20W/50Ω μDummy Load with Wattmeter

ASMV Electrical

Last Updated: February 6, 2024

Difficulty of Assembly: 3 out of 10
– Through-Hole Parts Only –

Contents

1 Overview

This micro-size 50Ω RF dummy load with built-in wattmeter is well-suited for testing portable rigs. The glass LCD provides time-average power readings between 0.15 and 20W with 0.1W precision. Batteries are not required, as the unit draws power from the RF source, consuming a maximum of 3.0mA at the full rated input power. The board itself serves as a heatsink provided the operator limits the duration of the RF input. Improve the accuracy by loading a calibration table of up to 60 rows into EEPROM using an Arduino microcontroller.

Table 1: Characteristics

Parameter	**Conditions**	**Min.**	**Typ.**	**Max.**	**Unit**
Input power		0.15[1]		20	W
Peak ac input voltage		3.9		45	V
Wattmeter op. frequency		dc[2]		50	MHz
Dummy load op. frequency		dc		150	MHz
Uncalibrated error ($f_{in} \leq 10$ MHz)	$P_{in} = 1.0$W		0.1	0.2	W
	$P_{in} = 20$W		0.7	1.3	W
Uncalibrated error ($f_{in} = 50$ MHz)	$P_{in} = 1.0$W		0.2	0.3	W
	$P_{in} = 20$W		1.0	2.0	W
Safe operating time ($T_A = 25$℃)	$P_{in} = 10$W			24	sec
	$P_{in} = 15$W			11	sec
	$P_{in} = 20$W			5	sec
80% cool-down time[3]				3.5	min

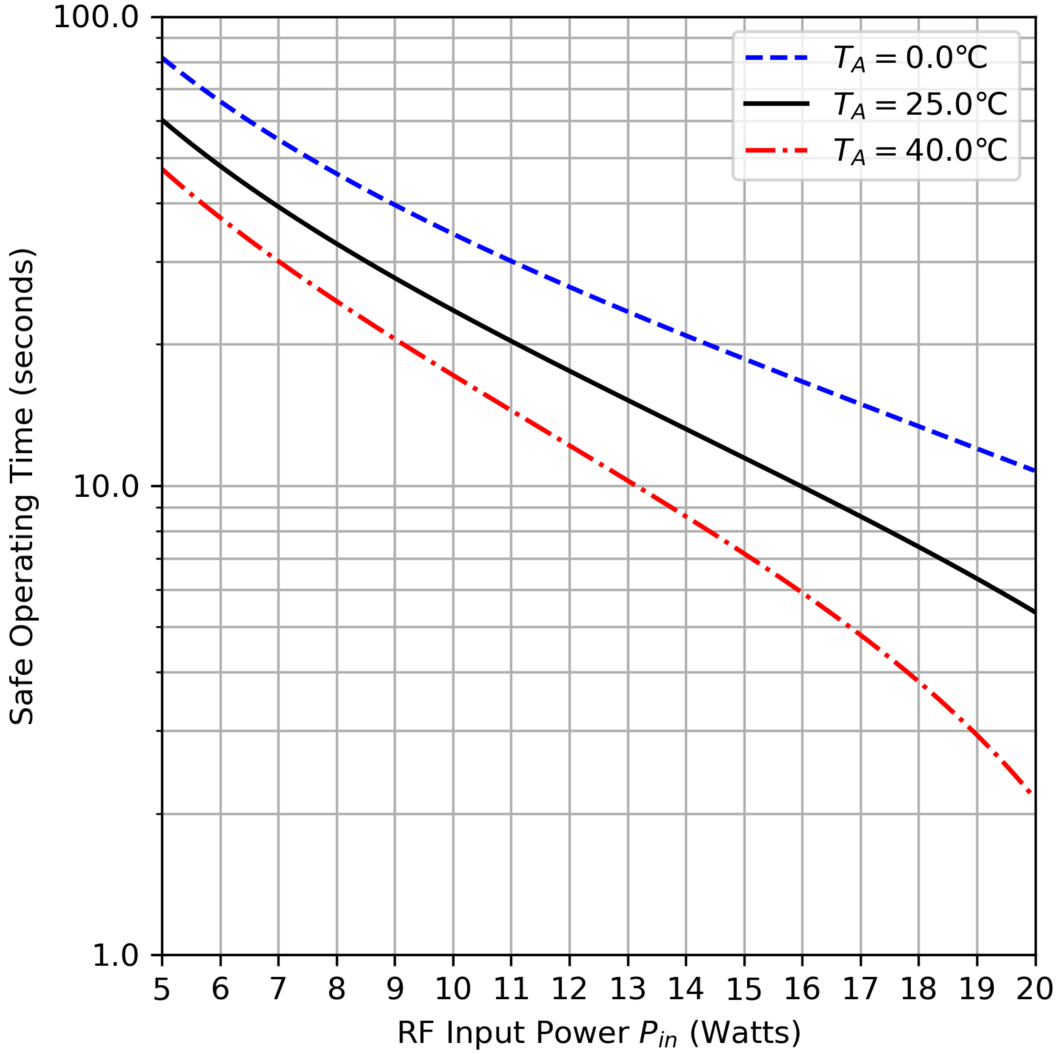


Figure 1: Safe Operating Time versus Input Power and Ambient Temperature

[1]The wattmeter will not operate when the input power falls below the rated minimum.
[2]To obtain the correct power at dc, double the meter reading.
[3]This is the cool-off time observed indoors with minimal air flow.

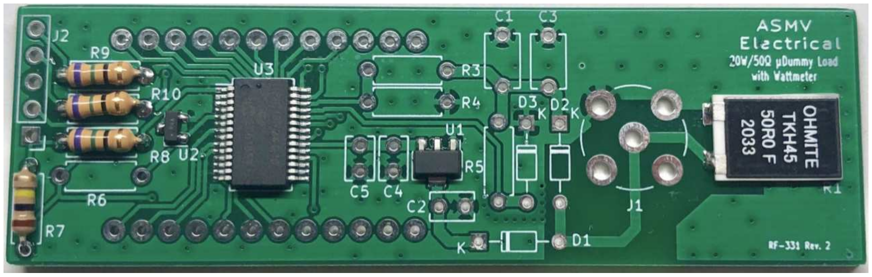
2 Assembly Instructions

Before proceeding, make sure that you have the parts in listed on this page and pictured on the next page. The board comes pre-populated with the surface-mount components. To complete the assembly, solder the remaining through-hole components to the board by following the steps on page 7. When complete, your board should look like the picture on on page 8. For best results, use rosin-core 63/37 PbSn solder, the eutectic alloy that melts at 181℃/361°F.

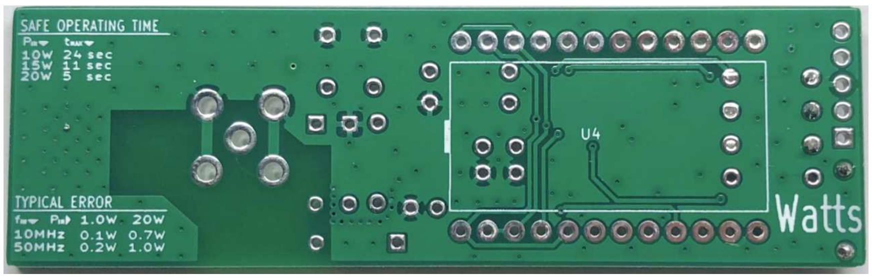
Parts List

Table 2: Kit Parts List

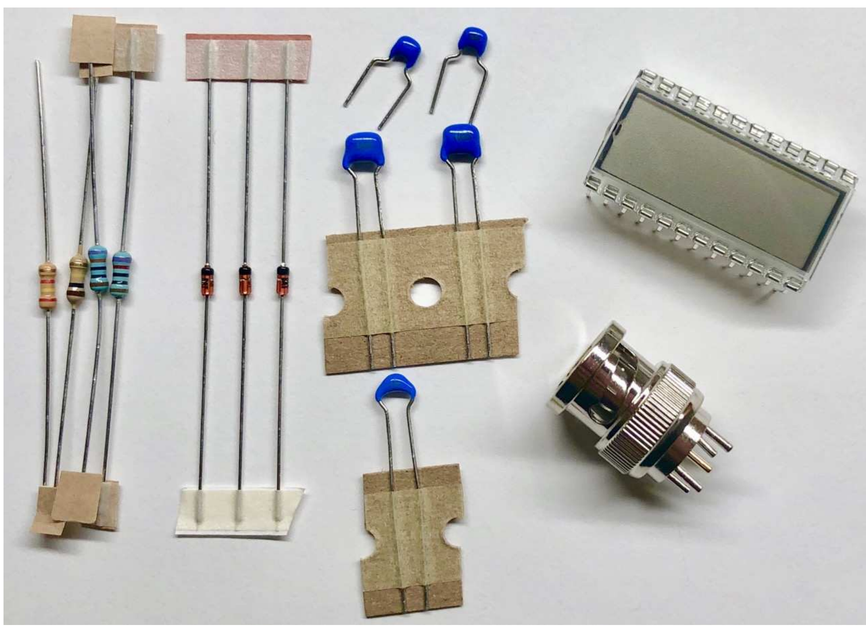
Qty.	Reference(s)	Description	Package Marking
1	PCB	μDummy Load PCB	RF-331 Rev. 2
3	D1, D2, D3	BAT46 Schottky diode	BAT46
2	C1, C3	5.6nF peak-detector caps	562
2	C2, C4	1μF 100V decoupling caps	105K
1	C5	10nF decoupling cap	103
1	R3	100kΩ 0.1% precision resistor	**BrownBlackBlackOrangeViolet**
1	R4	10kΩ 0.1% precision resistor	**BrownBlackBlackRedViolet**
1	R5	100kΩ 5% diode resistor	**BrownBlackYellowGold**
1	R6	2.4kΩ 5%V_{ref} resistor	**RedYellowRedGold**
1	J1	Male BNC 50Ω PCB-mount	—
1	U4	24-pin reflective LCD	—



(a) PCB Front



(b) PCB Back



(c) Parts

Figure 2: Kit before assembly.

Assembly Steps

1. Place and solder the Schottky diodes D1, D2, D3 onto the board. Make sure to orient the diodes so that the cathode band is closer to the pad marked "K".

2. Place and solder the peak-detector capacitors C1, C3, the rectifier capacitor C2, and the diode biasing resistor R5 onto the board.

3. Place ***but do not solder*** the precision voltage divider resistors R3, R4, the decoupling capacitors C4, C5, and the voltage reference biasing resistor R6 onto the board.

4. Turn the board over and cut leads that protrude out of the LCD area (U4) flush with the board. If necessary, remove the parts to cut the leads. ***Rough or jagged pieces of metal extending out from the board may damage the LCD.***

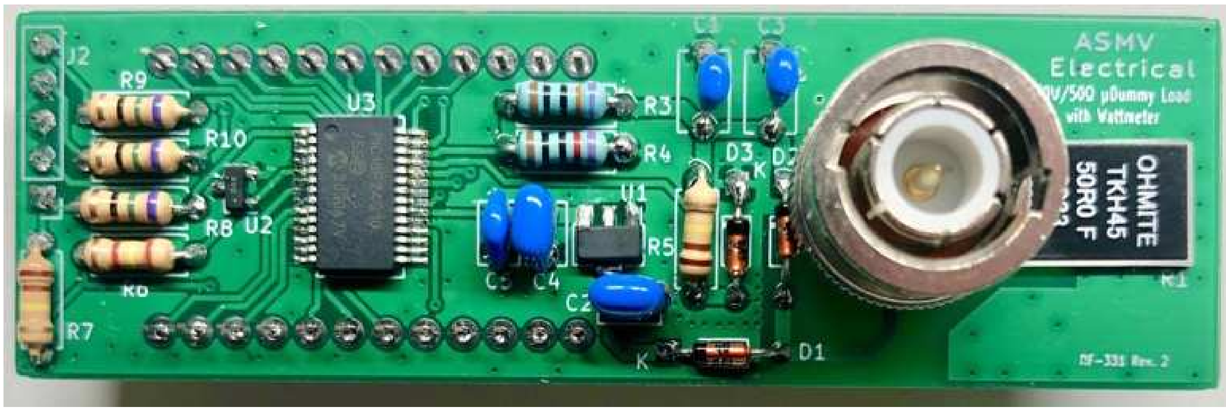
5. Solder the previously-placed parts R3, R4, C4, C5, R6 to the board.

6. Turn the board over and insert the 24-pin LCD (U4). Make sure to orient the LCD so that the edge with the raised notch aligns with the mark on the silkscreen. Turn over the board and solder the LCD in place.

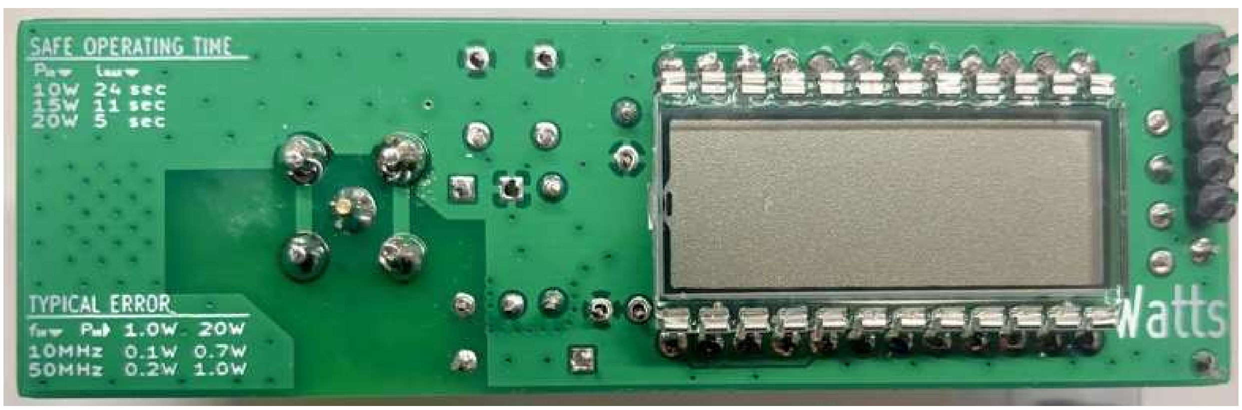
7. Place and solder the BNC connector J1 onto the board. Apply a rosin flux to outer shield pins before soldering. These pins may require additional heat to form a good joint.

8. Remove the protective film from the LCD.

Assembled Board



(a) Front



(b) Back

Figure 3: Assembled board.

3 Calibration Instructions

The μDummyLoad stores a calibration table and other configuration settings in the EEPROM of the on-board PIC microcontroller. The table consists of up to 60 rows mapping uncalibrated meter readings to corrected power values. The μDummyLoad linearly interpolates between the provided calibration points. Program the EEPROM using an Arduino board (Uno, Nano, etc) and the provided configuration sketch by following the steps below.

1. Download the Arduino IDE and install it on a computer.

2. Download the `uDummyLoadConfig` configuration sketch and open it within the Arduino IDE.

3. Follow the instructions in the configuration sketch to configure the μDummyLoad to operate in ***calibration mode*** (to bypass any previously-loaded calibration table) and with ***extended 0.001W precision*** (to increase the calibration accuracy.)

4. Perform the calibration measurements by applying known power levels and recording the meter readings. One way to do this is to insert a calibrated wattmeter in series with the feedline; another method is to measure the peak input voltage with a high-impedance oscilloscope and compute the input power as $P_{in} = v_{pk}^2/100$; yet another is to use a rig with a power output reading you trust.

5. Create a table mapping meter readings in milliwatts (first column) to the known power readings in milliwatts (second column.) ***Sort the table in ascending order by the column of meter readings. All values should be whole numbers of milliwatts.***

6. Follow the instructions in the Arduino sketch to disable calibration mode, set precision back to 0.1W, and load the calibration table.

Table 3: Configuration Options

Name	Description	Default	Range
precision	Selects the meter precision: Standard (STD): 0.1W Extended (EXT): 0.001W ***The display scans the last two mV digits in extended mode.***	STD	STD/EXT (1 bit)
enableCalibration	Enables calibration mode to bypass table lookup so that new calibration readings can be taken.	false	true/false (1 bit)
enableDiodeComp	Enables peak detector diode drop compensation by measuring the drop across a matched diode.	true	true/false (1 bit)
diodeOffsetMillivolt	Offset to the measured peak voltage to account for the difference in the current flow between the compensation diode and the peak detector diode [millivolts].	17 mV	0–65,535 (16 bit)
displayPeriodMillisec	Display update time period [milliseconds]. ***The display update routine requires at least 25ms to run.***	100 ms	0–65,535 (16 bit)
samplePeriodMillisec	A/D sampling time period [milliseconds]. ***The sampling routine requires at least 10ms to run.***	50 ms	0–255 (8 bit)
calibrationTable	Calibration table of up to 60 rows mapping the meter's readings to corrected power values in milliwatts. The μDummyLoad linearly interpolates between the table rows.	Absent	—

Table 4: μDummyLoad Error Codes

Error Code	Description
01	Timeout waiting for master (Arduino) to release DAT/CLK lines.
02	Timeout waiting for master (Arduino) to send data.
03	Receive buffer overflowed 255 bytes.
04	Data header missing or malformed.
05	Calibration table malformed.
06	Calibration table not sorted in ascending order.

4 Detailed Description

The block diagram of Figure 4 shows the functional units of the dummy-load module—primarily, a 50Ω load resistor, a PIC18 microcontroller, and a three-digit liquid crystal display (LCD). The radio-frequency (RF) input powers the PIC18 and LCD via a rectifier followed by linear regulator. The complete electrical schematic appears in Figure 5.

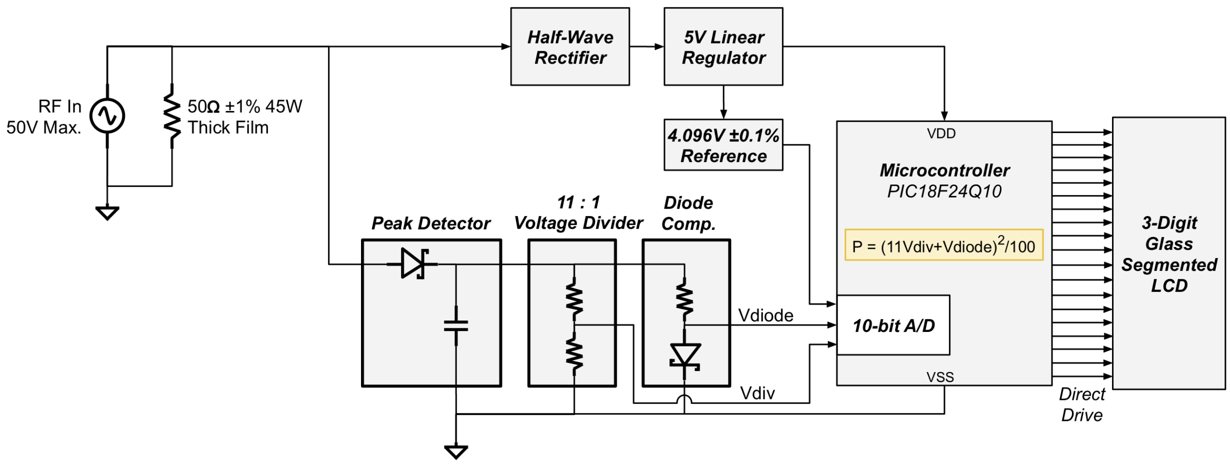


Figure 4: Block Diagram

The circuit detects the RF envelope voltage with a Schottky-diode peak detector. A 10-bit SAR A/D converter within the microcontroller samples the divided envelope voltage and the voltage across a matched diode to compensate for the diode drop of the peak detector. The PIC18 then computes the average power absorbed by the load resistor as

$$P = \frac{(A_{div}V_{div} + V_F)^2}{2R_{load}}$$

where $A_{div} = 11\text{V/V}$ is the division factor of the voltage divider, $R_{load} = 50\Omega$ is the load resistance, V_{div} is the voltage measured at the voltage divider output, and V_F is the forward voltage drop across the detector diode computed from the voltage measured across the compensation diode V_{diode}. In the Peak Detector section, it is shown that $V_F \approx V_{diode} + 17\text{mV}$.

From the 10-bit digital code C_{div} liberated by the A/D converter, the voltage divider output voltage is

$$V_{div} = \frac{C_{div}}{1023} V_{ref}$$

where $V_{ref} = 4.096V$ is the external 0.1% precision Zener voltage reference. In the following sections, we'll denote the units of C_{div} with least-significant bits (LSb).

Load Resistor

A 50Ω/45W thick-film resistor dissipates the input RF power P_{in}. This resistor is housed in a surface-mount package with heatsink pad in contact with the top and bottom ground pours on the circuit board. The board itself serves as the heatsink and its heat capacity limits the maximum time the load is able to withstand input power without damaging the resistive element. See the Thermal Considerations Section for details.

Manufacturing variation of the load resistance introduces error in the power reading. The nominal load resistance is $R_{load} = 50\Omega$ with a tolerance of $t = 1\%$ and temperature coefficient of $\alpha = 100\text{ppm/°C}$. Over the industrial temperature range, the maximum error in the load resistance is then $\Delta R_{load} = (t/100)R_{load} + (\alpha/10^6)R_{load} \times 65\text{°C}$, which comes out to $\Delta R_{load} = 0.825\Omega$. The maximum error in the power reading is

$$\Delta P_{err} \approx P_{in} \frac{\Delta R_{load}}{R_{load}}$$

The error is 0.017W when $P_{in} = 1.0\text{W}$ and 0.33W when $P_{in} = 20.0\text{W}$.

At frequencies above 50MHz, the load impedance deviates significantly from 50Ω due to parasitic inductance and capacitance of the thick-film resistor

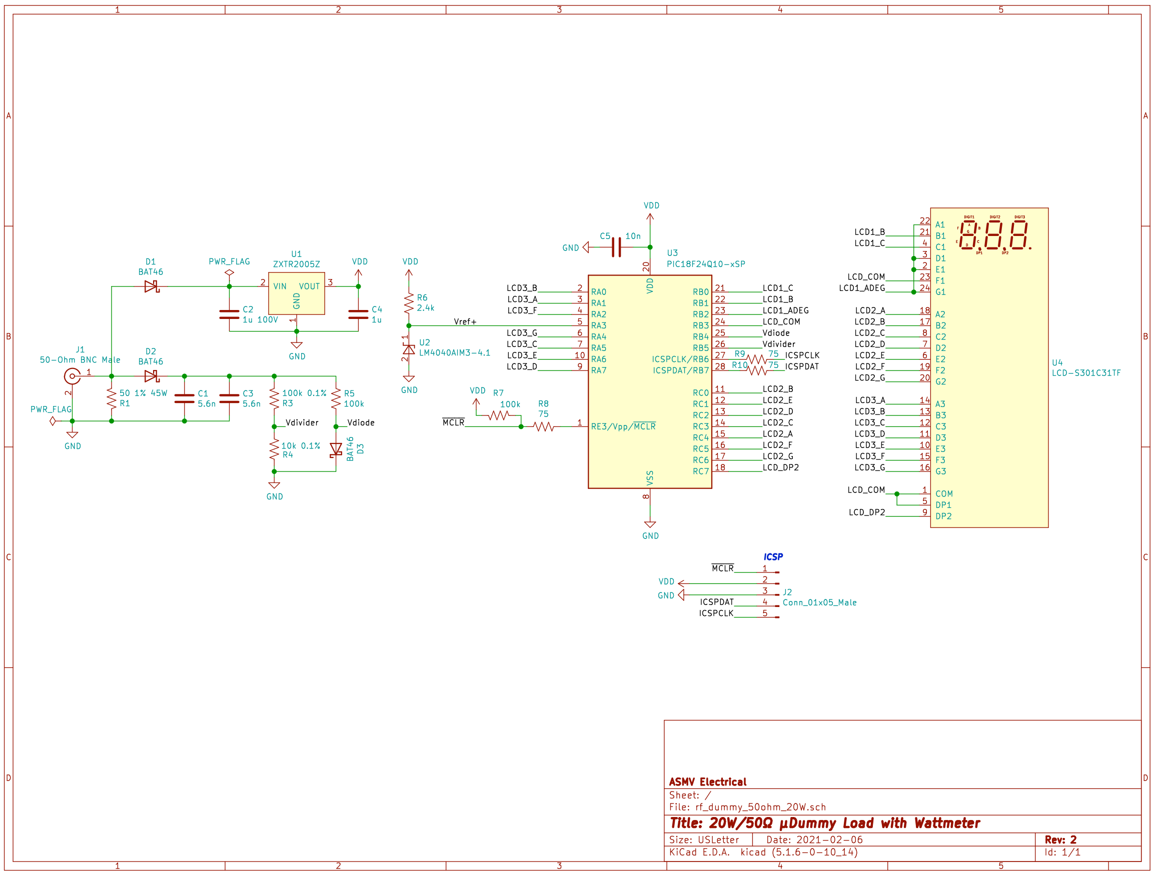


Figure 5: Electrical Schematic

and the circuit-board traces. A lumped-element model of the resistor, resistor case parasitics, and circuit-board trace parasitics appears in Figure 6. Figure 7 is a computer-generated plot of the resistor's impedance Z_R and the impedance Z seen at the input to the µDummy load. At an input frequency of 10MHz, the impedance differs from 50Ω by 0.075Ω. The resulting error in the power reading is 0.0015W when $P_{in} = 1.0$W and 0.03W when $P_{in} = 20.0$W. At 50MHz the difference is 1.88Ω; the error is 0.038W when $P_{in} = 1.0$W and

0.75W when $P_{in} = 20.0$W.

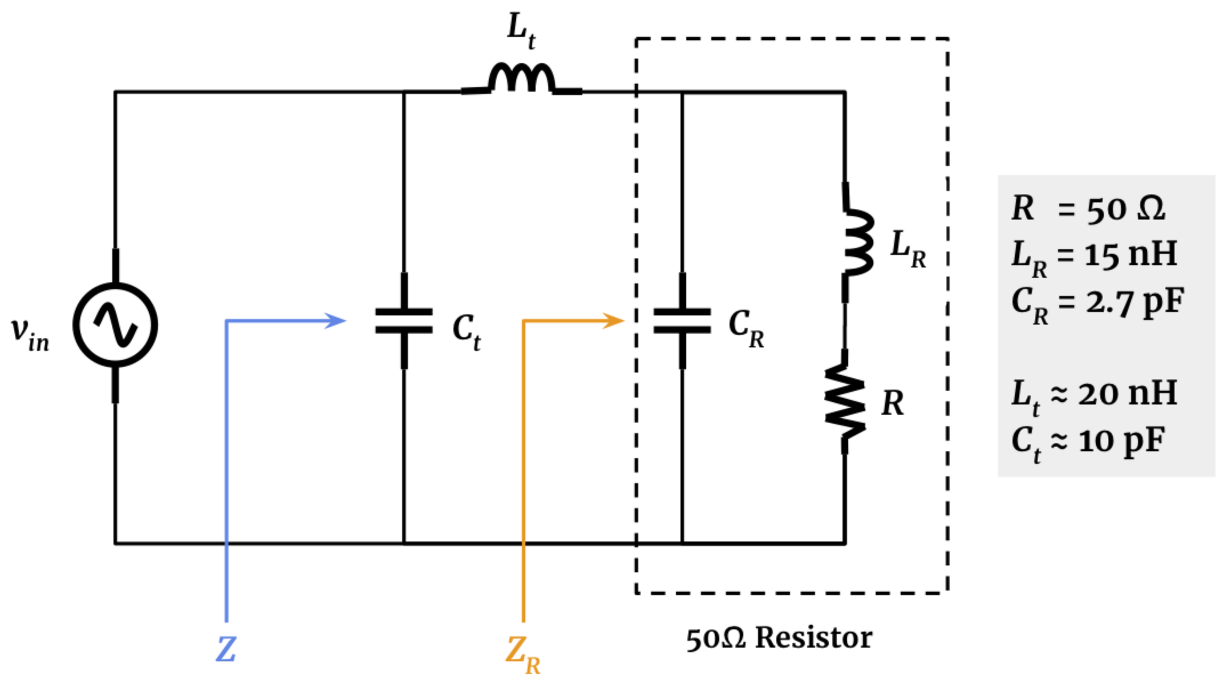


Figure 6: Equivalent Load Circuit

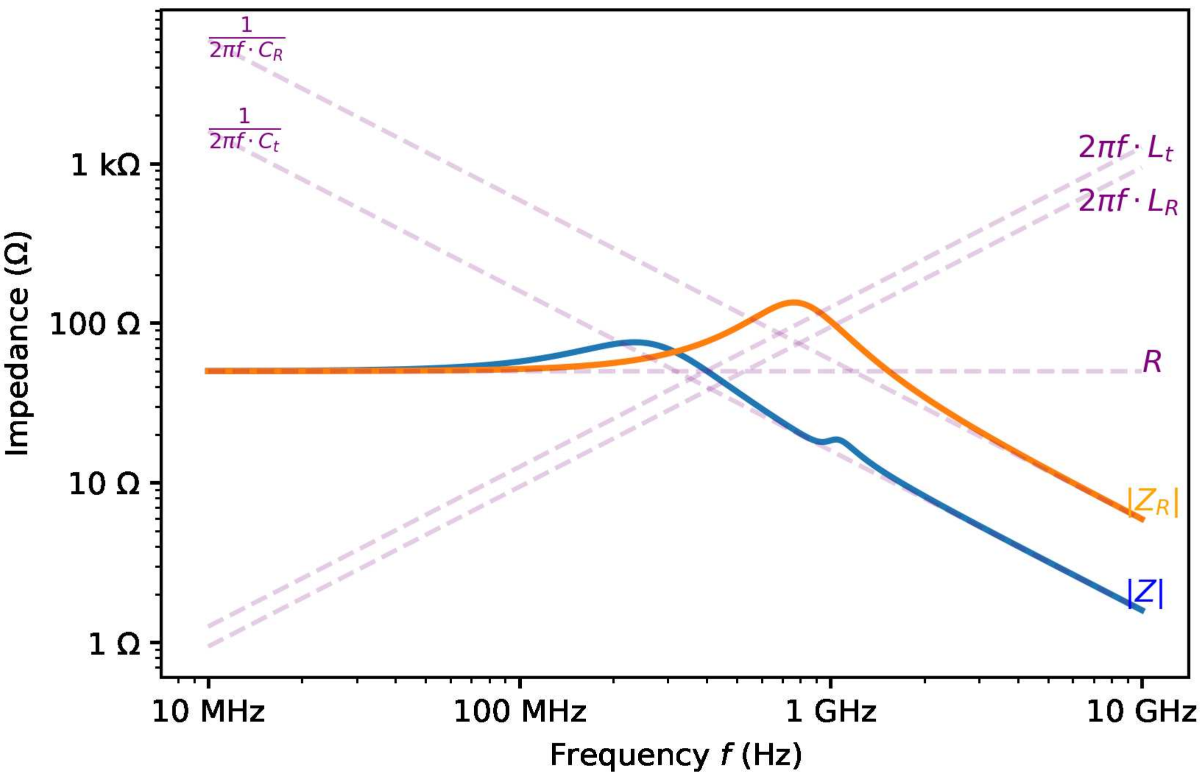


Figure 7: Load Impedance vs. Frequency

Peak Detector

The unit employs a BAT46 Schottky diode and two parallel-connected 5.6nF capacitors to detect the envelope of the RF input voltage. Positive half-cycles of the input forward bias the diode and charge the capacitors to the peak input voltage V_{pk}; in negative half-cycles, the diode is reverse biased with a maximum reverse voltage of $\max(V_R) = 2V_{pk}$. Reverse breakdown occurs at 100V for BAT46, limiting the peak input voltage to 50V and the input power to $V_{pk}^2/2R_{load} = 50^2/100 = 25$W.

The voltage divider loads the peak detector, somewhat reducing its accuracy. The total resistance of the divider is $R_{div} = 110k\Omega$, drawing a current of approximately $I_{div} = V_{pk}/R_{div}$ or about 450µA at 50V envelope voltage. The diode must conduct this current in positive half-cycles to charge the capacitors, resulting in a forward voltage drop V_F across the diode near 0.3V. The error in the power reading due to to an error in the measured peak voltage of ΔV_{err} is

$$\Delta P_{err} \approx \Delta V_{err} \cdot \sqrt{\frac{2P_{in}}{R_{load}}} \tag{1}$$

where P_{in} is the input power and $R_{load} = 50\Omega$ is the load resistance. Setting $\Delta V_{err} = V_F$, the error due to the diode drop is about 0.06W for $P_{in} = 1.0$W; for $P_{in} = 20$W, it is about 0.27W.

The µDummy load measures the voltage across a dc-biased BAT46 diode to partially compensate the drop in the peak detector. A diode from the same production lot as the detector diode is forward biased by the envelope voltage and a 100kΩ resistor. The PIC18 samples the forward voltage across this compensation diode $V_{F(comp)}$ and, from this measurement, computes the forward voltage drop across the detector diode V_F as follows. When forward voltage exceeds several tens of millivolts, the detector and compensation diode currents are

$$I \approx I_s e^{V/\eta V_T}$$
$$I_{comp} \approx I_s e^{V_{F(comp)}/\eta V_T}$$

where I_s is a diode parameter called the saturation current, V_T is the thermal voltage equal to 0.0259V at room temperature, and η is the diode ideality factor near 1.0 for Schottky diodes. Dividing the first equation by the second and solving for V_F results in the formula

$$V_F = V_{F(comp)} + V_T \ln\left(\frac{I}{I_{comp}}\right)$$

The saturation current I_s cancels out since the diodes are matched. This equation can be further reduced by noting the compensation diode current is $I_{comp} \approx V_{pk}/R_{comp}$,where $R_{comp} = 100\text{k}\Omega$ is the biasing resistance and the average detector diode current is $I \approx V_{pk}/(R_{div}||R_{comp})$ where $R_{div} = 110\text{k}\Omega$ is the voltage divider resistance:

$$V_F = V_{F(comp)} + V_T \ln\left(1 + \frac{R_{comp}}{R_{div}}\right)$$

At room temperature, $V_F = V_{F(comp)} + 0.017\text{V}$; the detector diode voltage equals the compensator diode voltage plus about 17mV. The change in the 17mV offset is less than ±4.0mV over the -40℃ to +85℃ industrial temperature range and is neglected in this application due to lack of a calibrated temperature sensor. The PIC18 contains an internal temperature sensor that could be manually calibrated for this application, though this will do little to improve the overall compensation accuracy.

This method of compensation still results in error due to diode mismatch and differences in the conduction methods. The compensation diode is dc-biased, while the current through the detector diode flows in pulses, remaining near zero except at peaks of the RF input, during which the instantaneous detector current $i(t)$ will exceed the averaged current I used in the above equations. This causes the detector diode's forward voltage drop to exceed the figures predicted by the foregoing equations. Suppose the error in V_F is limited to about 0.1V maximum. The resulting error in the power reading is then 0.09W when the input power is 20W and 0.02W when the input power is 1W.

Microcontroller and Display

A surface-mount package houses the PIC18 to reduce board area and routing complexity. This PIC18 is powered from a 5V linear regulator and is clocked by an internal 1MHz oscillator (HFINTOSC).

Power readings are output to a three-digit transflective LCD where the digits are 7-segmented. To “activate” a segment of a particular digit, the PIC18 alternates the voltage applied to that segment between +5V and -5V at a rate of 30Hz; to disable a segment, the PIC18 drives the segment voltage to zero. One side of the LCD segments contact a common line labeled “COM” and separate lines expose the other sides of the segments. There are a total of 24 lines on the display (COM line, 21 segment lines, and 2 decimal point lines), but the PIC18 has enough outputs to drive only two complete digits. The meter need only read up to 20.0W, and thus the first digit is wired to display the numbers “1” and “2” only, reducing the pin count.

When driving the LCD and performing periodic A/D conversions, the PIC18 draws about 800µA from the linear regulator. The external voltage reference draws an additional 600µA from the regulator, and the quiescent current of the linear regulator is about 600µA. The combined power draw of the PIC18 and voltage reference from the RF input is then $(800+600+600)\mu A \cdot V_{pk}$. Add to this the power dissipated by the envelope voltage divider and compensation diode $V_{pk}^2/(R_{div}||R_{comp})$ and the total parasitic power draw is

$$P_{parasitic} = (2.0 + V_{pk}/52.4)mA \cdot V_{pk}$$

With $V_{pk} = 45V$ ($P_{in} \approx$ 20.0W), $P_{parasitic} =$ 0.148W; with $V_{pk} = 10V$ ($P_{in} \approx 1.0W$), $P_{parasitic} =$ 0.022W. This parasitic power draw constitutes error in the power reading.

Additional Sources of Error

Aside from the diode drop of the peak detector, the parasitic power draw of the PIC18, and load resistance error discussed previously, several other factors contribute to error in the power reading. These include absolute error of the A/D converter, voltage reference drift, and error in the voltage divider resistances.

A/D Converter Error From the Electrical Specifications section of the PIC18 data-sheet[4], the worst-case integral nonlinearity is 1.0 LSb, worst-case offset error is 2.0 LSb, and worst-case gain error is 2.0 LSb. The maximum error is the sum of these contributions, 5.0 LSb. With a nominal reference voltage of $V_{ref} = 4.096\text{V}$ and voltage division factor of $A_{div} = 11\text{V/V}$, the worst-case error in the peak voltage reading is $\Delta V_{err} = 11 \times 4.096\text{V} \times (5\text{LSb}/1023) = 0.22\text{V}$. The corresponding error in the power reading given by Equation (1): 0.04W at $P_{in} = 1.0\text{W}$ and 0.2W at $P_{in} = 20.0\text{W}$.

Voltage Reference Error The LM4040 4.096V zener reference has an output voltage error of $\Delta V_{ref} = \pm 0.031\text{V}$ over the full industrial operating temperature range[5]. The resulting worst-case error in the peak voltage reading is $\Delta V_{err} = A_{div} \Delta V_{ref} = 0.341\text{V}$, and error in the power reading is 0.07W at $P_{in} = 1.0\text{W}$ and 0.3W at $P_{in} = 20.0\text{W}$. The error is lower when operating within a narrower temperature range. For example, within the 10℃ to 40℃ temperature range, $\Delta V_{ref} = \pm 0.0164\text{V}$, giving a power error of 0.036W at $P_{in} = 1.0\text{W}$ and 0.16W at $P_{in} = 20.0\text{W}$.

Voltage-Divider Resistance Error The division factor of the peak detector voltage-divider is $A_{div} = 1 + R_{top}/R_{bot}$ where $R_{top} = 100k\Omega$ (nominal) is the value of the upper resistor and $R_{bot} = 10k\Omega$ (nominal) is the value of the

[4] The PIC18 datasheet is available for download on Microchip's website via this link.

[5] The LM4040 datasheet is available for download on Texas Instrument's website via this link.

lower resistor. The error in the voltage division factor A_{div} due to deviation of the resistance values from nominal, ΔR_{top} and ΔR_{bot}, is given by the total differential approximation

$$\Delta A_{div} \approx \frac{1}{R_{bot}}\Delta R_{top} - \frac{R_{top}}{R_{bot}^2}\Delta R_{bot}$$

The maximum error occurs when ΔR_{top} and ΔR_{bot} have different signs (i.e. when the upper resistance is higher than nominal and the lower resistance is lower than nominal, or vise versa) and is given by

$$\max|\Delta A_{div}| \approx \frac{1}{R_{bot}}|\Delta R_{top}| + \frac{R_{top}}{R_{bot}^2}|\Delta R_{bot}|$$

Writing the resistance errors in terms of the resistor percent tolerance t as $|\Delta R_{top}| = (t/100)R_{top}$ and $|\Delta R_{bot}| = (t/100)R_{bot}$ results in the formula

$$\max|\Delta A_{div}| \approx \frac{2t}{100}\frac{R_{top}}{R_{bot}} = \frac{2t}{100}(A_{div} - 1)$$

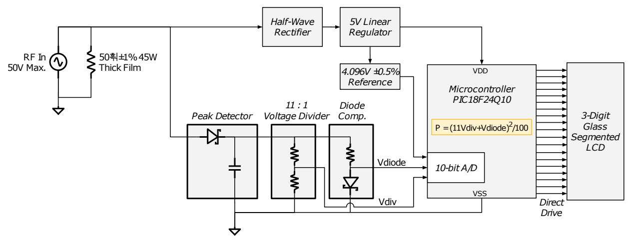
With a nominal division factor of $A_{div} = 11\text{V/V}$ and resistor tolerance of $t = 0.1\%$, the maximum error in the division factor is 0.02V/V. The corresponding maximum error in the power reading is

$$\Delta P_{err} \approx 2P_{in}\frac{\max|\Delta A_{div}|}{A_{div}}$$

The error is 0.004W for $P_{in} = 1.0\text{W}$ and 0.073W for $P_{in} = 20.0\text{W}$.

Thermal Considerations

A simplified thermal model of the µDummy load appears in Figure 8. The thermal model is similar to an electrical circuit where power (heat flow) replaces current, temperature replaces voltage, thermal resistance replaces elecrical reistance, and heat capacity replaces capacitance.



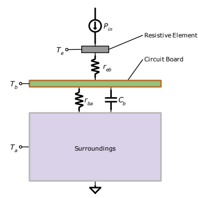


Figure 8: Thermal Diagram

In the model, T_e is the temperature of the resistive element, T_b is the temperature of the board (assumed isothermal for simplicity), and T_a is the temperature of the surroundings. The thermal resistance r_{eb} is a measure of the opposition that the resistor's casing presents to heat flow from the internal resistive element to the heatsink pad—i.e from the element (e) and the board (b). For the Ohmite part used in this application, $r_{eb} = 3$℃/W. Similarly, r_{ba} is the heat resistance between the board and the surroundings. Its value depends on the size of the board, air flow rate, and other factors. Last, C_b is the heat capacity of the board and may be approximated as

$$C_b \approx m_{Cu}c_{Cu} + m_{FR4}c_{FR4}$$

where m_{Cu} is the total mass of copper on the board, c_{Cu} is the specific heat capacity of copper, m_{FR4} is the mass of FR-4 dielectric in the board's interior, and c_{FR4} is the specific heat capacity of FR-4. Substituting the appropriate values, we find $C_b \approx 4.3$J/℃ for the µDummy load board.

Assuming $r_{ba} >> r_{eb}$ such that r_{ba} may be neglected, the initial temperature of the board is equal to the ambient $T_b(0) = T_a$, and that constant RF power P_{in} is applied starting at time $t = 0$, the solution for T_e is

$$T_e(t) \approx \frac{P_{in}}{C_b} t + P_{in} r_{eb} + T_a$$

The temperature of the resistive element increases linearly with time, eventually growing large enough to damage the resistor if the input RF power is not removed. According to the power derating curve in the resistor's data-sheet, to safely dissipate the full rated power of 20W, the element must be held below about $T_{e(max)} = 110$℃. The time at which T_e reaches $T_{e(max)}$ is

$$t_{max} = C_b \left(\frac{T_{e(max)} - T_a}{P_{in}} - r_{eb} \right)$$

A plot of t_{max} versus the input power appears in the Overview Section at several ambient temperature values. The safe operating time predicted by this formula is somewhat pessimistic since we neglect heat lost to convection and radation from the board to the ambient.

After we remove the input power, the temperature of the board decays exponentially to ambient with the termal time constant

$$\tau = r_{ba} C_b$$

which is the time required for the board temperature to decay to 37% of its initial value above ambient. Based on empirical observation, the board-to-ambient thermal resistance r_{ba} is approximately 30℃/W (indoors with minimal air flow). The time constant is then $\tau = (30)(4.3) = 129$ sec. The 80% cool-down time (the time required for the board to reach 20% of its initial value above ambient) is $1.6\tau = 206$ sec, or about 3.5 minutes.