

1A GUNN DIODE OSCILLATOR

1. Introduction

Gunn diode (strictly speaking, it is not a diode but rather a single n -type GaAs semiconductor bar with two contacts at its ends), discovered around 1960 by J. B. Gunn, enabled compact and low-cost microwave oscillators, thus bringing microwave applications to broad public. In this laboratory session we will get acquainted with basic properties of the Gunn diode oscillator.

2. Theoretical background

A DC-voltage applied to the Gunn diode contacts generates an electric field in the semiconductor, which causes electrons to move in the direction opposite to the one of the electric field. As a result, a DC-current flows through the semiconductor. A typical Gunn diode current vs. voltage curve is shown in Fig. 1A.1(a) (note that the current is proportional to the drift velocity whereas the voltage is proportional to the electric field). For a low voltage level, it is clear that the Gunn diode obeys Ohm's law. However, it is noticeable that the current reaches a maximum at a certain voltage threshold value, after which it starts to decrease. This, rather unusual, behaviour can be explained by the existence of two conduction bands in GaAs, illustrated in Fig. 1A.1(b). At a low electric field (voltage) level most of the electrons are in the lower conduction band, having relatively low energy but also relatively low effective mass and high mobility. As the electron mobility is proportional to the material bulk conductivity, we can say that the material is fairly conductive for such an electric field (voltage) level. However, by increasing the electric field, the electrons' energy increases and so they start to pass to the higher conduction band where their effective mass is higher and mobility (bulk conductivity) lower with respect to the lower conduction band. Therefore, in a certain range of the electric field, the total electron mobility and conductivity will decrease with the electric field. In other words, in this range the current through the semiconductor will decrease with the voltage, resulting in a negative differential (dynamic) resistance, essential for generating oscillations.

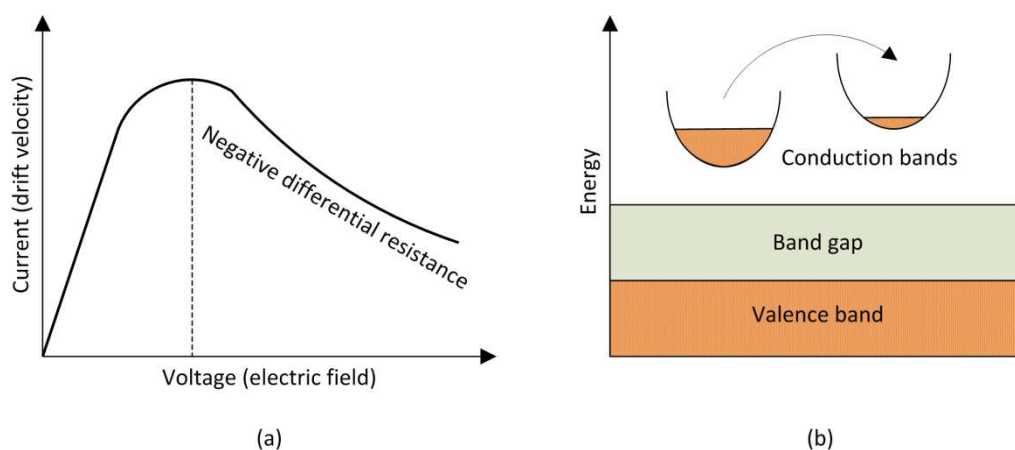


Fig. 1A.1 (a) Current (drift velocity) vs. voltage (electric field) curve of a Gunn diode; (b) Energy bands in GaAs.

In microwave electronics, a Gunn diode (and its virtue of negative differential resistance) is often employed to build oscillators, i.e. microwave sources. Apart from the negative differential resistance, a resonant load is required for an oscillator to work properly. This can be conveniently achieved by placing the Gunn diode in a waveguide cavity, as shown in Fig. 1A.2. The cavity is closed from the left by a metallic wall that can be moved in order to tune the oscillator frequency. On the right side, the cavity is partially closed by an iris, which forms the resonant load and also provides the exit for the generated signal. Gunn oscillators may also have dielectric adjustment screws for fine frequency tuning. This tuning principle relies on the effective dielectric permittivity variation. The deeper the screw is in the cavity, the higher is the effective permittivity in the cavity. This causes the resonant load seen from the Gunn diode position to vary, which in turn alters the oscillator operating frequency.

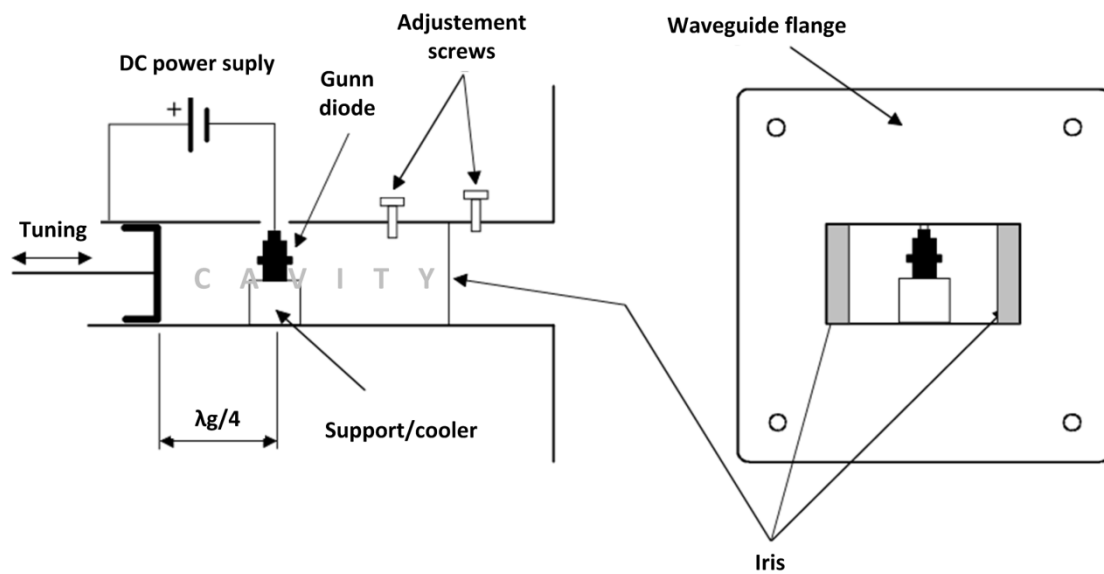


Fig. 1A.2 Gunn oscillator realised in the waveguide technology.

3. Experiments

3.1. Utilised equipment

- Gunn diode power supply *Marconi 6590*
- Gunn oscillator *Sivers Lab PM 7015X* (with the diode *CXY11C*)
- Digital voltmeter *Advance Instr. DMM2*
- Wavemeter *HP X532B*
- Directional coupler *HP X752C*
- Power meter *HP 432A* with the thermistor mount *HP X486A*
- Waveguide termination (matched load) *Sivers Lab 7220X*

3.2. Experiment setup

We will study a waveguide Gunn oscillator *Sivers Lab PM7015X* with diode *CXY11C*. The experiment setup is shown in Fig. 1A.3. The oscillator is connected to the power supply providing the DC-energy. The DC-current and DC-voltage are displayed on the power supply and the voltmeter, respectively.

The frequency of oscillations is precisely measured using the wavemeter, which is a cavity (connected in parallel to the waveguide) that absorbs a part of the microwave power when its resonance frequency is equal to the signal frequency. The wavemeter resonance frequency is variable and indicated on the instrument. The absorption causes a dip that can be registered by an instrument capable of measuring the signal level (such as a power meter).

The microwave power is measured through the 10 dB directional coupler that transmits 10% of the incident power (i.e. power provided by the Gunn oscillator) to the thermistor sensor (bolometer) of the power meter. The thermistor sensor operates by relating the microwave power to the variation of the resistance that is in turn caused by the dissipation of the microwave signal.

Finally, the setup is terminated by the matched load. Therefore, the reflected signal propagating back to the Gunn oscillator is negligible.

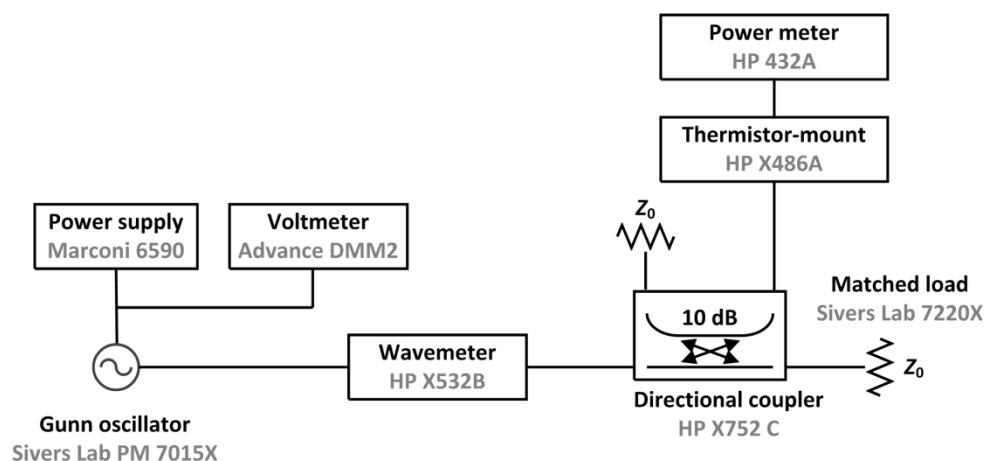


Fig. 1A.3 Experiment setup for the Gunn oscillator study.

3.3. Measurements

Prior to the measurements, the power meter must be set to zero. During this operation the microwave signal must be completely absent from the thermistor sensor. Therefore, turn off the DC power supply of the Gunn oscillator while zeroing.

Set the nominal DC-voltage to 7 V (shown on the voltmeter display) and the oscillator frequency precisely to 9.5 GHz (the frequency is measured by means of the wavemeter and a dip in the power meter reading). **Do not exceed the voltage of 7 V! (Risk of the Gunn diode failure).**

Lower the DC-voltage in steps of 0.5 V starting from the nominal value of 7 V, and for each step measure the DC-current (using the ampere-meter integrated in the power supply), power (using the power meter *and* taking into account the 10 dB coupling), and frequency (using the wavemeter; do

not forget to de-tune it while measuring the power). Write the measured values in the following table and plot the current vs. voltage, power vs. voltage, and frequency vs. voltage curves.

Table 1A.1 Gunn oscillator current, power, and frequency.

V_{DC} , V	7.0	6.5	6.0	5.5	5.0	4.5	4.0	3.5	3.0
I_{DC} , mA									
P , mW									
f , GHz									

Reset the voltage to the nominal value of 7 V. Tune the oscillator to frequencies 9.0, 9.5; 10; 10.5 GHz by shifting the tuning wall (verify the frequencies using the wavemeter) and measure the DC-current and power for each frequency. Plot the power vs. frequency curve (for $V_{DC} = 7$ V) and calculate the Gunn diode efficiency at each frequency using the following expression:

$$\eta = \frac{P_{\text{microwave}}}{V_{DC} \cdot I_{DC}}.$$

Table 1A.2 Gunn oscillator power and efficiency vs. frequency at $V_{DC} = 7$ V.

f , GHz	9.0	9.5	10.0	10.5
I_{DC} , mA				
P , mW				
η , %				

Comment the following aspects concerning the Gunn diode oscillator: power supply and efficiency; modulation possibilities; feasibility of implementation.

4. References

[1] David Pozar, *Microwave Engineering*, 4th edition, John Wiley & Sons, 2011.

1B MEASUREMENTS ON THE SLOTTED SECTION

1. Introduction

The goal of this exercise is to measure the reflection coefficient of various obstacles (loads) placed in a rectangular waveguide, and to determine their equivalent normalised susceptance B/Y_0 using the Smith chart.

2. Theoretical background

In general, there are two voltage waves existing on a loaded transmission line: an incident voltage wave V^+ propagating from a generator towards a load, and a reflected voltage wave V^- propagating back to the generator. The reflected voltage wave is caused by the reflection from the load. The reflection is quantified by the reflection coefficient defined as

$$\Gamma = |\Gamma| \cdot e^{j \arg \Gamma} = \frac{V^-}{V^+} = \frac{|V^-|}{|V^+|} \cdot e^{j(\phi^- - \phi^+)}.$$

The incident and reflected wave add up (interfere) along the transmission line, which forms a standing wave with maxima and minima. In the maximum, where the total voltage amplitude is V_{max} , the incident and the reflected wave are in-phase, therefore $V_{max} = |V^+| + |V^-|$. In the minimum, where the total voltage amplitude is V_{min} , the incident and the reflected wave are out-of-phase, therefore $V_{min} = |V^+| - |V^-|$. The voltage standing wave ratio, VSWR (often called just SWR), is defined by the ratio of the maximum and minimum amplitude:

$$\text{VSWR} = \frac{V_{max}}{V_{min}}.$$

Knowing the above-mentioned relations, we can also state that

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|}.$$

A slotted section is a device that allows probing the total voltage (electric field) envelope on a rectangular waveguide transmission line. A weakly coupled probe with detector provides a signal corresponding to the amplitude of the total transversal electric field, i.e. the standing wave. By sliding the probe along the slotted section, standing wave minima (V_{min}) and maxima (V_{max}) can be found and measured. This allows the direct VSWR measurement and hence the calculation of the reflection coefficient magnitude $|\Gamma|$. As for the reflection coefficient phase, it can be obtained by comparing the minimum position with a load placed on the reference plane to the minimum position when the load is replaced by a short circuit (details are described in Section 3.3).

The load impedance, Z_L , is related to the reflection coefficient as

$$Z_L = Z_0 \frac{1 + \Gamma}{1 - \Gamma},$$

where Z_0 is a characteristic impedance of the transmission line.

3. Experiments

3.1. Utilised equipment

- Gunn diode source Marconi 6058A
- Adapter coaxial to waveguide H&S 3102
- Ferrite isolator *Sivers Lab PM 7041X*
- Wavemeter *HP X532B*
- Variable attenuator *HP X382A*
- Slotted section *HP X809C* with the probe *HP 444A* and precision scale
- SWR meter *HP 415E*
- Three irises (inductive, capacitive, and resonant)
- Waveguide short
- Waveguide termination (matched load) *FMI 16/4*

3.2. Experiment setup

The experiment setup for the reflection coefficient (or impedance) measurements using the slotted section is shown in Fig. 1B.1. A microwave signal is delivered by the Gunn diode source whose operating frequency can be roughly adjusted by a knob that is causing the tuning wall to shift (see Fig. 1A.2). An integrated pin-diode attenuator allows output magnitude control (maximum output power is around 50 mW). The microwave signal is amplitude-modulated (AM) by a square wave signal at approximately 1 kHz. This is needed for the SWR meter as it can process only the AC signal component.

The microwave signal enters the rectangular waveguide thanks to the coax to waveguide adapter. The ferrite isolator protects the Gunn diode source from reflections that could cause a disturbance in its operation. Frequency is precisely controlled by the wavemeter (and a dip observed on the SWR meter). The precise variable attenuator is used to control the detector operation and to measure large VSWRs (>50).

The slotted section allows very precise determination (precision 1/100 mm) of standing wave minima and maxima. The obstacles to measure are three irises placed at the exit of the slotted line and terminated by the matched load.

The detector is essentially a diode rectifier. It provides a rectified DC signal (here a low frequency unipolar AC signal, as the input microwave signal is amplitude-modulated by the 1 kHz square wave) at its output. Normally detectors operate in a 'quadratic' zone, where the output voltage amplitude is proportional to the input RF power (not the amplitude). The SWR meter is in fact a low frequency amplifier that we use together with the detector. In principle it can be used to indirectly measure any relative RF level, and it is particularly well suited to measure VSWR. This is done in the following way: find the standing wave maximum and set the SWR meter needle to the maximum (by adjusting the RANGE and GAIN of the SWR meter). Now, find the standing wave minimum. There is a scale available that will directly show the VSWR.

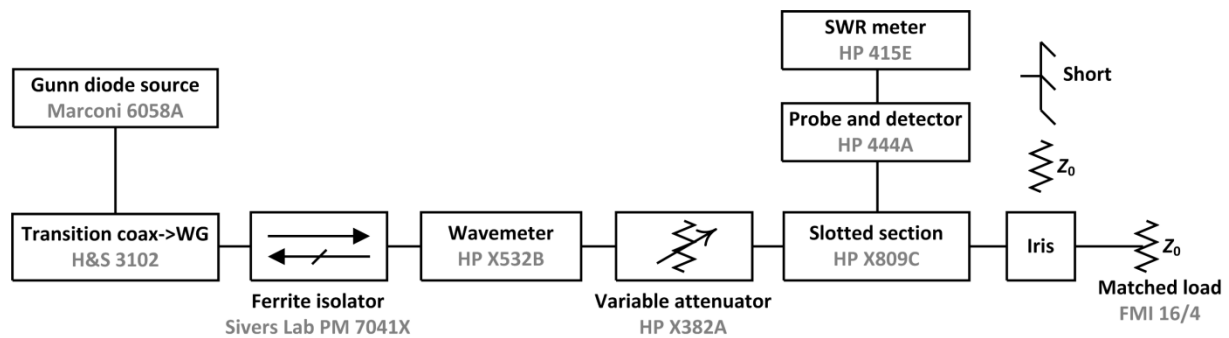


Fig. 1B.1 Experiment setup for the reflection coefficient measurements using the slotted section.

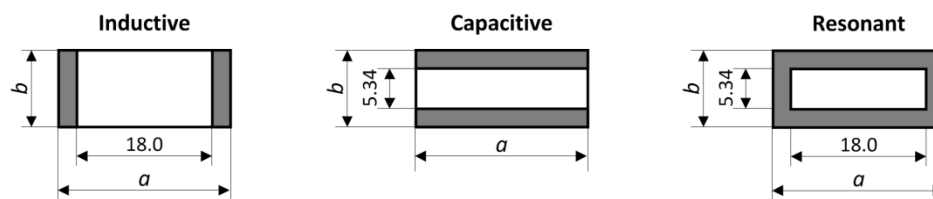


Fig. 1B.2 Irises ($a = 22.86$ mm; $b = 10.16$ mm).

3.3. Measurements

Measurement preparation

Set the SWR meter RANGE to 40 dB. The probe depth in the slotted section should be around 0.5 mm. Verify this qualitatively and then connect the short circuit to the output of the slotted line.

Turn on all the devices. Set the square modulation on the Gunn diode source; adjust the microwave frequency to 9.5 GHz; set the signal level somewhat below the 'EXT' mark. Set the variable attenuator to 0 dB.

Regulate the modulation frequency of the source (or the central frequency of the SWR meter pass-band) in order to have the maximum needle deviation on the SWR meter scale.

Control the frequency using the wavemeter, and if necessary adjust the source frequency to 9.5 GHz.

Check if the detector is in the quadratic zone. In order to do this, find the standing wave maximum and bring the needle of the SWR meter to 0 dB by regulating the gain of the SWR meter. Now, increase the attenuation of the variable attenuator to 10 dB. The SWR meter should indicate exactly -10 dB on its logarithmic scale, which indicates the proper operation of the detector. If this is not the case, the microwave power entering into the detector is too high. Therefore, lower the source level and redo this procedure. Once this is done, set the variable attenuator back to 0 dB.

Note: an open waveguide is an efficient radiator (antenna). Although the power levels used in this laboratory session are rather low, it is a good practice to avoid this radiation while changing the load (iris). Modern generators have a 'RF power on/off' button, which can be used for this. In this exercise, we will put the attenuation of the variable attenuator to maximum (50 dB) every time during the load exchange. This will reduce the radiated power to a completely negligible level.

Short circuit and termination verification

A short circuit has theoretically an infinite VSWR. We need to check how high it is in reality. Given the large VSWR and therefore very low amplitude of the standing wave minimum, it is hard to do this in the standard way, by using only the SWR meter (as it lacks the required dynamic range). We will have to employ the variable attenuator as well. Set it to some value A ($A = 40$ dB, for instance), find the maximum on the slotted section, and set the SWR meter needle to 0 dB. Now, find the standing wave minimum. This could be difficult to do directly as the signal becomes so weak that it starts to significantly interfere with the noise (the needle of the SWR meter starts to tremble). However, as the shape of the standing wave is symmetric around the minimum, you can find two positions around minimum where the detected level is the same; the minimum is then exactly in the middle. Once having found the minimum, set the SWR meter needle back to 0 dB by decreasing the attenuation (final attenuation a). This way, we have compensated the difference between the maximum and minimum signal by lowering the attenuation. Now we can calculate the VSWR as $VSWR = 10^{(A - a)/20}$. The precision of the measurement only depends on the attenuator precision, which is very high. During this measurement the source level can be set to maximum, even if it means leaving the detector quadratic zone (as we are relying on the linear attenuator and have the RF power on the detector equal at the beginning and the end of this measurement). However, do not forget to set the power back to the level at which the detector operates in the quadratic zone.

Connect the waveguide termination (matched load) directly to the slotted line output. Measure the VSWR (put the RANGE of the SWR meter to EXPAND in order to increase the instrument sensitivity and facilitate the measurement). A good matched load should have the VSWR no greater than 1.02. After this verification, decrease the SWR meter sensitivity (set the RANGE back to 40 dB).

Inductive iris measurement

Put the short circuit back and control the frequency using the wavemeter. Adjust if necessary to 9.5 GHz. Find one minimum, preferably in the middle of the slotted section. It is critical to know precisely its position, so use the standing wave symmetry and the approach described above. This is the position x_0 . For convenience, the precision scale of the slotted section can be set to show a round number for this position. Write the value of x_0 in Table 1B.1 and keep the precision scale setting constant for all measurements at the same frequency. Importantly, note that the distance between the load (reference plane) and this point is $n \cdot \lambda_g/2$, λ_g being the guided wavelength and n being an integer. As the input impedance on the transmission line is periodical with $\lambda_g/2$ periodicity, the input impedance (reflection coefficient) at the position x_0 is the same as the load impedance (reflection coefficient).

Find the adjacent minimum in the same manner as above, and note its position as x_0' . As the distance between two adjacent minima is $\lambda_g/2$, we can say that $\lambda_g = |x_0 - x_0'| \cdot 2$. Write down these two results in Table 1B.1.

Now, set the attenuation of the variable attenuator to maximum, remove the short circuit, and mount the inductive iris backed by the matched load. Set the attenuation back to 0 dB. Start moving the detector from the position x_0 towards left (therefore, *towards the generator*) until the first minimum is found, at the position x_1 . The distance $d = |x_0 - x_1|$ will be essential for determining the load impedance using the Smith chart. Write the values of x_1 , d , and d/λ_g in Table 1B.1.

Measure the **VSWR** directly using the SWR meter and write down the result in Table 1B.1.

Capacitive iris measurement

Replace the inductive iris by the capacitive one. Measure the VSWR and the position of the minimum x_1 in the same manner as above and write down the results in Table 1B.1. The values of x_0 and λ_g remain the same as the frequency has not changed.

Resonant iris measurement

Replace the capacitive iris by the resonant one. Measure the VSWR and the position of the minimum x_1 in the same manner as above and write down the results in Table 1B.1. The values of x_0 and λ_g remain the same as the frequency has not changed.

Calculate the resonant frequency f_{res} of the iris, for which the characteristic impedance in the reduced section is equal to the characteristic impedance of the waveguide:

$$\frac{a}{b} \sqrt{1 - \left(\frac{\lambda_0}{2a} \right)^2} = \frac{a'}{b'} \sqrt{1 - \left(\frac{\lambda_0}{2a'} \right)^2},$$

where $a = 22.86 \text{ mm}$, $b = 10.16 \text{ mm}$, $a' = 18.00 \text{ mm}$, $b' = 5.34 \text{ mm}$, $\lambda_0 = c/f$ (free space wavelength).

Other frequencies

Re-measure all irises at 9 GHz and 10 GHz. Clearly, for each frequency the reference position x_0 and the guided wavelength λ_g must be determined again.

Table 1B.1 Slotted section measurement results.

f , GHz		9.0	9.5	10.0
x_0 , mm				
x_0' , mm				
λ_g , mm				
IND	x_1 , mm			
	d , mm			
	d/λ_g			
	VSWR			
CAP	x_1 , mm			
	d , mm			
	d/λ_g			
	VSWR			
RES	x_1 , mm			
	d , mm			
	d/λ_g			
	VSWR			

4. Processing of the results

4.1. Tracing the impedances and admittances in the Smith chart

The Smith chart is essentially a plot of reflection coefficients overlaid with an impedance/admittance grid. It is a very useful tool for various problems concerning transmission lines. Here we will use it to find the load reflection coefficient and impedance from the measured VSWR and d/λ_g .

First, we know that the reflection coefficient magnitude along a transmission line terminated by a specific load is known and equal to $|\Gamma| = (VSWR-1)/(VSWR+1)$. This constitutes a circle of constant VSWR (called the SWR-circle) in the Smith chart. All reflection coefficients (and therefore all input impedances/admittances) along the transmission line terminated by this load are located on this circle. The SWR circle must be drawn in the Smith chart by using a drawing compass.

Second, it is known that in the minimum of the standing wave, corresponding to the position x_1 , the reflection coefficient is *real and negative*, i.e. $\Gamma = -|\Gamma|$. This point is in fact the intersection of the SWR-circle and the negative real axis in the Smith chart.

Next, one must move *towards the load* (anti clock-wise) by d/λ_g in order to reach the point corresponding to the position x_0 . This point reveals the exact reflection coefficient of the load as it is located at the distance $n\cdot\lambda_g/2$ from the load. The reason for moving towards the load comes from the instruction to find the first minimum x_1 in the direction of the generator (so we must move *back* towards the load to reach the point corresponding to the position x_0). Of course, it could have been the other way around (finding the first minimum towards the load, and then moving back towards the generator).

Finally, the load impedance is directly readable on the impedance Smith chart (as the one in Appendix). To acquire the load admittance, one must rotate the impedance point by 180° on the circle and then directly read the admittance. Note that the impedances (admittances) on the Smith chart are normalised with respect to the characteristic impedance (admittance) of the transmission line.

Plot the normalised impedance and admittance of each combination iris + termination in the Smith chart, in the frequency range from 9 GHz to 10 GHz. Use the expanded version of the Smith chart provided in Appendix. Comment their locations in the Smith chart.

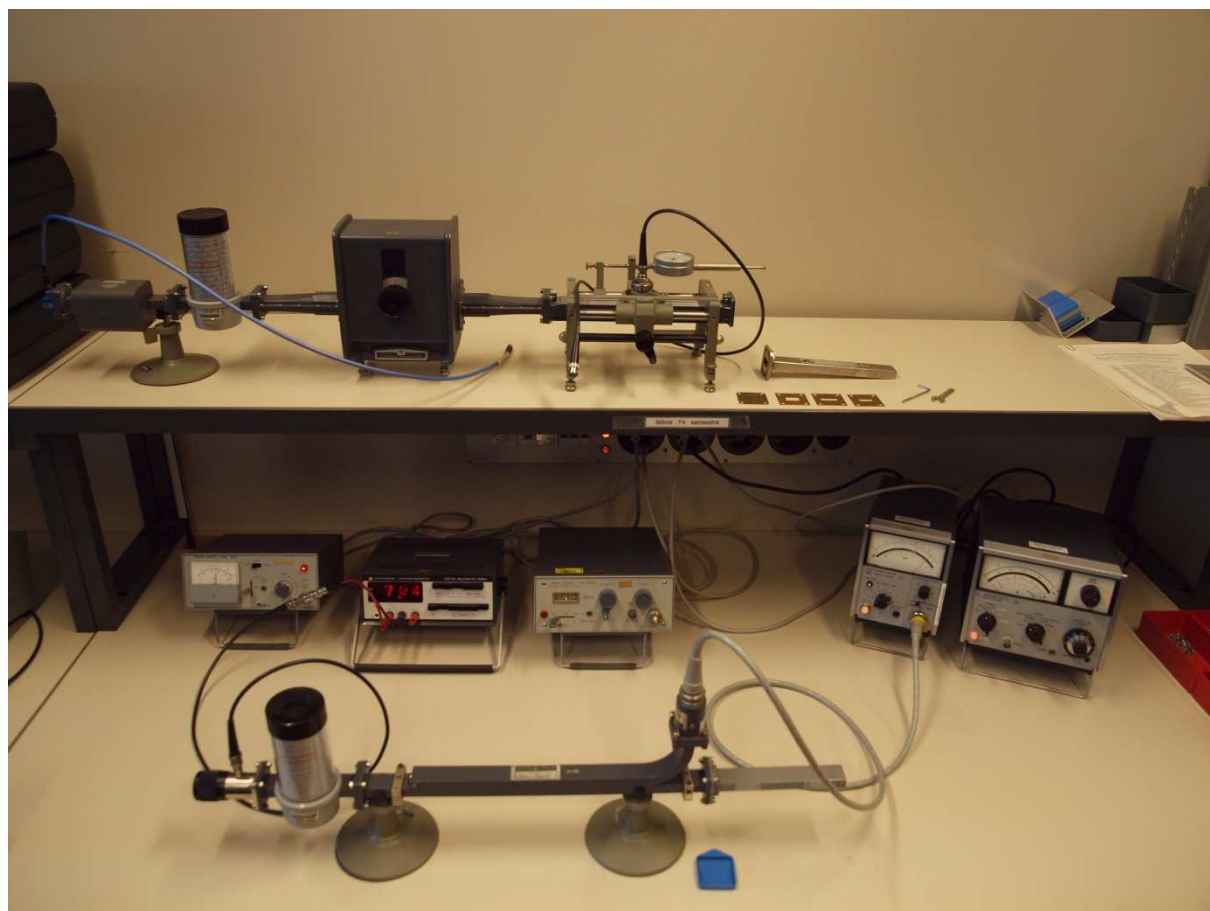
4.2. Calculation of susceptance

Using the graphs provided in Appendix, calculate the normalised susceptance B_L/Y_0 and B_C/Y_0 of the inductive and capacitive iris, respectively. The exact dimensions are given in Fig. 1B.2.

Compare the calculated values with the ones obtained experimentally. In addition, compare the measured value for the resonant iris B_{RES}/Y_0 with the sum $B_L/Y_0 + B_C/Y_0$. Is it true that the resonant iris acts as the parallel combination of the inductive and the capacitive irises?

5. References

[1] David Pozar, *Microwave Engineering*, 4th edition, John Wiley & Sons, 2011.



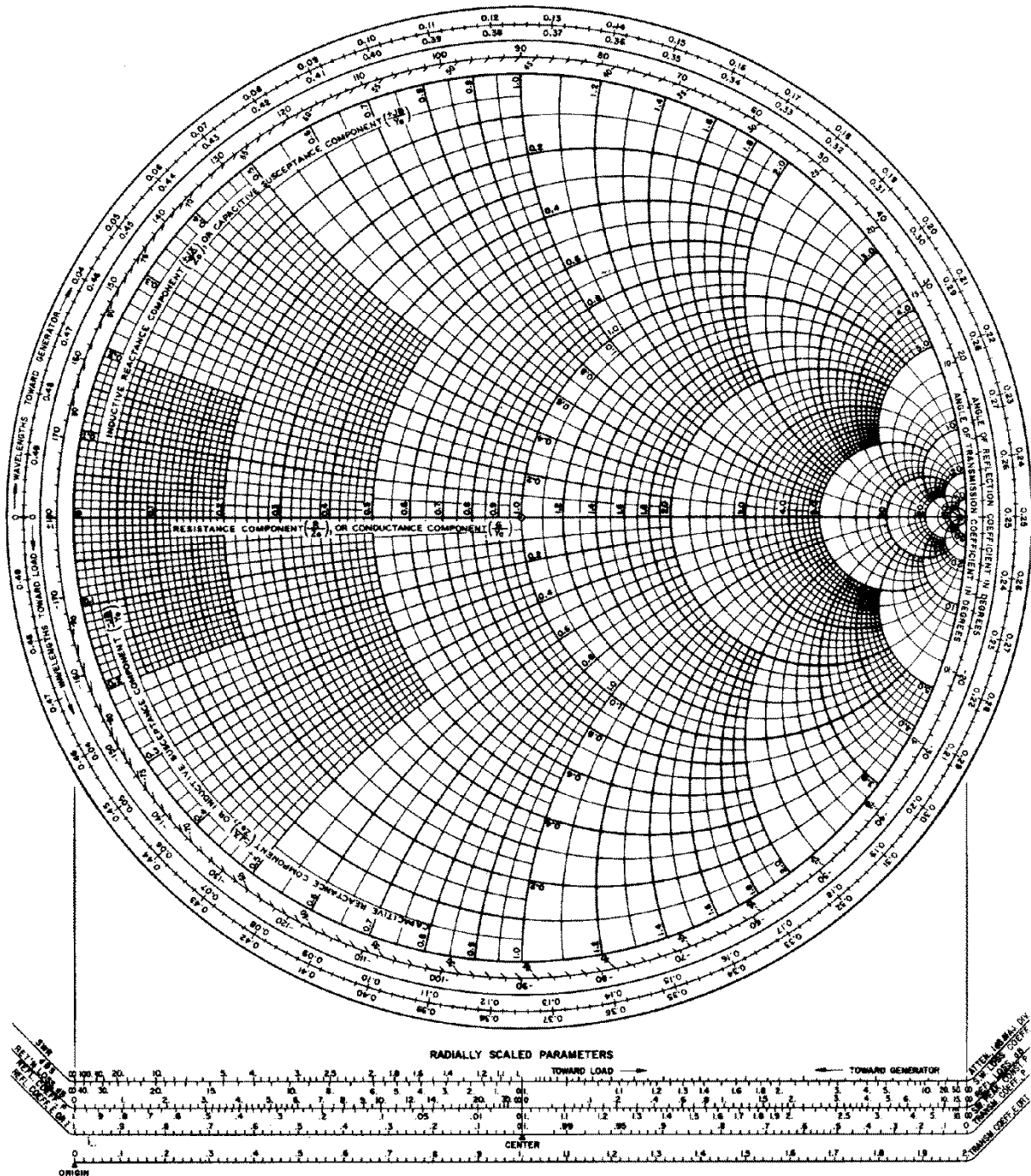
Photography of the experiment setups for Laboratory session 1.

Appendix

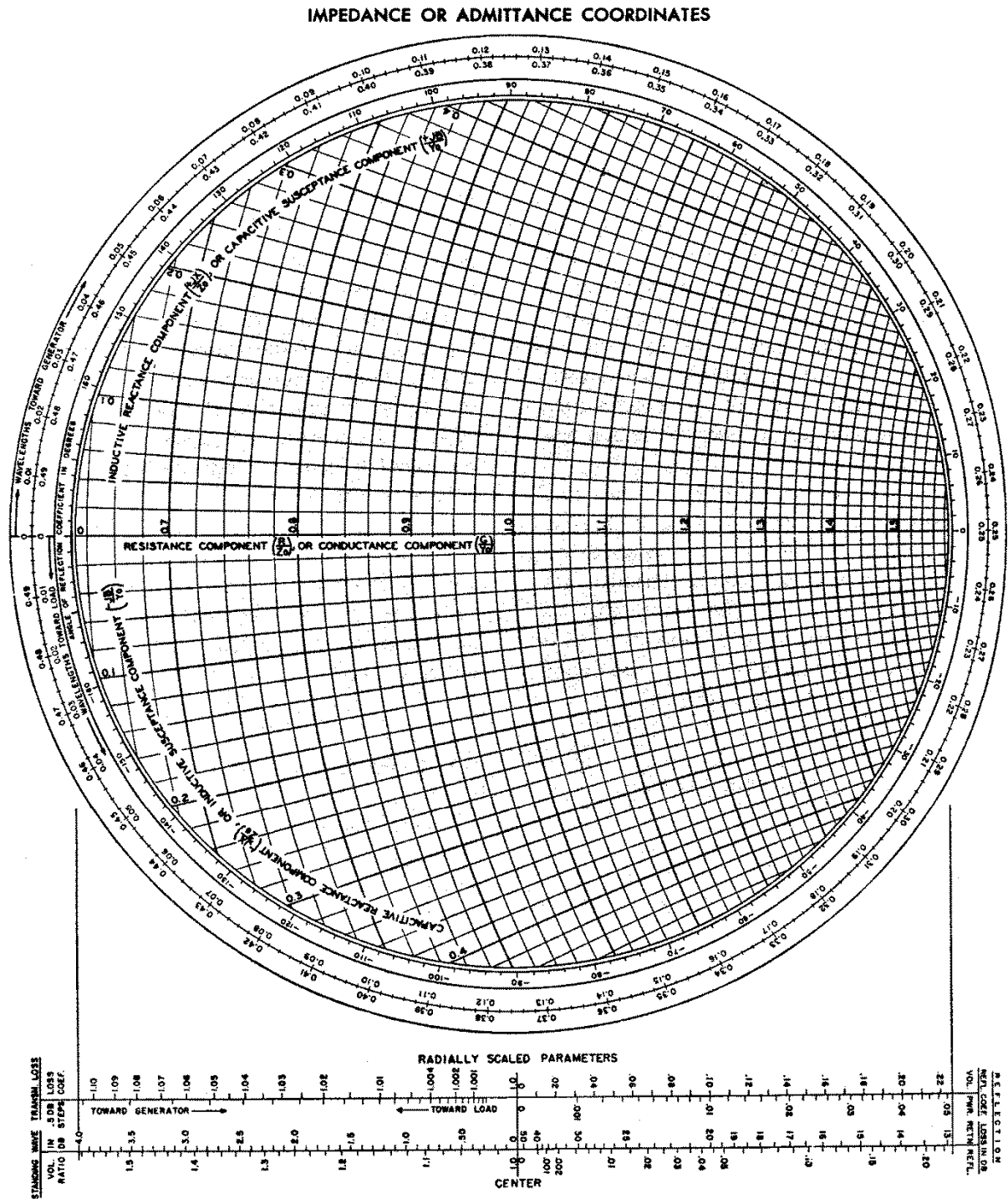
Smith chart

NAME	TITLE	DWG. NO. A
SMITH CHART FORM 82-BSPR (9-66)	KAY ELECTRIC COMPANY, PINE BROOK, N.J., © 1966. PRINTED IN U.S.A.	DATE

IMPEDANCE OR ADMITTANCE COORDINATES



Expanded Smith chart



Curves for calculating the iris susceptance

