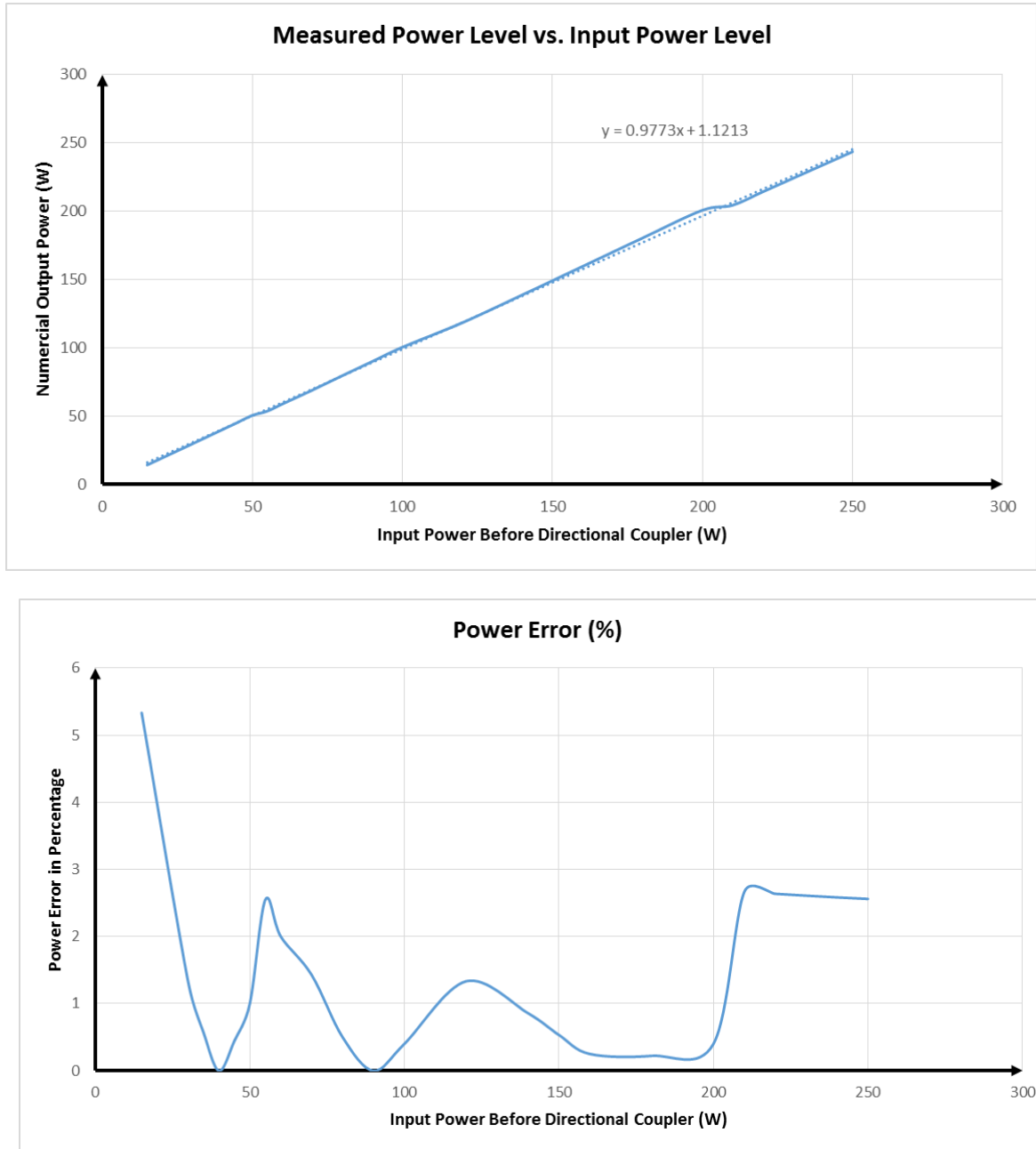

Figure 47: Test Plot

Figure 47 is the plot made by Excel, showing the relation of input power and output power. The approximate equation derived from the plot has the slope close to 1, in addition to a small y axis intersection. The ideal line should be y = x. The overall error plot shows the error is below 5% generally.

4   Conclusion and Reference

4.1 Conclusion

In technical aspect, it is a challenging topic to develop a RF power measurement system. This project integrates the knowledge from circuit, semiconductor, and electromagnetic areas. We need to review and learn these concepts for each component. The high technical requirement gives us a chance to use the knowledge we have known to make a real product out of the book.

In personal aspect, this project is a great opportunity to establish the personality such as leadership, cooperation, patience etc. Those qualities will follow us to the workplace in the future when we are all engineers. So it is important to communicate in an effective way as a team that will make us intelligent when we deal with more sophisticated projects.

4.2 Reference

[1] "Amidon IRON POWDER TOROIDAL CORES." *Amidon IRON POWDER TOROIDAL CORES*. http://www.qrz.lt/ly1gp/amidon.html
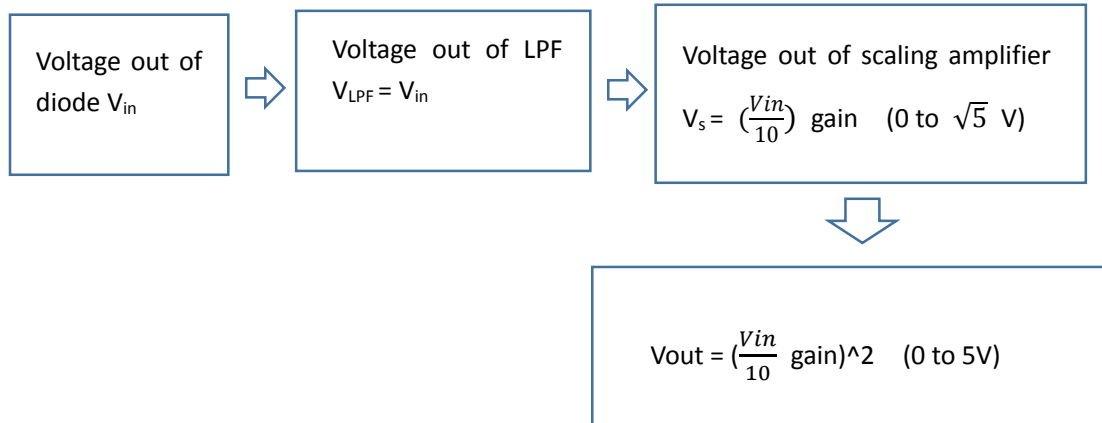
[2] "Toroid."   *Ness Engineering Technical Data Toroid Formulas.*
http://www.nessengr.com/techdata/toroid/toroid.html

[3] "AC Flux Density Limits." *Power Considerations.*
http://www.amidoncorp.com/product_images/specifications/1-35.pdf

Appendix A: Simple Block Diagram of Detection

<u>Simple block diagram:</u>

- When input voltage is pure sine wave:

| Voltage out of diode V_{in} | ⇨ | Voltage out of LPF $V_{LPF} = V_{in}$ | ⇨ | Voltage out of scaling amplifier $V_s = (\frac{Vin}{10})$ gain   (0 to $\sqrt{5}$ V) |

⇩

Vout = $(\frac{Vin}{10}$ gain)^2   (0 to 5V)

- When input voltage is pulse modulated sine wave:

| Voltage out of diode V_{in} | ⇨ | Voltage out of LPF $V_{LPF} = 0.5*V_{in}$ | ⇨ | Voltage out of scaling amplifier V_s = $(\frac{0.5*Vin}{10})$ gain   (0 to $\sqrt{5}$ V) |

⇩

Vout = $(\frac{0.5*Vin}{10}$ gain)^2   (0 to 5V)
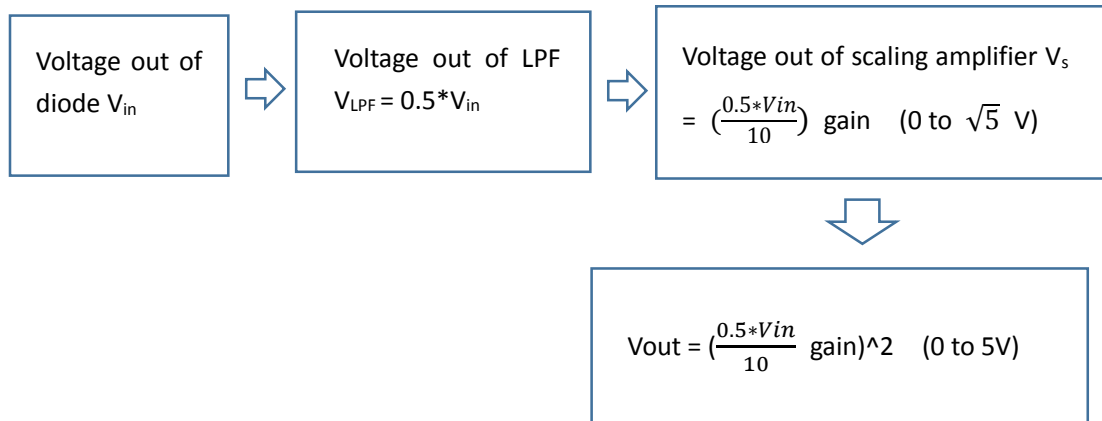
Appendix B: Part List and Cost

Part Description:	Quantity	Price/100Units ($)	Total Price ($)
Toroid	2	1.2	2.4
Wire Gauge	50 feet	0.159	7.95
Enclosure	1	8.71	8.71
Transmission Line	1 feet	2	2
Resistor	32	0.007	0.224
Trimmer Resistor	4	1.64	6.56
220pF capacitor	1	0.073	0.073
4700pF capacitor	2	0.248	0.496
0.1uF capacitor	8	0.082	0.656
1uF capacitor	2	0.081	0.162
100uH inductor	1	0.121	0.121
HSMS-282K diode	1	0.417	0.417
LMC6492 amplifier	2	1.42	2.84
AD633 multiplier	1	4.95	4.95
LM317 regulator	1	0.26	0.26
LM337 regulator	1	0.786	0.786
BNC connector	2	2.1	4.2
Rotary switch	1	5.27	5.27
AC to AC adapter	1	8.3	8.3
Barrel connector	1	0.3162	0.3162
1N4004 Diode	2	0.077	0.154
Pin connector	1	0.09427	0.09427
PCB board	1	30	30
Total:			87