

## Radio Frequency Power Meter Design Project

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### Abstract

This student paper discusses a radio frequency power meter developed and prototyped as part of a senior project capstone course in electronic engineering technology. Radio Frequency Power Meters find wide application as primary commissioning and maintenance tools within various industries, from communications systems of all types, to industrial systems incorporating radio frequency energy. Their primary purpose is to first of all, provide an indication of the radio energy delivered to the antenna system or other load from the transmitter for the purpose of carrying intelligence, or enabling industrial processes. Secondly, this instrument will provide an indication of the transmission line match characteristics that exist between the transmitter and transmission system, and the antenna or other load.

In this student project, a directional radio frequency power meter is developed for the purpose of measuring low frequency radio energy. Power measurement instruments of this type, operating at frequencies up to 50 MHz, are used primarily for the measurement of plasma excitation energy in the semiconductor process industry. In addition, these instruments also find wide application in the maintenance of high frequency (2-30 MHz) tactical military communications networks.

### Keywords

Antenna, Radio Frequency Power, Voltage Standing Wave Ratio (VSWR) Measurements

### Significance

The development of radio frequency power measurement technology must keep pace with the advancement of the communications systems, or other measurement settings that these instruments are intended to support. The mission of these instruments is to measure the delivered power to a load device, as well as to determine the quality of the electrical match that exists between the transmission system and the load device. Two of the more significant changes that are taking place with regard to radio frequency delivery systems in general are the measurement of complex waveforms and measurement of challenging VSWR signals.

Modern radio frequency delivery systems, whether associated with communications or industrial processing, involve the use of complex modulation and channel allocation techniques. Simple amplitude, frequency, or phase modulated approaches to the encoding of intelligence upon a radio carrier are becoming rare. In their place are modulation approaches involving the combination of previous techniques, resulting in noise-like waveforms with high peak to average power ratios. For example, today's digital broadcast systems such as 8 – Level Vestigial Sideband (8-VSB) television use modulation techniques involving both multiple carriers, as well as phase and amplitude modulation together, resulting in waveforms with peak to average power ratios as high as 11dB. In order to provide accurate average power measurement in this

environment, this design project incorporates square-law diode detector technology, which provides true average power measurement regardless of the nature of the input waveform. Many conventional power meters utilize diode detectors that respond to the peak power of the waveform, and as such respond to the modulation envelope of the signal being measured, rather than the radio frequency waveform, resulting in power measurement errors.

Today's communications systems operate at much lower transmitted power levels. This presents significant challenges in the measurement of antenna or other load match characteristics. For this reason, power meter approaches must incorporate higher directivity coupling technology in order to extract meaningful reflected power information from the standing wave conditions being measured. This project incorporates high directivity transformer based directional coupler technology for the purpose of addressing this issue.

### **Power Meter Design Details**

The goal of this design project is to develop a breadboard version of a fully functional dual channel (forward and reflected power) radio frequency power meter in accordance with the critical specifications outlined in Table 1. The power meter will measure both the forward and reflected power within the transmission system, and will use these parameters for the calculation of the Voltage Standing Wave Ratio (VSWR) of the transmission system. The components, circuits, and firmware developed for this breadboard version could be easily re-packaged into a portable directional power meter instrument, or configured as an in-situ power and VSWR monitor instrument. The following design elements were developed, prototyped, and tested within the context of this project, and are illustrated in the block diagram shown in Figure 1:

- **Transformer Based High Directivity Directional Coupler:** This component serves as the heart of any directional power meter design.
- **Square-Law Diode Detector Circuits:** These circuit elements provide for true-average power detection of the waveforms being measured.
- **Low Noise DC Gain Stages:** Using low offset voltage operational amplifiers, this circuit element provides amplification of the detector output voltages, as well as a means of calibrating the instrument.
- **Arduino Based Microcontroller and Firmware:** This prototype uses the on-board Analog / Digital converter in the Arduino in order to process the DC gain stage outputs, provides scaling of the output values, calculates VSWR based upon forward and reflected power values, and displays the results on a LCD character display.

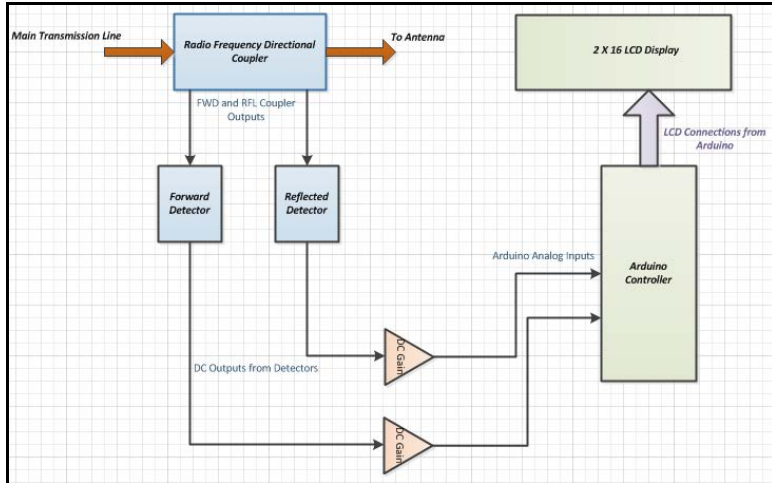


Figure 1, Power Meter Block Diagram

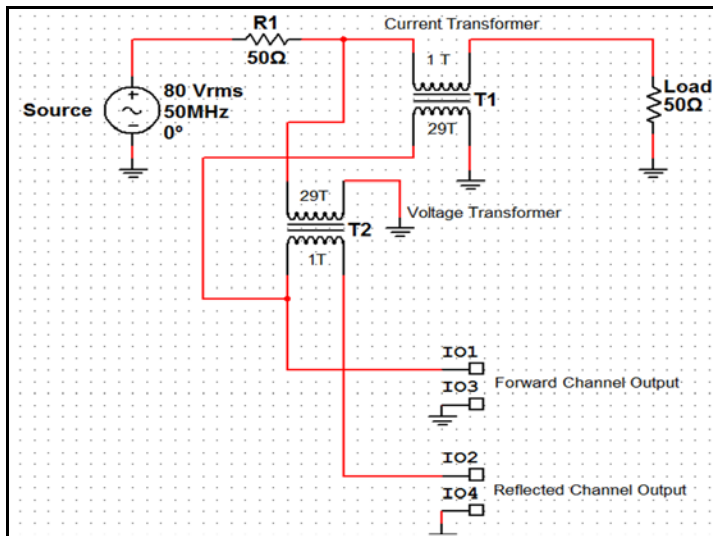


Figure 2, Directional Coupler Circuit

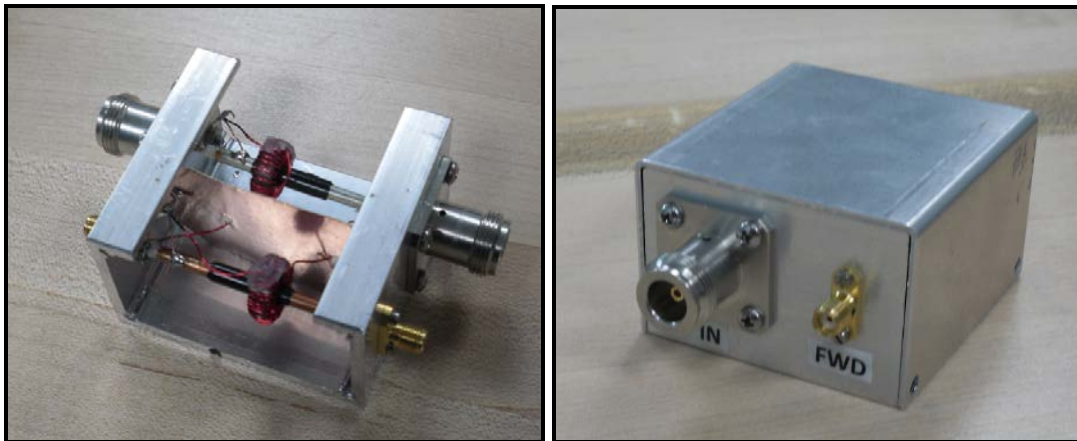


Figure 3, Directional Coupler Prototype

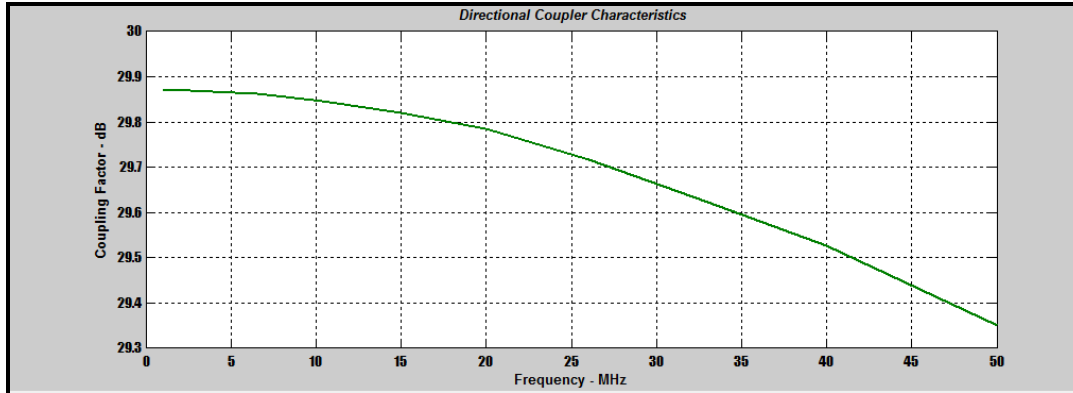


Figure 4, Directional Coupler Coupling Characteristics

Performance of the directional coupler is excellent relative to the critical specifications. Figure 4 demonstrates that the frequency response of the coupler varies less than 0.5 dB from 1 MHz to 50 MHz. Directivity performance of the coupler is also excellent compared to the critical specifications, with data indicating directivity values greater than 66 dB at 1 MHz, and 33 dB at 50 MHz.

**Detector Circuits and System Performance Testing:** This power meter design incorporates diode detector circuits operating within the square law portion of the diode conduction characteristics. Diode detectors, when operated at input signal levels below -23 dBm for Schottky type diode detectors, exhibit characteristics such that the output voltage of the detector is proportional to the square of the input voltage, regardless of the modulation characteristics of the signals appearing at the detector input. This detector approach was chosen in order to provide optimum performance of the power meter when measuring modern communication systems waveforms incorporating digital modulation techniques. The schematic diagram for the radio frequency detector circuits, as well as the microcontroller and display is shown in Figure 5. Note the input attenuator circuits, the Schottky diode detectors, and the low noise, low offset DC gain stages. The completed breadboard prototype is shown in Figure 6. Note the completed directional coupler, with the main transmission line input connected to a 50 watt transmitter, and the output connected to a 3.0:1 VSWR mismatch operating at a 10 watt power level. Figure 7 shows a close-up of the power meter display, indicating a VSWR of 3.05 of the calibrated 3.0 mismatch. Also note the area of the printed circuit board in the lower right-hand corner, containing the RF detector and low noise amplifier circuits, as well as calibration potentiometers for the forward and reflected measurement channels. The directional coupler output ports are connected via coaxial cables to the detector inputs on this part of the printed circuit board.

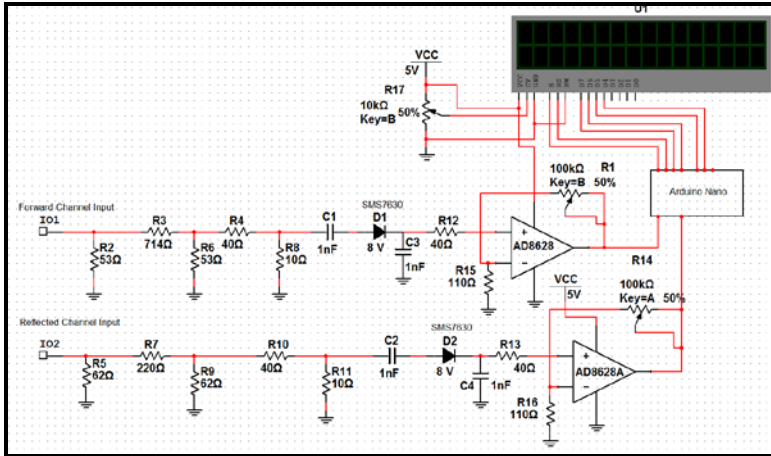


Figure 5, Detector, Amplifier, and Processing Circuits

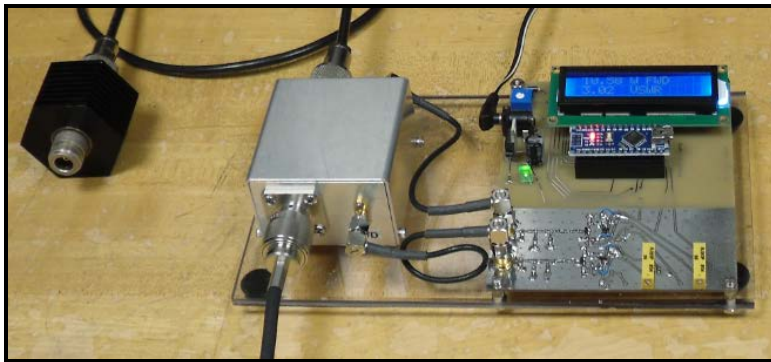


Figure 6, Completed Prototype Power Meter

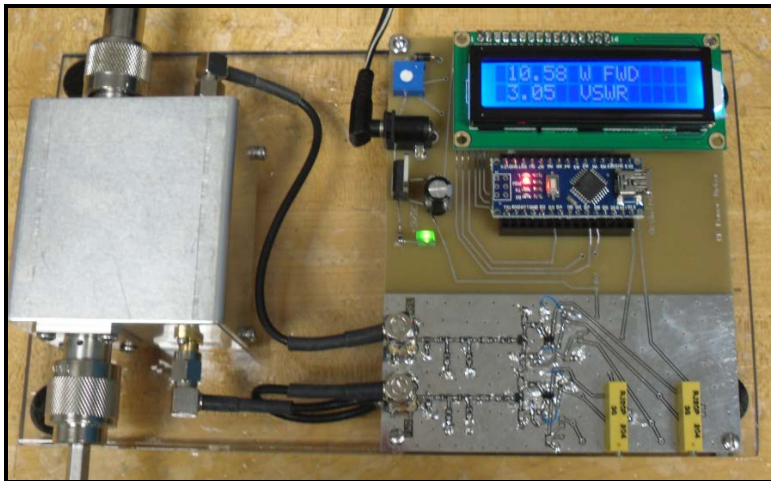


Figure 7, Completed Prototype Measuring 3:1 Mismatch

## Results and Conclusions

The Radio Frequency Power Meter prototype design met or exceeded all of the critical specifications established at the onset of the project. It should be noted that these specifications are based upon actual system measurement requirements for high quality radio frequency power

and VSWR measurements. A summary of the performance of the power meter, as compared to the critical specification is illustrated in the Table 2.

Table 2 - Comparison of Actual Test Results to Critical Specifications				
	Specification	Goal	Actual	Comments
1	Frequency Range	2 MHz to 50 MHz	500 kHz to 50 MHz	Exceeds Specification
2	Forward Channel Measurement Range	2.5W to 100W	2.5W to 100W	Meets Specification
3	Reflected Channel Measurement Range	0.25W to 10W	0.25W to 10W	Meets Specification
4	Coupler Directivity	30 dB Minimum	66dB at 2 MHz to 33dB at 50 MHz	Exceeds Specification
5	Power Measurement Accuracy	+/- 10% of Reading	+/-4.1% of Reading	Exceeds Specification
6	Insertion VSWR	<1.5	1.12 Maximum	Exceeds Specification

### Future Enhancements

The technology developed during this project may be further enhanced and applied to other measurement systems. Following is a partial listing of improvements that will further expand the applicability of this measurement approach:

- Temperature Compensation:** The performance of the diode detectors in this system, as well as the coupler components are somewhat dependent upon temperature. In order to compensate for these effects, the instrument performance would normally be characterized in terms of temperature, with compensation coefficients stored in a table within the microcontroller. With the addition of a simple means of determining ambient temperature, these correction coefficients might easily be applied to the power measurements.
- Mechanical Packaging:** An appropriate instrument enclosure, designed for the intended operating environment must be developed.
- Alternative Connectivity:** Ethernet, Bluetooth, or other connectivity options will further expand the utility of the approach as a measurement tool.
- Directional Coupler Compensation:** The frequency range of the coupler circuits could be expanded through the use of compensation techniques. This would involve developing an appropriate network with frequency response characteristics that are able to offset the negative effects of parasitic reactances within the coupler.
- Development of Instrument Error Budget:** The performance of measurement instruments of this type may be predicted and monitored through the use of carefully

constructed instrument error budgets. For a power measurement instrument of this type, the components of the error budget would include calibration standards accuracy, mismatch uncertainty, temperature, frequency response, dynamic linearity, and instrumentation noise. These error components are generally independent, and as such may be combined using Root Sum of Squares (RSS) statistical approaches in order to arrive at the probable system error. Normally, the results of the error budget are then compared to actual performance data over time as a means of confirming the viability of the approach.

### **Knowledge – Sharing Concepts and Strategy**

The results of this senior project could be adapted as a basis for the laboratory exercises in an electronic engineering technology course. There are several approaches that may be used to incorporate the technological concepts used in the development of this radio frequency power meter project, such that these elements of technology might be shared with other students. First of all, since this instrument is intended for the measurement of transmission line parameters, the directional coupler component of the design, or the entire instrument might be used as a means of identifying and thereby enhancing the understanding of the nature of standing waves within transmission structures. A laboratory exercise could be constructed such that 50Ω transmission lines are terminated in mismatched impedances, with the degree of mismatch (voltage standing wave) calculated based upon the impedance mismatch and the transmission line characteristic impedance. Next, the directional power meter could be used to make measurements of the forward and reflected power within the transmission line, and the resultant voltage standing wave ratio. The calculated and measured values could then be compared, with students being asked to discuss the reasons for any differences between measured and calculated values.

A second lab exercise might involve the design and construction of the directional coupler as a component, then using the constructed coupler to make simple transmission line measurements at low frequencies. The construction of the coupler should be undertaken with emphasis upon the operation of the coupler as a means of extracting samples of the electric and magnetic field within the transmission line. Since the transformer turns ratio for both the current and voltage transformer relates directly to the coupling factor between the main transmission line, and the coupled ports of the directional coupler, this particular design approach is very valuable as a teaching aid as a part of communications systems and related coursework. Materials for the construction of couplers of this type are inexpensive and readily obtained.

Yet another lab exercise, as part of a course in signal or waveform analysis could be developed using this power meter as a means of measuring the power in various types of communications related waveforms. This lab would begin with simple analog modulated signals (amplitude and frequency modulation), where it is a simple matter to calculate the power characteristics of signals of this type. Next, the lab exercise would focus upon more complex modern waveform types such as Binary Phase Shift Keying (BPSK), or Quadrature Amplitude Modulation (QAM), where the calculation of signal power based upon waveform characteristics is not straightforward. Since this power meter design incorporates square-law detectors, the measured power values are equivalent to those obtained using heating power techniques. Another component of this lab exercise could be focused on the measurement of multiple carrier signals, using simple power dividers as a means of combining traditional analog signals

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Tim Holt is an undergraduate student at the University of Akron, and a Systems Engineer at Bird Electronic Corporation in Cleveland, Ohio. Tim is currently completing a Bachelor of Science degree in Electronic Engineering Technology, and will graduate in May 2017. Tim has served for four years developing Radio Frequency Metrology Standards with the Semiconductor Equipment and Materials International (SEMI) RF Diagnostics Task Force and holds three United States patents in the area of radio frequency instrumentation technology.

## Andrew Milks

Andrew Milks is an Associate Professor of Electronic Engineering Technology at the University of Akron. Before joining the University of Akron, he worked in the process control industry, and continues to consult in the area.