Mixer Design
Radiometry System

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ABSTRACT

The purpose of the radiometer project was to research and demonstrate the working principles of a radiometer system.

The radiometer design team was composed of five members, each contributing a specific component to the final system.

A radiometer system is a device that detects microwave emissions from noise producing objects [1]. These noise sources are typically objects that emit heat and thereby produce noise in the microwave region as expressed by Plank’s Radiation Law [1]. These objects are called blackbody radiators.

The practical implementation of such a system was the construction of a microwave receiver system that would accept the incoming noise power from the source and convert the power to a proportional voltage. By this method, a radiometer directed toward point A (at room temperature) should output an increased voltage when directed toward point B (at a higher temperature--such as human body temperature).

The author was tasked with the design of the down-conversion stage of the receiver, which is typically termed mixer.

A mixer accepts two inputs--the desired signal (in this case noise), and a standard sinusoidal signal generator or voltage controlled oscillator. The mixer generates the sum and difference frequencies of the two input signals. In this application, the output signal of interest was the difference frequency. This signal transmitted to the output stage.

The primary parameter of concern in the design of a mixer is conversion loss. Conversion loss is a measure (in dB) of how much power is lost in the conversion from the input frequency to the output frequency. The design goal for conversion loss was 10 dB. Simulations indicated a projected conversion loss of 7.9 dB.

The measured results of the author’s mixer design indicated a conversion loss of 8.2 dB with an input signal of -30 dBm and an LO signal level of +8dBm.

The measured results of the student-designed radiometer system indicated that the radiometer was able to sense a microwave energy change (caused by a temperature change) in the power region between -85 dBm and -90 dBm.

The project was considered successful as the system design effectively demonstrated the basic principles of radiometry and Plank’s radiation law. The mixer design worked as designed/simulated and worked successfully with the intended application.
1. INTRODUCTION

The purpose of a radiometer system is to detect the power produced in the microwave region by objects that radiate heat or other sources of noise [1]. This radiation of noise in the microwave region is commonly referred to as blackbody radiation as the ideal blackbody radiator would be completely non-reflective (perfectly absorptive).

Radiometer systems are used in applications where the remote sensing of heat is necessary. These applications include defense, homeland security, search and rescue, meteorology and oceanography. Radiometers can be used to detect concealed weapons by detecting cold spots on the body where the weapon is located [2]. The military uses radiometer systems for target detection/recognition, surveillance, and mapping [1].

Among the several types of available radiometer systems is the total power radiometer. The total power radiometer detects the microwave noise produced (noise power) by the source, but it also detects the inherent noise power of the system. The total power radiometry system is a super-heterodyne receiver system that receives the noise power signal from the source and converts it to a DC voltage that is proportional to the incident power of the incoming noise signal.

Because the system also detects the internal noise of the circuitry the receiver must exhibit extremely low noise and high sensitivity. Typically, these stringent requirements cause total power radiometer systems to be unsuited for practical application [1].

The goal of the radiometer project at the system level was to build a system that would emulate the response typical of a total power radiometer system. To implement this objective, a receiver system was constructed to receive a 7 GHz input and output a DC voltage value proportional to the incoming RF power.

The goal of the author’s participation at the sub-system level was to design and build the down-conversion stage of the receiver such that the device would accept the incoming 7 GHz noise signal and down-convert it to 1 GHz. Such a device is typically classified as a mixer.

In order to maximize the sensitivity of the system, the mixer was expected to operate with low noise and minimize loss of power in the conversion process. The primary design specification for the mixer was to operate with less than 10dB conversion loss.

Research was conducted through reference texts, class lectures [2], and direct consultation with professors/graduate students. The two primary sources of written references were [1], a theoretical text on the broad spectrum of microwave engineering topics and [3], a text purposed for the design of microwave circuits.
2. **THEORY**

The following paragraphs explain the basic theoretical elements of the system and the sub-system design.

### 2.1 System Theory

The concept of a radiometer system is based on (1) which is the expression for Planck’s radiation law in the microwave region [1] where \( k \) is Boltzmann’s constant, \( T \) is the temperature of the source, and \( B \) is the bandwidth of the system.

\[
P := k \cdot T \cdot B
\]

This expression holds true for ideal blackbody radiators--that is, radiating materials that are perfect absorbers of energy and are therefore perfect emitters of energy [1].

Because radiometry system subjects are typically not ideal blackbody radiators, (2) describes emissivity which is a relative measure of the power radiated by some non-ideal body to that of an ideal body [1] where \( P \) is the power of radiated from the non-ideal body.

\[
e := \frac{P}{k \cdot T \cdot B}
\]

\[
T_B := e \cdot T
\]

Equation (3) describes the brightness temperature which is an indication of the apparent temperature of the subject having taken into account the emissivity of the object.

This apparent temperature is the source of noise that the radiometer antenna receives.

The total power radiometer system measures this power (from the \( T_B \)), but it also measures the power generated by the temperature of the system (thermal noise). Thermal noise is also expressed by (1) where the \( T \) is the temperature of the system \( T_R \) [1].

This combination of noise and desired signal (also noise) travels through the various down-conversion, filtering, and amplification stages of the receiver system until it arrives at the output where the power is converted to a voltage that is proportional to the power of the signal.
The voltage output of the system will be (assuming linear power to voltage conversion) $V_0$ as expressed in (4), where $G$ is the gain constant of the system [1].

$$V_0 := G(T_B + T_R)k_B$$

(4)

### 2.2 Subsystem Theory

The function of the mixer circuit is to receive the incoming 7 GHz noise power signal from the receiving stage of the radiometer and down-convert to 1 GHz for submission to the output stage of the radiometer.

The mixer accepts two inputs: the signal input and the local oscillator input. The local oscillator signal is generated by a VCO or a function generator and provides a continuous 6 GHz sinusoidal input.

The mixer superimposes the incoming signal with the local oscillator signal through the use of a coupler. The coupler combines the two signals and divides the power of the resultant signal equally between the two output ports [3].

There are two predominate types of couplers used in the design of mixer circuits: The rat-race hybrid and the quadrature hybrid [3]. The quadrature hybrid is the coupler type utilized in this design. The quadrature hybrid coupler is composed of four straight sections of microstrip line arranged in a square.

The lengths of these line sections are 90 degrees long at the desired frequency. As a result, each port of the coupler (each corner of the square) is separated (or isolated) from adjacent ports by an electrical length of 90 degrees. If the two input ports are adjacent, then each corresponding input signal will be “isolated” from the other input signal.

The widths of the lines are calculated to give an equal distribution of impedance along the conductance path(s) from one port to any of the other three ports.

Connected to the two output ports of the coupler are diodes. The diodes generate the sum and the difference of the signal frequency (7 GHz) and the local oscillator signal (6 GHz).

For the diodes to work efficiently, it is critical that there be no excess DC voltage at the anode of the diode, otherwise the diode will be prematurely biased and some output power will be lost. DC returns may be added to the anode side of the diode to bleed the bias voltage to ground. The implementation of a DC return consists of DC shorted stub one-quarter wavelength long at the desired open-circuit frequency.
The sum and difference terms are generated due to the non-linear voltage-current characteristics of the diode. This non-linearity may be expressed as (5), a variation of conductance with time.

\[ g(t) := G_0 + G_1 \cos(\omega_p t) \]  

(5)

Based on Kirchoff’s law, the current characteristics can be expressed by (6) where \(v_s(t)\) is considered to be the voltage representation of the superposition of the local oscillator and signal frequencies [3].

\[ i(t) := G_0 v_s \cos[(\omega_s - \omega_p) t] + \cos[(\omega_s + \omega_p) t] \]  

(6)

Because the conductance characteristics of the diodes do not typically vary as a sinusoid with time, the conductance waveform contains harmonics, and these harmonics result in the generation of higher order mixing products.

The output section of the mixer typically uses *harmonic tuning stubs* to eliminate these harmonics and re-direct the power into the IF (output) frequency. These stubs are a quarter wavelength long at the desired cancellation frequency(s) with DC open terminations.
3. **DESIGN**

The design of a radiometer system requires close attention to detail at both the system level and the sub-system level in order to maximize system performance and to minimize problem parameters such as noise figure and power loss.

### 3.1 System Design

The goal of the system design was to minimize noise figure while maximizing sensitivity.

**Figure 1. System Schematic**

**Input Stage.** The input stage consisted of the antenna, the input filter, and the input amplifier. The goal of the input stage was to receive, filter, and amplify the noise signal for use by the down-conversion stage. The amplifier had an approximate gain of 35 dB and the filter had a bandwidth of approximately 500 MHz.

**Down-conversion Stage.** The down-conversion stage consisted of the mixer and the local oscillator source. The goal of the down-conversion stage was to down-convert the noise signal from 7 GHz to 1 GHz.

**Output Stage.** The output stage consisted of the output filter, the output amplifier, and the detector. The goal of the output stage was to filter, amplify, and convert the RF power to a DC voltage.

### 3.2 Sub-System Design

The goal of the mixer design was to maximize the power transfer from the input frequency to the output frequency. Each section of the mixer circuit was carefully designed and tuned to achieve this result.
The design was simulated with ADS and Momentum software (please see Measured/Simulated Results section).

**Input Section.** The signal (noise) input was matched to 50 ohms through the use of a distributed element matching network to minimize input reflection and maximize power transfer.

**Coupler Section.** The coupler section was designed to maximize the passage of 7 GHz and 6 GHz (RF and LO respectively). The hybrid quadrature coupler configuration was chosen for its broader RF—LO bandwidth (up to 20% difference as opposed to the 15% offered by the rat race configuration [3]).

The broad bandwidth required for a 1 GHz output signal makes the HQ configuration the preferred choice. The lengths of each line section were adjusted for a center frequency of approximately 6.7 GHz (please reference figure 3).
**Diode Section.** The diodes chosen for this design were medium-barrier Schottky diodes with beamlead packaging. Medium barrier diodes typically exhibit better rejection of intermodulation distortion and spurious harmonic generation [3] over the low-barrier diodes. Beamlead packaging offers improved performance at high frequencies [3].

The primary drawback is that medium-barrier diodes require greater local oscillator power [3]. In this application, LO power was readily available and was therefore not a significant consideration.

The anodes of the diodes were connected to DC returns. The assymetrical properties of these stubs, (as can be observed from figure 3) are attributed to the dual function of the stubs--both for DC short to ground and impedance matching of the diode to the coupler section [4].

**Output Section.** The output section includes harmonic tuning stubs for the elimination of the input signal and the 2\textsuperscript{nd} harmonic of the LO. Elimination of as many frequencies as possible assists the radiometer system by reducing the total amount of insignificant noise.

The output section also included a *RF choke* implemented with a 12 nH inductor to eliminate the DC portion of the output.
4. MEASUREMENT

The following paragraphs explain the measurement techniques used for testing at the system and sub-system levels.

4.1 System

Two systems were measured. The first system consisted of entirely of commercial components. The second system was constructed with the available student-designed parts with the addition of the commercial components that did not have a student-designed counterpart.

The first objective for radiometer testing was to characterize the system. System characterization was accomplished by measuring the voltage output with respect to an ideal sinusoidal input signal at power levels comparative to theoretical noise levels produced by blackbody radiators.

The second objective for radiometer testing was to determine how the system responded with a pure noise input. This theoretical input was obtained by cooling/heating a load to two known temperatures. The load was dipped in liquid nitrogen to obtain an input noise temperature of 77 K. The load was allowed to warm to room temperature to obtain an input noise temperature of 297 K.
This approach simulated the results of an ideal antenna in a noiseless environment.

<table>
<thead>
<tr>
<th>Radiometer with Direct Temperature Input</th>
<th></th>
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<tbody>
<tr>
<td>Temperature (K)</td>
<td>Vout (mV)</td>
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<table>
<thead>
<tr>
<th>Radiometer with Antenna Input</th>
<th></th>
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<tbody>
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<td>Vout (mV)</td>
</tr>
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<td>77</td>
<td>4.92</td>
</tr>
<tr>
<td>297</td>
<td>5.02</td>
</tr>
</tbody>
</table>

Figure 5. Ideal temperature input vs. antenna input

The third objective for radiometer testing was to determine how the system responded with an antenna input. This measurement was accomplished by pointing the antenna at a beaker of liquid nitrogen (T=77 K) and then subsequently at the ambient temperature of the room.

### 4.2 Sub-System

The primary mixer measurement was conversion loss. Conversion loss is the amount of power loss involved in the conversion from the input frequency (measured at the input port) to the output frequency (measured at the output port).

**Measured Conversion Loss = 8.2 dB**

Conversion loss measurements are made by supplying the mixer with two sinusoidal signals—the LO signal and the RF signal. The output of the mixer was viewed on a spectrum analyzer. Loss of all the cables except for the LO supply cable were measured.

The loss of the cables (and attenuators), the known output level of the RF signal generator, and the known input power to the spectrum analyzer were used to calculate conversion loss.
5. MEASURED/SIMULATED RESULTS

The actual results were similar to theoretical/simulated results at both the system level and the sub-system level.

5.1 System Results

As shown in Figure 3, the student-designed radiometer system performed similarly to the theoretical system. Figure 3 also indicates that the student designed system also exhibited a marked improvement in sensitivity at low power levels.

The measured results of the system for both ideal temperature input and antenna temperature input confirmed that a change in temperature can be detected.

5.2 Sub-System Results

As shown in Figure 6, the simulated output power for 0 dBm input power was -7.98 dBm. This signifies a simulated conversion loss of 7.98 dB. This value compares favorably with the measured conversion loss of 8.2 dB.

The mixer circuit responded as the precisely as design intended. The signal input was matched to properly to 50 ohms. The coupler section simulation of Figure 3 determined the filter response as expected. The output section of the mixer responded as simulated, canceling the appropriate frequencies from the output (please reference figure 6).

![Figure 6. Simulated output spectrum of the mixer.](attachment:image)
Conclusion

The radiometer system project was considered to be successful in all aspects. The primary goals of the project were (a) education for the students and (b) research, design, and fabrication of a radiometer system.

The first objective was fulfilled. The students, and specifically, the author, advanced their education through the use of measurement equipment, the design process, and wireless circuit design.

The second objective was fulfilled. Although the constructed radiometer type was not ideal, the results indicated that the system performed as expected given the limitations of the environment. The student-designed radiometer demonstrated the basic principles of radiometry and Plank’s radiation law.

The primary obstacle in the development and testing of the radiometer was system stability. Noise fluctuations due to temperature and other sources caused variation in the system’s output to be large.

The students and the professor are optimistic that with more testing, design modifications, and environmental controls, the radiometer system would improve in terms of lower noise and higher sensitivity—lending more accurate and stable results.
Appendix A--ADS Schematic #1

Input and Coupler Sections
Appendix B--ADS Schematic #2

Diode and Coupler Sections
Appendix C--Works Cited

[1] David M. Pozar. *Microwave Engineering*  
Addison Wesley, 1990

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Appendix D--Referenced Works

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