Direct-Reading Milliwatt Power Sensor for your Digital Wattmeter
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Introduction

Today's amateur marketplace includes high-end digital wattmeters that accurately measure ham power levels of typically 1-2000 watts or so. While this power range satisfies most station requirements, experimenters often need to measure much lower RF power levels. Therefore I decided to investigate the possibility of building a power meter sensor that would permit accurate readings of milliwatt RF power levels on a digital wattmeter display. As I own both an Array Solutions PowerMaster (QST January 2006) and a Meterbuilder MB-1 (QST September 2013), I focused on a PowerMaster design as the same detector will work for both wattmeters. My goal was to read power from 1-3000 milliwatts from 160-6 meters, and include 2-meters if possible. And these readings must directly correspond to the 1-3000 watt PowerMaster reading. The design involves determining the detected voltage at a specific power level into the coupler, and then building a detector that provides the same detected voltage at 1/1000th of this level. A similar approach can be used with other digital wattmeters that use an external coupler. However the design may need to be modified based on the actual coupler power or detected voltage available. Note that the Telepost LP-100A (QST August 2007) already includes a low power direct input measurement capability.

Detector Design

The PowerMaster coupler has a transformer turns ratio of 29:1. A $\pm$15% menu power trim setting compensates for any component variations. A 1N5711 shottky detector diode drives a 500K composite impedance (coupler and display termination). I measured several 1N5711 diodes with source voltages from 1-15VDC into this impedance and found a typical diode junction voltage drop of 0.225VDC. For my calculations I chose 1-watt coupler power as 1-watt is the minium power measured by the PowerMaster, and so 1-milliwatt would be my lowest measurable detector power.

Since $P = Vpk^2/2R$, for 1-watt into 50 ohms: $Vpk = \sqrt{(2PR)} = \sqrt{(2x1x50)} = 10V$

With a 29:1 turns ratio, the detector peak voltage is 10V/29 = 0.345V. This is very close to the 1N5711 detector junction voltage. While the PowerMaster includes low level diode linearization compensation, accuracy does begin to suffer as you approach this level.

Now, what is the peak voltage of a 1-milliwatt signal into 50 ohms?

$Vpk = \sqrt{(2PR)} = \sqrt{(2x0.001x50)} = 0.316V$

This is even closer to the 1N5711 junction voltage, which can result in even more inaccuracy at low power levels. Further, the 9.04% voltage difference (0.345/0.316 = 1.0904) corresponds to a power difference of 19% ($0.345^2/0.316^2 = 1.19$). So a trim of +19% is needed, which is 4% above the PowerMaster trim range. This combination of degraded accuracy and inadequate trim adjustment range means that something other than a simple detector is required.

My solution was to use a broadband RF transformer with a 5:5.5 primary-to-secondary ratio to boost the signal level prior to detection. The 10% voltage boost results in a power reading 2% above the calculated value (we need 19% but the transformer gives us 21%). I used an auto-transformer wound on a BN-43-202 binocular core. An auto-transformer uses the same winding for both the primary and secondary. It is smaller and more efficient than a two-winding transformer for small voltage ratios, and it is easy to build. The low frequency response is determined by the ferrite material and number of turns, and the high frequency response is at least partially due to the parasitic inductance of the total wire length. As a binocular core provides twice the inductance of a toroid core when the winding passes through both holes as part of a single turn, the number of turns and hence the total wire length is minimized.

In this application, one turn is defined as one pass through both holes in the core as shown in Figure 1. The final transformer is shown in Figure 2 (for clarity, not all turns are shown). On the 5^{th} turn, extend the wire a couple of inches, fold the wire back on itself, twist it, scrape the enamel coating and tin it. Then pass the wire end through one hole for the last (5-1/2^{th}) turn. The 5-turn input tap point has a reactance of over 600 ohms on 160 meters.

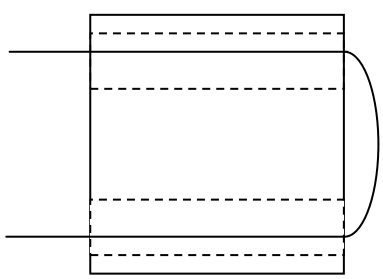

Figure 1: Definition of 1-turn thru core

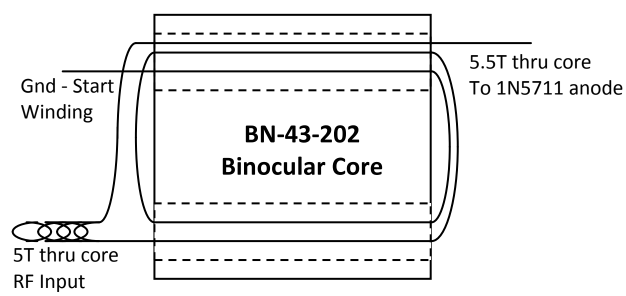

Figure 2: 5.5 turns total, tap at 5 turns

The schematic of the complete detector circuit is shown in Figure 3. This is not a directional coupler so SWR is not measured. Either a stereo cable with the ring grounded, or a mono cable is used to interface to the PowerMaster. Either cable will automatically ground the ring (reflected power) input on the PowerMaster and so the SWR will always read 1:1.

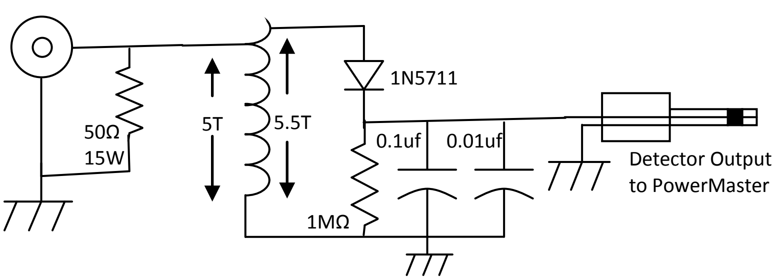

Figure 3: Broadband Milliwatt Detector

A Caddock 50 ohm 15-watt thick film resistor provides the precision termination inside the detector. Figure 4 is the measured SWR/return loss response of the detector. The worst case return loss is 30dB (1.07:1 SWR) at 1.8- and 148MHz, and it is better in between.

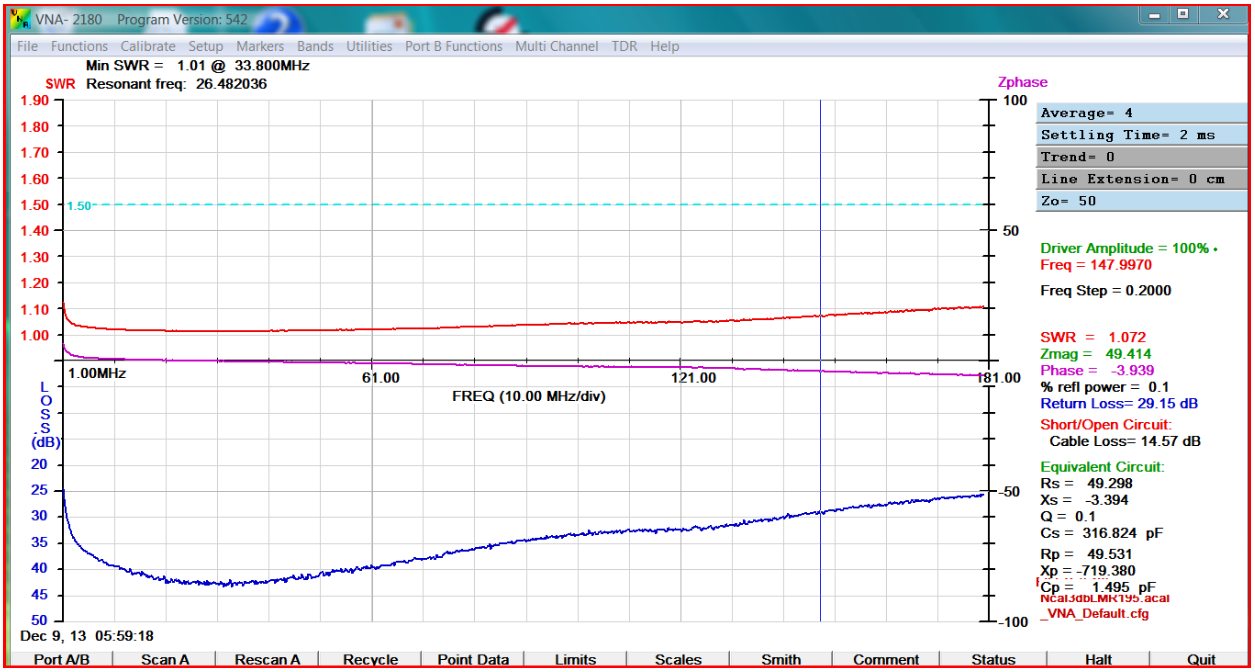

Figure 4: Detector SWR/Return Loss performance

The Parts List is given in Table 1, and Figure 5 shows the internal wiring. Keep all lead lengths as short as possible. I prefer an N-connector for my experimantal work, but a UHF or BNC connector can be substituted. Double-sided tape holds the transformer in place. Sand the paint beneath the mounting hardware and thick-film resistor for good RF ground and heat-sinking – or use an unpainted aluminum box (Mouser 537-M00-PLN).

Table 1 - Parts List (Mouser: www.mouser.com, All Electronics: www.allelectronics.com, Dan's Small Parts: www.danssmallpartsandkits.net)

QTY	Description	Part Number
1	50Ω 15-watt thick film resistor	Mouser 684-MP915-50
1	1N5711 shottky diode`	Mouser 511-1N5711
1	1M ohm ¼-watt resistor	Mouser 279-LR0204F1M0
1	0.01uf ceramic capacitor	Mouser 581-SA101C103KAR
1	0.10uf ceramic capacitor	Mouser 581-SA105E104MAR
1	Mono 1/4" plug/cable assy	Mouser 172-3101
1	Aluminum box	Mouser 537-M00-P
1	Terminal strip	Mouser 534-817
2	#4 solder lug	Mouser 534-7325
1	N connector, male bulkhead	Mouser 523-172118
1	BN-43-202	Dan's Small Parts BLN43-202
1-ft	#26 enamel wire	All Electronics MW-26-4
Miscl	4-40 & 2-56 screws, lockwashers, nuts - and double-sided tape from local hardware store	

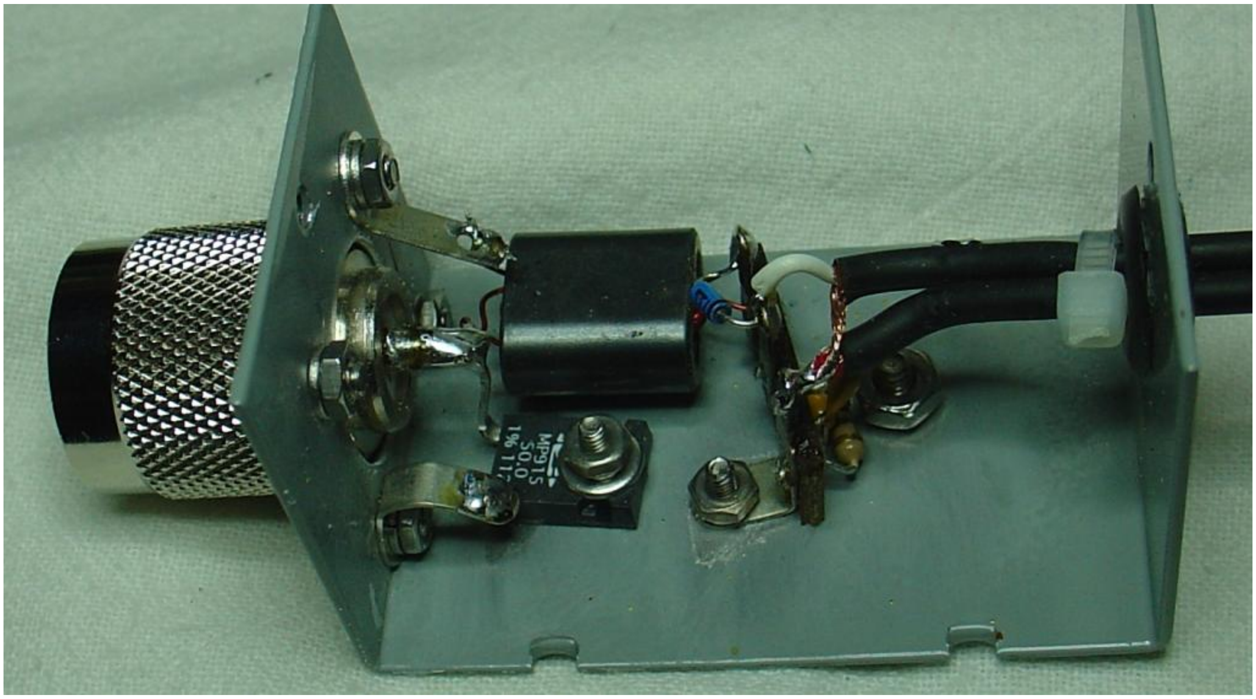

Figure 5: Internal detector wiring. The transformer ground is on the upper solder lug, the 5-turn tap solders to the connector center pin, and the 5-1/2 turn output solders to the diode anode.

Next I compared the PowerMaster detector power reading to a NIST-traceable MiniCircuits PWR-6GHS+ (accurate to within $\pm$3%) from 160-2 meters. My test set-up is as shown in Figure 6. The ZAPD splitter and 20dB attenuator were cal'd against the PWR-6GHS+ power sensor. The PowerMaster trim value was set to 0%. I also recorded the detected voltage so this information can be used in the Meterbuilder MB-1 sensor set-up.

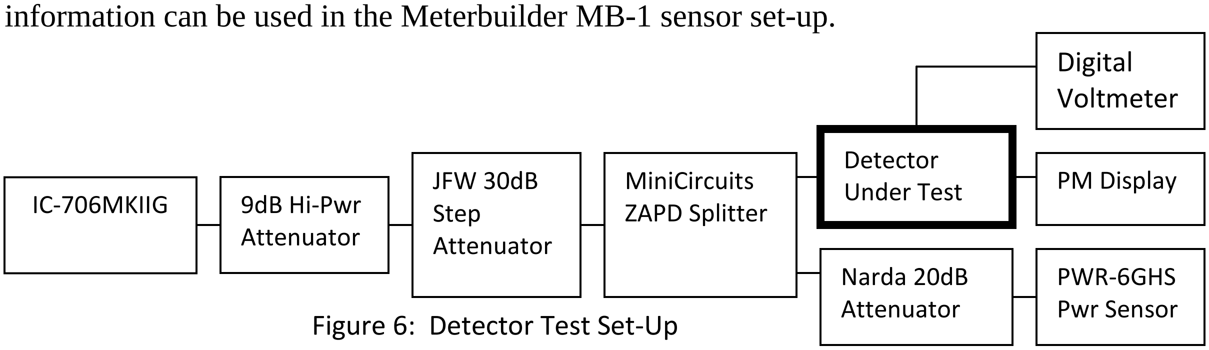

Figure 6: Detector Test Set-Up

The measured results are shown in Table 2. As you can see, the PowerMaster readings are quite accurate down to 10-milliwatts from 160-6 meters. Frankly, I was surprised by the accuracy on 2-meters. Below 10-milliwatts you can see the accuracy beginning to suffer due to the proximity of the detected voltage to the detector diode junction voltage. However, the measurements are still reasonably accurate even at 1-milliwatt. For those who own the Meterbuilder MB-1, the accuracy can be much better. This is because the MB-1 has a relatively large number of calibration points at low power levels. These calibration points can be assigned on a per-band basis thus handling detector diode nonlinearities better at low power levels. See www.meterbuilder.com/mb1/interfacing-couplers.html for MB-1 coupler calibration details.

Table 2: Detector Voltages vs. PowerMaster Readings

	160M	20M	10M	6M	2M
MC Pwr	Det/PM/Error	Det/PM/Error	Det/PM/Error	Det/PM/Error	Det/PM/Error
2000mw	15.05/1960/-2%	15.11/1980/-1%	15.25/2000/0%	15.37/2040/+2%	16.11/2240/+12%
1000mw	10.54/971/-3%	10.62/990/-1%	10.75/1000/0%	10.77/1017/+2%	11.3/1120/+12%
500mw	7.35/483/-3%	7.46/500/0%	7.46/500/0%	7.60/510/+2%	7.97/562/+12%
100mw	3.16/96/-4%	3.22/100/0%	3.23/100/0%	3.27/102/+2%	3.33/111/+11%
50mw	2.17/48/-4%	2.18/48.5/-3%	2.21/49.5/-1%	2.23/50.3/+1%	2.36/55.5/+11%
10mw	0.854/9.2/-8%	0.870/9.4/-6%	0.871/9.62/-4%	0.888/9.85/-2%	0.91/10.8/+8%
1mw	0.163/0.86/-14%	0.169/0.88/-12%	0.17/0.90/-10%	0.17/0.92/-8%	0.19/1.05/+5%

Note that the detector voltage occurs after the transformer, so it should be the calculated peak voltage multiplied by 1.1, minus the 1N5711 junction voltage (0.225VDC). Theoretically at 100mw, $V_{pk} = 1.1\sqrt{(0.1x100)} - 0.225 = 3.25$VDC. As you can see in Table 2, the measured voltage is quite close to the calculated value.

Most hams don’t have access to precision equipment. However, as my measured data corresponds closely to the calculated values, I believe that calibration is unnecesary. I.e., detectors built as described should be very consistant with my measured data. Trim is necessary for the Array Solutions coupler because the coupler has a very high primary/secondary turns ratio. Therefore, any small variation in the secondary winding pitch and distance to the primary can have some impact on the total coupling. This is not the case with the milliwatt detector. The auto-transformer has very few turns, the primary and secondary share the same winding, and there is a very small primary/secondary turns ratio.

To try to verify this hypothesis, I built a second auto-transformer with a core purchased from www.CWSbytemark.com. I spot checked 14-, 28-, and 50-MHz at 10mw and 500mw and found no measurable differences from my original measurements. I then substituted a 1N5711 obtained from a Chinese source on eBay and again found no measurable differences. Of course this is a tiny sample, but the conclusion feels right.

However, there is a way to check the detector accuracy. A constant DC voltage applied to the RF input will look just like the peak voltage of an RF signal. Connect the coupler to the PowerMaster display with the trim value set to zero. Disconnect the auto transformer ground as this is a DC short. Connect a 1.5V battery from the RF input to ground and record the PowerMaster reading. Now measure the actual battery voltage with an accurate digital volt meter, multiply it by 29 (the PowerMaster coupler turns ratio) and then calculate the equivalent peak power. Remember that the auto-transformer will not give any boost to a DC signal.

As an example, I connected a 1.5V battery to the detector RF connector. The measured DC voltage was 1.58V. The expected PowerMaster peak RF voltage would ideally be 1.58 X 29 = 45.82V, and so the PowerMaster should read $45.82^2/(2x50) = 20.99$ watts. The PowerMaster actually read 21.4 watts, or 2% high – very close to the expected reading.

Now if the 1.58V peak input was a real RF signal, the actual power would be $1.58^2/100 = 25$mw. The PowerMaster should read 25 watts as the watt reading correlates directly to milliwatts with this detector design. Since the autotransformer gives a 21% increase in power reading to an RF signal, the 21.4 watt reading would read 25.9 watts, or 3% high. This is still very close to what is expected. When finished, don't forget to re-connect the auto-transformer ground!

The final unit is shown in Figure 7. I labeled the detector using Casio "Black on Clear" 9mm labeling tape.

Figure 7: Completed Milliwatt Sensor. Only a mono plug/cable is necessary (see text).

<u>Final Comments</u>

The PowerMaster does not read power above 3000 watts, which corresponds to 3000 milliwatts with this detector. To measue power above 3-watts use an external 10dB attenuator, or use the original PowerMaster 3000 watt coupler.

Also, exceeding about 10 watts into the detector can damage the detector diode. The 1N5711 70-volt reverse breakdown rating corresponds to the maximum permissible peak-to-peak level of the signal being measured. 70Vpp = 35Vpk = 24.75Vrms, so the maximum applied power is:

$P = V^2/R = 24.75^2/50 = 12.25$ watts.

However, in this application the diode is connected to the secondary of a 5:5.5 turn autotransformer. Therefore we must reduce the limit on the input voltage by 10%. I.e., 63.6 V across 5-turns yields 70 V across 5.5-turns. This gives a maximum power of

$P = V^2/R = 22.48^2/50 = 10.11$ watts.

Even when measuring QRP power levels with a turned-down 100-watt transceiver the detector breakdown voltage may be exceeded if the transceiver has significant overshoot. As an example, my IC-706MKII overshoots to 140 watts regardless of the output power setting. So even when it is set to minimum power (about 3-watts), the output overshoot can burn out the detector diode. I know - I've done it! Fortunately, 1N5711 diodes are very inexpensive.

Conclusion

Experimenters often need a means of measuring very low RF power levels. The detector described provides an accurate, inexpensive and broad-band milliwatt measuring capability for those who own an Array Solutions PowerMaster or Meterbuilder MB-1. The same design approach may be applicable to other digital power meters that employ an external coupler.