Aspects of Calibration – Power Splitters and Detector Linearity

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1. Introduction.

This paper describes the calibration and possible estimated measurement uncertainty of rf power splitters/dividers and describes a technique for measuring the linearity of diode power sensors or mixers. The paper is in two parts, dealing with power splitters first.

2. Part 1. Resistive RF Power Splitters

Resistive rf power splitters are three port devices, having an input port and two output ports. There are two types, the two resistor splitter or three resistor power divider. They look physically similar but are used for different purposes and it is most important to identify them correctly.

Diagram 1.

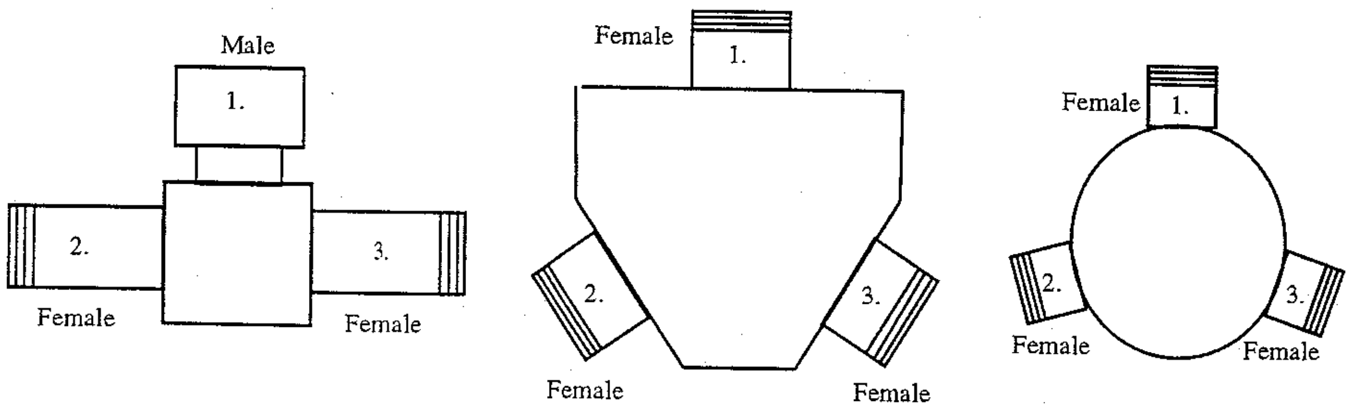
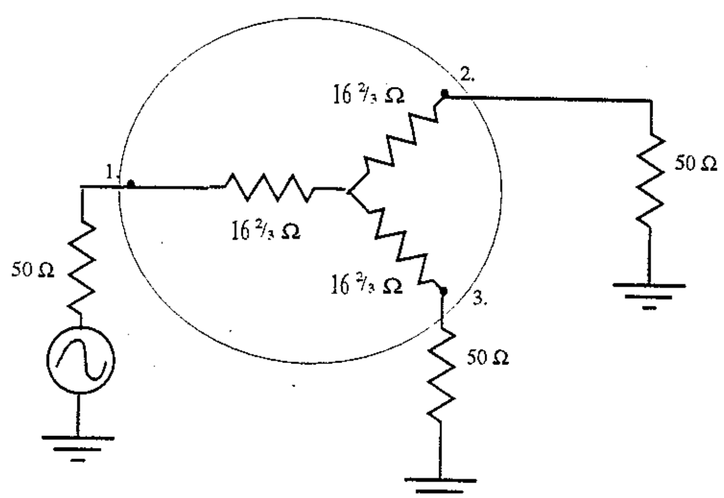


Diagram 1. shows the general appearance of these devices. The resistors are formed upon a substrate which is housed within the body of the splitter. These resistors are carefully matched for frequency response (phase and magnitude), over a wide frequency range, typically dc to 18, 26.5, 40 or 50 GHz dependant upon the connector used. The devices are low power, typically 0.5 watts cw, with a temperature coefficient of < 0.005 dB/watt.

3. The Three Resistor RF Power Splitter (Power Divider)

Diagram 2.

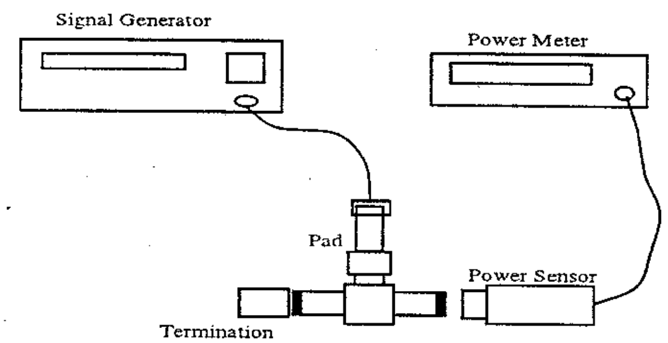


The three resistor *power divider* shown in diagram 2. contains three matched resistors of $16^2/_3$ Ω each. With any two ports terminated in 50 Ω, the impedance measured at the third port will be 50 Ω. This device may be used for dividing power to two antennas, or tracking a reference signal in a laboratory, ie. calibrating a counter or receiver sensitivity by connecting the signal source to one port, a reference power meter to another port and the device under test to the third port.

This power divider may not be used for precision measurements however as the tracking between ports may be ± 0.5 dB at 18 GHz and the reflection coefficient 0.15 at 18 GHz, with ± 2^o nominal phase tracking. Any power reflected back into a port will be seen at the remaining ports (though attenuated by the 6 dB typical insertion loss between ports), and may be re–reflected. If the complex transmission and reflection coefficients of the power divider were known, together with those presented to the ports, then the power at each port could be calculated – not a very practical job though.

When calibrating this power divider the important parameters to be measured are, tracking between ports and reflection coefficient at each port. Tracking is calibrated by comparing the measured insertion loss from port to port in a 50 Ω system. This may be accomplished using a signal generator and power meter. Inevitably adaptors will have to be used where the divider input and output connectors are of the same sex, and this will increase the measurement uncertainty. The reflection coefficient at each port may be measured using a SWR Bridge.

Diagram 3.



4. Typical uncertainty budget for measurements up to 18 GHz

Insertion loss

a. Power meter instrumentation	± 0.005 dB
b. Power meter resolution	± 0.03 dB
c. Adaptor	± half the measured adaptor pair insertion loss
d. Repeatability	Nominally ± 0.02 dB at 18 GHz using good type 'N' connectors, but must be properly assessed using multiple measurements

e. Mismatch uncertainty :

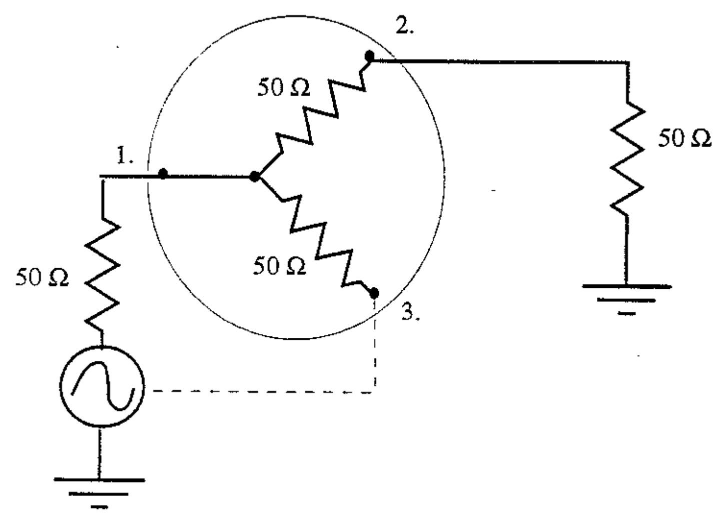
$$\frac{1 \pm \{|\Gamma G S11| + |\Gamma L S22| + |\Gamma G \Gamma L S11 S22| + |\Gamma G \Gamma L S12 S21|\}}{1 -/+ |\Gamma G \Gamma L|} \qquad *1.$$

where: ΓG is the reflection coefficient of the pad on the signal generator
ΓL is the reflection coefficient of the power sensor
S11 and S22 are the reflection coefficients of the divider input and output port
S12 and S21 are the transmission coefficients between the measured ports

Reflection coefficient

Bridge Directivity	± 0.02
Bridge Test Port Match	± 0.005

5. The Two Resistor RF Power Splitter
Diagram 4.



The two resistor power splitter is constructed to have a 50 Ω resistor in series between port 1 and port 2, and an identical resistor between port 1 and port 3. It is only ever used in a generator levelling circuit configuration as in diagram 4, and must never be used as a power divider in a 50 Ω system. (If you connect a 50 Ω termination to port 1. and port 2. then the impedance seen at port 3. is approximately 83.33 Ω)!

This power splitter has been specifically designed to level the power from a signal source and to improve the generator source match. In diagram 4, if a detector is connected to port 3. and the output of the detector is compared with a stable reference and then connected to the signal generator amplitude control via a high gain amplifier (levelling loop), then any change in the generator output at port 1. is seen across the 50 Ω series resistors and detected at port 3. This change is used to correct the generator output for a constant level at port 3 . As port 2 is connected to port 1. by an identical resistor, port 2 is also held level.

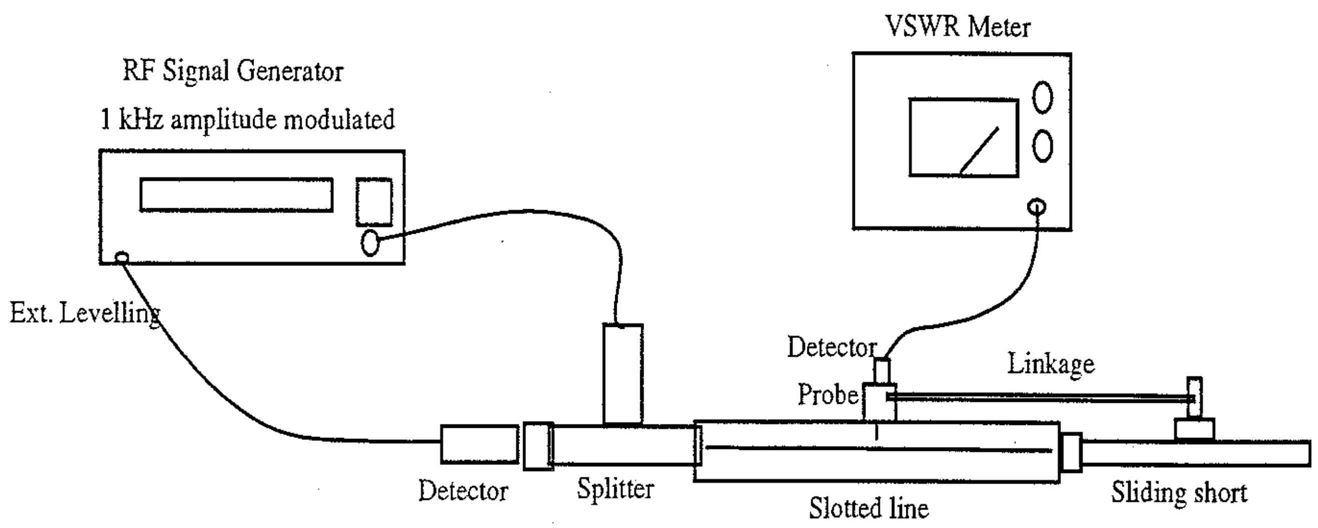
If an imperfect termination is connected to port 2 then voltage will be reflected back into port 2 at some phase. This voltage will be seen across the 50 Ω resistor and the generator internal impedance. If the generator internal impedance is imperfect then some of the voltage will be re– reflected by the generator, causing a change in level at port 1. This change in level is detected at port 3 and used to correct the generator to maintain a constant output level at the junction of the two resistors. Port 1 can be perceived as a virtual earth, thus when the levelling circuit is active, the impedance measured at port 2. will effectively be the impedance of the 50 Ω series resistor.

Two resistor splitters are characterised in terms of output tracking and equivalent output reflection coefficient. A typical specification for a splitter fitted with type 'N' connectors would be ± 0.2 dB tracking between ports at 18 GHz, and an effective reflection coefficient of ± 0.025 to ± 0.075 from dc to 18 GHz. The splitter has a nominal insertion loss of 6 dB between the input and output ports.

There are a number of ways that a two resistor splitter may be calibrated, but in truth, no single method is available to fully characterise this device.

6. Calibration Method 1.

Diagram 5.



A simple way to determine the effective source match of the splitter is to connect it into an active levelling loop as in diagram 5. The slotted line and sliding short circuit are mechanically linked so that the separation between them remains constant as the probe is moved, The probe detects the voltage standing wave due to interaction between the signal reflected by the short circuit and the re–reflected by the effective source match.

The same effect can be achieved by using a modified sliding short, (or sliding known high reflection), fitted with a detector. The modulus of the equivalent source reflection coefficient is found from the ratio of maximum to minimum reading as the position of the detector is varied. The phase angle is found from the position corresponding to the minimum.

From diagram 5. the major contributions to the measurement uncertainty are due to the slotted line reflection coefficient and slope (insertion loss), linearity of the levelling detector, gain of the sweeper levelling loop and resolution of the vswr meter.

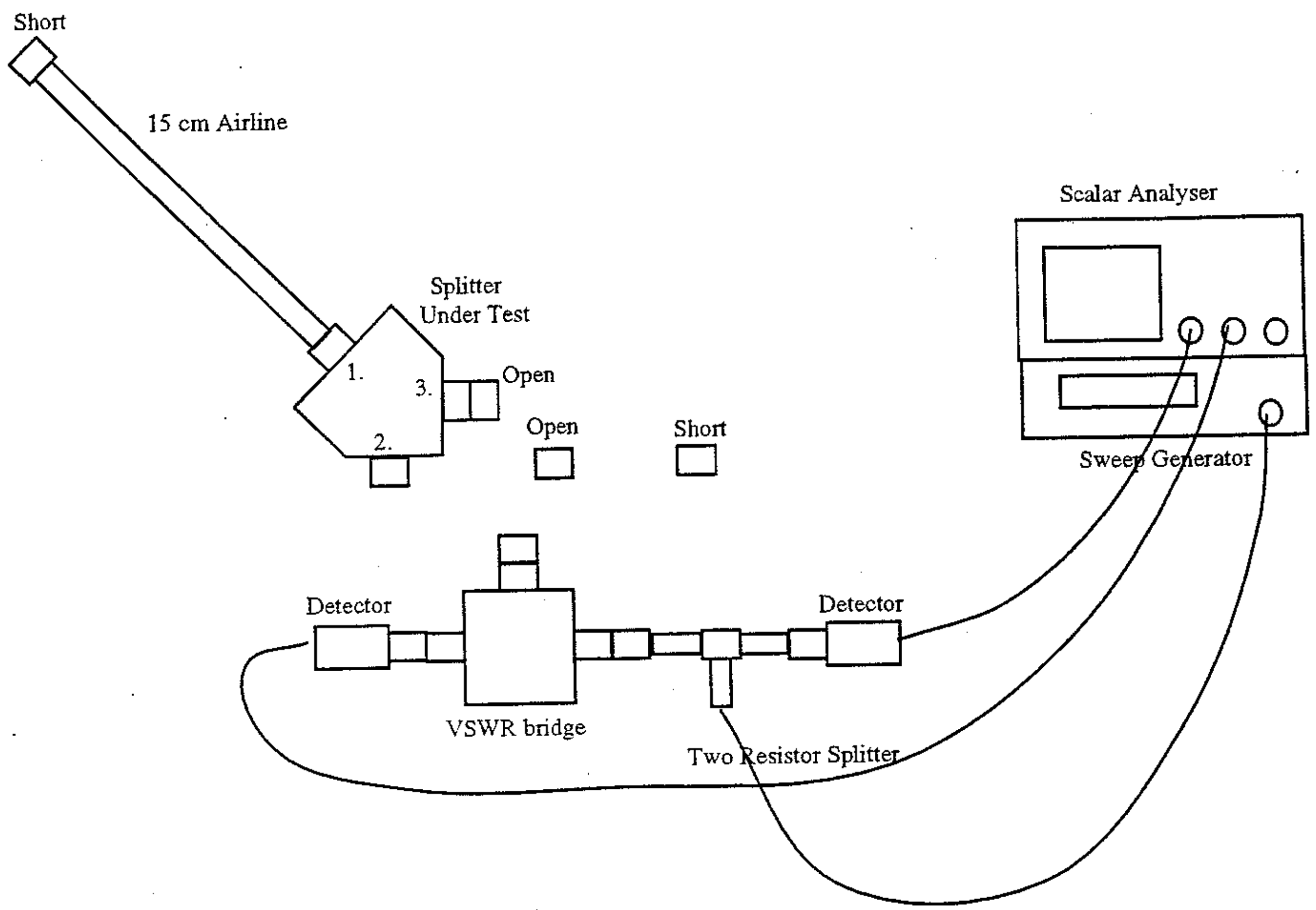
This method is limited by the frequency range of the slotted line and sliding short/termination. It is possible that the generator levelling circuits are unable to cope with a short/open circuit connected to the rf output of the splitter. If this is the case then the sliding short may be replaced by a sliding termination having a known high reflection coefficient.

7. Calibration Method 2.

See diagram 6. This method involves using a SWR bridge to measure the return loss of the series resistors inside the splitter. The measurement system is normalised for open and short on the bridge test port and then, with port 2. of the splitter connected to the bridge, the frequency is swept from 2 GHz to 18.5 GHz. As the frequency changes, the short circuit will eventually appear at port 1 where the two resistors are joined. The analyser displays a ripple pattern where the troughs of the ripple correspond to the return loss of the series 50 Ω resistor.

At each trough, the bridge is removed from port 2. and connected to port 3. and the return loss at port 3. noted for exactly the same frequency. If the two resistors were identical then the measured return loss would be the same for both ports. In practice, the worst case of the two measurements is used to determine the effective source reflection coefficient.

Diagram 6.



8. Typical Measurement Uncertainty Budget 2 GHz to 18 GHz

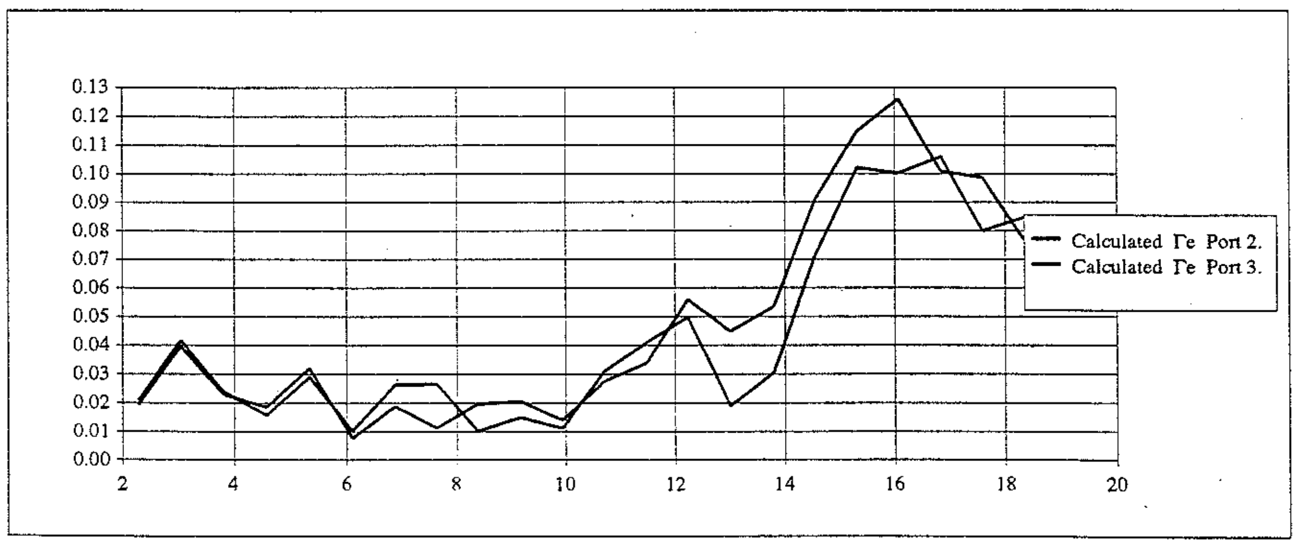
a. Bridge directivity and test port match	± 0.020
b. Detector linearity and scalar analyser resolution	±0.005
c. Signal Purity	±0.005

Note.
The unused port of the splitter is shielded using an open circuit, (I am not sure of the effect that this open line has on the measurement). The input to the SWR bridge is levelled using a two resistor splitter to improve the source match to the bridge.

Port 1. of the splitter, which is connected to the airline and short circuit, is not actually within the levelling circuit when the splitter is used for active levelling. It cannot, however, be excluded from the results of this calibration method.

9. Typical Calibration Results Using method 2.

Frequency GHz	Measured Return Loss Port 2. dB	Measured Return Loss Port 3. dB	Calculated Γe Port 2.	Calculated Γe Port 3.	Measurement Uncertainty ±
2.2922	33.66	34.31	0.0207	0.0193	0.015
3.0475	27.61	28.07	0.0416	0.0395	0.016
3.8171	32.42	32.78	0.0239	0.0230	0.016
4.5796	36.11	34.65	0.0156	0.0185	0.016
5.3444	30.77	29.89	0.0289	0.0320	0.017
6.1045	39.78	42.29	0.0103	0.0077	0.017
6.8765	31.61	34.52	0.0263	0.0188	0.018
7.6366	31.50	39.00	0.0266	0.0112	0.019
8.3848	39.89	34.13	0.0101	0.0197	0.019
9.1686	36.49	33.75	0.0150	0.0205	0.019
9.9525	39.04	37.06	0.0112	0.0140	0.020
10.7126	30.20	31.24	0.0309	0.0274	0.020
11.4917	27.74	29.40	0.0410	0.0339	0.021
12.2328	26.06	25.04	0.0498	0.0560	0.021
13.0024	34.45	26.96	0.0189	0.0449	0.022
13.8005	30.33	25.45	0.0304	0.0534	0.023
14.5558	22.92	20.81	0.0714	0.0911	0.023
15.3254	19.82	18.80	0.1021	0.1148	0.023
16.0736	19.99	17.99	0.1001	0.1260	0.024
16.8432	19.50	19.93	0.1059	0.1008	0.024
17.5914	21.93	20.11	0.0801	0.0987	0.025
18.3417	21.43	22.29	0.0848	0.0768	0.025



10. Calibration Method 3.

Method 3. involves measurement of the splitter scattering parameters and calculating the effective port reflection coefficient Γe.

Diagram 7.

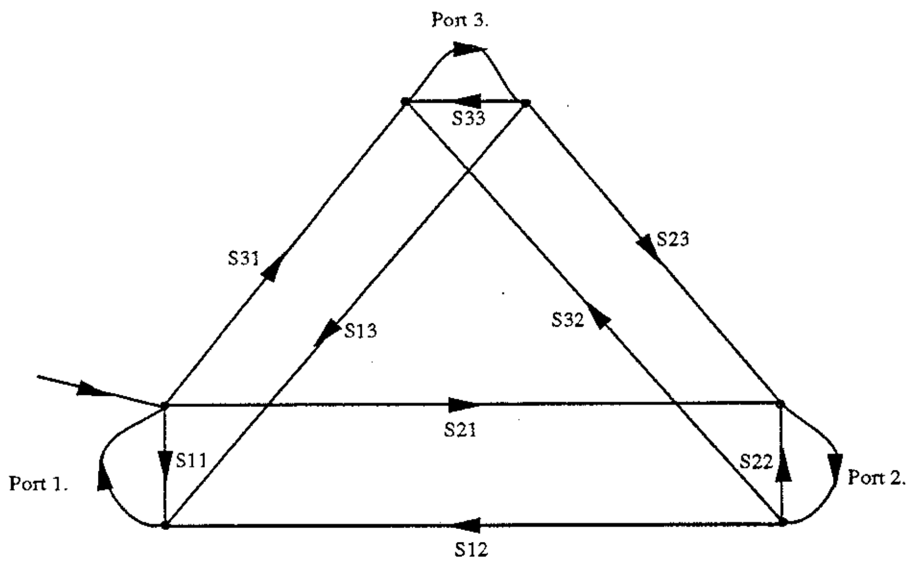


Diagram 7. is the flow graph representation of a three port device. It has been shown * [2,3] that for a coupler or splitter, the effective reflection coefficient may be calculated using:

Γe	= S22 – S21 X (S32 / S31)	for port 2.
Γe	= S33 – S31 X (S23 / S21	for port 3.

For the effective reflection coefficient at port 2. the measurement process involves:

a. Measure attenuation between port 1 and port 2 and convert to transmission coefficient (S21)
b, Measure attenuation between port 2 and port 3 and convert to transmission coefficient (S32)
c. Measure attenuation between port 1 and port 3 and convert to transmission coefficient (S31)
d. Measure the reflection coefficient at port 2. (S22)

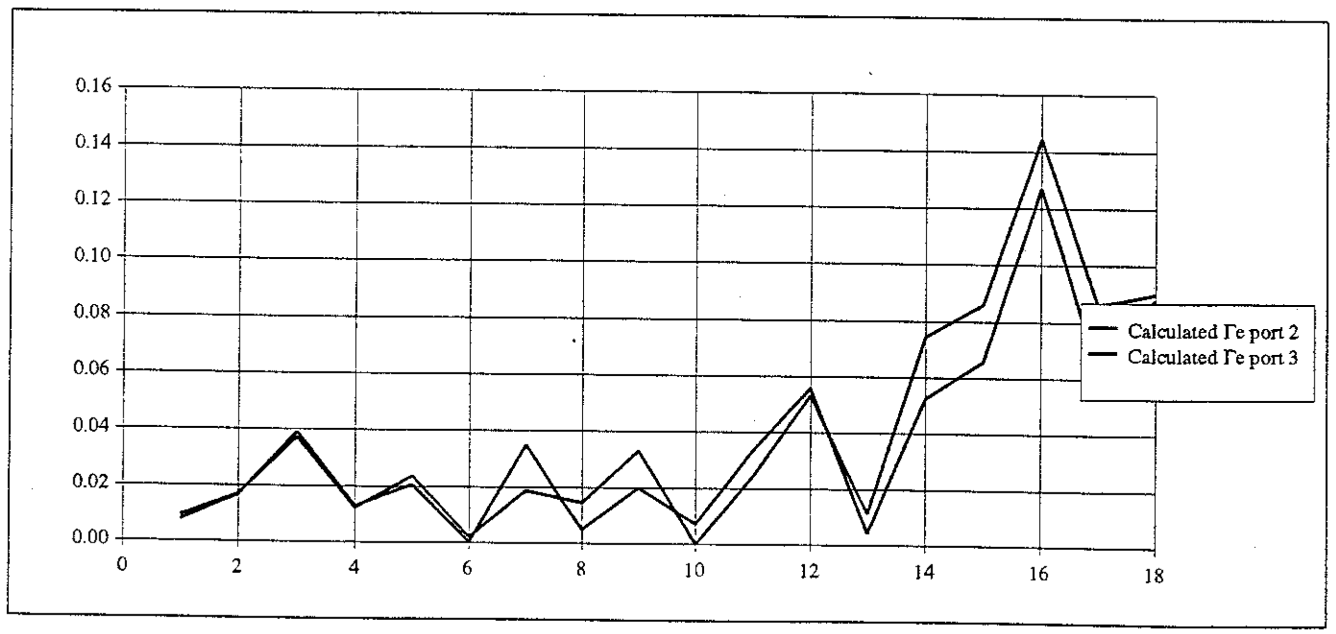
Note. All unused ports are terminated in 50 Ω

Measurement of attenuation ratio may be made using a power meter and well matched power sensor as shown in diagram 3. S12, S21, S13 and S31 are nominally 6 dB and S23 and S32 nominally 12 dB. The reflection coefficients S22 and S33 are typically 0.25, and may be measured using an SWR bridge as in diagram 6.

A typical uncertainty budget for measurements up to 18 GHz is essentially the same as in para. 4. for the three resistor power divider. The sensitivity of these contributions on the overall measurement uncertainty for Γe may be determined by partial differentiation or by changing one of the input variables while keeping all other inputs constant, and noting the changed uncertainty output * [4]

11. Typical Calibration Results using method 3

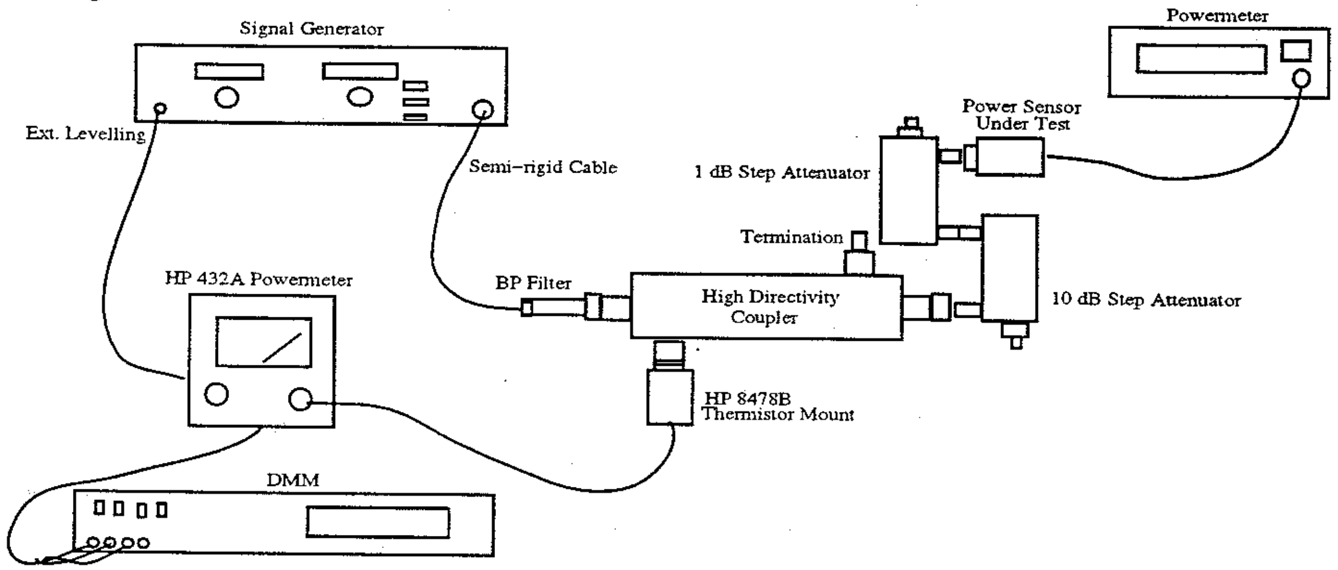
Frequency GHz	VRC (S22) Port 2.	VRC (S33) Port 3.	Atten. (S21, S12) 1 to 2 dB	Atten. (S32, S23) 2 to 3 dB	Atten. (S31, S13) 1 to 3 dB	Calculated Γe port 2	Calculated Γe port 3
1	0.254	0.255	6.100	12.182	6.110	0.0077	0.0093
2	0.256	0.256	6.303	12.426	6.307	0.0167	0.0169
3	0.279	0.277	6.289	12.406	6.290	0.0393	0.0373
4	0.247	0.246	6.349	12.622	6.355	0.0130	0.0123
5	0.255	0.257	6.373	12.627	6.392	0.0208	0.0238
6	0.236	0.234	6.341	12.544	6.335	0.0002	0.0021
7	0.267	0.251	6.463	12.688	6.457	0.0351	0.0188
8	0.240	0.221	6.486	12.568	6.477	0.0050	0.0145
9	0.218	0.205	6.177	12.463	6.172	0.0200	0.0333
10	0.249	0.242	6.355	12.327	6.350	0.0072	0.0000
11	0.270	0.262	6.574	12.504	6.551	0.0336	0.0243
12	0.284	0.282	6.481	12.828	6.469	0.0560	0.0533
13	0.218	0.234	6.600	13.054	6.596	0.0044	0.0114
14	0.277	0.303	6.603	12.901	6.525	0.0526	0.0745
15	0.279	0.299	6.919	13.426	6.925	0.0657	0.0860
16	0.335	0.353	6.845	13.635	6.832	0.1272	0.1446
17	0.258	0.282	7.134	14.181	7.105	0.0632	0.0859
18	0.282	0.286	6.818	14.203	6.775	0.0880	0.0901



12. Part 2. Calibration of Detector Linearity

This paper describes a simple but accurate method of calibrating the linearity (departure from square law), of a detector or mixer. It is a variation of the technique described at 22nd ARMMS Conference 1995 and BEMC 1995.

Diagram 8.



The calibration technique involves applying a precise and repeatable 5 dB step, at various levels, to the power sensor or detector under test. If the signal generator is externally levelled from the power meter recorder output, as in diagram 8. then switching to a consecutive range, say 3 mW to 1 mW, produces a nominal but highly repeatable 5 dB step. * [5] The power level applied to the device under test is adjusted using the step attenuators, such that the 5 dB step is applied over the instrument's operating range.

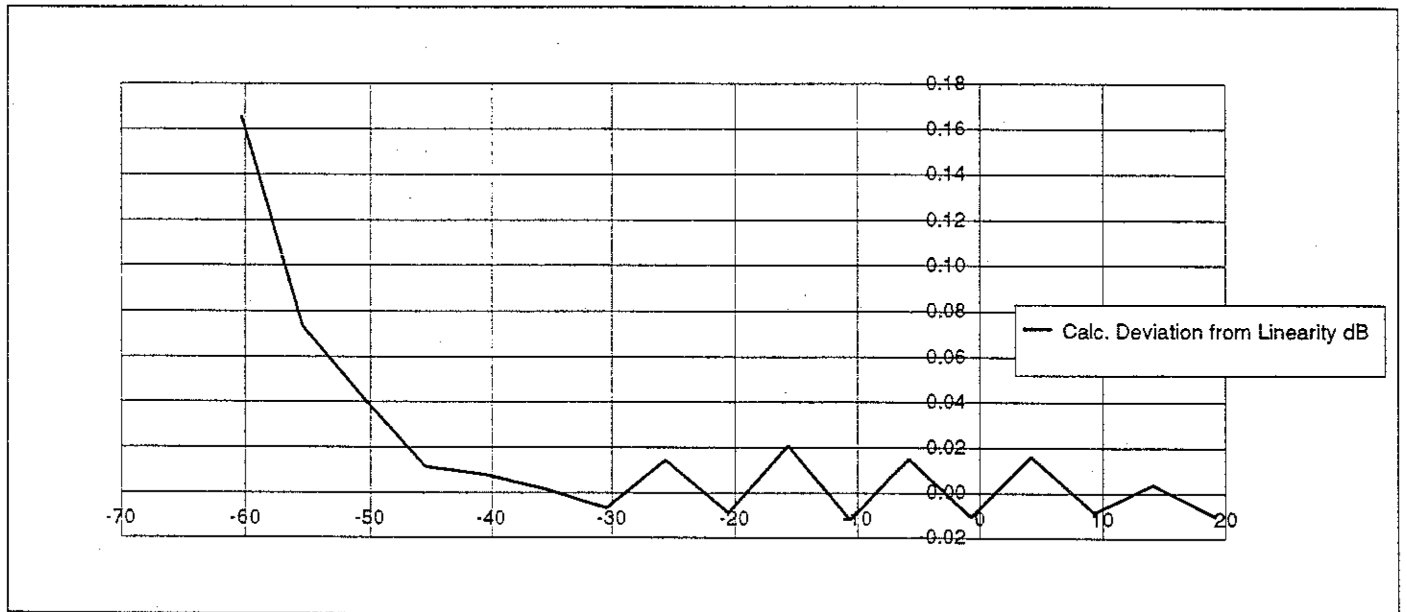
Note. Measurements are best made starting with minimum power applied to the DUT and increasing the power to a maximum. If the system is to be automated using a GPIB controller, then the signal generator output must be switched, and the step measured using the HP432A power meter bridge output voltages v0, v1, vcomp.

13. Measurement uncertainty budget

Repeatability of 5 dB step	±0.0005 dB * [6]
Measurement repeatability	±0.01 dB nominal, but should be determined by multiple measurements.
Drift	Determined by experiment and dependant upon power meter range.
Leakage	Effect is dependant upon step attenuator setting * [7]
Mismatch	Effective source match Γe remains constant for the 5dB step. Any change in load (DUT) impedance is seen as contributing to the measured non–linearity.

14. Typical diode power sensor linearity calibration results

Switched Atten. Setting dB	DUT rdg. HP432 3 mW	DUT rdg. HP432 1 mW	DUT rdg. HP432 3 mW	DUT rdg. HP432 1 mW	DUT rdg. HP432 3 mW	DUT rdg. HP432 1 mW	Calc. step run 1 dB	Calc. step run 2 dB	Calc. step run 3 dB	average of runs dB	Type A Uncert. dB	Calc. Deviation from Linearity dB
80.0	−60.278	−65.317	−60.491	−65.702	−60.381	−65.406	5.039	5.211	5.025	5.092	0.060	0.166
75.0	−55.412	−60.320	−55.467	−60.516	−55.450	−60.491	4.908	5.049	5.041	4.999	0.046	0.073
70.0	−50.329	−55.267	−50.340	−55.294	−50.311	−55.318	4.938	4.954	5.007	4.966	0.021	0.040
65.0	−45.506	−50.434	−45.503	−50.434	−45.470	−50.423	4.928	4.931	4.953	4.937	0.008	0.011
60.0	−40.419	−45.361	−40.409	−45.345	−40.370	−45.293	4.942	4.936	4.923	4.934	0.006	0.008
55.0	−35.522	−40.461	−35.522	−40.448	−35.482	−40.399	4.939	4.926	4.917	4.927	0.006	0.001
50.0	−30.444	−35.373	−30.438	−35.359	−30.407	−35.314	4.929	4.921	4.907	4.919	0.006	−0.007
45.0	−25.598	−30.550	−25.593	−30.537	−25.575	−30.500	4.952	4.944	4.925	4.940	0.008	0.014
40.0	−20.518	−25.441	−20.512	−25.426	−20.498	−25.412	4.923	4.914	4.914	4.917	0.003	−0.009
35.0	−15.684	−20.640	−15.677	−20.624	−15.679	−20.616	4.956	4.947	4.937	4.947	0.005	0.021
30.0	−10.607	−15.528	−10.598	−15.510	−10.604	−15.513	4.921	4.912	4.909	4.914	0.004	−0.012
25.0	−5.782	−10.730	−5.779	−10.716	−5.786	−10.724	4.948	4.937	4.938	4.941	0.004	0.015
20.0	−0.704	−5.625	−0.699	−5.611	−0.706	−5.619	4.921	4.912	4.913	4.915	0.003	−0.011
15.0	4.199	−0.751	4.205	−0.737	4.186	−0.748	4.950	4.942	4.934	4.942	0.005	0.016
10.0	9.289	4.366	9.294	4.379	9.272	4.358	4.923	4.915	4.914	4.917	0.003	−0.009
5.0	14.102	9.166	14.107	9.176	14.071	9.149	4.936	4.931	4.922	4.930	0.004	0.004
0.0	19.192	14.276	19.198	14.286	19.160	14.241	4.916	4.912	4.919	4.916	0.002	−0.010



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