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Lab 3
ECEN 5634

Part I

Q1: We found that the power meter is well-matched from 8 GHz to 10 GHz, as the reflection coefficient has a maximum magnitude of -17.9 dB over this frequency range. Based on this observation, our power meter measurements should be very accurate, since very little power is reflected back, so almost all of it goes into the power meter. Since it is not perfect, however, we expect our measurements to be slightly below the actual incident RF power.

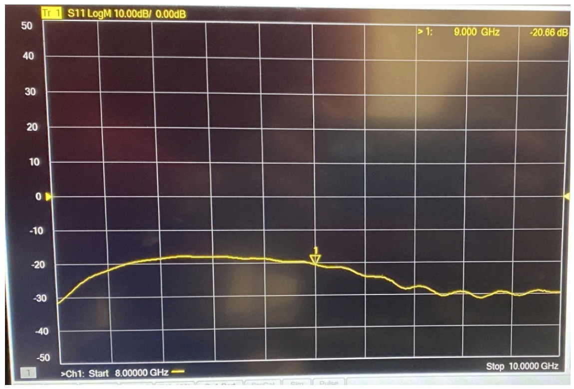

Figure 1: VNA display of $|S_{11}|$ for the power meter.

Q2: If there is no current flowing through the ammeter, then we know that $R_S = R_T$. This is because the voltage across the ammeter must be 0 V, so the voltage across R_S must equal the voltage across R_T. The voltage across R_S is $V_S = V\frac{R_S}{R_S+100}$, and the voltage across R_T is $V_T = V\frac{R_T}{R_T+100}$, and these equations can only be equal to one another if the resistors have the same value.

Q3: The power in the thermistor is equal to the squared voltage across it divided by its resistance, or $P_T = \frac{V_T^{\,2}}{R_T} = \frac{(V\frac{R_S}{R_S+100})^2}{R_S} = \frac{V^2 R_S}{(R_S+100)^2}$.

Rt (Ω)	V (mV)	S11 (dB)	Pt (mW)
1000	1638	-3.19	2.217391736
900	1736	-3.42	2.7123264
800	1820	-3.72	3.271506173
700	1890	-4.08	3.906984375
600	1954	-4.57	4.675244082
500	2011	-5.20	5.616834722
400	2067	-6.29	6.8359824
300	2131	-8.04	8.514676875
200	2240	-12.09	11.15022222
100	2573	-24.70	16.5508225

Table 1: Measurements of thermistor resistance, voltage across bridge circuit, reflection coefficient, and power in thermistor.

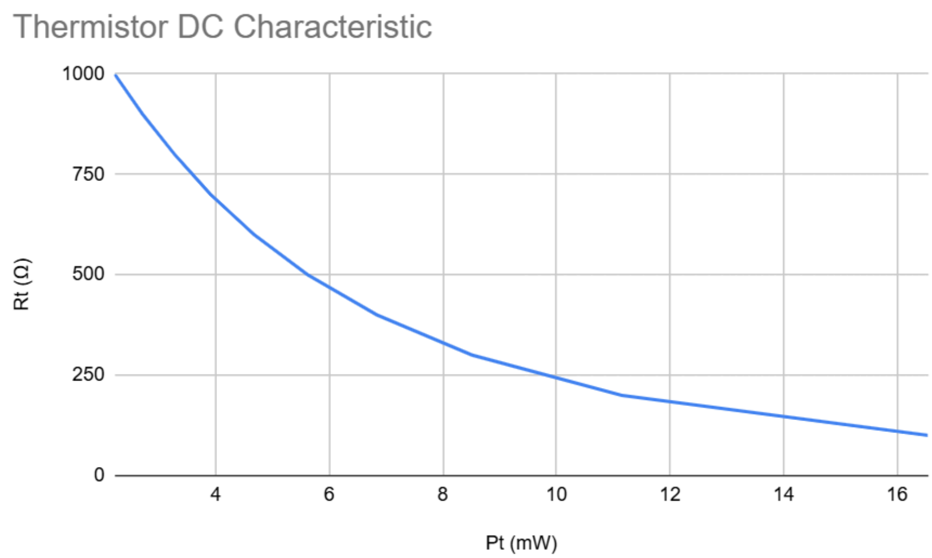

Figure 2: Thermistor resistance vs. thermistor power.

Q4: $|S_{11}|$ decreased as the power increased, because the thermistor resistance decreased and brought the load impedance closer to the waveguide impedance (matched). The best operating point for the thermistor is P_T = 17 mW, or R_T = 100 Ω, since this was where the thermistor was best matched to the waveguide out of the resistance values we tested. In addition to having a low reflection coefficient, this operating point is also advantageous because it is more sensitive to small changes in power than a very low thermistor resistance would be, as is shown in Figure 2 by the curve's decreasing slope.

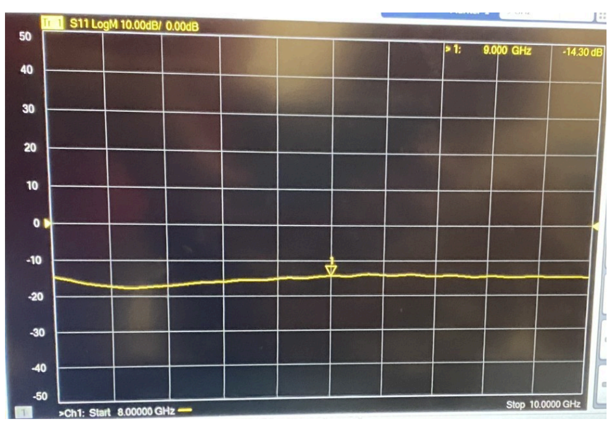

Figure 3: VNA display of $|S_{11}|$ for the waveguide-mounted diode.

Q5: We found that at 9 GHz, the reflection coefficient $|S_{11}|$ of the waveguide-mounted diode was -14.30 dB, which is not well-matched. We expect that these measurements will be less accurate than (and lesser than) those of the power meter, because more of the incident power is reflected backwards. They may, however, be more accurate than the thermistor power measurements because at an operating point of R_T = 300 Ω, the reflection coefficient for the thermistor is -8 dB.

Part II

Q6: Since we are keeping R_S at a constant value of 300 Ω, as long as the bridge is balanced, we know that R_T = 300 Ω. The thermistor resistance is related to the power dissipated in it, so we therefore know that the total power in it (the sum of DC and RF power) remains the same as long as the resistance does. When we had no RF input power, we measured the power in the thermistor to be 8.89 mW (the DC power). As we add RF power, but maintain this total power P_0, we will be able to measure the decreasing DC power, and calculate the RF power as $P_{RF} = P_0 - P_{DC}$.

Power from	Power Meter	DC Voltage V Across Bridge	Calculated DC Power	Calculated RF Power
(dBm)	(mW)	(mV)	(mW)	(mW)
5.06	3.20627	1767	5.8543	3.0401
4.05	2.54097	1861	6.4937	2.4007
3.03	2.00909	1931	6.9914	1.9030
2.07	1.61065	1984	7.3805	1.5139
1.01	1.26183	2027	7.7039	1.1905
0.00	1.00000	2060	7.9568	0.9377
-0.99	0.79616	2089	8.1824	0.7121
-2.00	0.63096	2106	8.3161	0.5783
-3.00	0.50119	2121	8.4350	0.4595
-4.00	0.39811	2134	8.5387	0.3557
-4.98	0.31769	2144	8.6189	0.2755
-	0	2178	8.8944	0

Table 2: Power meter observations and calculations of RF power from thermistor bridge using R_T = 300 Ω. The last row represents P_0, the baseline power with no RF.

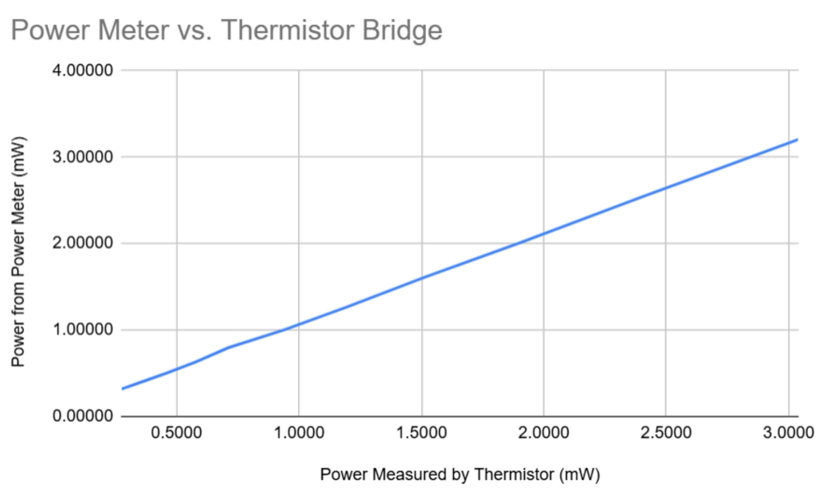

Figure 4: Power measured by power meter vs power measured by thermistor. As we expected, the power measured by the thermistor is lower than that measured by the power meter, since more of the RF power is reflected by the thermistor circuit due to mismatch ($|S_{11}|$ ws approximately -8 dB for R_T = 300 Ω).

Part III

Q7: We first measured the Thévenin voltage and resistance at the four given power levels. At each power level, the Thévenin voltage was equal to the open-circuit voltage ($V_{TH} = V_{OC}$). We found the Thévenin resistance as $R_{TH} = R_{DEC}(\frac{V_{TH}-V_{DC}}{V_{DC}})$, where R_{DEC} is the value of the decade resistor and V_{DC} is the voltage across the decade resistor measured by the voltmeter for the third measurement (in which we got the voltage V_{DC} as close to half the open circuit voltage as we could). The Thévenin voltage increases because as more power is added to the diode, its behavior moves further up the I-V curve (both higher current and higher voltage). The slope of the curve, which is the conductance G, increases as well, which explains why we see the resistance decrease while adding more power. The nonzero values of R_{TH} are not likely to degrade the accuracy of our measurements significantly because we will connect the diode output only to a voltmeter, which has very high resistance (ideally infinite). This means that the current across the Thévenin resistance is ~0 A, so there is neither power dissipated in it nor voltage drop across it. We will relate the RF power to the DC voltage across the diode for an open circuit.

RF Power	From Meter	Meas. 1		Meas. 2		Meas. 3		Vth	Rth	Max Pdc	η
(dBm)	(mW)	V (mV)	Rdec (Ω)	V (mV)	Rdec (Ω)	V (mV)	Rdec (Ω)	(mV)	(Ω)	(nW)	
-30	0.001	0.044	Infinite	0.025	1000	0.022	1000	0.044	1000.0	0.00048	0.00000048
-20	0.010	0.383	Infinite	0.175	1000	0.195	1200	0.383	1156.9	0.03170	0.00000317
-10	0.100	4.14	Infinite	2.01	1000	2.1	1100	4.140	1068.6	4.00993	0.00004010
0	1.000	47.65	Infinite	28.87	1000	23.01	600	47.650	642.5	883.46731	0.00088347

Table 3: Measurements of voltages across different decade resistances when connected to the diode to determine the diode's Thévenin equivalent parameters.

Q8: The maximum power that can be extracted from the diode at a given RF power level is for a load matched to the Thévenin resistance of the diode, and is given by $P_{DC} = \frac{(0.5V_{TH})^2}{R_{TH}}$, since the voltage across the external resistor will be half the Thévenin voltage. These maximum power values are 0.00048 nW, 0.0317 nW, 4.01 nW, and 883 nW for -30 dBm, -20 dBm, -10 dBm, and 0 dBm of RF power, respectively. We then calculated the ratio of these maximum extracted DC power levels to the RF power input to the detected, as the RF to DC conversion efficiency. These values are shown in the rightmost column of Table 3.

Part IV

Q9: After plotting the voltage across the diode versus the incident RF power, we found that the points very closely followed a linear relationship ($R^2 = 0.993$). The trendline has a slope of 1.86, which is represented by K in the relation $V_{DC} = K * P_{RF}$.

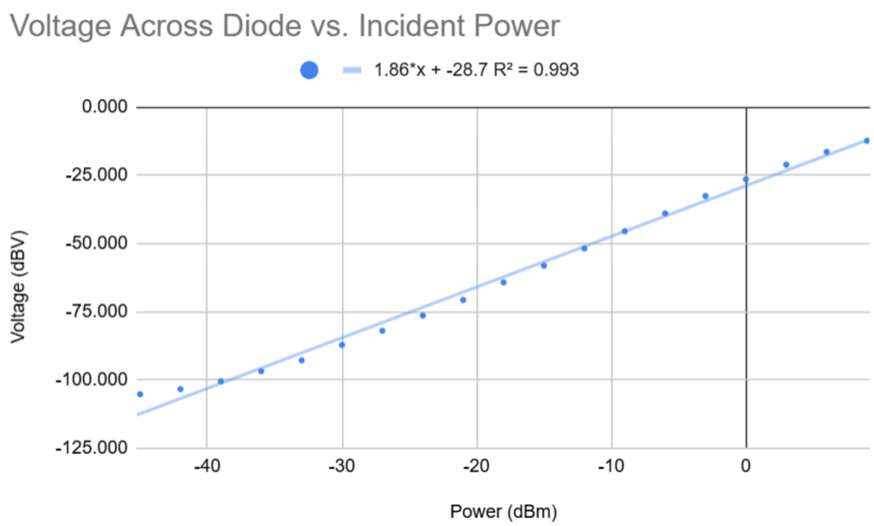

Figure 5: Voltage in dBV versus incident RF power in dBm. We found that it followed a linear relationship given by the equation $V_{DC} = 1.86 * P_{RF} - 28.7$.

Incident RF Power		Voltage Across Diode	
(dBm)	(mW)	(mV)	(dBV)
9	7.943	244.3	-12.242
6	3.981	152.2	-16.352
3	1.995	89	-21.012
0	1.000	48	-26.375
-3	0.501	23.7	-32.505
-6	0.251	11.36	-38.892
-9	0.126	5.36	-45.417
-12	0.063	2.58	-51.768
-15	0.032	1.25	-58.062
-18	0.016	0.617	-64.194
-21	0.008	0.294	-70.633
-24	0.004	0.152	-76.363
-27	0.002	0.08	-81.938
-30	0.001	0.044	-87.131
-33	0.001	0.023	-92.765
-36	0.000	0.0145	-96.773
-39	0.000	0.0095	-100.446
-42	0.000	0.0068	-103.350
-45	0.000	0.0055	-105.193

Table 4: Measurements of voltages across diode and incident RF power.