Exercise 1: impedance measurement and matching

February 28, 2025

This exercise is the simulation of the measurement and matching processes of certain impedance, using waveguides. The simulation is performed using Matlab, by means of a function (that is provided), whose output is the measurement of the standing wave pattern of a loaded WR-90 waveguide. Three different loads may be specified: the unknown one, short and open circuit. Using this function you must find both the unknown load and the operation frequency used for the measurements.

After the measurement, you must design two matching networks for the measured load, using basic transmission line models[1] and the graphic and simulation tools in Cadence AWR Microwave Office[2].

1 Load measurement

The objective of this exercise is to find an unknown load Γ_L, that is connected to the end of a waveguide. The electric field amplitude (that we may identify as a voltage) is measured along the length of the waveguide. Since, in general, the load is not matched, a standing wave pattern will appear. The standing wave ratio (SWR) is the ratio between the voltage level at the maxima of said standing wave pattern, and the voltage at the minima. Therefore, the SWR is related to the magnitude of the reflection coefficient through the expression

$$\mathrm{ROE} = \frac{1 + |\Gamma(z)|}{1 - |\Gamma(z)|}$$

or, equivalently,

$$|\Gamma(z)| = \frac{\mathrm{ROE} - 1}{\mathrm{ROE} + 1}$$

If the waveguide is non dissipative, $|\Gamma(z)|$ is constant along the waveguide, and there is also the value at the load, $|\Gamma_L|$. Thus, once the SWR is determined from the maximum and minimum voltage levels, it is immediate to compute $|\Gamma_L|$. For example, if $\mathrm{ROE} = 4$, then $\Gamma(z) = \Gamma_L = 0.6$.

In order to find the phase of Γ_L, a reference load with a well-defined phase is required. This is typically a short circuit ($\Gamma_{\mathrm{sc}} = -1 = 1_{180^\circ}$) or an open circuit ($\Gamma_{\mathrm{oc}} = 1 = 1_{0^\circ}$). Since the standing wave pattern and $\Gamma(z)$ are periodical, with period $\lambda/2$ (where λ is the wavelength[3]) the locations along the waveguide where the diagram has the same phase than at the load will be separated by multiples of $\lambda/2$ from said load. Therefore, once the unknown load is connected, measuring the phase at one of those locations is enough to

[1] Notice that you will use a transmission line (TEM mode) to model the TE_{10} of a rectangular waveguide. This is possible thanks to the definition of generalized voltages and currents, that you will study in the course, soon.

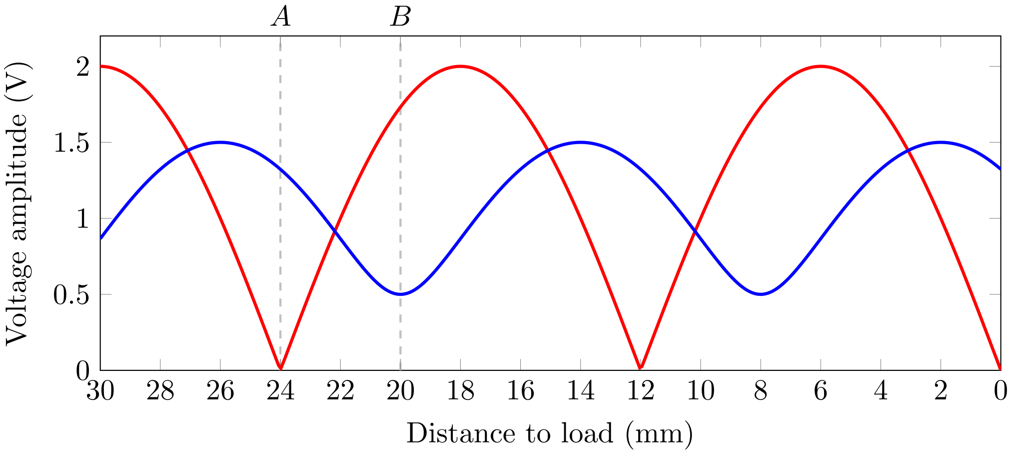
[2] You may download the software and obtain a student license (valid for 180 days) from https://awrcorp.com/register/customer.aspx?univ.

[3] Do not forget that the wavelength λ depends on the dielectric that fills the waveguide and the frequency, but also on the cutoff frequency of the mode.

determine the phase of the load. The phase can be obtained by measuring the distance from the locations to the surrounding maxima and minima of the standing wave pattern, taking into account the $\lambda/2$ pattern.

An example may help to clarify the procedure. Let's suppose that $\lambda = 24\,\text{mm}$, and that when a short circuit is used to load the waveguide, a minimum of the standing wave (a null, in fact) will appear at position A. When the unknown load is connected there is a minimum at B, 4 mm closer from the load.

With the short circuit, the phase of $\Gamma(A)$ is 180°, that is the same as Γ_{sc}. Therefore, A is located at a distance multiple of $\lambda/2$ from the short circuit. If now the short circuit is substituted by the unknown load, the phase at A will change, but it will be the one of the unknown load (it is still at a multiple of $\lambda/2$). Now, the 180° phase is at B, where a minimum of the standing wave is measured. To go from B to A is to travel $4\,\text{mm} = \lambda/6$ towards the generator, or what is equivalent, to decrement the phase of $\Gamma(B)$ by 120°. The phase of $\Gamma_L = \Gamma(A)$ is, therefore, $180° - 120° = 60°$.



1.1 Procedure

The Matlab function (`waveguide_voltage`) generates values of voltage inside a WR-90 waveguide (it is empty, with cross section $22.86\,\text{mm} \times 10.16\,\text{mm}$), loaded with three different terminal loads, and excited by a signal with unknown frequency. The loads are:

1. The unknown load under test.
2. Short circuit.
3. Open circuit.

The full specifications of the function are:

Definition of `waveguide_voltage`

```
v = waveguide_voltage(load_type, d, nia)
```

Input arguments:

- `load_type`: load type, from `'unknown'`, `'open'`, or `'short'`.
- `d`: distance (m), measured from the load along the waveguide. It may be a vector. Take into account that it has an unknown offset, that is, `d` $= 0$ is **not calibrated** at the load position.
- `nia`: vector with the NIA of the students, for example, `[100123456, 100654321]`. If there is only one student, use a one-element vector, `[100123456]`. Use the correct NIA or NIAs, since they will be used to check your answers.

Output arguments:

- `v`: normalized voltage along the waveguide. It is a variable with the same dimensions of `d`.

Example of use of `waveguide_voltage`

```
>> nia = [100123456, 100654321];
>> d = linspace(0, 3e-3, 4);
>> v = waveguide_voltage('open', d, nia)

v =
  -0.4441 -0.8158 -1.1561  -1.4521
```

Notice that the function code is not available[4], and it must be used as a black box.

1.2 Results

You must compute:

1. The frequency of the excitation (GHz).
2. The reflection coefficient of the load Γ_L (magnitude and phase, in radians).

2 Design of matching networks

The second exercise consists of the design of two matching networks using sections of the same non-dissipative waveguide from the previous questions, for the load Γ_L and frequency that you have measured. The networks are the following ones:

1. A single stub matching network, with open circuit stub, and connected to the main waveguide in parallel.
2. A double stub matching network with an intermediate $\lambda/6$ waveguide section. The stubs are terminated by short circuits, and they are connected one in series and the other in parallel (but which one is each is not determined).

[4] The file is `waveguide_voltage.p`, that is compiled.

The objective of both networks is to achieve a good input matching, that is, that the input reflection coefficient is $\Gamma_{in} \approx 0$ when loaded by Γ_L.

2.1 Procedure

You must use AWR Microwave Office simulation and plotting capabilities to design the matching networks. The use of the following circuit elements is suggested[5]:

- `TLIN`: ideal lossless transmission line, where the characteristic impedance and the electrical length (in degrees) are specified (the length at certain frequency, that is also specified). There are only one terminal at each end, since the others are considered common, ground connected.
- `TLIN4`: similar, but with four terminals, suitable for series connections.
- `TLOC`: transmission line section loaded by an open circuit (parallel connected stub), same parameters than the previous ones.
- `TLOC4`: identical, with four terminals.
- `TLSC`: transmission line section loaded by a short circuit (parallel connected stub), same parameters than the previous ones.
- `TLSC4`: identical, with four terminals.
- `OST`: equivalent to `TLOC`, for series stubs.
- `SST`: equivalent to `TLSC`, for series stubs.
- `IMPED`: complex impedance, where real and imaginary parts are specified.
- `GND`: ground connection.

Consult the help of each element if you do not understand it.

Under the simulation options, use only one frequency point, the one you have computed in the first part of the exercise. Use an `IMPED` with the impedance under test (also computed in the first part). It is recommended the use of normalized impedances, that is, specify that both the port reference impedances and the characteristic impedances are one. For the simulation results you may use Smith chart plots, with markers to show interesting values.

2.2 Results

You must compute:

1. Single stub matching network: lengths of the stub and the line section (mm).
2. Double stub matching network: lengths of both stubs (mm), and connection type (series-parallel or parallel-series).

Important: the solutions are only valid if the input return losses are higher than 40 dB.

[5] The element names are links to the online help