Principle of the reflectometer

As demonstrated in Experiment 10, incident and reflected waves can be separated with the aid of a directional coupler (here specifically the cross directional coupler). Thus the directional waveguide coupler constitutes an important component in the measurement of reflection coefficients. This special measuring technique is called reflectometry as opposed to the reflection coefficient measurement using the slotted measuring line. The greatest advantages over the slotted measuring line method are; one, it takes considerably less time to conduct the measurement and two, it can be used in automatic sweep measurements.

Various measurement principles of reflectometry

(1) Use of only one coupling guide and comparing the result with reflection at the short

In the measurement configuration according to Fig.11.1, port 4 remains terminated reflection-free throughout the entire measurement procedure. Thus, reflection-free termination can be an integral part of the directional coupler in the practical design of a reflectometer. The wave travelling via the feed-through guide from port 1 to port 2 (weakening of the amplitude by $\sqrt{1-k^2}$) is reflected at the measurement object with the unknown reflection coefficient r. A portion of the wave incidenting port 2 with the amplitude:

$$|\underline{a}_2| = |\underline{r}| \cdot |\underline{b}_2| = |\underline{r}| \cdot \sqrt{1-k^2} \cdot |\underline{a}_1| \tag{11.1}$$

is transmitted to port 3 via the coupling guide so that the magnitude of the wave exiting at port 3 is given by:

$$|\underline{b}_3| = k \cdot |\underline{a}_2| = k \cdot \sqrt{1-k^2} \cdot |\underline{r}| \cdot |\underline{a}_1| \tag{11.2}$$

The coupling coefficient k of the directional coupler is known in advance, but not the amplitude $|a_1|$ of the wave incidenting at port 1. For that reason this measurement only suffices to determine $|r|$. Thus a reference measurement is performed with a short ($r = -1$) at port 2. For this you obtain from Eq. (11.2)

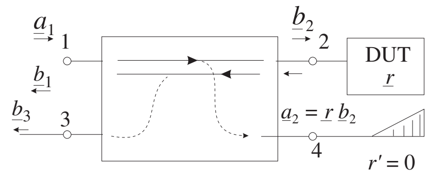

Fig. 11.1 Measurement configuration 1

$$|\tilde{\underline{b}}_3| = k\sqrt{1-k^2} \cdot |\underline{a}_1| \tag{11.3}$$

and consequently by forming the ratio we obtain the desired magnitude of the reflection coefficient

$$\frac{|\underline{b}_3|}{|\tilde{\underline{b}}_3|} = |\underline{r}| \tag{11.4}$$

However, the Equation (11.4) only applies under the assumptions made above; i.e.

(α) Ideal directional coupler with infinitely high directivity and free of reflection at its ports.

(ß) The wave b_1 exiting port 1 is not reflected by the circuit connected at port 1.

If condition (ß) is violated, we have a situation (due to multiple reflection) where in the reference measurement with short circuit, the wave entering port 1 is different from the wave entering port 1 in the measurement of the device under test (DUT). Under the assumption that an ideal directional coupler is present, a precise mathematical analysis supplies the equation

$$\frac{|\underline{b}_3|}{|\tilde{\underline{b}}_3|} = |\underline{r}| \cdot \left| \frac{1+\sqrt{1-k^2} \cdot \underline{r}_G \cdot e^{j\psi}}{1-\sqrt{1-k^2} \cdot \underline{r}_G \cdot e^{j\psi}} \right| \tag{11.5}$$

instead of Eq. (11.4). Here r_G is that reflection coefficient which is present for wave b_1 leaving port 1. It can be seen from equation (11.5) that $|r_G|$ must be kept as small as possible to avoid measurement errors. This can be accomplished by, for example, connecting an isolator or an attenuator with $a \approx 10$ dB in series. If it is assumed that $r_G = 0$ but the directivity factor is finite – as in the case of all real waveguide couplers, then using equation (11.4) we obtain a maximum error of

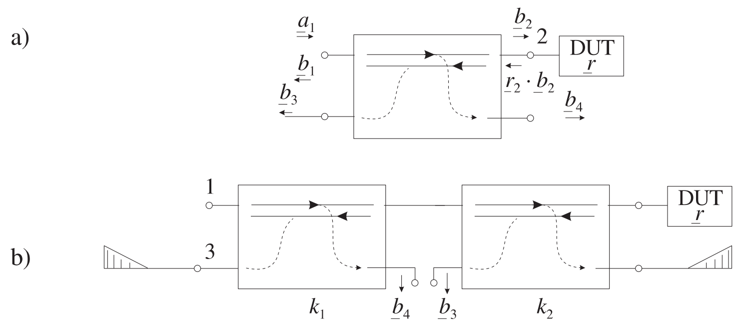

Fig. 11.2: Measurement configuration 2
a) Measurement with a directional coupler
b) Measurement with two directional couplers

$$\varepsilon \overset{\text{def}}{=} \left(\frac{|\underline{b}_3|}{|\tilde{\underline{b}}_3|} - |\underline{r}| \right)_{\max} \approx 10^{-\frac{a_D}{20}} \qquad (11.6)$$

which for a directivity of $a_D = 60$ dB is smaller than 0.001, but at a directivity of only 20 dB amounts to approx. 0.1.

(2) Utilizing two coupling paths

In the measurement configuration according to Fig. 11.2 a) with one directional coupler, the waves exiting from port 3 and port 4 are measured and their amplitudes compared. The following holds true for ideal directional couplers:

$$|b_4| = k \cdot |a_1|$$

and

$$|\underline{b}_3| = k \cdot \sqrt{1-k^2} \cdot |\underline{r}| \cdot |\underline{a}_1|$$

and thus

$$\frac{|\underline{b}_3|}{|\underline{b}_4|} = \sqrt{1-k^2} \cdot |\underline{r}| \qquad (11.7)$$

Since k is unknown, Eq. (11.7) can serve to determine $|r|$. In this procedure a reference measurement with a short is not needed and a reflecting circuit ($r_G \neq 0$) does not create any fault source (as $|a_1|$ is the same for the measurement of $|b_3|$ and $|b_4|$). In the case of less than ideal directional couplers the use of Eq.(11.7) also leads to errors in the determination of $|r|$. When using two separate directional couplers in the configuration according to Fig. 11.2 b) coupling errors have less of an impact on the final result (naturally the coupling coefficients of the two directional couplers must be known).

(3) Prospects for more modern measurement methods of reflectometry

In the previous investigations it was assumed that only the magnitudes of the waves exiting ports 3 or 4 could be measured and that furthermore only the magnitude of r could be determined. Nevertheless, not only the amplitudes but also the phases of the waves can be compared as, for example, in the configuration according to Fig. 11.2.

For this you can use a so-called network analyzer, which is a special kind of dual channel receiver, in which the signals in both channels are converted to a lower frequency range while maintaining their amplitudes and phase relationships. This frequency conversion can be carried out with mixing or sampling. In the low frequency range the amplitudes and phase relationships of the signals can be determined by electronic means. One of the great advantages of using the network analyser is the possibility of correcting errors arising from components with less than ideal characteristics (e.g. finite directivity of directional couplers) in the measurement circuit. For this several calibration measurements are first conducted on known components and the results entered into a computer. Since the “faulty” characteristics of the measurement circuit are also contained in the results of the calibration measurements, they can be corrected using suitable algorithms.

Required equipment

1 Basic unit	737 021
1 Gunn oscillator	737 01
1 Diaphragm with slit 2 x 15 mm, 90°	737 22

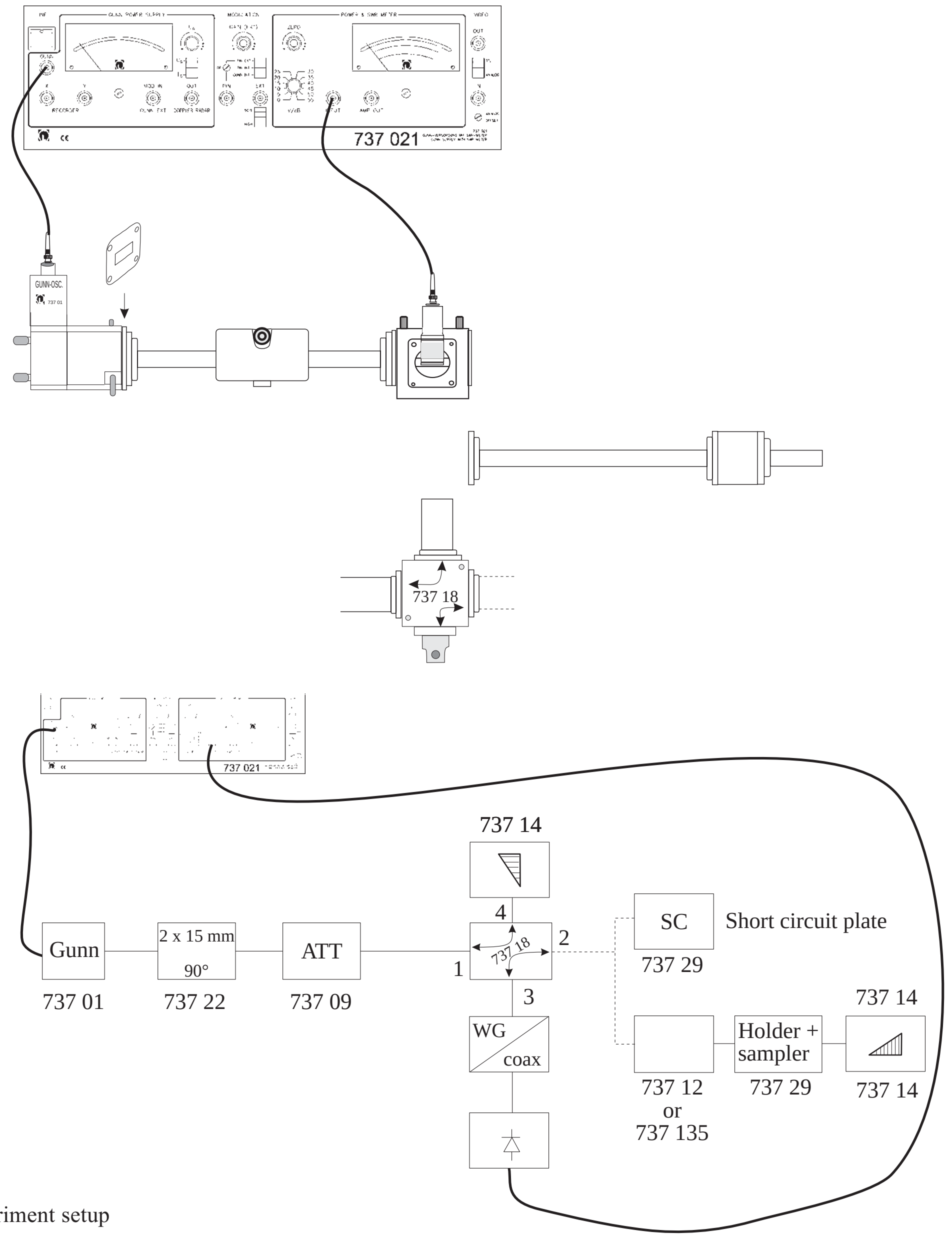

Fig. 11.3 Experiment setup

1 Variable attenuator	737 09
1 Cross directional coupler	737 18
1 Transition waveguide/coax	737 035
1 Coax detector	737 03
1 Waveguide termination	737 14
2 Sets of thumb screws (12 each)	737 399

For the assembly of the measurement object or DUT the following is required:

1 Sample holder	737 29
1 Absorbing material sample (graphite)	737 29
1 Waveguide termination	737 14
1 Waveguide 200 mm	737 12
or	
3 screw transformer (*)	737 135

Additionally required equipment

2 Coax cables with BNC/BNC plugs, 2 m	501 022
3 Stand bases	301 21
3 Supports for waveguide	737 15

(*) : The 3-screw transformer serves only as an intermediate piece to permit attachment. For this all screws must be set to a penetration depth of 0. In this case the thumb screw requirement is reduced to 8 each (1 set).

2 Stand rods 0.25 m 301 26

Recommended:

1 PIN modulator 737 05
1 Isolator 737 06

Experiment procedure

Note:
When using the isolator and PIN modulator the experiment setup specified in Fig. 11.3 must be changed in accordance with the preface!

1. *Set up a reflection-free one port as the device under test, DUT).*

1.1 In Experiment 6 the reflection coefficient of a DUT was determined using the slotted measuring line. Use the same DUT to permit a comparison of the reflectometer measurement with the slotted measuring line measurement. In accordance with Fig. 11.4 use the sample holder ①, the absorbing graphite sample ② and a reflection-free waveguide termination ③ for set up of the DUT.

2. *Measurement of the reflection coefficient using only one coupling path and comparison with reflection at the short-circuit plate.*

2.1 Set up the measurement circuit as specified in Fig. 11.3. Use the coupling plate with 2 cross-shaped holes in the cross coupler.
Note:
The attenuator set to approx. 10 dB should be used to reduce the reflection coefficient for waves propagating out of port 1 and reflected backwards to the microwave source. Port 4 is terminated reflection-free and the measurement head (transition waveguide/coax with coax detector) is connected to port 3.

2.2 Calibration measurement with short-circuit plate.
For this attach the short-circuit plate to port 2. After the power supply voltages have been switched on, calibrate the display of the SWR meter (port 3) to 0 dB using the “ZERO” control knob. (Set the modulation to Gunn-Int., U_G to 8 V)

2.3 Replace the short-circuit plate with the DUT. Read off the display ***a*** (port 3) in dB ($a < 0$).

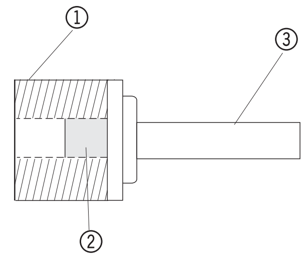

Fig. 11.4: Assembly of the device under test (DUT)
① Sample holder
② Graphite sample
③ Waveguide termination

According to Eq. (11.4) a represents the reflection coefficient in dB, i.e.:

$$a / \text{dB} = 20 \log |r|.$$

Calculate $|r|$ and enter the value into Table 11.1.

3. *Measurement of the reflection coefficient when using 2 coupling paths*

3.1 The DUT remains connected to port 2.

3.2 First terminate port 3 reflection-free by replacing the measurement head (transition waveguide/coax to the coax detector) with the reflection-free waveguide termination. Attach the measurement head to port 4. Set the display ***a*** of the SWR meter (port 4) to a value of 0 dB using the “ZERO” control knob and keep this setting steady.

3.3 Reverse the connection configuration of ports 3 and 4, i.e. connect reflection-free termination to port 3. Read display a of the SWR meter off in dB ($a < 0$). According to Eq. (11.7) the following applies:

$$a/\text{dB} = 10 \log (1 - k^2) + 20 \log |r| \approx 20 \log |r|$$

Enter the values determined for |r| in Table 11.1.

Table 11.1

	a/dB	$\lvert r \rvert$
Experiment point 2		
Experiment point 3		

Questions

1. Compare all the values determined for |r| to each other and with the results from Experiment 6 (measurement principle with slotted measuring line).
2. Compute the ratio of $|b_4| / |b_3|$ from the configuration in Fig. 11.2 b). The coupling coefficients are k_1 and k_2. What is the ratio for the special case $k_1 = k_2 = k$?

The cavity resonator

Fundamentals

First of all a completely enclosed cavity resonator is considered with (theoretically) an ideally conductive metallic surface. In this resonator unattenuated electromagnetic oscillations can exist at discrete frequencies (= resonance frequencies). Fig.12.1 shows the TE_{101} resonance in a rectangular waveguide resonator with the frequency:

$$\frac{f_0}{\text{GHz}} = 15 \cdot \sqrt{\frac{1}{\left(\frac{a}{\text{cm}}\right)^2} + \frac{1}{\left(\frac{l}{\text{cm}}\right)^2}} \qquad (12.1)$$

Due to the losses in the metallic walls of real resonators, natural oscillations are attenuated. One measure for attenuation in a cavity resonator is its unloaded Q value:

$$Q_0 = \frac{\omega_0 \cdot W}{P_V} \qquad (12.2)$$

Here W is the stored energy, $\omega_0 = 2\,\pi\,f_0$ is the (angular) resonance frequency and P_V is the power dissipation. Fig. 12.1 shows the electromagnetic field in the cavity resonator at various points in time ($T = 1/f_0$). In order to couple a resonator to a microwave circuit, you can use a diaphragm with aperture, for example, as illustrated in Fig. 12.3a. Fig. 12.3b shows the corresponding waveguide equivalent circuit diagram in which the resonator is represented by a short-circuited waveguide and the diaphragm with aperture by a shunt inductance $j\omega L = jX$. Fig. 12.4 shows Z_0/X as a function of the relationship of the aperture diameter d to the waveguide width a (22.86 mm). If you mathematically convert the parallel connection of the resistance Z_0 and jX into a series connection, the result is an equivalent circuit diagram for $X << Z_0$ as specified in Fig. 12.2.

In accordance with the transformation ratio:

$$n = \frac{Z_0}{X} \qquad (12.3)$$

the resistance Z_0 is transformed to lower resistance $Z'_0 = Z_0/n^2$. Thus, the diaphragm with aperture can also be understood as a transformer. If we suppose that the reactance jX is taken (or ignored)

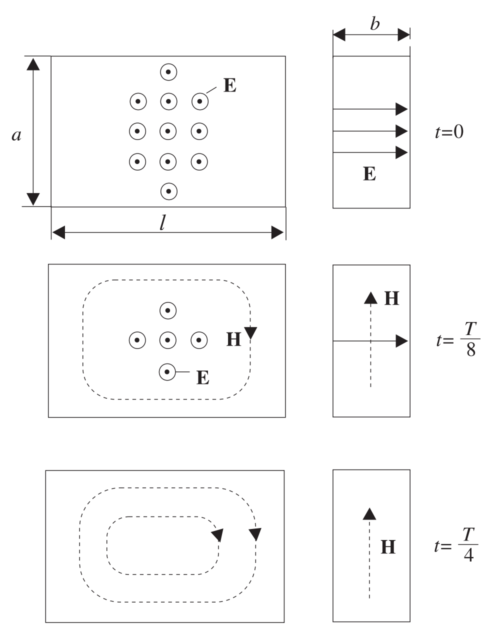

Fig. 12.1: TE_{101} resonance in a rectangular cavity resonator

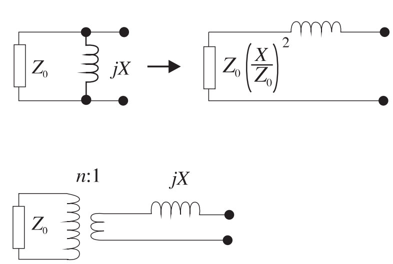

Fig. 12.2: Series equivalent circuit diagram for resonators with coupling diaphragm

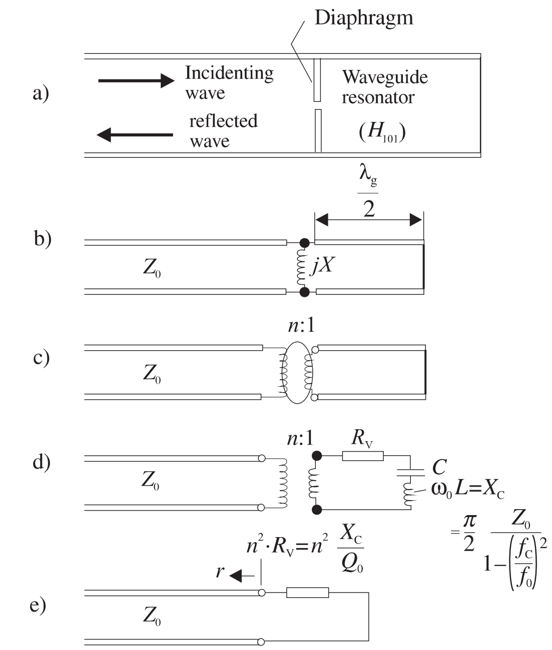

Fig. 12.3: Development of an equivalent circuit diagram for the cavity resonator coupled via a diaphram with aperture

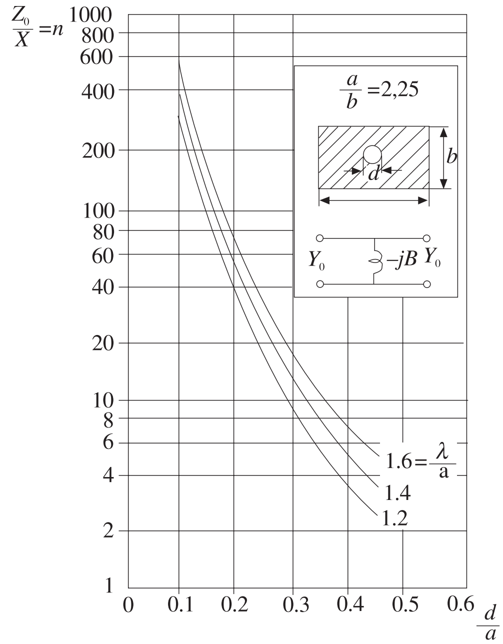

Fig. 12.4: Normalized transformation ratio for the coupling diaphragm Z_0/X. λ corresponds here to the free-space wavelength λ_0

together with the waveguide, we obtain the equivalent circuit depicted in Fig. 12.3 c). At approximately the resonance (angular) frequency $2\pi f_0$ the $\lambda_g/2$ long waveguide can be designed by a resonance circuit with:

$$\frac{1}{2\pi \cdot f_0} = \frac{1}{\sqrt{L \cdot C}}$$

$$L \approx \frac{\pi}{2} \cdot \frac{Z_0 \cdot \omega_0}{\omega_0^2 - \omega_c^2} \approx \pi \frac{Z_0}{\omega_0} = \frac{X_c}{\omega_0}$$

and

$$R_V = \frac{X_c}{Q_0} \tag{12.4}$$

Finally, we obtain for resonance $\omega = \omega_0$ the equivalent circuit diagram according to Fig. 12.3 e).

Required equipment

1 Basic unit	737 021
1 Gunn oscillator	737 01
1 Diaphragm with slits 2 x 15 mm, 90°	737 22
1 Variable attenuator	737 09
1 Cross directional coupler	737 18
1 Transition waveguide/coax	737 035
1 Coax detector	737 03
1 Waveguide termination	737 14
1 Accessories waveguide propagation	737 29
1 Moveable short	737 10
1 Set of thumb screws (8 each)	737 399

Additionally required equipment

2 Coax cables with BNC/BNC plugs, 2 m	501 022
2 Stand bases	301 21
2 Supports for waveguides	737 15
1 Stand rod 0.25 m	301 26

Recommended:

1 PIN modulator	737 05
1 Isolator	737 06

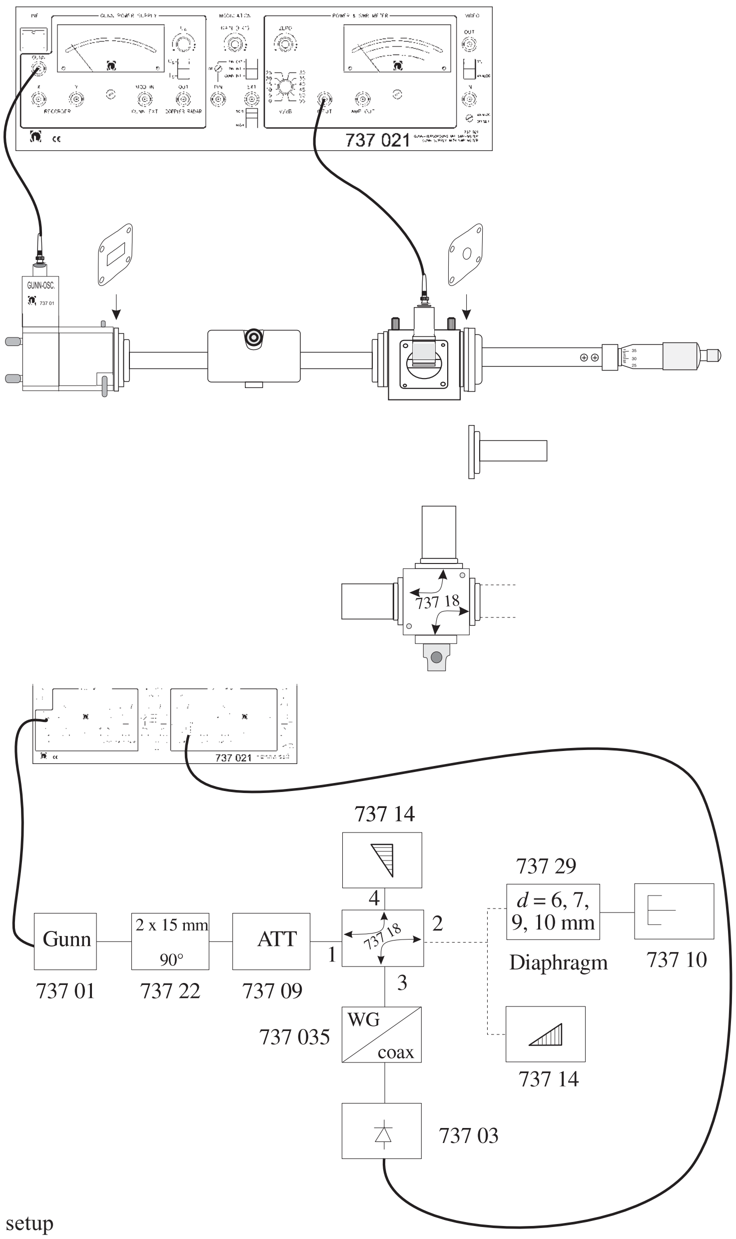

Fig. 12.5: Experiment setup

Experiment procedure

Note:
When using the isolator and PIN modulator modify the experiment setup shown in Fig. 12.5 in accordance with the preface!

1. Set up the experiment according to Fig. 12.5. Use the coupling plate with 2 cross-shaped holes in the cross directional coupler. Set the attenuator to approx. 10 dB (see Experiment 11, subpoint 2.1).

2. *Calibration*
Determination of the reflection coefficient is performed like in Experiment 11, point 1, i.e. using only one coupling path and then comparing the results to the reflection ocurring during short-circuit.
Thus for calibration insert the moveable short with the diaphragm *d* = 6 mm into the experiment setup and set the moveable short to 0 mm (i.e. implement short in front of port 2). The voltage displayed for this at the SWR meter corresponds to the reflection

coefficient $|r| = 1$ and can thus be used for calibration. Set the SWR meter to 0 dB using the “ZERO” control knob. As a further reference for the matching case you can insert a reflection-free waveguide termination instead of the moveable short.

3. *Resonator measurements*
Insert the moveable short with diaphragms (one after the other d = 6, 7, 9, 10 mm). Change the position of the moveable piston and observe how the reflection coefficient is dependent on the setting of the micrometer. Determine the minimum of $|r| = |r|_{min}$ for each diameter of the diaphragm aperture. Enter the values into Table 12.1.
Using Fig. 12 .4 carry out the exact determination of the value ***n*** corresponding to each aperture diameter ***d*** and enter it into the table. (First compute the parameter value λ_0/a, ($f \approx$ 9.4 GHz, a = 22.86 mm), but bear in mind the logarithmic scaling).
Sketch the measured values of $|r|$ as a function of n/n_0. Here n_0 is the value corresponding to $|r| = 0$. Assume that you achieve matching at an aperture diameter of **d = 8 mm** (standard diaphragm aperture of the Gunn oscillator).

Questions

1. Compute the value of the transformation ratio $n = n_0$ using the equivalent circuit diagram according to Fig. 12.2 e) so that the reflection coefficient becomes $r = 0$. For this use approximately $X_c = \pi \cdot Z_0$ and enter the result in the form $n_0 = f(Q_0)$.

2. Compute and plot the characteristic magnitude of the reflection coefficient $|r|$ in dB as a function of n/n_0 in the range 0.1 to 2.5.

3. Estimate the unloaded Q_0 of the resonator using the experiment results according to 3 and the relationship between the aperture diameter d and the transformation ratio n in Fig. 12.3.

Table 12.1

n_0 = ___________

d / mm	$\frac{\lvert \underline{r} \rvert_{min}}{dB}$	$\lvert \underline{r} \rvert_{min}$	n	$\frac{n}{n_0}$
6				
7				
9				
10