A Home-Made UHF/SHF Power Meter

by O. Frosinn, DF 7 QF

A power meter is to be described that operates according to the bolometer principle, and can be constructed with simple components and tools. The most important characteristics are:

- **The calibration canbemade with a DC-voltage**
- **The meter continues to use its linear scale**
- **Usable in the frequency range from DC to several GHz**
- **3 measuring ranges (full scale): 10 mW / 100 mW / 500 mW**
- **Accuracy: ± 0.5 dB**

The only disadvantages are that the measuring and cooling phase require several minutes, and that suitable attenuators will be required to measure higher power levels.

METHODS OF RF POWER MEASUREMENTS

The normal way of measuring RF-power is to rectify the RF-voltage across the consumer impedance, or a part of it, and to indicate the resulting DC-voltage. **Figures 1 and 2** show the principle of this in the form of diagrams: Home-construction is also possible, but the difficulties increase with the frequency. In the case of absolute-value indication, it is necessary for the power meters to be calibrated by comparing them to professional power meters.

Instead of measuring the DC-voltage after rectification, it is possible to measure the heating of a terminating resistor by the RF-power. Such circuits are shown in **Figures 3 and 4**, and the two interconnected circles represent a thermal coupling.

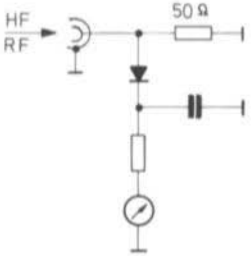

Fig. 1:
Direct RF-voltage measurement at the load resistor

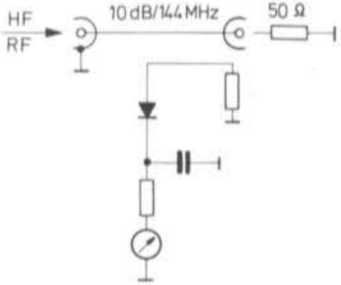

Fig. 2:
RF-voltage measurement using a directional coupler

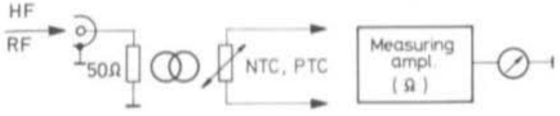

Fig. 3:
Heat measurement at the load resistor using a temperature-dependent resistor

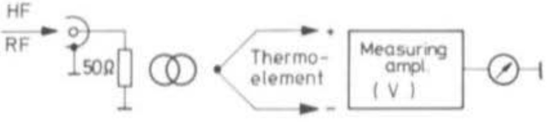

Fig. 4:
Heat measurement at the load resistor using a thermo-element

The heat generated in the 50 Ω resistor also heats a temperature-dependent resistor or thermo-element. This variation in the secondary circuit is evaluated, which means that the power effective in the primary circuit can be indicated. It is completely immaterial whether the electric energy used for heating is a DC-voltage, or alternating voltage, or whether it is a low-frequency or a high-frequency voltage. This allows the meter to be calibrated with the aid of a DC-power.

Measuring errors result due to the difference between the impedance of the terminating resistor and interconnection cable, in other words from too low a return loss, or too high a standing-wave-ratio. However, when the SWR remains below a value of 2, this error will be less than 0.5 dB, and usually negligible for amateur applications. These values can be taken from **Table 1**, which is given in more detail since it is not readily available to all radio amateurs.

In order to complete this section, it should be noted that all four methods of measuring power are used in commercially available power meters: Through-line and dummy-load wattmeters suchasthose from »Bird« operate according to Figures 1 and 2. Power meters manufactured by Siemens and HP usually operate according to the principle shown in Figures 3 and 4. For amateur applications, virtually only wattmeters operating according to principle 1 and 2 are available; their accuracy is very often unsatisfactory even on the specified frequency range. Outside of this range,itis always necessary for a recalibration to be made, which usually means that an extra scale must be made on the meter. Another problem with this type of measuring equipment is that the measuring diode is usually destroyed at high RF-power levels. If an absolutely identical diode is not available, it will then usually be necessary to make a new alignment, and redrawing of the scales.

THE BOLOMETER

The construction details of a reflectometer in (1) led the author to design a bolometer (heat meter) as the heart of a very-accurate power meter, which was usable from DC-voltage to several GHz. As can be seen in Figure 3, the power meter consists of three main modules:

- Terminating resistor (50 Ω)
- Temperature probe
- Measuring-amplifier with readout

The construction of these is now to be described.

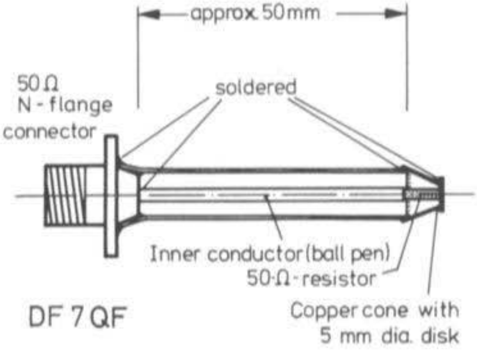

Fig. 5:
Coaxial terminating resistor onto which the temperature probe is mounted

THE TERMINATING RESISTOR

Since the temperature probe is in the form of a Wheatstone bridge, one requires two terminating resistors that should be as identical as possible. The construction is described in **Fig. 5** and should be made as carefully as possible, since the specifications are mainly dependent on it. After completion, the matching (VSWR or return loss) should be measured at the highest possible frequency. The best one is then used as measuring resistor, and the other as compensating resistor. The values obtained by the author are given in curve A of **Figure 6**; for comparison, curve B shows the VSWR-run of a 50 Ω terminating resistor manufactured by HP.

It is now necessary to obtain two suitable resistors. In order to ensure that low powers can also be measured, it is necessary to use a mechanically small version (providing sufficient heat at low power levels); of course, this also limits the rating towards higher power levels. The author used metal oxide resistors manufactured by Draloric, type MLAD 0309/ 50 Ω. These resistors do not possess helical windings and are rated at 62.5 mW. However, the measuring resistor has been loaded up to 500 mW in the described circuit for more than three years, and even overloaded up to several Watts for short periods. No deterioration has been noted. If other resistors are used, it may be necessary for the mechanical dimensions of the inner and outer conductors to be changed in order to compensate for the jumps in diameter.

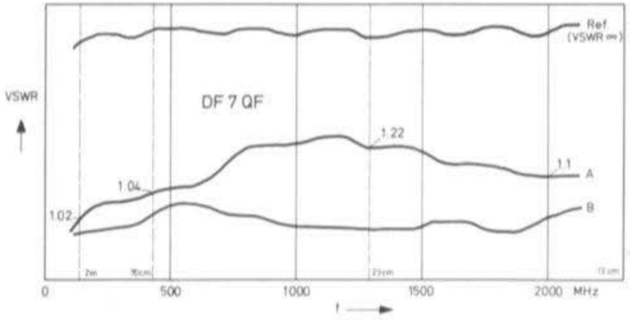

Fig. 6:
Matching of the terminating resistor shown in Fig. 5 between 100 and 2300 MHz

Return loss a_r/dB	Reflection factor r	Matching factor m	Voltage standing wave ratio s	Attenuation due to mismatch a/dB
0,1	0,988	0,006	173,368	16,42
0,2	0,977	0,011	86,835	13,46
0,4	0,957	0,022	45,436	10,74
0,6	0,933	0,034	28,971	8,89
0,8	0,912	0,046	21,725	7,74
1,0	0,891	0,058	17,349	6,86
1,5	0,841	0,086	11,578	5,35
2,0	0,794	0,115	8,709	4,32
2,5	0,750	0,143	6,997	3,59
3,0	0,708	0,171	5,842	3,02
3,5	0,668	0,199	5,024	2,57
4,0	0,631	0,226	4,442	2,20
4,5	0,595	0,254	3,933	1,90
5,0	0,562	0,280	3,571	1,65
5,5	0,531	0,306	3,263	1,45
6,0	0,501	0,332	3,012	1,25
6,5	0,473	0,358	2,793	1,10
7,0	0,447	0,382	2,618	0,97
7,5	0,422	0,406	2,463	0,85
8,0	0,398	0,431	2,320	0,75
8,5	0,373	0,453	2,203	0,66
9,0	0,355	0,476	2,101	0,58
9,5	0,335	0,498	2,008	0,51
10,0	0,316	0,520	1,923	0,45
10,5	0,298	0,541	1,848	0,40
11,0	0,282	0,561	1,780	0,36
11,5	0,266	0,579	1,726	0,32
12,0	0,252	0,598	1,671	0,28
12,5	0,237	0,618	1,618	0,25
13,0	0,224	0,634	1,578	0,22
13,5	0,211	0,650	1,538	0,20
14,0	0,199	0,668	1,497	0,17
14,5	0,183	0,684	1,462	0,15
15,0	0,178	0,699	1,480	0,13
15,5	0,165	0,716	1,396	
16,0	0,158	0,727	1,374	0,11
16,5	0,150	0,740	1,350	
17,0	0,141	0,752	1,329	0,09
17,5	0,133	0,766	1,304	
18,0	0,126	0,777	1,285	0,07
18,5	0,119	0,789	1,268	
19,0	0,112	0,799	1,251	0,05
19,5	0,106	0,809	1,235	
20,0	0,100	0,819	1,220	0,04
20,5	0,094	0,828	1,208	
21,0	0,089	0,887	1,193	
21,5	0,084	0,846	1,180	

Return loss a_r/dB	Reflection factor r	Matching factor m	Voltage standing wave ratio s	Attenuation due to mismatch a/dB
22,0	0,079	0,853	1,171	0,03
22,5	0,075	0,861	1,160	
23,0	0,071	0,868	1,151	
23,5	0,067	0,857	1,142	
24,0	0,063	0,882	1,133	0,02
24,5	0,060	0,888	1,124	
25,0	0,057	0,894	1,118	
25,5	0,053	0,900	1,111	
26,0	0,050	0,904	1,105	0,01
26,5	0,047	0,909	1,100	
27,0	0,045	0,914	1,094	
27,5	0,042	0,919	1,088	
28,0	0,040	0,924	1,082	
28,5	0,038	0,928	1,078	
29,0	0,035	0,932	1,073	
29,5	0,034	0,934	1,069	
30,0	0,032	0,938	1,064	
30,5	0,030	0,942	1,060	
31,0	0,028	0,945	1,056	
31,5	0,027	0,947	1,054	
32,0	0,025	0,951	1,051	
32,5	0,024	0,953	1,048	
33,0	0,022	0,956	1,045	
33,5	0,021	0,958	1,043	
34,0	0,020	0,961	1,040	
34,5	0,019	0,963	1,038	
35,0	0,018	0,965	1,036	
35,5	0,017	0,967	1,034	
36,0	0,016	0,969	1,032	
36,5	0,015	0,971	1,030	
37,0	0,014	0,972	1,028	
37,5	0,013	0,974	1,027	
38,0	0,013	0,975	1,025	
38,5	0,012	0,976	1,024	
39,0	0,011	0,973	1,022	
39,5	0,011	0,979	1,021	
40,0	0,010	0,980	1,020	

Table 1:
Four different ways to look at mismatch;
Last column: Attenuation caused by mismatch

CONSTRUCTION OF THE TERMINATING RESISTORS

As can be seen in Figure 5, the terminating resistor is constructed in conjunction with an N-flange connector. The inner conductor of this connector is lengthened using a metal tube (from a ball pen) which also has a diameter of 1/8 inch. The outer conductor is made from a thin brass plate by winding this around a 7.5 mm diameter drill, after which it is soldered. This arrangement results in an impedance of approximately 51 Ω ($Z = 138 \log D/d$).

The lacquer at the ends of the resistor is carefully removed after which the connection wires are soldered out, since they are only 1 mm from each other in the ceramic body of the resistor. It is now possible for the resistor to be soldered onto the tinned inner-conductor tube.

The outer conductor should be cut at one end, bent out in the form of a cone, and soldered to the flange of the connector as shown in Fig. 5.

The other end of the outer conductor is cut to the same length as the inner conductor so that the resistor now protrudes.

This is followed by making a suitable cone from 0.1 to 0.2 mm thick copper foil which is then soldered to the outer conductor. The narrow end is finally soldered quickly to the resistor and a small copper disk of 5 mm diameter. The temperature probe is glued to this disk afterwards with a quick-drying glue.

Both terminating resistors are now mounted onto a thick aluminium front panel so that the connectors are accessible from the front, with a spacing of several cm from another. A heat-insulating casing should be constructed, which is placed around both terminating resistors. This can be made from aluminium plates onto which styrene foam has been glued. This ensures that no short-term temperature fluctuations will have an effect on the measurement.

TEMPERATURE PROBE

The temperature probe circuit given in **Fig. 7** is in the form of a Wheatstone bridge. Nothing is connected to input »K«; this resistor with temperature probe maintains the bridge balance during slow variations of the ambient temperature. If, on the other hand, power is provided to connector »M«, the terminating resistor will heat the PTC-resistor, which unbalances the bridge. A voltage is generated between connections A and B, which is evaluated and indicated.

A silicon temperature sensor with a high positive temperature coefficient (PTC-resistor) has been found successful as temperature probe. Experiments with NTC-resistors and with diodes, on the other hand, were not satisfactory. Such a probe is found in the Siemens product range as type KTY 10, with four different tolerances of the nominal resistance of 2000 Ω: KTY 10 A: ± 1%; .....B: ± 2%; .....C: ± 5%; ..... D: ± 10%. All four classes are suitable; however, the alignment is easiest when using themore expensive,low-tolerance types A, or B. By the way, the external shape is in the form of a plastic case similar to TO 92.

Due to their low temperature coefficients, metal oxide resistors are used in the bridge circuit (2 x 2 kΩ, 1 x 100 Ω, and 1 x 20 Ω). The 500 Ω potentiometer is a ten-turn helical trimmer potentiometer, and the 100 Ω potentiometer is a carbon potentiometer with linear characteristic. This potentiometer can be operated on the front panel. The two 2 kΩ resistors are coupled together thermally using a strip of copper foil.

The construction of the bridge circuit is made according to Figure 7 on the rear of the heat insulating case of the two terminating resistors, and is not in the form of a PC-board. The voltage stabilizer 7806, however, must be mounted so that it does not heat this case and the bridge circuit.

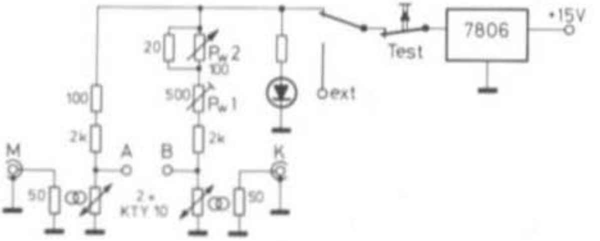

Fig. 7:
A Wheatstone-bridge as temperature-probe circuit

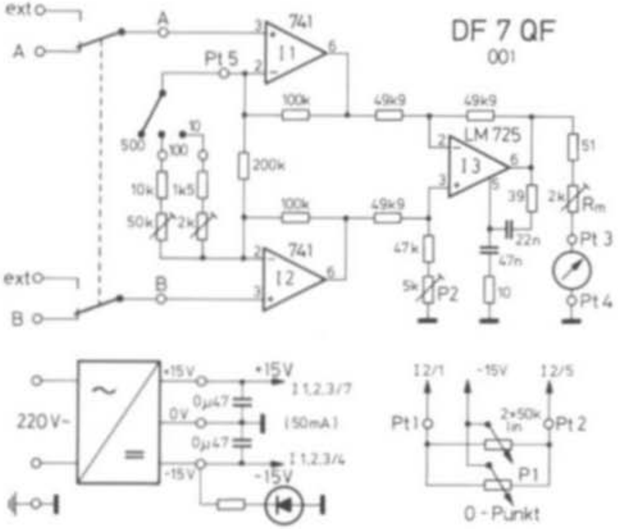

Fig. 8:
The evaluation circuit of the bridge voltage, including power supply

MEASURING AMPLIFIER

As can be seen in **Figure 8**, three integrated amplifiers are connected together in such a manner that the common-mode suppression at P 2 is brought to values of over 100 dB. The gain is determined by only one resistor, and both inputs have approximately the same impedance.

If type 741 is used as integrated amplifier, Pin 5 of I 3 may not be connected. The given frequency response compensation need only be provided when a LM 725 is used for I 3.

A 80 mm x 70 mm PC-board was designed for accommodating the amplifier circuit as shown in Figure 8 (without small power supply), which is shown in **Figure 9**. Sockets are provided for the operational amplifiers. The PC-board is soldered into an RF-tight case, and all connections are made with the aid of feed-through capacitors.

All lines are screened, and the power supply is also screened in an RF-tight manner, since it was found that the amplifiers could be effected by spurious RFvoltages. An abrupt deflection of the meter during a measurement will show that an unwanted RF-voltage is being rectified somewhere and indicated. If this is noticed, the screening should be checked and the leads bypassed in a more efficient manner.

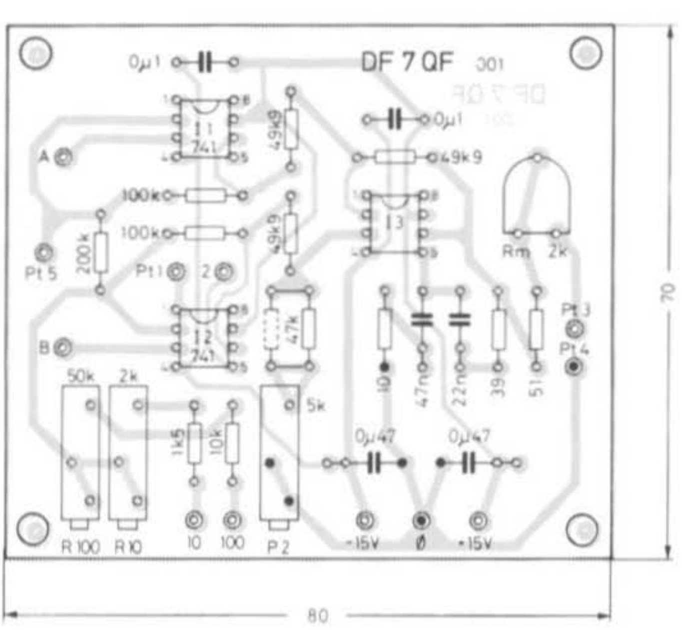

Fig. 9: Component locations on the single-coated PC-board for the evaluation circuit

ALIGNMENT

Resistor R_m is set to its maximum value, potentiomters P 1 and P 2 set to a center position, and the range switch set to position 500 mW. Connections A and B are connected together and to ground. The »Test«-switch is placed in the »open« position, after which the power supply of ± 15 V (approximately 50 mA) is switched on.

The needle of the meter is now set to zero with the aid of P 1. Close the test switch and align the indication once again to zero with the aid of P 2. This optimization of the common-mode suppression is repeated and improved in the 100 mW and 10 mW ranges.

The short-circuit and the ground connection of points A and B are now removed, after which they are connected to A and B of the bridge circuit. The test switch is closed in the 500 mW range, and the meter-reading set to zero with the aid of P_W 1. Potentiometer P_W 2 is in its center position, and is only used for fine alignment during practical operation . This bridge alignment is also made in the 100 mW and 10 mW ranges, whereby the amplifier is set to zero with P 1, with the »Test«-switch open.

The range switch now is set to 500 mW, and 5 V DC-voltage connected to the measuring input M. The meter needle starts to move slowly. When the power across the 50 Ω resistor amounts to 500 mW according to Ohm's Law, this value should also be indicated. After a period of several minutes when the needle stops moving, it should be adjusted to read 500 with the aid of R_m. The large time constant is the disadvantage of this measuring principle.

After allowing several minutes for cooling, the 100 mW full scale can be adjusted with R 100 (spindle trimmer), and the 10 mW full scale with the aid of R 10. The required voltage U can be calculated according to Ohm's Law:

$$U = \sqrt{P \times R}$$

This results in the following values:

100 mW: U = 2.236 V
10 mW: U = 0.71 V

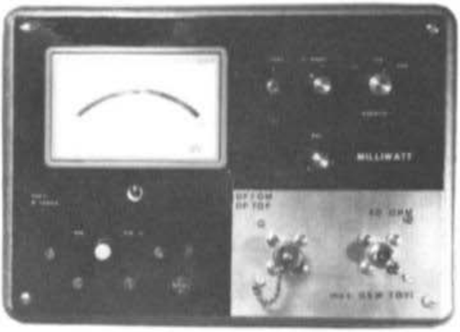

Fig. 10:
The author's prototype

Fig. 11:
Inside are 3 screened modules and a meter

It is advisable for the whole alignment to be repeated several hours later. If everything is stable and working correctly, it is now possible for the power meter to be installed in a case.

FINAL NOTES

Before every measurement, the wattmeters should be allowed to »warm up«. After this, the zero alignment should be made with the aid of P 1 with the »Test«-switch open, which is then followed by balancing the bridge with the switch closed with the aid of P_w2.

As can be seen, the measuring accuracy is mainly dependent on the accuracy of the DC-voltage used for calibration, on the accuracy of the 50 Ω resistor up to the highest possible frequencies, on the linearity of the PTC-resistor, and on the accuracy of the meter. However, this should not stop you constructing this power meter even if you do not have access to high-precision laboratory measuring equipment. A good meter, and a good (borrowed) multimeter – or better a digital multimeter – for calibration will allow you to construct a valuable power meter that can be used also for microwave measurements !

The author is also experimenting with a measuring and compensating resistor that can be connected to the »external« input. This is even more simple to construct, and seems to allow measurements even in the 3 cm band.

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