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Tel Aviv University

Engineering faculty

Electrical engineering school

The Advanced Microwave Laboratory

Course No. 0512.4890

Experiment Instructions

Version 1.0

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Preface

1. The Advanced Microwave Laboratory course meets the student directly with microwave effects, as well as devices measurement techniques and basic microwave circuits.
2. Fundamental element in the experiments is the comparison between theory and experiments, using analytical approach. Additionally, numerical simulations verify the results, and add experience with this tool. This course includes design and implementation, using engineering approach.
3. This lab is equipped with new and expensive devices (such as Agilent E5071C vectoral Network analyzer) that allow the updated curriculum. This guide is updated accordingly. Remark, and suggestions regarding to this guides are welcome.
4. The course includes 12 experiments of 90 minute each. Each 3 hour meeting includes 2 following experiments.
5. Each experiment includes educational goal, read list and preparation question, equipment needed, experiment goal, experiment sequence and conclusions.
6. Experiments are done in pairs, as well as the laboratory report.
7. The preparation work includes background materials according to the guide, using also online sources. The questions should be answered in the preparation report, and the setup and the experiment sequence should be learned before. In particular, the operation of the equipment should be studied according to the manufacturer instructions.
8. A short quiz is done before each meeting.
9. Each operation should be hand-write documented in dedicated notebook including scheme of the experimental setup, equipment details, devices tested, raw experimental data with directions to the files, according to the good laboratory practice (GLP) accepted for laboratory work.
10. The final report should contain the experimental setup description used, and all the data measured. The results should be analyzed according to the theory. Additionally, the final questions of each experiment should be answered.

Safety

1. The safety instruction of the university and the faculty of engineering are valid here. In particular, the general safety instructions must be read and followed as available here (http://safety.tau.ac.il/information), in addition to the following instructions.
2. Never work alone in the lab. Additional person must be in presence while working.
3. At the beginning of the work, the position of the main power switch, the emergency phone numbers, and the fire extinguisher must be known (all next to the door).
4. It is prohibited to operate equipment without permission of the instructor.
5. In particular, it is prohibited to turn on transmission device without permission of the instructor.
6. For any case of broken device (e.g. electrical outlet), it is forbidden to work with it.
7. Do not operate microwave transmission device without load.
8. Do not transmit with any antenna, microwave power above 1 mW (0 dBm).
9. Transmit microwaves as short as possible.
10. For any safety problem, first, turn off the main power switch.
11. Never try to fix yourself, or change, any electrical equipment.
12. Do not touch with wet hands any electrical device. If something wet, let the instructor know.
13. Do not touch any equipment that is not needed for the experiment.
14. In case of fire, use the fire extinguisher. Additionally alert the safety unit of the university in phone number 5555 or 8222 (prefix 03-640 from external line)
15. At the end of the experiment turn off the devices, disconnect the mobile units from the outlet, and get back the devices to their original places.

List of Experiments:

1. **Wave propagation**
   a. Fundamental effects in rectangular waveguide (dispersion, cutoff, modes).
   b. Slotted waveguide – measuring wavelength and load impedance.
   c. Cutoff frequency in waveguide.
   d. Illustration of standing wave in a rectangular waveguide.
2. **Microwaves measuring equipment**
   a. Schottky diode as a power measurement device.
   b. Resonator for frequency measurement.
   c. Spectrum analyzer: internal structure and measuring.
   d. Network analyzer: internal structure and initial calibration.
3. **Passive rectangular waveguide microwave devices**
   a. Reflectometer – measure the reflection and transmission coefficients by directional coupler.
   b. Microwave devices implemented by rectangular waveguide for X-Band.
   c. Measure the scattering parameters using network analyzer.
4. **Microwave signal sources**
   a. Gunn oscillators and VCOs, amplifies with positive feedback.
   b. Measure the noise figure and stability using spectrum analyzer.
5. **Detectors and mixers**
   a. Schottky diode detector
   b. General mixer parameters, characterization, and mixer types
6. **Impedance matching**
   a. Smith chart for impedance presentation.
   b. Single stub matching technique.
   c. Double stub matching using E-H tuner.

7. **Amplifiers**

   a. Amplifier characteristics, parameters of amplifiers, IP3, 1 dB compression.

   b. Signal to noise ratio (SNR), cascade of amplifiers.

   c. Amplifier measurements as "black box".

   d. Open microstrip amplifier.

8. **Microstrip devices**

   a. S-parameters of passive microwave devices.

   b. Microstrip line, power divider, coupler, BPF filter, Hybrid $90°$.

9. **Designing and building passive microstrip devices**

   a. Design and simulate microstrip devices, using Ansoft Designer or similar.

   b. Self-construction of passive elements using adhesive metal tapes.

   c. Designing and simulating of filters, corners, impedance matching.

10. **Dielectric permittivity measurement**

    a. Measuring dielectric coefficients of materials using microstrip resonator.

    b. Measuring dielectric coefficients of powders and liquid.

11. **EM Radiation and antennas**

    a. Far-field measurements, Horn antenna gain.

    b. Radiation pattern measurements at different polarizations.

    c. Computerized antenna measurement equipment.

12. **Radar applications**

    a. Doppler Effect, velocity measurement, RCS.

    b. RCS of many objects.

    c. FM detection, Linear-FM Radar.

13. **Communication applications (Optional)**

    a. Linear-FM transmission.

    b. Audio channel communication, modulated on microwave frequency carrier.

Books for self-learning:

The following is a partial list. Other online resources are allowed to be used.

i. S. J. Orfanidis, "Electromagnetic Waves and Antennas," Rutgers University, http://www.ece.rutgers.edu/~orfanidi/ewa/

ii. R. E. Collin, “Foundation for Microwave Engineering,” McGraw Hill, 2nd Edition, 1992 (or 3rd Edition, 2000).

iii. D. M. Pozar, “Microwave Engineering,” Wiley, 3rd Edition, 2005.

iv. C. Balanis, “Antenna Theory, Analysis and Design,” Wiley, 2nd Edition, 1997.

Figure Legend

WR90 to WR90 connection

Coax to coax connection (sma or N-type)

Free space radiation

WR90 to coax adapter

Low frequency or DC connection

Existing connection

1. Wave propagation in waveguides

Goals

1. Studying several fundamental phenomena in waveguides, e.g. propagation modes, cutoff, standing wave, and dispersion.
2. Slotted waveguide as experimental measurement device.
3. Using of frequency and network analyzers.

Background

In this experiment we will get to know the WR90 waveguide, and we will measure its S-parameters. The WR90 is a rectangular waveguide with cross-section of $0.4'' \times 0.9''$ ($10.2 \times 22.9\ \text{mm}^2$). The fundamental mode of the electromagnetic (EM) wave, TE_{10}, exists solely in the range of 6.6-13.1 GHz. However, the popular working range is 8-12 GHz, which is known as X-Band (specified by IEEE).

The fundamental experimental setup used to demonstrate the basic phenomena is described in Fig. 1.1

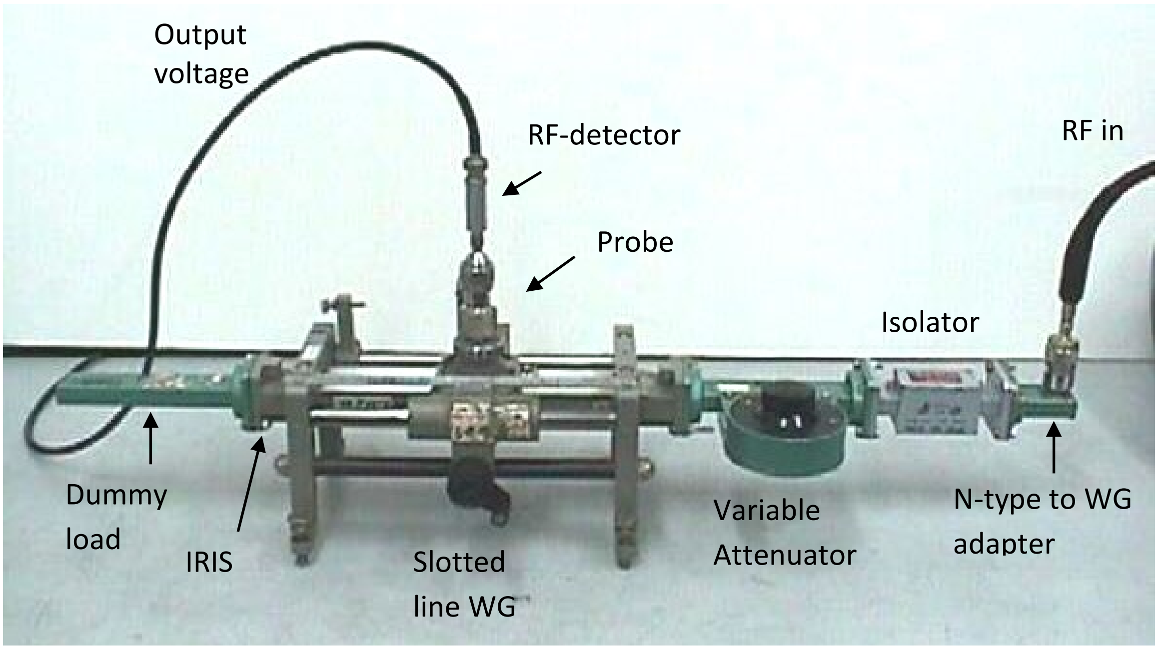


Figure 1.1: Fundamental experimental setup for measuring EM wave propagation in a rectangular waveguide.

Standing wave ratio (SWR)

In this part we will measure the standing wave ratio (SWR) or the voltage-SWR (VSWR) in the slotted waveguide, for variety of loads. We will use this value to calculate their impedances. We will observe their differences between matched and short load for example. The following Fig. 1.2 shows standing wave formation by summation of incident and reflected waves at different times.

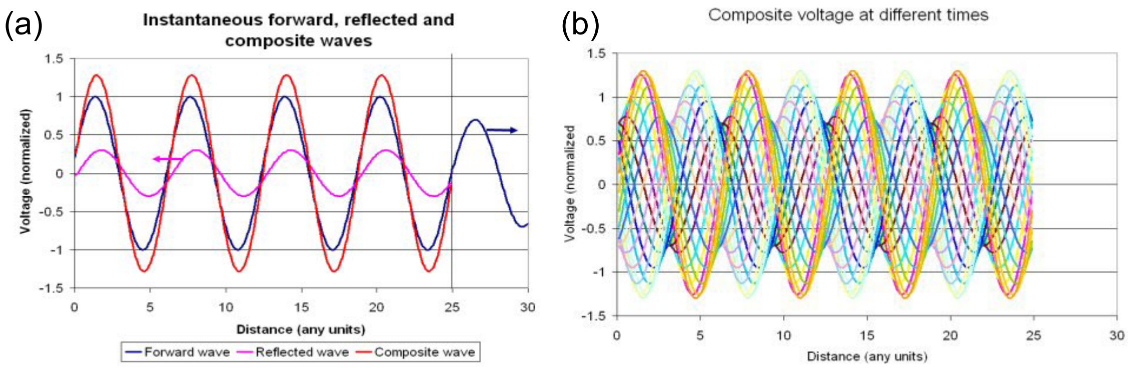


Figure 1.2: (a) Stranding wave pattern formation as summation of incident and reflected wave in an unmatched transmission line.
(b) Temporal variation of the standing wave pattern (by voltage)

The EM fields at each position along the transmission line are composed of the incident and the reflected wave from the discontinuity in the line, which is the variant load in this case. The amplitude and the phase of the reflected wave are determined by the impedance and the reflected position, and by the loss along the waveguide. The reflection coefficient Γ, determine the ratio between those waves that creates the standing wave. The VSWR is defined as the maximal to minimal ratio of the voltage in the line (which is relative to the electric field) along the standing wave pattern

$$SWR = \frac{|V_{\max}|}{|V_{\min}|}$$

Here, we will measure this pattern directly along the slotted waveguide. Additionally, by knowing this ratio, we can verify the transmitted frequency.

The slotted line

The sampling of the electric field inside the waveguide is done by the slotted line composed of WR90 waveguide as seen in Fig. 1.3. The boundary conditions (BC) of this mode support the location of the slot by not interfering with the current lines as seen in Fig. 1.4. Reactive elements (inductive and capacitive) implemented for waveguide by irises are presented in Fig. 1.5.

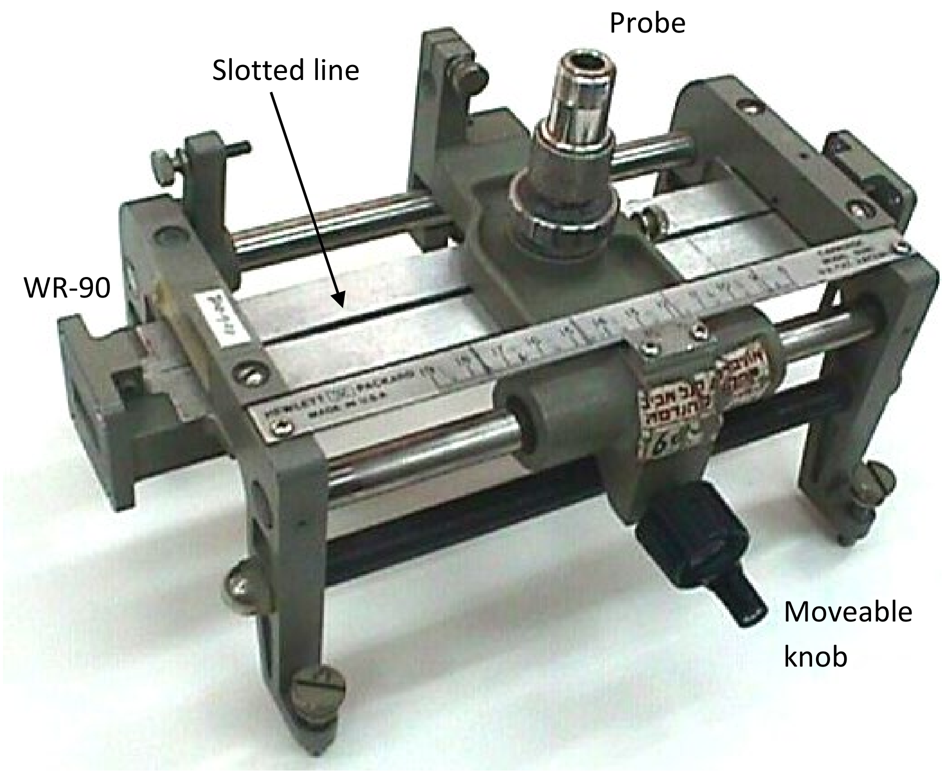


Figure 1.3: Slotted line for VSWR measurement.

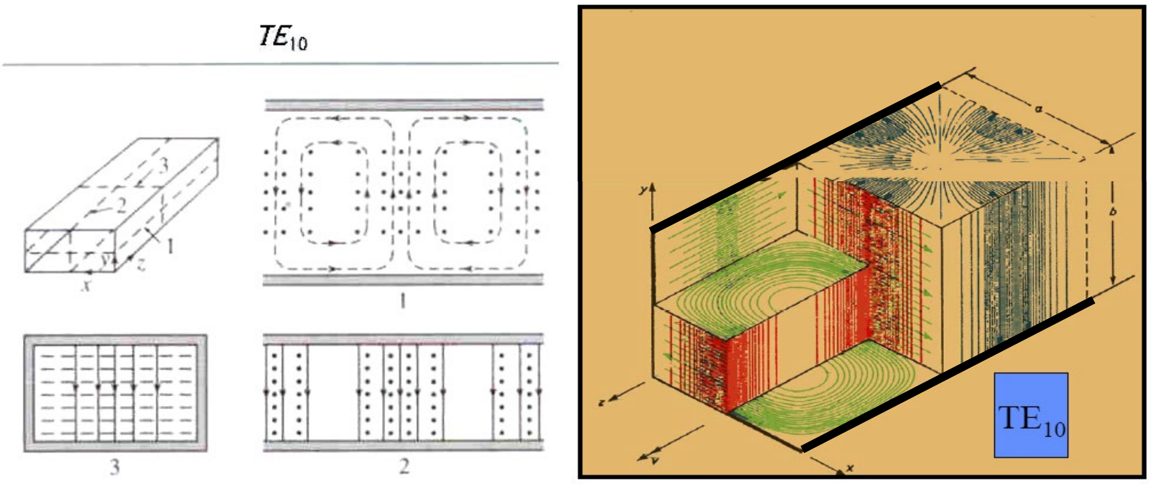


Figure 1.4: Fields distribution of the fundamental mode in rectangular waveguide.

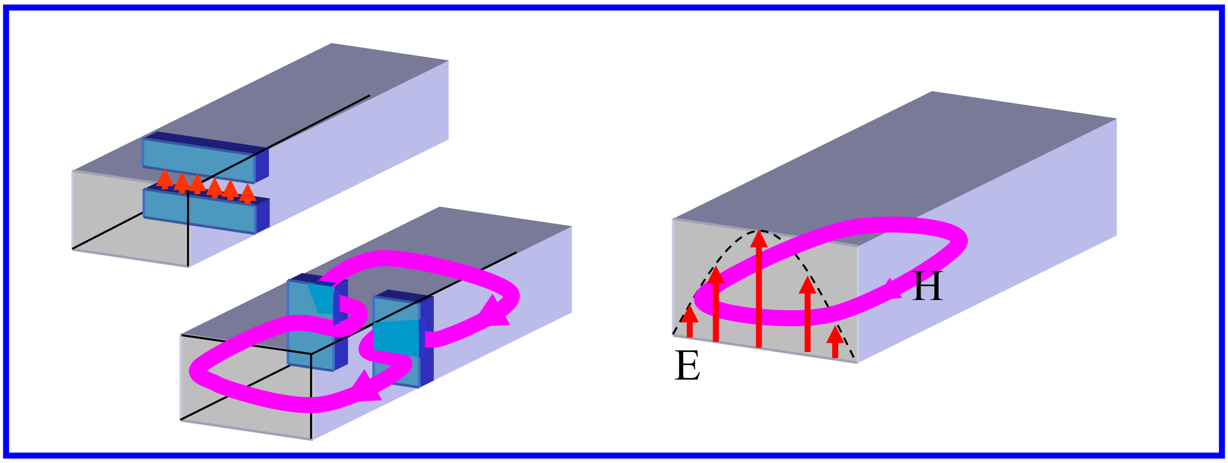


Figure 1.5: Electric and magnetic fields in a rectangular waveguide (right), and inside a waveguide with inductive (canter) and capacitive (left) elements.

By using a Schottky diode detector to convert the sampled energy to a DC signal, we can measure the relative voltage to the electric field in the waveguide, and calculate the VSWR. A calibration is needed for the Schottky diode in which is done at the next section.

Paper scorching

In this part we will use a high-power microwave source to feed a WR340 slotted line by magnetron. A paper package will be inserted to the slot, and we will observe the scorching pattern on the papers. We will verify the magnetron frequency from this pattern, and by knowing the WR340 dimensions. This experiment is done inside an altered home microwave oven, with a waveguide inside. Due to safety issues, **this part is executed by the instructor only**.

Preparation questions

(You can use Posar, pp. 92-98, 106-126 as a reference for these questions.)

1. Define "dispersion" generally, and explain how it can be observed in a rectangular waveguide?
2. Name a waveguide in which the dispersion is not exist there, and explain why. How does the boundary conditions affect?
3. Why the slotted WR90 is similar to the regular WR90?
4. What is the aspect ratio of WR90? Why does it so?
5. What are the cutoff frequencies of the first four modes of the WR90?

6. Where on the WR90 cross-section you need to install the probe to sample the modes from the previous question? Refer to the electromagnetic field distribution

7. WR90 waveguide of 1 m long is excited by pulsed signal with f_0 frequency and T_0 long. Describe qualitatively how the signal is observed at the exit plane for three f_0 and T_0 values for your choose.

8. A current 4G cell phone is transmitting a 2.2 GHz signal. Calculate the maximal perimeter of a circular waveguide that support propagation of this signal.

9. Name the major advantages and disadvantages of rectangular waveguide in respect of a coaxial waveguide.

Equipment

1. Slotted line setup, WR90.
2. Isolator.
3. Voltmeter.
4. Schottky diode detector.
5. X-Band generator.
6. Coaxial to WR90 adapter.
7. Matched load.
8. Coaxial cables.
9. Diverse irises for WR90.

Experiment goals

1. Measuring VSWR in WR90 slotted line.
2. Measuring cutoff frequency of the first two modes.
3. Scorching papers according to the standing wave pattern.

Experiment sequence

1. Measuring standing waves in the slotted line waveguide:

   1.1. Assemble the slotted line waveguide with a short used as a load according to Fig. 1.6.

   1.2. Assemble Schottky diode to the probe.

   1.3. Measure the probe voltage along the waveguide. Make sure to sample sufficient locations along the waveguide to establish the whole pattern. Especially the locations of the minimum voltage, and the period shape of the VSWR pattern.

   1.4. Repeat 1.3 for the following loads:

      A. Capacitive iris with matched load.

      B. Inductive iris with matched load.

      C. Open (open waveguide).

      D. Matched load

   1.5. Repeat 1.3 for short at additional frequency according to your choose.

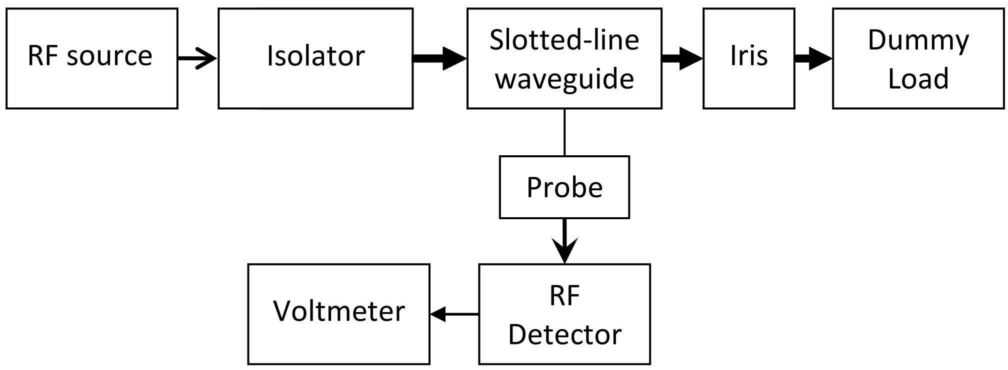


Figure 1.6: Experimental setup scheme for VSWR measurement.

2. Cutoff frequency measurement:
   locate a spot where the maximal power is sampled correctly. Lowered the frequency gradually up to 6 GHz while you keep follow the maximal location sample. Record the maximal power vs. the frequency.

3. Paper scorching inside a microwave oven (executed by the instructor):

3.1. Feed the slotted line shown in Fig. 1.7 with about 5 paper sheets, and turn on the microwave oven for 10 seconds.

3.2. Take off the paper sheets after the microwave shut down and observe the scotching pattern.

3.3. Find the wavelength according to the peaks observed.

Figure 1.7: Slotted waveguide in a microwave oven for shielding, as a 1D resonator.

Processing the results

1. Present the standing wave pattern for each impedance load measured. Use the diode calibration according to the next part of this experiment.
2. Calculate the wavelength according to your results, and compare it to the expected from the theory for each load.
3. Calculate the VSWR, and the reflection coefficient for each load.
4. Extract the impedance for each load, and the equivalent lumped model of the load and the measuring setup.
5. Extract the cutoff frequency and compared to the theory.
6. From the paper scorching pattern; calculate the wavelength and the frequency of the magnetron. Assume that the waveguide width is a = 84 mm.
7. Why the central papers are different in their scorching from the external papers of the pack?
8. (Bonus) compare the capacitive iris impedance with the theory.

2. Microwave measuring equipment

Goals

Get to know the microwave measuring equipment and experience it. In Particular,

1. Using Bolometer and Schottky diode as a means for power measurements.
2. Using resonator.
3. Using spectrum analyzer.
4. Using network analyzer.

Background

Schottky diode calibration

The voltage generated by the diode is related to the RF power according to the voltage-current characteristic of the diode at the Square Law region. In this experiment we will find this function using a calibrated power meter, and a voltage meter accordingly.

Frequency and wavelength measurement

In this experiment we will measure the frequency of the microwave source using resonator. There are two goals for this experiment. The first one is to use the resonator to measure the frequency, and the second is to verify the dispersion. As seen in Fig. 1.8a, the resonator is composed of variable cylinder by a movable piston that changes the length of the resonator. The RF signal is sampled into it by a dedicated coupler (e.g. by a slot). By changing the resonator dimensions, the sampled power is changed. By knowing the resonator dimensions we can extract the RF frequency. A calibration graph is shown for example in Fig. 1.8b. In this example the solution is not a single since there are additional modes are supported. In our experiment the resonator is calibrated as seen on its scale, so we can get a single frequency measurement.

Impedance measurement by the smith chart

In this part we use the network analyzer to measure the impedance of given device, using the smith chart view of the measurement. The ratio between the incident and the reflected waves gives the absolute value of the reflection coefficient. The phase is calculated relative to a short (from the calibration). Example of a smith chart is shown in Fig. 2.2 with the relevant parameters.

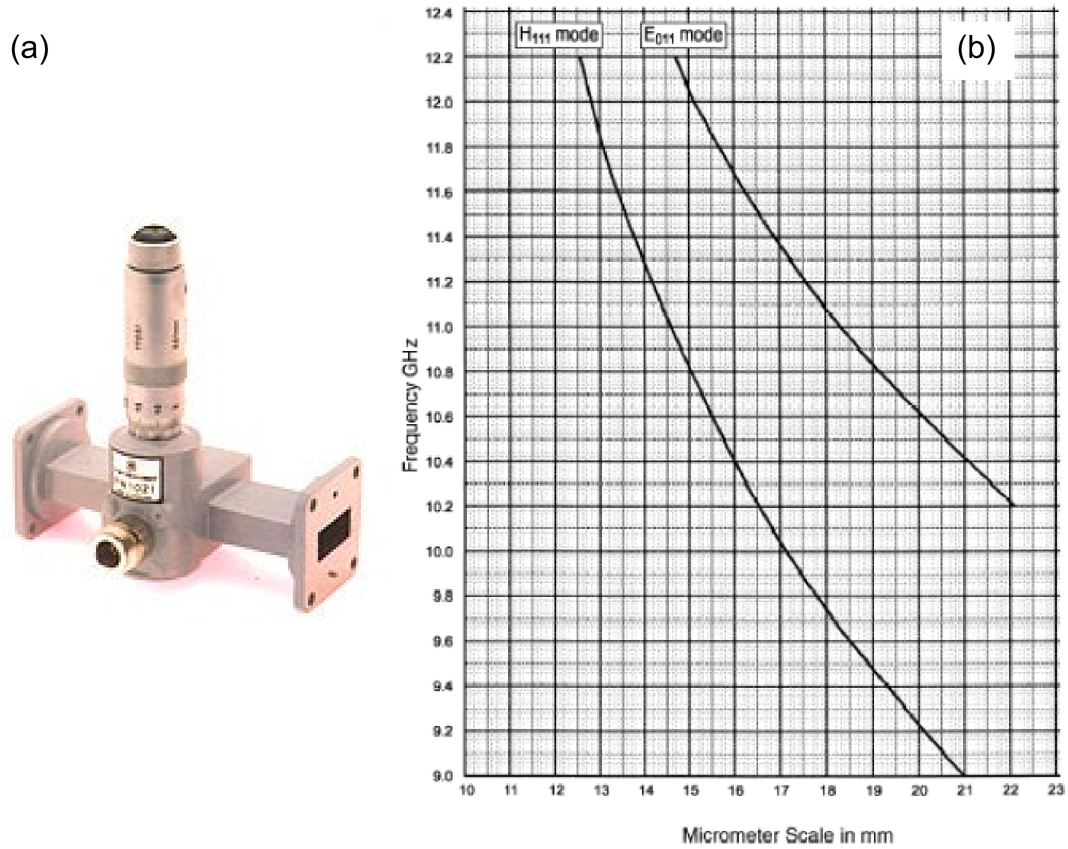


Figure 2.1: (a) Resonator. (b) A clibration chart for cylindrical resonator.

Network analyzer

The network analyzer presented in Fig. 2.3 (note the smith chart view) is one of the basic instruments in each microwave lab. We use vectorial (magnitude and phase) network analyzer up to 14 GHz. With this instrument we can measure several frequency dependent variables such as reflection and transmission coefficients, impedance, VSWR, group delay, and Smith chart for the reflection coefficients. Vectorial network analizers allow phase measurement, however due to their high price, scalar (magnitude only) network are also usable.

General N-port network is seen in Fig. 2.4. This network can be defined by Z or Y matrix to connect voltage and current at each port. Another way to define this network is by the relation between the incident and reflected voltage vector matrix. This matrix is the scattering matrix of this network.

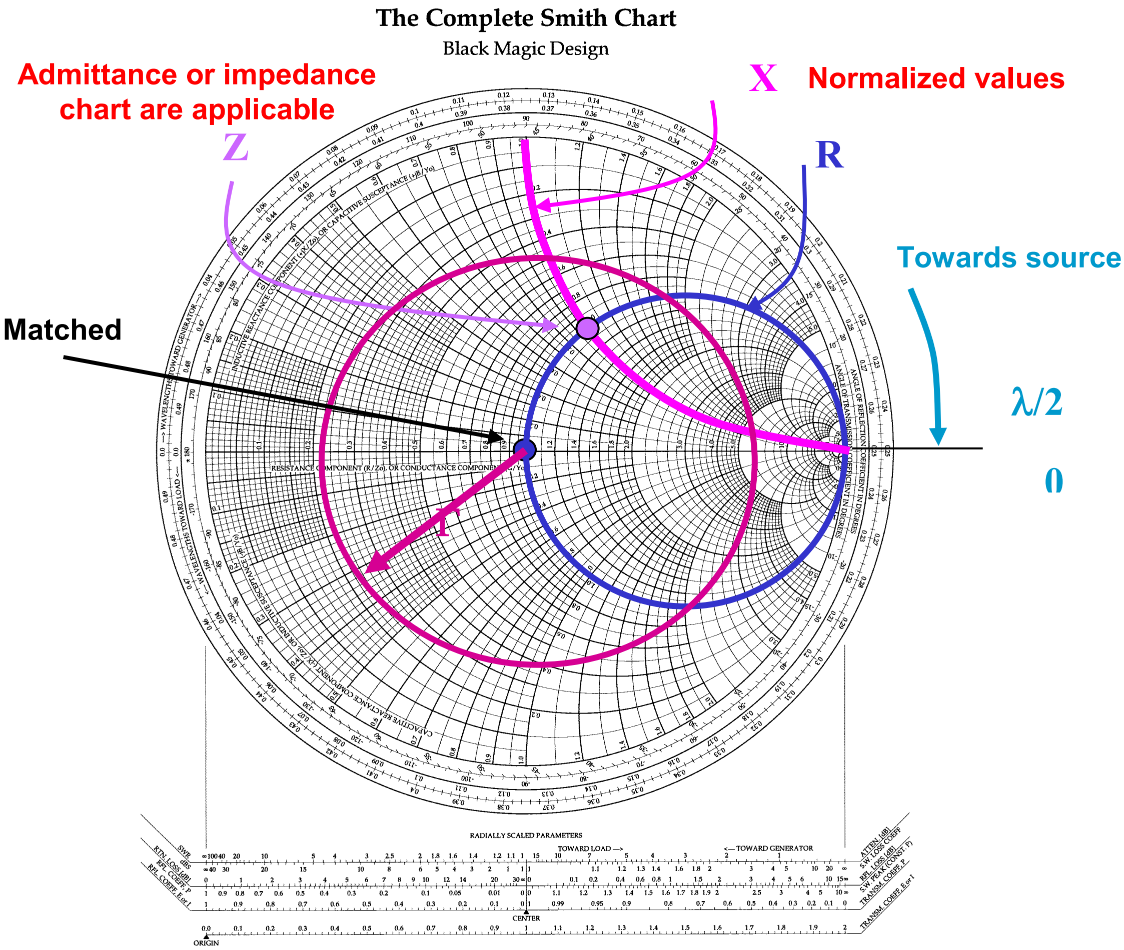


Figure 2.2: Smith chart with main relevant parameters.

Figure 2.3: Network analyzer with smith-chart view.

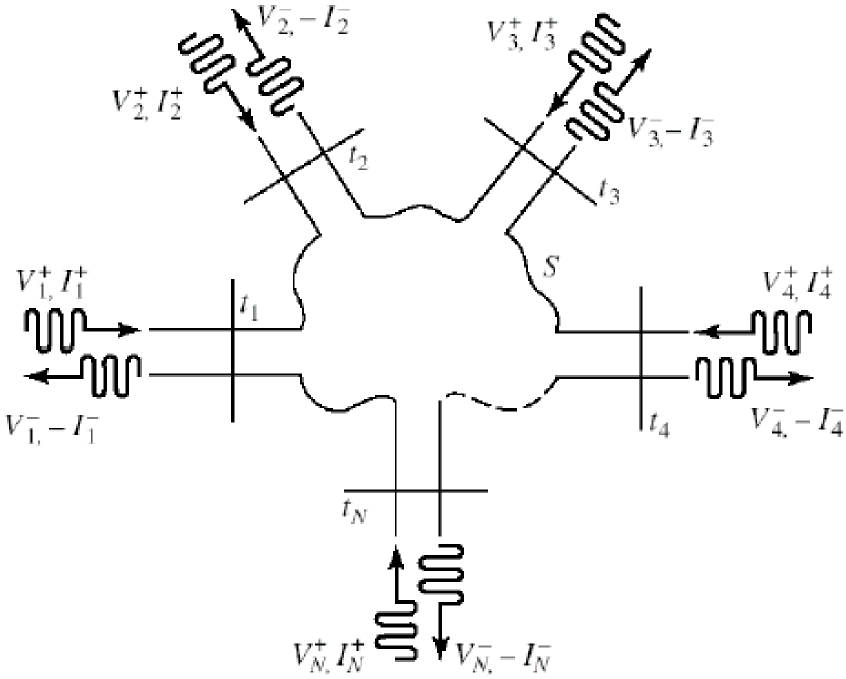


Figure 2.4: Arbitrary N-port network.

$$\begin{bmatrix} V_1^- \\ V_2^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1N} \\ S_{21} & S_{22} & & S_{2N} \\ \vdots & & \ddots & \vdots \\ S_{N1} & S_{N2} & \cdots & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \\ V_N^+ \end{bmatrix}$$

$$V^- = S \cdot V^+ \qquad S_{ij} = \left. \frac{V_i^-}{V_j^+} \right|_{V_k^+ = 0 \ \text{for} \ k \neq j}$$

Each value in the matrix is a ratio between two voltages in the network, while in the numerator is the output port *i* phasor and in the denominator is the input port *j* phasor (marked by '-' and '+' respectively). Note that the diagonal values are the reflection coefficient by definition at each port (while the other ports are matched). Additionally, the rest of the values are the transmission coefficient between them.

The S-matrix defines the network, in particular:

- When the diagonal is zero, all the ports are matched.
- When the matrix is symmetrical, the network is mutual, i.e. there is not a preferred direction of propagation.
- When the matrix is unitary, the network is lossless.

$$\sum_{k=1}^{N} S_{ki} S_{ki}^{*} = 1$$

$$\sum_{k=1}^{N} S_{ki} S_{kj}^{*} = 0 \qquad \text{for } i \neq j$$

Unitarily is achieved when the multiplication of each row/column by its conjugated same row/column yields 1, and a multiplication of each row/column by other row/column (and vice versa) yields 0.

The internal construction of the network analyzer include sweeping oscillator that its output is transferred to the output port of the network analyzer. The input port of the network analyzer is connected to the output port of the tested device as well. The reflections at the output port (using directional coupler) and the transmission at the additional port are done by detectors (in the scalar network) or by internal mixers (in the vectorial network) they allow the scattering parameters measurements in absolute or complex values according to the measurement type. Here we use the FSH network analyzer of Rohde & Schwarts for scalar measurements only.

The first stage of the working procedure is the calibration of the setup. The calibration is done referring to the tested network port as close as possible. For that we execute reflection and transmission calibration. In this process the device scans the requested frequency range and compensates the magnitude and phase loss from the network that connects the tested device to the analyzer. The ports that used for the calibration are the reference ports of the measurements. The calibration is done by a dedicated calibration kit including short open and load. Basic calibration kit is shown in Fig. 2.5.

Spectrum analyzer

In this part we use the spectrum analyzer to analyze spectral content of arbitrary signal generator. The spectrum analyzer shows the power density vs. the frequency. This device measures the absolute power (as opposed to the network analyzer), therefore it suitable for generator characterization and arbitrary signals. However, the total power measurement is less accurate than the bolometer due to the wide frequency scanning. The bolometer measurement requires settling time which is not impossible when scanning like here.

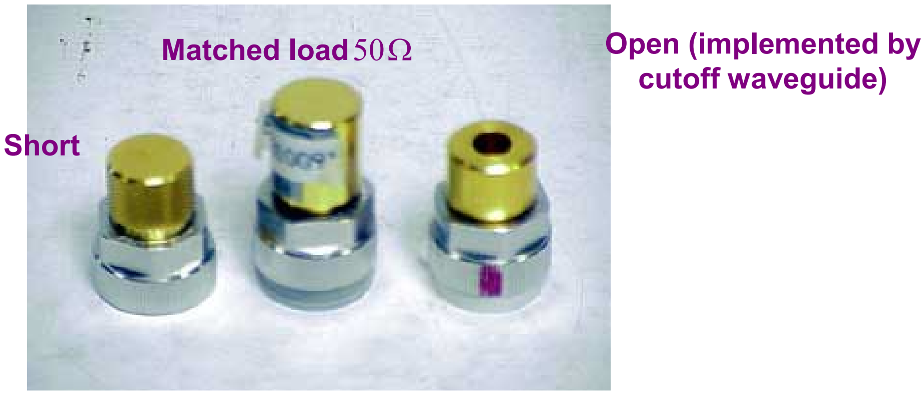


Figure 2.5: Basic calibration kit.

Preparation questions

(You can use Posar, pp. 182-183, 282-287, 509-514 as a reference)

1. Describe the Bolometer power meter principle of operation, and the Schottky diode. Compare the versatile power measurement techniques, and discuss the pros and cons of each method.
2. Explain the structure and the operation principle of the resonator. How the reflection and transmission coefficients are changed at the resonance frequency?
3. Describe the internal structure of the spectrum analyzer using a block diagram and explain its principle of operation.
4. Learn and explain the working procedure of the spectrum analyzer. What are the main parameters that the operator controls, and how they take effect on the measurement?

5. You have a YIG band pass filter with bandwidth of BW (parameter) around voltage-controlled frequency f (i.e. $f \pm BW/2$). Sketch a new spectrum analyzer with this device, and elaborate the advantages if exist.
6. Show the block diagram of typical vectorial network analyzer. And explain its internal structure, the operation principle, and the operating procedure.
7. What is the calibration purpose of the network analyzer, and how does it done?
8. Study the operational procedure of the Agilent E5071C network analyzer according to the manufacturer data.

Equipment

1. Schottky diode
2. Variable attenuator
3. Voltage meter
4. Coaxial cables
5. Power meter
6. Connectors (SMA, N-Type)
7. Signal generator
8. FSH-3 mobile network and spectrum analyzer (by Rhode & Schwartz)
9. Spectrum analyzer
10. Network analyzer (Agilent E5071C)

Experiment goals

1. Experience versatile calibrations (Schottky diode, network analyzer).
2. Measuring resonator frequency response
3. Spectral measurements of signal generator
4. Measuring the scattering parameters of arbitrary device.

Experiment sequence

1. Schottky diode calibration:

   1.1. Assemble the setup shown in Fig. 2.6.

   1.2. Use the bolometer to measure the power in the range of -40 to 0 dBm.

   1.3. Measure with the diode and the voltmeter the same data.

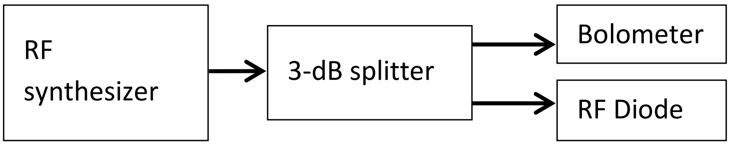


Figure 2.6: Diode calibration setup.

2. Spectral measurements of the signal generator:

   2.1. Connect the signal generator to the spectrum analyzer with 10dB attenuator.

   2.2. Frequency measurement:

      2.2.1. Use the Marker to get the power and the frequency of the generator.

      2.2.2. Change to manual mode.

      2.2.3. Lower the span significantly, and follow the image. Capture the screen at the best shot image.

   2.3. Noise measurement:

      2.3.1. Decrease the intensity of the signal until it is equal to the noise floor, so you cannot identify it anymore on the spectrum analyzer. Write down this value.

      2.3.2. Repeat 2.3.1 for different RBW values (at least four). Record the power and the noise floor as a function of the RBW, and capture the screen. Is the minimal signal power of the measureable signal changed? If so, explain the change referring to the RBW.

3. S-parameter measurement

   3.1. Calibrate the network analyzer (including the connected cables required for the setup), using the calibration kit according to appendix A.

   3.2. Verify the calibration by testing an attenuator and another known device (according to the instructor). Save the data to a CSV file (using the Save/Recall menu).

   3.3. Measure S-matrix of a two-port component according to:

3.3.1. Connect the input port to Port 1 and the output port to Port 2 of the network analyzer.

3.3.2. Choose the measured parameter under the Meas. menu (for S_{11} measurement the rest of the ports should be matched)

3.3.3. Save the data in a CSV format (by the Save/Recall menu).

4. Resonator for frequency measurement:

4.1. Connect the resonator as tested device to the network analyzer, for S_{21} measurement.

4.2. Measure Network analyzer output frequency by the resonator (using the movable piston). What is the on-screen image?

Processing the results

1. Present the calibration graph of the Schottky diode using your measurements (voltage vs. power), and explain the results.
2. Mark on the graph the Square Law region in the graph and explain its meaning.
3. What is the diode conversion coefficient?
4. What are the on-screen spectrum analyzer axis units?
5. How the Span variation affects the spectrum analyzer image? Does the image represent the signal correctly? Explain.
6. Outline the noise level in respect of the RBW parameter. Extract the noise level to BW ratio of the analyzer. In how much this value differs from the thermal noise, and what is the reason for this difference?
7. What is the reason of the signal to noise ratio (SNR) change, as a result of the RBW variation of the spectrum analyzer?
8. What parameters of the frequency scan are changed as a result of the RBW change, and what is the connection between them?
9. Show the reflection and transmission coefficients of the tested devices for the calibration validation by a graph.
10. What are the deviations between the resonator and the network analyzer measurements, given in the frequency measurements output using the resonator?

3. Passive rectangular waveguide microwave devices

Goals

1. Measuring scattering parameters, and experience with their use.
2. Get familiar with microwave devices
3. Use directional coupler as a means to measure transmission and reflection scalar coefficients.
4. Experience with vectorial network analyzer.

Background

In this experiment we study the following devices: circulator, magic tee, directional coupler and variable attenuator, and measure their scattering parameters, as presented in Fig. 3.1. These devices are implemented by rectangular waveguide either because of high microwave power or due to the inevitable implementation by the rectanugular waveguide.

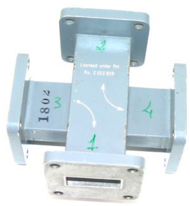
	
Circulator	Magic Tee
	
Directional coupler	Variable attenuator

Figure 3.1: Rectangular waveguide based devices.

Preparation questions

1. Regarding the following items, explain shortly: the physical structure, the principle of operation of the device, the scattering matrix with sketch according to the port numbers, and describe the implementation by rectangular waveguide.
    a. Directional coupler.
    b. Tee junction in E and H plane.
    c. Magic-Tee
    d. Variable attenuator.
    e. Phase shifter.
2. For the directional coupler, explain the meaning of its Coupling and Directivity.
3. How can you measure with directional coupler and power meter the magnitude of the reflection coefficient of single port arbitrary element?
4. Regarding the following list of properties, explain their meaning and how it is represented in the scattering matrix.
    a. Lossless
    b. Mutual
    c. Perfectly matched.
5. How many properties mentioned in the previous question can exist in a three-port network.

Equipment

1. Signal generator
2. Power meter
3. Network analyzer (Agilent E5071C)
4. Microwave devices (WR-90): directional coupler, circulator, magic-tee, variable attenuator.
5. Dummy load.
6. Connectors and adapters.

Experiment goals

Measure the scattering parameters of the devices shown in Fig. 3.1.

Experiment sequence

1. Measure the S-matrix by network analyzer.

   1.1. Calibrate the network analyzer (as in the previous experiment).

   1.2. Use the setup described in Fig. 3.2 according to the following directions to measure the scattering parameters. You can assume the mutual property, for mutual device using a proper explanation.

   A. Directional coupler

   B. Magic Tee

   C. Circulator

   D. Variable attenuator

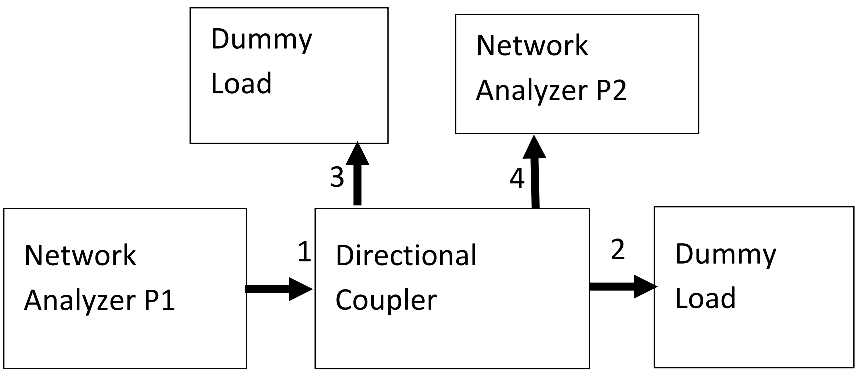


Figure 3.2: Setup to measure the S-matrix of directional coupler.

The measurement with the network analyzer should be followed this sequence of orders:

a. Set the frequency range to the requested value: 6-14 GHz, and calibrate accordingly.

b. Mark the port numbers according to your choice, and take photo or sketch your marks.

c. Connect the ports 1 and 2 to the input and output ports, respectively.

d. Connect dummy loads to the rest of the ports.

e. Choose the requested measurements from the "Measurement" menu. For example, choose "Phase" in the "Format" list.

f. Measure the reflected and transmitted values.

g. Save the graphs using the Save/Recall menu, by Save Trace option. The file type saved is csv that can be processed by Excel.

Processing the results

1. Mark the frequency range of operation for each device, and explain the difference.
2. Show the S-matrix for the center frequency for each device according to your port marks. Show the sketch of the port numbers accordingly.
3. Compare the results to the theoretical prediction, according to the device properties, explain the differences if exist.
4. Compare the phase between the ports of the Magic-T to the theoretical values.
5. Show the reflectance, transmission, coupling and isolation of the directional coupler as a function of the frequency. Why the results depend on the frequency?
6. How can you implement an Isolator, using a dummy load and circulator?
7. What is the gyromagnetic ratio of the circulator, and how it is expressed in the results?

4. Microwave signal sources

Goals

Observe microwave generators, and study their properties.

Background

Diverse microwave sources are shown in Fig. 4.1 (not up-to-date but represented) according to their power and frequency range. There are two major distinct device types in this map, the vacuum tubes, and the solid state devices. Generally, the solid state devices are limited by their power, however they smaller. Thus, vacuum tube technology are in use for high power applications (>1 kW) at high frequency (>10 GHz). Additionally crystal based microwave sources are existed with high accuracy and frequency stability however they typically function as a reference frequency source.

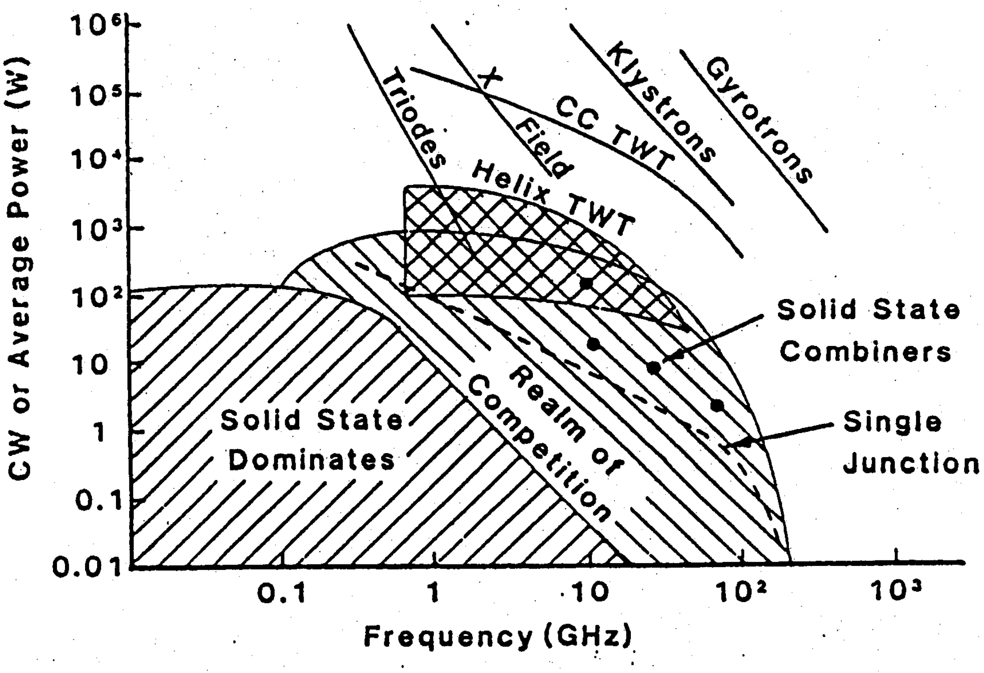


Figure 4.1: microwave sources as a function of frequency and power.

Choosing the microwave source is done according to the application. At low power and frequency rates, where not exceptional demand for frequency stability or for some switching purposes exists, a single oscillator implemented by feedback and transistor (like Hartley or Colpitts) can be used. In a case that the accuracy is more critical, a crystal oscillator can be used. Because it is limited by the maximal frequency, a frequency doubling can be used to established similar operation at higher frequencies.

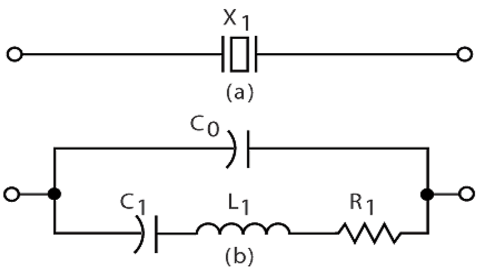


Figure 4.2: Commercial crystal oscillators, with electrical model.

The following general properties can be used to describe microwave sources:

Accuracy – the accuracy of a microwave source is used to estimate the maximal frequency change of the signal source relative to the frequency it is design to emit ($\Delta f / f$). This figure can be given in absolute values (Hz) for the frequency variation or in relative values (ppm), respectively. Since this value can be changed over time we use the additional property.

Stability – the stability of the source is defined as the accuracy measured during a certain time period. For few hours range it is called as Short-term Stability, and for few days it is called as Long-term Stability. The stability therefore is defined according to the use. For example, Radar requires short term operation due to the time period of the tracking and discovery. A cellular channel works for long terms in which it should be synchronized properly. Figure 4.3 presents the difference between these properties.

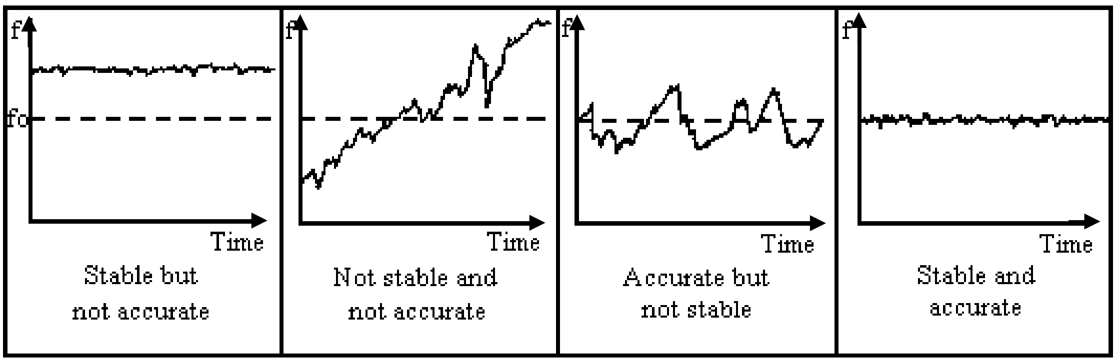


Figure 4.3: The accuracy and stability factors of microwave source.

The phase noise of the source involves the following factors:

- Random walk FM – determined by environmental sources (mechanical shocks, temperature, motion)

- Flicker FM – determined by noise in the resonator, and by other active components.
- White FM – wide range noise depends on the Q-factor of the resonator.
- Flicker noise – noise in active devices (generated by discontinuity of the semiconductor parts)
- White (Johnson) noise – thermal noise.

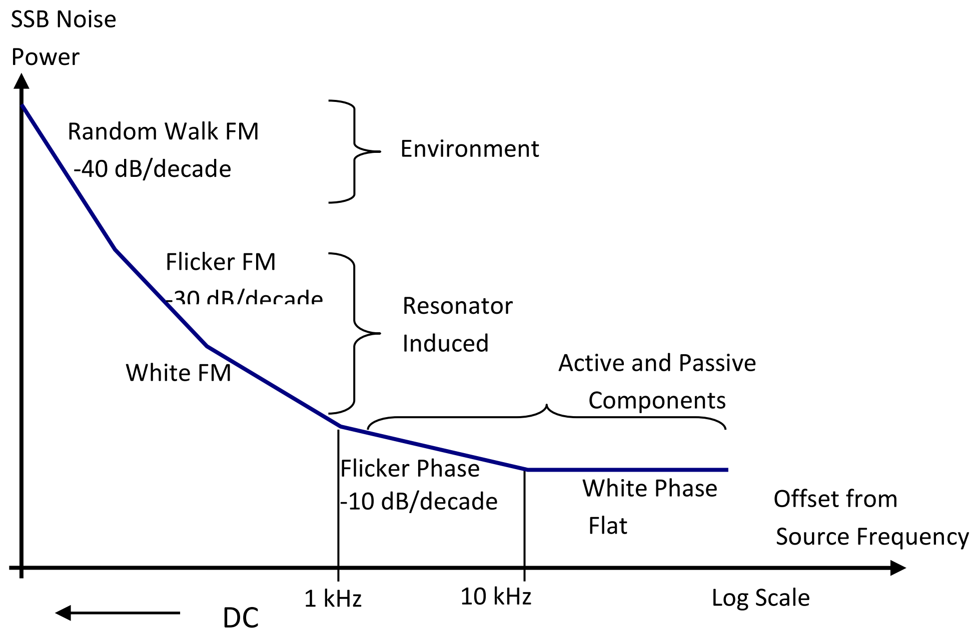


Figure 4.4: main noise factors and their frequency dependence (log scaled).

Note that the phase noise is measured in dBc/Hz at certain frequency shift. For example, to measure the noise phase of 10 GHz source at 100 kHz shift, we use a resolution bandwidth of the spectrum analyzer of 1 Hz. We will measure the power at the main frequency, and then the power at 10.0001 GHz (the spectral image of pure sine wave is the delta function). This ratio of the power determines the single-side band (SSB) noise figure. The thermal noise $N = kTB \cong -174$ dBm in this case limits the phase noise at higher frequency shift from the center frequency.

Crystal oscillator can be used as a reference source to establish stable source at high frequency by building frequency doubler). A thumb rule to estimate the noise phase in this case is to add 6 dB of noise for each multiplication of the frequency (the heuristic explanation is that a mixer is used to multiple the signal, and the energy is proportional to the square of the voltage).

A voltage controlled oscillator (VCO) sources in the GHz range depicted with deteriorated phase noise calculated from the multiplication of the crystal frequency noise. Therefore, the phase-locked loop (PLL) based circuits involve more complex calculation according to the additional parameters. In those systems the high frequency of the VCO is divided and compared to the reference signal. The feedback loop latches the phase and produces a stable output according to the scheme presented in Fig. 4.5. the trainer kit includes such a circuit.

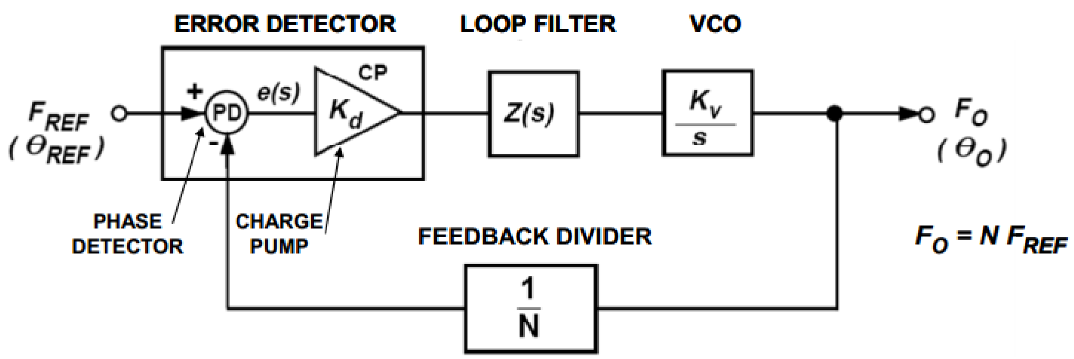


Figure 4.5: A basic PLL scheme

In addition to the solid state sources we examine a vacuum tube source as exist in the familiar microwave oven. Typical magnetron produces 1 kW at 2.45 GHz in a Duty Cycle of ~50%. It is fed by 4 kV and a heating filament of 3 V. The power is generated by energy coupling from the free electrons accelerates in a circular track, to the electromagnetic wave in the resonators within the tube.

Preparation questions

1. What is phase noise, how it is shown in the spectral image of the signal, and how it is measured?
2. What is a thermal noise, how it depends with other sources, and what is its spectral density?
3. Describe the principle of operation of Gunn device. What are its modes of operation?
4. Explain the structure and the principle of operation of crystal oscillator.
5. Find the datasheet of <100 MHz crystal oscillator, and other ~10 GHz source. Explain the main parameters and determine the differences according to accuracy and frequency stability.
6. Explain the structure and principle of operation of VCO. How it can be implemented?
7. Explain the structure and principle of operation of a PLL system. Why the feedback exists, and how the VCO involves?

8. Explain the structure and principle of operation of dielectric resonance oscillator (DRO). Describe how the output frequency can be changed.
9. Explain the structure and principle of operation of typical magnetron. What is the Hartree and Rieke diagrams? What is the peak of the output power that can be extracted from relativistic magnetron?
10. How the frequency of the Gunn oscillator is determined?
11. What is the (Total Harmonic Distortion) THD parameters, and how it is measured?

Equipment

1. Gunn oscillator
2. VCO
3. DRO
4. Signal generator
5. Vacuum tube source
6. Trainer kit
7. Connectors and adapters.
8. Voltage source
9. Coaxial cables
10. Spectrum analyzer
11. DVM

Experiment goals

1. Measure the spectrum of an arbitrary microwave source.
2. Measure the Gunn oscillator as a function of the input voltage.
3. Measure the VCO frequency as a function of the voltage.
4. Spectral characteristics of the signal generator output.

Not that the microwave sources are replaceable and might be change according to the instructor, and the available equipment. As a result, the appropriate question only should be done.

Experiment sequence

1. VCO or other signal source as DRO:

   1.1. Attach the source to the spectrum analyzer using appropriate attenuator. The VCO should be connected to an additional DC source from the Vtune port. Use DVM to measure this voltage.
   For the DRO: connect it to the power supply according to the requirements.

   1.2. Change the tune voltage according to the spec, and measure the output frequency.

   1.3. Measure the phase noise of several frequencies by the spectrum analyzer.

   1.4. Turn off the power supply and wait for a minute. Measure the spectrum again and compare it to the previous measurement.

   1.5. Chose tune voltage and measure the whole spectral range, including the fundamental frequency and its harmonics.

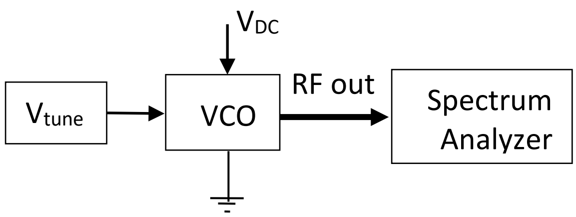


Figure 4.6: Setup for VCO connections.

2. Gunn oscillator

   2.1. Attach Gunn oscillator to the spectrum analyzer using Isolator. Connect it to the power supply (validate with the instructor) of 7 V @ 300 mA (current limit).

   2.2. Change the frequency by moving the frequency knob, and record the output spectrum.

   2.3. Measure the phase noise of the Gunn oscillator.

   2.4. Turn off the power supply and wait for a minute. Turn on again and record the output spectrum.

2.5. Measure the whole spectral range, including the fundamental frequency and its harmonics.

3. Signal generator or vacuum tube generator.

3.1. Attach the source to the spectrum analyzer using appropriate attenuator. Change the transmitting frequency and record the results.

3.2. Measure the phase noise of the source.

3.3. Turn off the power supply and wait for a minute. Turn on again and record the output spectrum.

3.4. Measure the frequency stability, using the Max-hold function.

3.5. Use attenuator and increase the output power. Record the whole spectrum including the harmonics, how they evolve relative to the output power?

4. Cristal oscillator

4.1. Connect the generator in the trainer kit to the spectrum analyzer. Choose the operating frequency using the control program in the PC.

4.2. Record the output spectrum for several operating frequencies.

4.3. Measure the phase noise of the source.

4.4. Turn off the power supply by disconnecting the trainer kit, and wait for a minute. Turn on again and record the output spectrum.

4.5. Measure the harmonics in the output spectrum, including the fundamental frequency.

Processing the results

VCO/DRO:

1. (for VCO only) Show the frequency-voltage characteristic of the VCO.
2. What is the phase noise? Compare to the datasheet.
3. Explain the differences of similar measurements (if exists)
4. Compare the harmonic energy to the manufacturer data. What is the THD?

Gunn:

5. Explain the change by moving the knob in the device. What is the reason for this?

6. What is the phase noise?

7. What are the accuracy and the stability of the Gunn oscillator?

8. Is the frequency changed after turning on and off the device? How much, and what is the reason?

9. What is the THD of the Gunn?

Frequency generator and vacuum tube generator:

10. What are the phase noise and the THD of the generator? Compare to the datasheet or to other similar source.

11. What is the stability and accuracy?

12. What is the mechanism that generates the oscillations? How is it implemented, and what is the principle of operation?

Cristal oscillator:

13. What are the phase noise and the THD? What is the accuracy and stability?

Summary:

14. Compare the microwave sources by the properties in means of accuracy, stability, noise, and THD.

5. Detectors and mixers

Goals

1. Use Schottky diode as a non-linear device at microwave frequencies.
2. Use diode as microwave detector.
3. Get familiar with models and parameters of diverse mixer types

Background

The systems up to now included one independent signal source. In many cases there are non-linear elements like amplifiers, multipliers, diodes and mixers. As a result, additional signals are generated in a form of harmonics and intermodulation signals. We can use the spectrum analyzer to detect those signals and characterizes them. According to the purpose, different signals might be wanted and others considered as parasites that we want to eliminate.

Preparation questions

1. What is the difference between Schottky to PN junction? What is the cause for the non-linear characteristics?
2. How can we use diode as a basic mixer? Use the non-linear I-V curve in your explanation.
3. What are the differences between Detector and Mixer?
4. Find datasheet of commercial mixer and explain the main properties, especially the IP3.
5. Explain how Super-heterodyne receiver works. Refer to the mixer role in the receiver.
6. What is balanced mixer, and what is the difference from basic mixer?
7. How balanced mixer is implemented by Magic Tee?
8. Explain IQ mixer structure. What is the Hybrid role there?

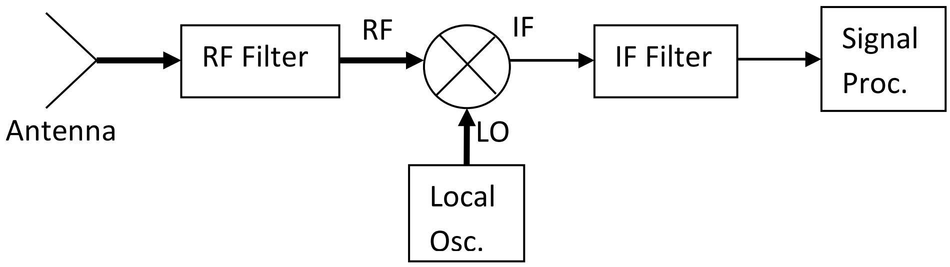


Figure 5.1: Scheme of Super-heterodyne receiver

Equipment

1. Mixer.
2. Signal generator
3. Diode detector
4. Trainer kit
5. Magic Tee
6. Cables and connectors
7. Spectrum analyzer

Experiment goals

1. Use diode as a detector and mixer
2. Measure the spectrum of a mixer
3. Characterize mixers

Experiment sequence

<u>Mixer characterization</u>

1. Connect the LO port of the mixer to the RF generator, and the RF port to other generator. Connect the IF port to the spectrum analyzer as shown in Fig. 5.2. Use LO power as required by the datasheet, and apply RF power 10 dB less. Record the spectrum analyzer output in this case.

2. Change the LO and RF frequencies, and record the changer accordingly.

3. Increase the RF power until the intermodulation signals at the 3rd order appear. Record the output spectrum as a function of the power. Note the threshold level for the IP3 signal, and the corresponding harmonics level. Increase the power and reveal high order signals.

4. Repeat the previous orders for balanced mixer, or for other mixer according to the instructor.

Implementation of mixer by detector diode

5. Connect diode detector to RF source as done in experiment No. 1. Modulate the signal with square wave, or pulse train (AM), and use the sope to observe the output. Measure the rise and fall time.

6. Connect two RF source at the E and H planes of the Magic Tee. The other two ports are connected to a dummy load and to the detector. Show the IF spectrum using the spectrum analyzer.

7. Change the input frequencies, explain the corresponding spectral output.

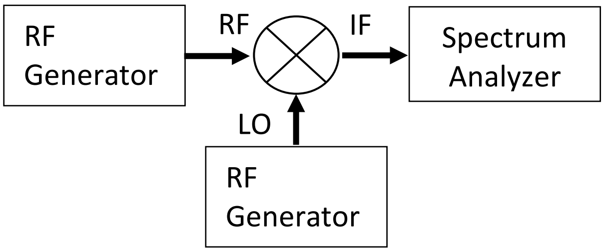


Figure 5.2: Setup for output spectrum analysis

Processing the results

1. Describe the output spectrum of the mixer in your data, and explain their origin. What is their power relative to the fundamental frequency?

2. What are the desirable spectral lines of the mixer for several applications?

3. What are the disadvantages of a mixer with a single diode element?

4. Compare the mixer performance between different architectures. Especially, refer to the conversion efficiency (ratio between the output to input power) and to the spectral clarity (ratio between the desired frequency in the output spectrum to the whole spectrum).

5. In which scheme of the mixer the isolation between the two input ports is the best? What is the necessity of this factor?

6. What is the meaning of the IP3 parameter, and what is its value for the measured mixers?

7. Present the mixer characteristics (output to input power of the first intermodulation). Mark the IP3 spot.

6. Impedance matching

Goals

1. Standing wave and impedance mismatch in distributed systems
2. The need for impedance matching
3. Try several matching techniques especially:
    a. Single stub matching by changing its location and depth (using a slide-screw tuner)
    b. Use the Magic-Tee with two variables stubs (E-H tuner)
4. Use smith chart for impedance matching

Background

The necessity for impedance matching emerges from the following reasons:

1. Maximize the transferred power to the load, and avoiding power loss.
2. Avoiding the reflected power to the source.
3. Avoiding standing waves that can harm the system and distort the signal.
4. Effective use of the spectral band.
5. Radiation safety.

Common method to implement the impedance matching is by stubs. The implementation of these stubs is according to the waveguide type (rectangular waveguide, coaxial cable, microstrip, etc.), as shown in Fig. 6.1, but the principle of operation is similar. The number of the stubs determines the freedom factor, and therefore the operating bandwidth, and the reflectance in the matched range. Transformers for impedance matching are implemented with parallel or serial elements, and by continuous variation along the waveguide (Tapered transmission line).

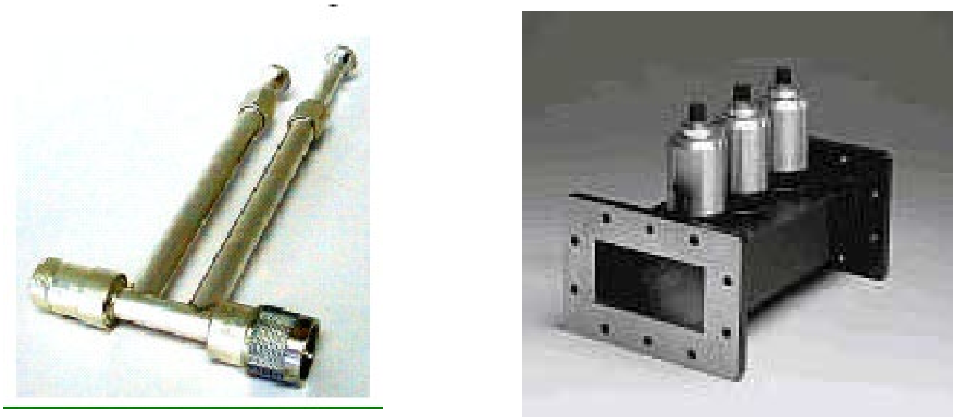


Figure 6.1: Implementation example of two tubs in coaxial waveguide and tree subs in rectangular waveguide.

In this experiment we use two methods for impedance matching, the Slide-screw tuner (as shown in Fig. 6.2) and the E-H tuner implemented by Magic-T. The Slide screw tuner is equivalent to single stub matching in a single transmission line. Here, we find the distance to the load and the screw depth for match in the requested frequency.

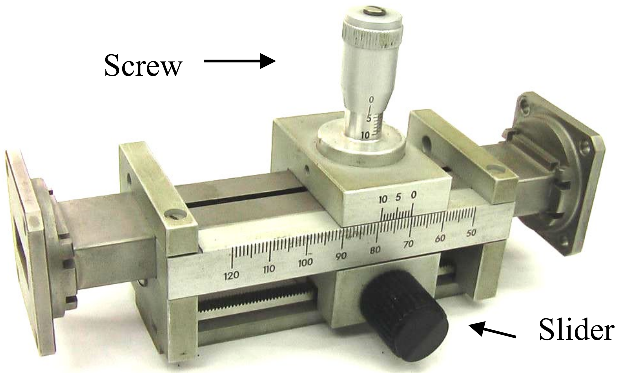


Figure 6.2: Slide-screw tuner for impedance matching in a rectangular waveguide.

We use the Magic-T as shown in Fig. 6.3 to implement two stub matching system. For this we assemble two stubs at ports 2 and 3, and in ports 1 and 4 the load and the source will be connected respectively.

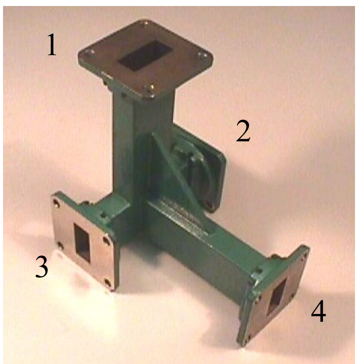


Figure 6.3: Port numbers in the Magic-T for impedance matching

Preparation questions

1. In this experiment we use the Slide-screw tuner as in Fig. 6.2 to match arbitrary impedance. The match is done by changing the location and the depth of the screw in the waveguide. According to the scheme presented in Fig. 6.4:

    a. Construct an expression for the impedance at the entrance to the waveguide as a function of load impedance, the location and the depth of the screw, according to the circuit model in Fig. 6.5.

    b. Is this system can match any load impedance to the waveguide?

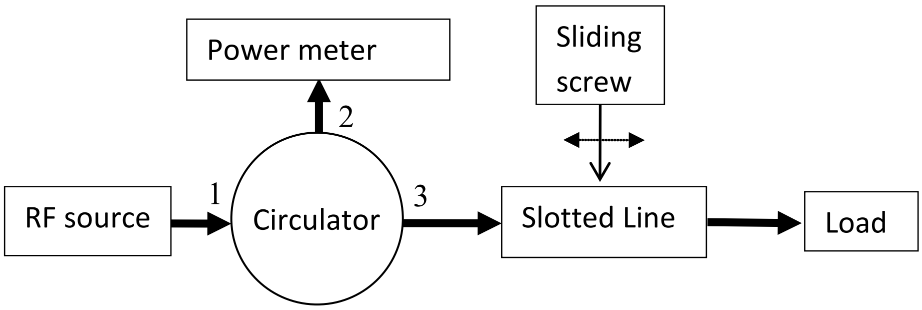


Figure 6.4: Matching impedance system using single stub tuner.

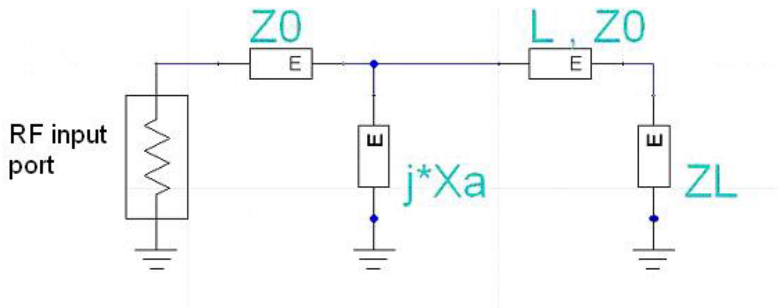


Figure 6.5: Electrical circuit model for the Slide screw tuner.

2. In the Double-stub tuner we use other method to match impedance, with constant distance between two stubs so we can change only their length and not their location (as opposed to the single stub). Is this method can be used to match any load to the source? Under which circumstances if so?

3. A system for impedance matching by Magic-T and two variable short stubs (E-H tuner) is shown in Fig. 6.6:

    a. Is this method equivalent to double-stub tuner?

    b. Construct an expression to the load at the entrance in port 1 as a function of the load at port 4 and the short locations at ports 2 and 3 (i.e. the l_2 and l_3 lengths). Use the S-matrix of the ideal Magic-T with two ideal shorts at l_2 and l_3 lengths from the ports.

c. Find the l_2 and l_3 lengths required for matching several loads according to your choice on the smith chart.

d. Is this method applicable to match for any load to the waveguide?

4. Compare those impedance matching methods to the Triple-stub tuner.

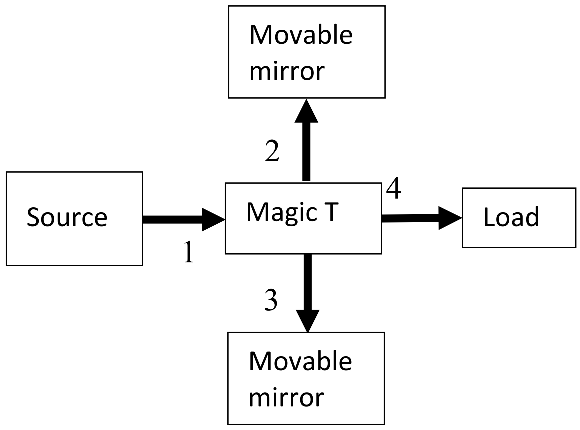


Figure 6.6: E-H tuner setup implemented by Magic-T and two variable shorts

Equipment

1. Slide-screw tuner.
2. Power meter
3. Loads with iris
4. Network analyzer
5. Magic-T with two shorts
6. Cables and connectors

Experiment goals

1. Impedance matching of several loads
2. Slide screw tuner
3. E-H tuner

Experiment sequence

In this experiment we match the following impedances, for each method:

- open waveguide
- inductance iris and load
- capacitive iris and load

1. Slide screw tuner

    a. Construct the setup according to Fig. 6.4 for each load, or use the network analyzer instead. By changing the location and depth of the screw, try to match the load. Use a single frequency in the X-Band according to your choice with 10 MHz span at the smith chart presentation

    b. Record the complex impedance where the screw is out of the waveguide – without match, and extract (can be done later) the impedance.

    c. By changing the depth and location of the screw, match the load in the desired frequency.

    d. By changing the frequency, estimate the matched bandwidth for reflection coefficient smaller than 0.1.

    e. After matching the load, measure the reflection as a function of the screw location for small variations. Use at least 3 samples for the depth multiplied by another 3 for the location. Use another measurement at random location.

    f. Find additional matching spots. How the distance between the matching spots are related to the waveguide properties?

2. E-H tuner

    a. Use the setup shown in Fig. 6.6 to match the load by the network analyzer or by directional coupler and scalar detector.

    b. Try to match the load by changing the short (mirror) length.

    c. By changing the frequency, estimate the matched bandwidth for reflection coefficient smaller than 0.1.

    d. Find additional matching spots.

Processing the results

1. For each matching, plot a graph for the reflection coefficient as a function of the element length (screw, mirror …), for three locations according to your choice.
2. Calculate the load impedance before and after the matching.
3. What is the corresponding power transmission increase to the load for each case (with and without match)?
4. For the successful match case, what is the bandwidth? Explain how you extract this value from your measurements.
5. Describe the matching sequence using the Slide-screw tuner in a means of single stub matching. What is the screw depth effect on, and what is its location effect?
6. For several matching spots, what is the relation between the distances to the waveguide properties?
7. Explain the matching sequence according to your expression for the reflection coefficient you developed in the preparation work. Compare the results.
8. Compare the matching methods. Relate to the quality, sensitivity, limitation, and total complexity.

7. Amplifiers

Goals

1. Typical properties of amplifiers
2. High frequency amplifiers type
3. Amplifier structure as active distributed system

Background

In this experiment we use the spectrum analyzer to measure several parameters of RF amplifier, in particular the gain, bandwidth, response curve, and 1 dB compression point. The gain saturation emerges from the output power limitation of active components in the system. At its linear region of operation, the gain is constant. When the input power increases, the amplifiers enters to the region where the output power cannot be amplified at the same gain factor, as small signal. The point where the amplification decreases in 1 dB relative to the small signal is referred as the 1 dB compression point. Larger decrease occurs beyond this point, where the amplifier saturated as shown in Fig. 7.1. Higher input power can further damage the amplifier.

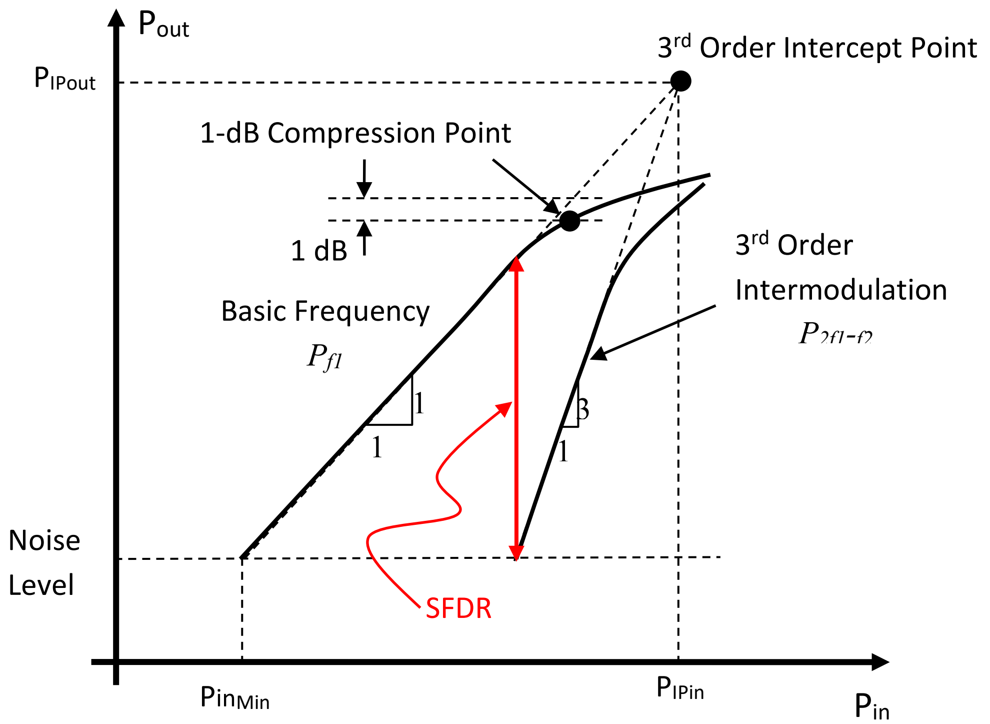


Figure 7.1: Output power as a function of the input power and the typical characters.

As observed previously at mixers, intermodulation signals are generated by nonlinear devices, and creates new signals which are sum and difference of the original ones, and their harmonies. In this experiment we will focus up to the 3rd harmony ($2f_1 - f_2$, where f_1 and f_2 are the two original signals at the input). The 3rd intermodulation harmony depicted by its frequency location which is in the band of the input signal, which is hard to filter. The slope of this harmony is three time higher than the first harmony, in respect to the input signal power, as shown in Fig. 7.1. However, the third harmony is observed only at high input power above the noise floor, so there is a dynamic range of the fundamental signal where it is observed alone. This range is called Spurious-free dynamic range (SFDR) as shown in Fig. 7.1. At higher power rates, an interception point is given between the two gain lines. This point is imaginary (achieved by extrapolation), hence named as 3rd order interception point (IP3). Normally, this point should be far as possible to decrease distortion at the output. Practically, the amplifier is saturated at lower power rates, so the 1-dB compression point might be lower by 10 dB than the IP3.

Preparation questions

1. Explain shortly the following terms, and explain how they can be measured
   a. Gain
   b. 1 dB compression point
   c. Intermodulation
   d. IP3
   e. Noise Figure
2. Which differences exist between high and low frequency implementation of an amplifier (for example 10 GHz and 1 kHz respectively)? Refer to the design rules you know, and sketch the electrical circuit.
3. Find some amplifier designed for microwaves (>1 GHz), and explain the main parameters there.
4. What is the order of operations for turning on an amplifier for microwave range? Refer particularly to the DC operating voltages, the output and input ports.
5. Extract an expression for the total noise figure of cascade of two amplifiers with known gain and noise figure.
6. You need to cascade two amplifiers with gain and noise figure of 20 dB, 6 and 10 dB and 3 respectively. What is the total gain and noise figure referring to the two options of connectivity? What does it means?

Equipment

1. An open microstrip amplifier
2. Network analyzer
3. Spectrum analyzer
4. RF generator
5. Connectors and adapters
6. Coaxial cables

Experiment goals

1. Measuring gain
2. Measuring IP3
3. Measuring 1 dB compression point
4. Measuring SNR and Noise Figure in RF amplifiers

Experiment sequence

1. Amplifier measurements:

   1.1. Choose two attenuators of at least 20 dB, verify their frequency response using the network analyzer.

   1.2. Assemble the setup shown in Fig. 7.2. Make sure that you use the attenuators to protect the equipment.

   1.3. Use the network analyzer for Frequency Sweep in variety of power rates from -50 dBm to -10 dBm. (at least 5)

   1.4. What are the bandwidth and the center frequency of the amplifier?

   1.5. Use the network analyzer in Power sweep mode in the working band. Measure the amplification as a function of the input power. Extract the 1 dB compression point, and the linear amplification. Alternately, you can use the microwave generator and the spectrum analyzer with the Max Hold function instead of the Network Analyzer.

   1.6. Connect the amplifier to the spectrum analyzer according to Fig. 7.3. Use two input signals in the working band where the amplification is constant (from the previous measurement). Increase gradually the input power until the 3rd intermodulation appears. Save the data to extract later the IP3.

1.7. Present the output spectrum from the previous measurement and analyzer its spectral content.

2. SNR measurement:

2.1. Connect the amplifier input to the RF generator and the output to the Spectrum Analyzer using the same attenuators. Measure the signal power and the noise power at the output and at the input ports.

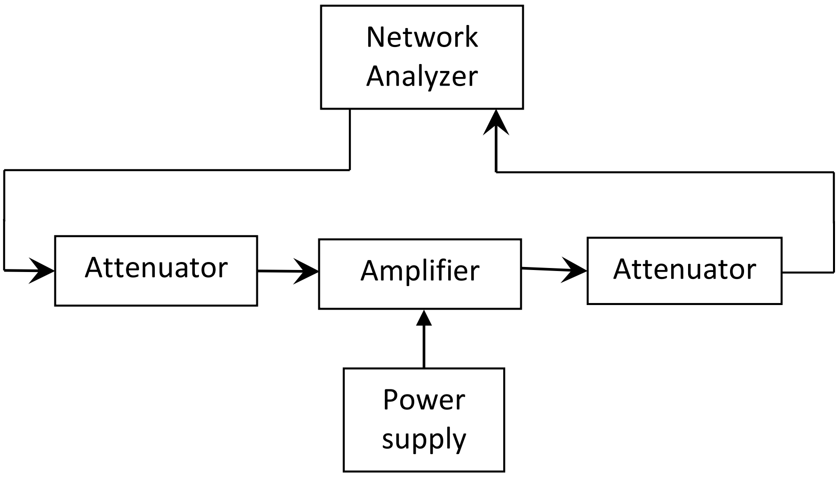


Figure 7.2: Amplification measurement setup, using Network Analyzer

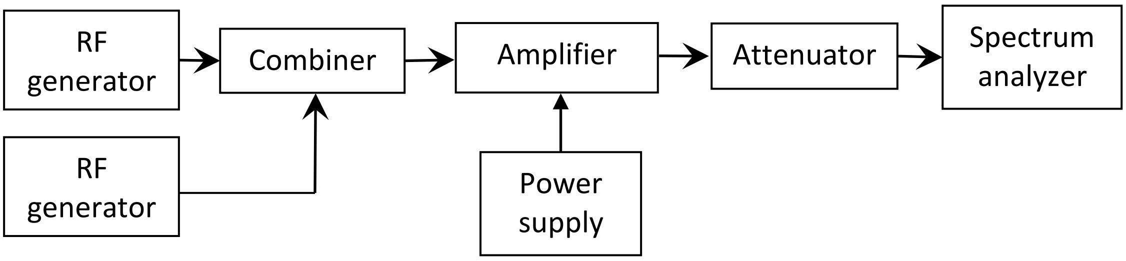


Figure 7.3: Amplification measurement setup, using Network Analyzer

Processing the results

1. Show the frequency response of the amplifier for different input power rates. Explain the differences.

2. Plot the Pin-Pout characteristic curve of the amplifier as in Fig. 7.1. Extract the amplification in the linear region and the 1-dB compression point.

3. What is the minimal input power that generates 3rd order intermodulation? What is its frequency? Extract the IP3 value, and mark it on the plot from the previous question.

4. In which frequencies other harmonies are observed at the output spectrum, where two signals are inserted to the amplifier?
5. Calculate the SNR at the input and output of the amplifier. Extract the Noise Figure of the amplifier.
6. Summarize the amplifier factors as the Pin-Pout curve, 1-dB compression point, linear gain, frequency bandwidth, IP3, Noise Figure, etc. compare these data to the known parameters of this amplifier, or to other arbitrary amplifier according to your choice.

8. Microstrip devices

Goals

1. Knowing microstrip technology.
2. Experience with passive microwave devices implemented by microstrip.

Background

The advantage of using monolithic microwave integrated circuit (MMIC) is the lack of parasitic coupling between the system components; however, the disadvantage is the excess of weight and volume, and their high price. The MMIC technology allows integrating of full miniature systems of both active and passive devices. However, extended multidisciplinary knowledge is needed including semiconductors, physics, thermal design, etc. Because of that, it is a formidable task to design such MMIC systems. Currently there are transmitters and receivers that are produced in MMIC technology as state-of-art devices for millimeter waves in reasonable prices. In this experience we will measure and characterize surface mount (SMT) devices.

Preparation questions

1. Find formulas for analyzing and designing of the impedance of microstrip structure as a function of the waveguide dimension, the material's dielectric permittivity and the frequency.
   a. Implement the analysis formulas to a microstrip waveguide according to your choice, and find the characteristic impedance and the wave velocity.
   b. Implement the synthesis formulas for designing new waveguide according to the required impedance.
2. For each of the following devices, describe one implementation by microstrip structure, explain shortly the operation principle, and present the S-matrix with corresponding sketch of the ports.
   a. Waveguide
   b. Directional coupler
   c. Wilkinson power divider
   d. Hybrid 90°

e. Impedance matching for single frequency

f. Impedance matching for wide BW

g. Band pass filter (BPF)

h. Rat-race coupler

Equipment

1. Microstrip devices:
    a. Coupler
    b. Wilkinson power divider
    c. Hybrid 90°
    d. Band pass filter (BPF)
2. Network analyzer
3. Caliper
4. Ohm-meter
5. Connectors and adapters
6. Coaxial cables

Experiment goals

Measure the scattering parameters of passive microwave devices implemented by microstrip technology.

Experiment sequence

1. Calibrate the network analyzer for 2-port calibration.
2. Measure the relevant device dimensions, i.e. the width, length and thickness of the lines, and the passive components if exist.
3. Measure the S parameters of the following devices, and take a sketch (or photo) of the device according to the port number you choose.
    a. Coupler

a. Wilkinson power divider

b. Hybrid 90°

c. Band pass filter (BPF)

Processing the results

1. Analyze each of the devices according to these guidelines:

   1.1. Show sketch of the device including the port numbers

   1.2. According to the measured data, show for each device the S-matrix of it as a function of the frequency. What is the frequency band of operation? Explain.

   1.3. Show the S-matrix for the center frequency of operation.

   1.4. Compare the reflected and transmitted properties to the theoretical values predicted. Explain the differences, if exist.

2. For the Hybrid 90°, calculate the frequency-dependent dielectric constant of the substrate from the measured data, according to the device dimension.

3. For the Wilkinson power divider, explain how the resistor can be measured, and why it is needed. Find its value.

9. Designing and building passive microstrip devices

Goals

Experience with design and build of passive microstrip devices using low-cost means.

Preparation questions

1. What are the purposes of the dielectric substrate in the microstrip structure?
2. What parameters of the EM propagation in the microstrip are affected by the dielectric substrate?
3. Implement the following structure using a simulation tool (Ansoft Designer is recommended). Use Teflon with 9.5 mm thick as the substrate according to the following scheme:

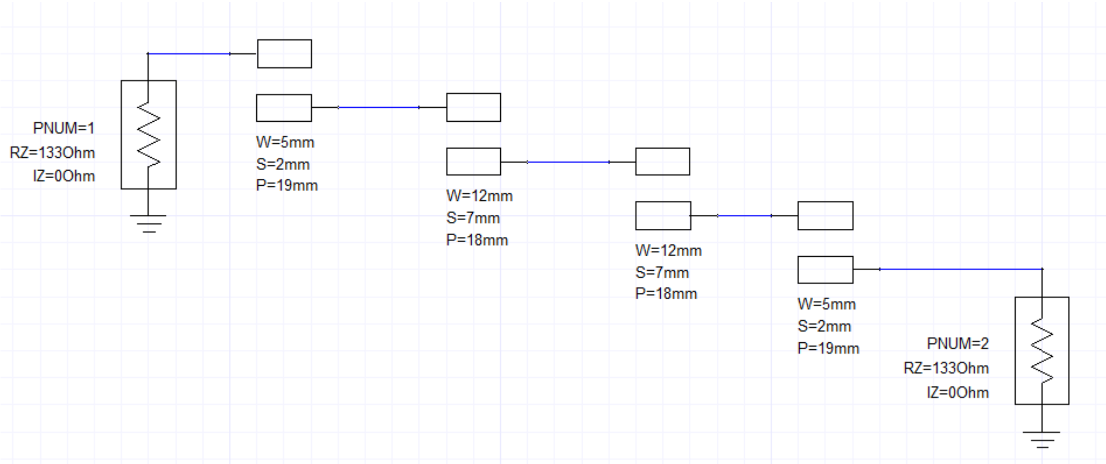


Figure 9.1: filter design by Ansoft designer

Simulate the device and explain, what filter is achieved? Calculate the characteristic impedance and the electrical length of the lines in the scheme at 3 GHz. Explain qualitative the principle of operation of the device while referring to those parameters.

4. Choose one of the following devices: LPF, Notch filter, BPF, HPF.
   You have ~9 cm length, ~5 cm width dielectric substrate shown in Fig. 9.2. The substrate is Teflon with 9.5 mm thickness. Design implementation of your filter to this microstrip. Simulate the device, and explain the principle of operation.

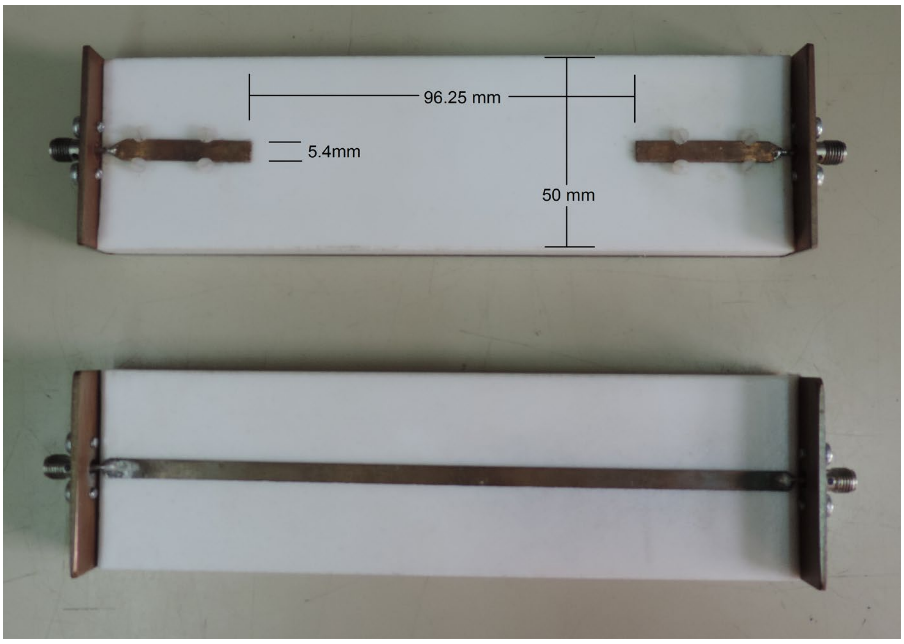


Figure 9.2: Basis of the microstrip structure for implementing the designed scheme.

Equipment

1. Microstrip basis
2. Aluminum tape
3. Network analyzer
4. Connectors and adapters
5. Coaxial cable

Experiment goals

1. Design by simulation tool and build of 2-port passive microstrip device (BPF, HPF as an example).
2. The device is built as an addition on microstrip structure by metal adhesive tape.
3. Compare the simulation and experimental results.

Experiment sequence

1. Build the device that you designed.

2. Measure the relevant parameters using the network analyzer.
3. Try to improve performance by fine tuning of the structure.

Processing the results

1. Compare the experimental results to the simulation from the design presented in the report.
2. Explain the differences between the model and the experimental performance, and their origin.

10. Dielectric permittivity measurement

Goals

Measurement and estimate the complex dielectric permittivity of materials.

Preparation questions (Appendix available in the course website)

1. The dielectric coefficient represents microscopic effects at the molecular level in the material. Describe it shortly, and explain how it is reflected in the macroscopic level.
2. Explain the different and the common between the electric conductivity and the dielectric loss (imaginary part of the permittivity) mechanisms. Describe the Drude model for the dielectric coefficient of conductors.
3. What is the dielectric coefficient at the microwave frequencies of the following materials: Air, Delrin, Teflon, Perspex.
4. Explain what is Resonator, and how it can be implemented by a waveguide.
5. Explain the resonator parameters, resonance frequency and the quality factor. Describe how they are measured.
6. Explain how small dielectric interference changes the resonator response. Find formula for this case, and explain the assumptions you used.
7. Find formula for finding the resonator parameters by knowing the dielectric coefficient and loss tangent of the dielectric substrate, of rectangular waveguide.
8. How the material of the waveguide affect the resonator properties?
9. How the dielectric coefficient of the material inside the rectangular waveguide affects the cutoff frequency of the different modes?

Equipment

1. Basis for microstrip structure with option for substrate change.
2. Dielectric materials
3. Network analyzer
4. Rectangular waveguide with changeable dielectric material

5. Connectors and adapters
6. Coaxial cables

Experiment goals

1. Measuring dielectric coefficient of materials using microstrip structure.
2. Measuring dielectric coefficient of materials using rectangular waveguide.

Experiment sequence

Using a microstrip resonator:

1. Use the following substrates inside the microstrip resonator and measure the vectoral reflectance coefficient (amplitude and phase) as a function of the frequency, while a short is connected to the second port of the resonator:
   1.1. Air
   1.2. Delrin
   1.3. Teflon
   1.4. Perspex
   1.5. High loss material
   1.6. Dry sand
   1.7. Wet sand
   1.8. Water
2. Measure the physical dimensions of the device.

Using a rectangular waveguide:

3. Connect the rectangular waveguide filled with the dielectric material to the rectangular waveguide-coax adapter, while it is open.
4. Connect the adapter to the network analyzer port and measure the reflectance as a function of the frequency. Find the cutoff frequency.
5. Measure the physical dimensions of the device.

Processing the results

1. For the microstrip resonator, calculate the complex dielectric permittivity coefficient, and the loss tangent of the substrate materials. Compare the data to theory, and explain the limitation and condition of the measurement.
2. Extract the transmission line loss, and explain the relation to the resonator properties.
3. Is the effective dielectric permittivity in the transmission line equal to the one that you calculate before? Explain.
4. For the rectangular waveguide, extract the dielectric permittivity of the material filled in, according to the measurements and the resonator dimensions.
5. Did you observe some frequency dependence of the dielectric permittivity with the frequency? Explain.
6. Explain the measurements limitations and the estimation of the different methods.

11. EM Radiation and antennas

Goals

1. Knowing basics of the antenna theory.
2. Experience antenna and radiation measurements.

Preparation questions

1. What is the difference between near- and far-field of the antenna? How this difference is expressed quantitatively?
2. What is the radiation pattern of the antenna? How it is measured?
3. The antenna directivity $D(\theta,\phi)$ is marked where θ,ϕ are spherical coordinates. How this directivity is defined, and how it is related to the radiation pattern?
4. Define the antenna gain *G*. Explain the meaning while using the power density for angular per solid angle $S(\theta,\phi)$ relative to the transmission of same input power to an isotropic antenna.
5. What is the effective aperture of the antenna and how it is defined for horn antenna at its fundamental mode, for its two main transmission planes (E, and H)?
6. What are the side lobes? How the main lobe width is determined?
7. Using two identical antennas, how the gain is found by free-range measurements according to Friis formula?
8. Describe plane wave propagation at linear polarization (horizontal and vertical), circular polarization (right and left), elliptical polarization (right and left), from the transmitter and receiver point of view?
9. How the polarization affects the antenna transmission? Assuming we have identical antennas, and polarization, can we transmit effectively between them while:
   9.1. The antenna polarization is linear and it is at the same direction for both of them.
   9.2. The antenna polarization is linear and one is tilted at 90° in respect of the other one.

9.3. The antenna polarization is right hand circular and it is at the same direction for both of them.

9.4. The antenna polarization is right hand circular and one is tilted at 90° in respect of the other one.

9.5. Both of the antennas are circular and one is right hand circular and the other is left hand circular.

10. What is the polarization for the following cases:

10.1. $\vec{H}(\vec{r})=(j-1)\hat{x}e^{-jk_z z}$

10.2. $\vec{E}(\vec{r})=(2\hat{y}+j\hat{x})e^{-jk_z z}$

10.3. $\vec{E}(\vec{r})=[(1+j)\hat{x}+(1-j)\hat{z}]e^{jk_y y}$

11. For a horn antenna, what are the E-plane and H-plane directions, in respect to the antenna aperture? What is the directivity given the antenna dimensions? What is the gain of this antenna, assuming 60% efficiency?

12. Find an expression for the radiation pattern at the E and H planes of a horn antenna, where the mode transmitted is TE_{10} (assuming it remains the same at the aperture).

13. [Bonus] Simulate the radiation pattern for the E- and H-planes of a horn antenna (use CST for example). The mode is TE_{10} (assuming it remains the same at the aperture). How the dimensions of the antenna affect the gain? Given the antenna dimensions, what is the proper frequency band of operation?

Equipment

1. RF Source and power meter, or Network analyzer
2. Antenna tripod
3. Different antennas
4. Connectors and adapters
5. Coaxial cables

Experiment goals

1. Measuring power distribution at far field, and horn antenna gain.
2. Measuring the radiation pattern of some different antennas.

Experiment sequence

1. Horn antenna gain measurement:

   1.1. Measure the physical dimensions of the antenna.

   1.2. Use the setup shown in Fig. 11.1, or use RF source and power meter (scalar measurement) instead of the Network analyzer. The angular scan is performed manually.

   1.3. Direct the receiving antenna to the transmitting antenna

   1.4. Transmit constant power for different distances for the near field and far field, at about 20 measurements. Record the received power.

   1.5. Measure the radiation pattern of the following antennas:

      1.5.1. Horn antenna at both E- and H-planes, including single cross-polarization measurement.

      1.5.2. Horn antenna with different aperture.

      1.5.3. Horn antenna with different frequency.

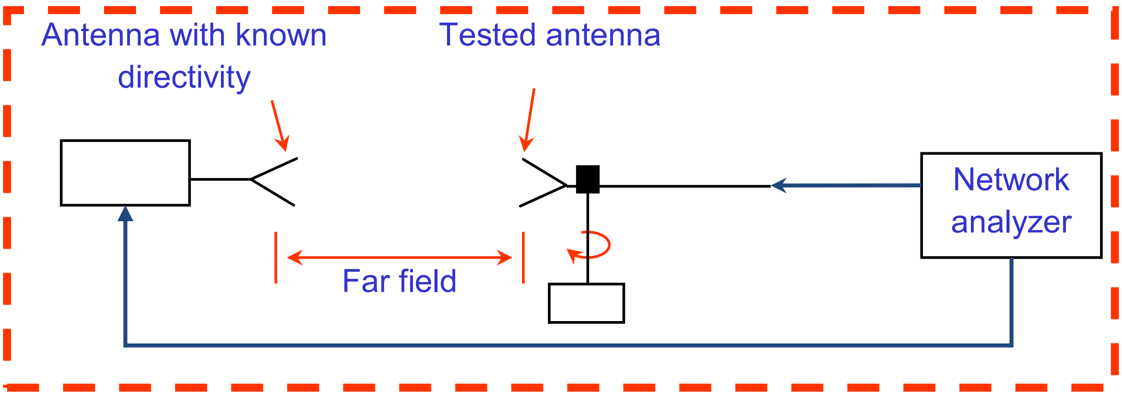


Figure 11.1: Setup for radiation pattern measurement.

Processing the results

1. Using Friis formula, extract the horn antenna gain from the variable distance measurements.
2. What is the range of the far field? Compare to the theoretical prediction.
3. Sketch the radiation pattern of the measured antennas. Extract the relevant properties such as: directivity, gain, main lobe width, polarization, side lobes level (if applicable).
4. Compare the experimental results with the theory.
5. Compare the antennas using your measured data. Refer to the extracted properties, and show the relation between those properties (e.g. gain to main lobe width).
6. The measurement is performed inside the lab, or at the corridor instead of anechoic chamber. Estimate the error as a result of this issue.

12. Radar applications

Goals

1. Knowing Doppler Effect.
2. Simple implementation of Doppler radar.
3. Implementation of FM detector.
4. Spread spectrum and Linear-FM.
5. Knowing radar cross-section (RCS).

Preparation questions

1. Explain shortly the Doppler Effect. Give an expression for the relation between the Doppler frequency and the target velocity for fixed transmitter and moving target with velocity v.
2. Explain how the experiment setup operates as shown in Fig. 12.1. Explain the role of the nonlinearity of the circulator.
3. What is the Radar cross section (RCS)?
4. Find formula for RCS of ball, cylinder, and corner reflector, as a function of their dimensions.
5. Explain the structure and the principle of operation of Linear-FM radar.
6. Give a formula for the distance detected by pulse radar.
7. Extract formula for the distance detected by Linear-FM radar, as a function of the difference frequency f_{IF}, given by the subtraction of the incident and reflected signals.
8. For $B = 4\,\text{GHz}$ bandwidth, $f_m = 100\text{Hz}$ modulated signal, and $d = 20\text{cm}$ distance, what is the frequency difference f_{IF} output?
9. Explain how FW detection is possible using of resonator and diode detector. Refer to the voltage-frequency characteristic of the resonator you have measured before.

Equipment

1. Horn antenna
2. Diode
3. Circulator
4. Corner reflector
5. Metal reflective devices: cylinder, ball, corner.
6. Power meter
7. Oscilloscope
8. RF generator, with FM modulation.
9. Function generator
10. Meter tape

Experiment goals

1. Measure velocity by Doppler Effect.
2. FM detection
3. Measure the RCS of objects.
4. Measure distance using Linear-FM Radar.

Experiment sequence

1. Doppler Effect:
    1.1. Assemble the setup according to Figure 12.1.
    1.2. Move at constant speed the reflector on the trail, at both directions.
    1.3. Measure the velocity using stopper and a meter tape.
    1.4. Measure simultaneously the Doppler frequency.
    1.5. Repeat measurements for several velocities.
    1.6. Rotate the reflector to the opposite direction and repeat the experiment.

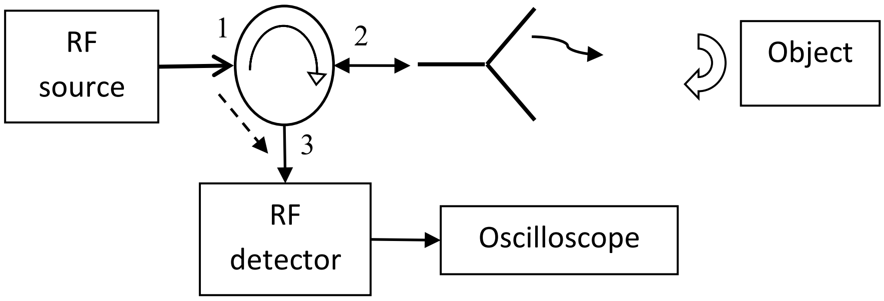


Figure 12.1: Setup for radiation pattern measurement.

2. RCS

2.1. Measure the power transmitted from the source to the antenna (replace the antenna with power meter). Reconnected the antenna after recording the data.

2.2. Replace the diode with power meter to measure the reflected power to the antenna.

2.3. Measure the reflected power as a function of the distance for the following items:

2.3.1. Corner reflector.

2.3.2. Sphere

2.3.3. Cylinder

3. FM detection

3.1. Connect the function generator to the FM modulation input of the RF generator, as the IF source. Tune it to 1 kHz signal.

3.2. Connect the RF generator to the resonator. Connect the second port of the resonator to the diode detector. Connect the detector output to the oscilloscope.

3.3. Tune the resonator frequency to the RF generator's output and observe the result at the oscilloscope.

3.4. Change the IF generator signal shape to square or triangle wave and watch the results.

4. Linear-FM Radar

4.1. Use the experimental setup shown in Fig. 12.1, and connect RF generator to the circulator.

4.2. Use the diode detector instead of the power meter if you have used it before.

4.3. Tune the RF generator to *sweep* mode, so it generate a saw wave at the sweep output port, and the RF signal changes in the 8-12 GHz range with 10 ms time scan.

4.4. Measure the distance according to:

4.4.1. Put the reflector at a certain distance from the antenna

4.4.2. Measure the distance with the meter tape.

4.4.3. Record the signal received (Measure the received frequency at the oscilloscope. You can use the math FFT, or analyze it further at home).

4.4.4. Repeat the measurement for several distance values (including close proximity).

Processing the results

1. Using the Doppler frequency measured, calculate the reflector velocity and compare it to the measured speed manually.
2. Analyze the error causes at the Doppler Effect.
3. Find the RCS of the object you have measured, and compare it to the theory.
4. Describe the FM detection process. Did you observe any distortion? Why and to what signals distortion occurs?
5. Present the distance measured according to the Linear-FM radar. Estimate the error, and the error causes in this case.
6. How the time scan affect the Linear-FM radar?