

FIELD: Electronics Engineering  
SPECIALITY: Advanced Applied Electronics

## **Microwave Application: Project Report**

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# Chapter 1

## Introductory tasks

### 1.1 Problem statement

The goal of the first task was to perform basic calculations and answer question related to principal knowledge in the area of microwave engineering.

The first task is to calculate the delution level of milk in the Baltic sea in decibels, while the second one is to answer how the complex impedance can be matched in microwave circuits.

### 1.2 Tasks realization

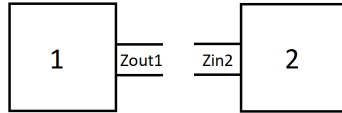
a) One liter of milk deluted in entire Baltic sea – how many dB does it mean?

$$V_{milk} = 1 \text{ liter} = 1 \text{ dm}^3 = 10^{-3} \text{ m}^3$$

$$\begin{aligned} V_{Baltic} &= 21\,700 \text{ km}^3 = 21\,700 \cdot 10^9 \text{ m}^3 = \\ &= 2.17 \cdot 10^{13} \text{ m}^3 \end{aligned}$$

$$\begin{aligned} Ratio_{dB} &= 10 \log_{10} \left( \frac{V_{milk}}{V_{Baltic}} \right) = \\ &= 10 \log_{10} \left( \frac{10^{-3} \text{ m}^3}{2.17 \cdot 10^{13} \text{ m}^3} \right) = \\ &= -163.22 [dB] \end{aligned}$$

b) How to match the complex impedance?



Q: What should be the relation between  $Z_{out1}$  and  $Z_{in2}$ , so the impedances are "matched"?

A: The one of the numbers should be equal to complex conjugate of tother one, as presented in the equation below.

$$Z_{out1} = Z_{in2}^*$$

The complex conjugate ( $Z^*$ ) of given complex number  $Z$  is defined in the following way:

$$\begin{aligned} Z &= x + j \cdot y \\ Z^* &= x - j \cdot y \end{aligned}$$

### 1.3 Summary

The introductory tasks covered basic, but essential aspects of microwave engineering. Expressing the ratio of powers or intensities in decibels is a common way to present these dependencies and matching impedances in the circuits is a common step in electrical equipment design.

As of the essential conclusions – the second task was to find the relation between impedances in terms on matching them. As it was presented, to match two impedances, one should be a complex conjugate of the another.



# Chapter 2

## Basics of Microwave Engineering

### 2.1 Problem statement

The assignment is to collect and present the information about microstrip, stripline and waveguides usage in the microwave engineering.

These three approaches differ among themselves, have their advantages and disadvantages – detailed review of these aspects will be presented.

### 2.2 Task realization

Waveguides and transmission lines are both elements designed to be interconnects between receivers and transmitters of the EM waves (to be more precise – in range of radio frequencies and microwaves). Despite having similar role, there are essential differences among their properties.

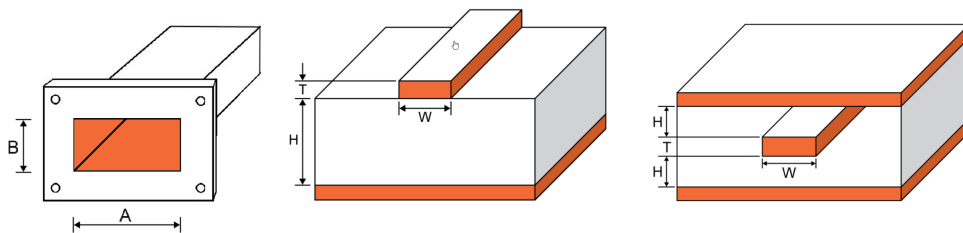


Figure 2.1: From left: waveguide, microstrip and stripline  
(source: <https://www.allaboutcircuits.com>)

#### Waveguides review

The waveguide is manufactured out of one conductor (in opposite to printed lines, what will be cleared in next paragraph). It is said, that waveguide has certain advantages over the printed lines – due to its shielding, it can provide the isolation between adjacent signals. In addition, it is capable to transmit high peak powers, while having negligible losses in range of microwave frequencies.

It is also worth mentioning, that all kind of waveguide components are available (circulators, isolators, attenuators, loads, mixers, amplifiers).

On the other hand, there still remain the disadvantages such as small manufactured volumes coming with high prices of waveguides materials (copper and silver). Also the dimensions and weight of waveguide are significant. Because of above-mentioned single conductor, the waveguide cannot provide a transverse-electromagnetic mode of transmission.

### Printed lines review

Transmission lines used in printed circuits boards manufacturing are microstrips and striplines.

The stripline is a conductor placed between a dielectric pair of ground planes ("sandwiched"). It is a TEM (Transverse Electro-Magnetic) transmission line, what means it is non-dispersive. It is one of stripline's advantage over the microstrips. Also, the isolation between adjacent traces can be achieved.

One of the disadvantages of stripline is its complexity in fabrication, what also makes it more expensive than microstrip. The second one is a result of the second ground plane. The strip widths shall be narrower for a given impedance and board thickness than microstrips. An example to illustrate, for replacing N mils thick microstrips, the stripline should be 4N mils thick.

The microstrip transmission lines is a conductive strip of certain dimensions (width and thickness) with the wider ground plane. They are separated by a dielectric layer called "substrate" (also characterized by another thickness dimensions).

According to the "Microwave Encyclopedia", microstrips are the most popular transmission lines especially for MIMICs (Monolithic Microwave Integrated Circuits). Its advantage over stripline is that all active components can be mounted on top of the boards. However, for filtering, they may be required to provide external shielding of the circuit. In addition to disadvantages, the microstrip circuits can radiate and are dispersive (signals of different frequencies travel with different speeds). The TEM mode is not supported.

## 2.3 Summary

The waveguides are able to transmit high peak powers with very low losses in microwaves frequencies. Unfortunately, they are expensive and heavy equipment.

The striplines (conductor sandwiched between dielectric) are non-dispersive transmission lines supported TEM modes. They are more expensive than microstrip and more complex in fabrication.

The microstrips are at the moment very commonly used because of the ease of fabrication and usage. Unfortunately, they do not support TEM modes, often require external shielding and the circuit radiation has to be taken into consideration during the design process.

# Chapter 3

## Microstrip vs stripline – loss calculation using PCAAD

### 3.1 Problem statement

During the class, there were given sets of parameters such as laminate and paths thickness, frequency, dielectric constant and impedance.

The goal of the following task was to calculate total loss given in [dB/cm].

When the calculations are finished, the results shall be compared to total loss of the waveguides.

### 3.2 Task realization

To perform the calculation, the PCAAD software version 7.0 was used ( PCAAD – Personal Computer Aided Antenna Design).

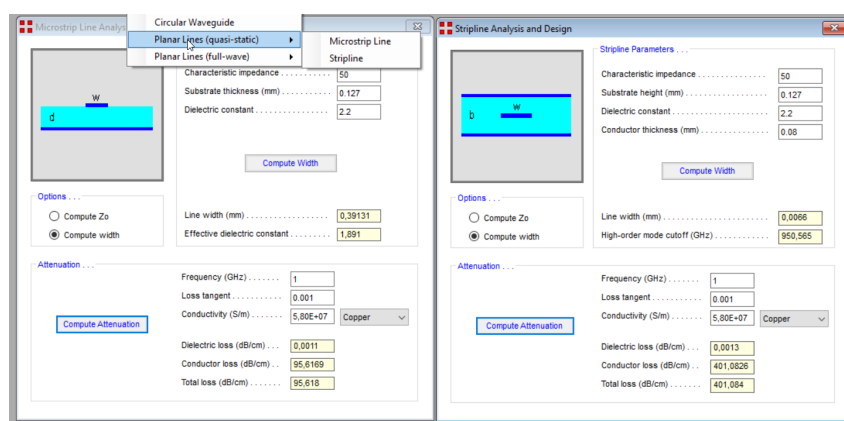


Figure 3.1: The quasi static methods interface for planar lines calculations (screenshot taken during the usage of PCAAD v7.0)

Microstrips						Striplines					
0.127 mm						0.127 mm					
FR thickness [mils]	5	5	5	5	5	FR thickness [mils]	5	5	5	5	5
Impedance [ $\Omega$ ]	50	70	100	25	40	Impedance [ $\Omega$ ]	50	70	100	25	40
$\epsilon$	2,2	2,2	2,2	2,2	2,2	$\epsilon$	2,2	2,2	2,2	2,2	2,2
Width [mm]	0,39131	0,22848	0,11382	0,99502	0,53914	Width [mm]	0,0066	0,0163		0,0577	0,0173
Total Loss at 1 GHz [dB/cm]	96,0	94,6	104,2	107,6	98,8	Total Loss at 1 GHz [dB/cm]	401,1	406,8	465,9	403,5	402,4
Total Loss at 20 GHz [dB/cm]	427,6	423,0	466,1	481,2	427,6	Total Loss at 20 GHz [dB/cm]	1793,7	1819,4	2083,6	1804,6	1799,4
0.3048 mm						0.3048 mm					
FR thickness [mils]	12	12	12	12	12	FR thickness [mils]	12	12	12	12	12
Impedance [ $\Omega$ ]	50	70	100	25	40	Impedance [ $\Omega$ ]	50	70	100	25	40
$\epsilon$	2,2	2,2	2,2	2,2	2,2	$\epsilon$	2,2	2,2	2,2	2,2	2,2
Width [mm]	0,93914	0,54834	0,27318	2,38805	1,29393	Width [mm]	0,115	0,0386		0,3964	0,1846
Total Loss at 1 GHz [dB/cm]	39,8	39,4	43,4	44,8	41,2	Total Loss at 1 GHz [dB/cm]	106,0	116,6	148,3	95,4	101,8
Total Loss at 20 GHz [dB/cm]	178,2	176,3	194,2	200,5	184,2	Total Loss at 20 GHz [dB/cm]	473,9	521,6	663,3	426,4	455,2
0.508 mm						0.508 mm					
FR thickness [mils]	20	20	20	20	20	FR thickness [mils]	20	20	20	20	20
Impedance [ $\Omega$ ]	50	70	100	25	40	Impedance [ $\Omega$ ]	50	70	100	25	40
$\epsilon$	2,2	2,2	2,2	2,2	2,2	$\epsilon$	2,2	2,2	2,2	2,2	2,2
Width [mm]	1,56524	0,91391	0,45529	3,98008	2,15655	Width [mm]	0,2674	0,117	0,018	0,8059	0,4014
Total Loss at 1 GHz [dB/cm]	23,9	23,6	26,1	26,9	24,7	Total Loss at 1 GHz [dB/cm]	60,0	67,5	87,9	52,2	56,9
Total Loss at 20 GHz [dB/cm]	106,9	105,8	116,5	120,3	110,5	Total Loss at 20 GHz [dB/cm]	268,4	301,9	393,3	233,7	254,7
0.7874 mm						0.7874 mm					
FR thickness [mils]	31	31	31	31	31	FR thickness [mils]	31	31	31	31	31
Impedance [ $\Omega$ ]	50	70	100	25	40	Impedance [ $\Omega$ ]	50	70	100	25	40
$\epsilon$	2,2	2,2	2,2	2,2	2,2	$\epsilon$	2,2	2,2	2,2	2,2	2,2
Width [mm]	2,42612	1,41655	0,70571	6,16	3,34265	Width [mm]	0,4826	0,2353	0,0637	1,3774	0,7083
Total Loss at 1 GHz [dB/cm]	15,4	15,3	16,8	17,4	15,9	Total Loss at 1 GHz [dB/cm]	38,3	43,6	57,7	32,6	36,0
Total Loss at 20 GHz [dB/cm]	69,0	68,2	75,2	77,6	71,3	Total Loss at 20 GHz [dB/cm]	171,1	195,1	258,0	145,7	161,1

Figure 3.2: First part of the calculations made for listed parameters and  $\epsilon = 2.2$ . Most of the results are calculated correctly, however there can be observed two examples where PCAAD software failed to give a results. They are marked with gray color.

The results from the first striplines table show quite a significant total losses ( 400 dB/cm for 1GHz and almost 1800-2000 db/cm for 20 GHz). At the very beginning it was considered a mistake, but after retrying, the results were simply the same:

**Stripline Parameters ...**

Characteristic impedance ..... 50
Substrate height (mm) ..... 0.127
Dielectric constant ..... 2.2
Conductor thickness (mm) ..... 0.08

**Attenuation ...**

Frequency (GHz) ..... 20
Loss tangent ..... 0.001
Conductivity (S/m) ..... 5.80E+07
Dielectric loss (dB/cm) ... 0,027
Conductor loss (dB/cm) .. 1793,696
Total loss (dB/cm) ..... 1793,723

Figure 3.3: Recalculated example of stripline – it was necessary to be sure, that the high value of loss is not a mistake.

Microstrips						Striplines					
0.127 mm						0.127 mm					
FR thickness [mils]	5	5	5	5	5	FR thickness [mils]	5	5	5	5	5
Impedance [ $\Omega$ ]	50	70	100	25	40	Impedance [ $\Omega$ ]	50	70	100	25	40
$\epsilon$	9,8	9,8	9,8	9,8	9,8	$\epsilon$	9,8	9,8	9,8	9,8	9,8
Width [mm]	0,13425	0,06208	0,02016	0,42068	0,20245	Width [mm]	-	-	-	0,005	-
Total Loss at 1 GHz [dB/cm]	186,5	228,0	391,6	183,2	178,5	Total Loss at 1 GHz [dB/cm]	1026,6	1681,5	5017,1	846,3	898,1
Total Loss at 20 GHz [dB/cm]	833,9	1019,7	1751,2	819,3	798,5	Total Loss at 20 GHz [dB/cm]	4591,2	7519,9	22437,2	3784,8	4016,3
0.3048 mm						0.3048 mm					
FR thickness [mils]	12	12	12	12	12	FR thickness [mils]	12	12	12	12	12
Impedance [ $\Omega$ ]	50	70	100	25	40	Impedance [ $\Omega$ ]	50	70	100	25	40
$\epsilon$	9,8	9,8	9,8	9,8	9,8	$\epsilon$	9,8	9,8	9,8	9,8	9,8
Width [mm]	0,29724	0,13395	0,04169	0,95281	0,45314	Width [mm]	-	-	-	0,1005	0,0104
Total Loss at 1 GHz [dB/cm]	82,0	103,3	183,9	79,0	77,8	Total Loss at 1 GHz [dB/cm]	332,1	594,2	1863,5	226,2	271,7
Total Loss at 20 GHz [dB/cm]	366,8	462,1	822,5	353,4	347,8	Total Loss at 20 GHz [dB/cm]	1485,3	2657,4	8333,8	1011,7	1214,9
0.508 mm						0.508 mm					
FR thickness [mils]	20	20	20	20	20	FR thickness [mils]	20	20	20	20	20
Impedance [ $\Omega$ ]	50	70	100	25	40	Impedance [ $\Omega$ ]	50	70	100	25	40
$\epsilon$	9,8	9,8	9,8	9,8	9,8	$\epsilon$	9,8	9,8	9,8	9,8	9,8
Width [mm]	0,49538	0,22324	0,06948	1,58801	0,75523	Width [mm]	0,0088	-	-	0,2394	0,0571
Total Loss at 1 GHz [dB/cm]	49,2	62,0	110,4	47,4	46,7	Total Loss at 1 GHz [dB/cm]	197,6	360,0	1139,5	128,5	159,2
Total Loss at 20 GHz [dB/cm]	220,1	277,3	493,6	212,0	208,7	Total Loss at 20 GHz [dB/cm]	883,9	1609,9	5096,2	574,9	712,2
0.7874 mm						0.7874 mm					
FR thickness [mils]	31	31	31	31	31	FR thickness [mils]	31	31	31	31	31
Impedance [ $\Omega$ ]	50	70	100	25	40	Impedance [ $\Omega$ ]	50	70	100	25	40
$\epsilon$	9,8	9,8	9,8	9,8	9,8	$\epsilon$	9,8	9,8	9,8	9,8	9,8
Width [mm]	0,76786	0,34603	0,10769	2,46142	1,17061	Width [mm]	0,046	-	-	0,4397	0,1334
Total Loss at 1 GHz [dB/cm]	31,7	40,0	71,2	30,6	30,1	Total Loss at 1 GHz [dB/cm]	129,9	239,1	761,0	82,1	103,7
Total Loss at 20 GHz [dB/cm]	142,0	178,9	318,4	136,8	134,6	Total Loss at 20 GHz [dB/cm]	581,0	1069,5	3402,5	367,2	463,9

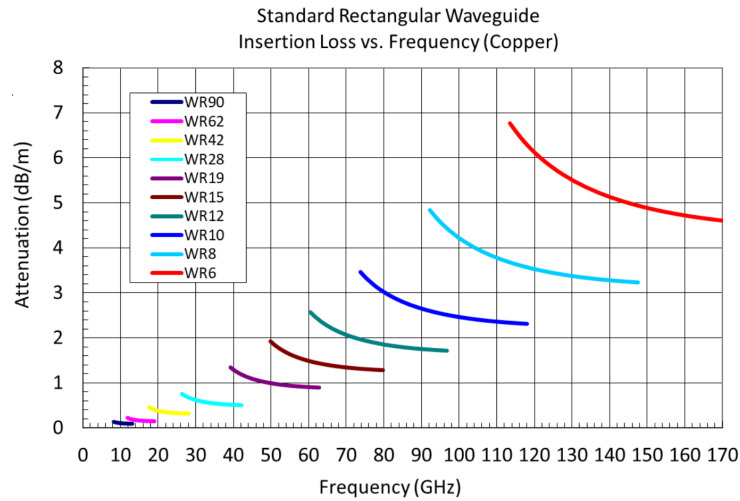
Figure 3.4

Some calculations (cells marked with gray color) were plain wrong either due to obtaining negative values of width or receiving NaN result (NaN means "Not a Number" in floating point representation).

Professor's piece of advice during the lab was to compare quasi-static analysis with full-wave. In some cases the results improved, however still there remain few unresolved.

That lead to a very important conclusion – the software for simulation has its limitations and it's much appreciated to use different tools (PCAAD, MicrowaveStudio,  $\mu$ Wave Wizard etc.).

The assignment's second part was to compare the obtained results to the losses of waveguides:



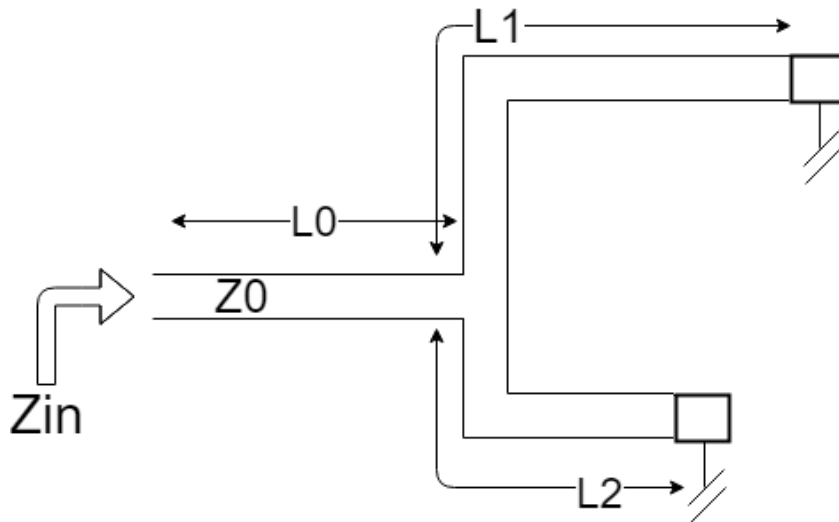
As it can be read from the plot – waveguides offer much lower losses (and the Y-axis scale is in dB per METER).

The highest losses are presented for waveguide WR6, which is around **7 dB/m = 0.07 dB/cm**. In terms of total losses, the microstrips and striplines cannot compete with the waveguides.

# Chapter 4

## Impedance transformation

### Problem statement



The presented above model was given to calculate the impedance transformation. The data was defined in the following way:

$R1$   $[0, 50, 70] \Omega$ ,

$R2$   $[0, 25, 50, 70] \Omega$ ,

$L0$   $<5, 200>$ mm with 25mm step,

$L1$   $[13, 42, 72]$ mm

$L2$   $[25, 42, 93]$ mm

$f_0 = 5$  GHz

$\epsilon_r = 2.3$ ,  $\tan \delta = 0.001$ , laminate\_thickness = 0.508mm, copper =  $18\mu$

By utilizing the presented during classes equations, the impedance was calculated.

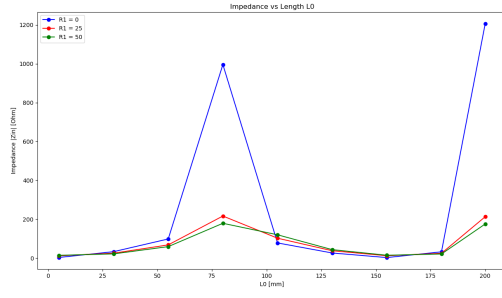
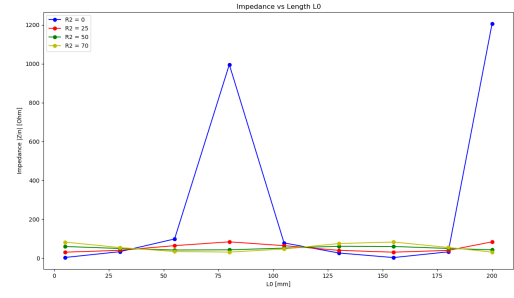
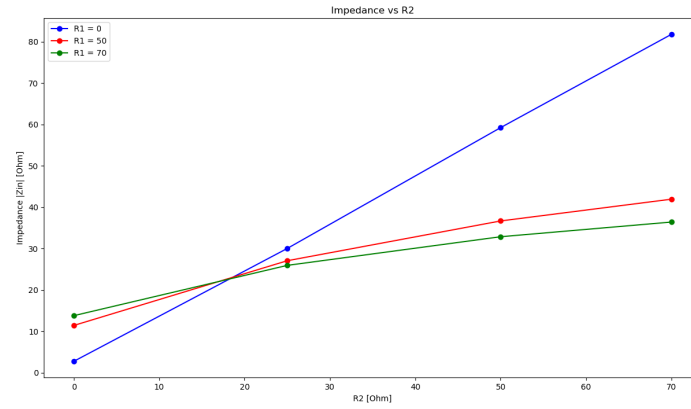
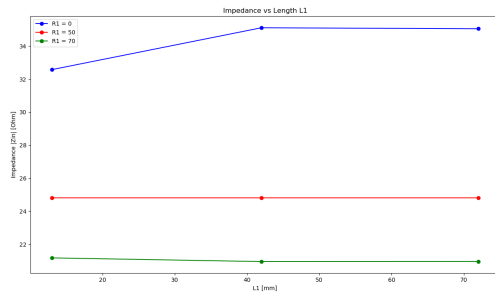
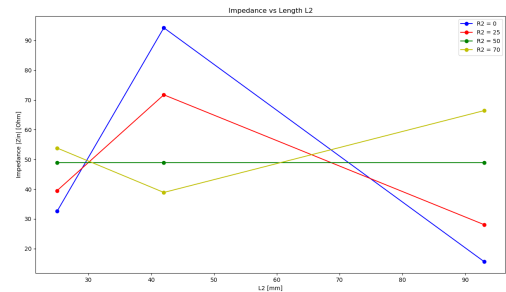
$$Z' = \frac{Z'_1 Z'_2}{Z'_1 + Z'_2}$$

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan(\beta L)}{Z_0 + jZ_L \tan(\beta L)}$$

With the given data almost 1000 results were obtained (there was dedicated software script prepared in the Python language to calculate the impedance and automatically save the results as Excel file).

To maintain the clean view in the report, the results will be presented as the plots.



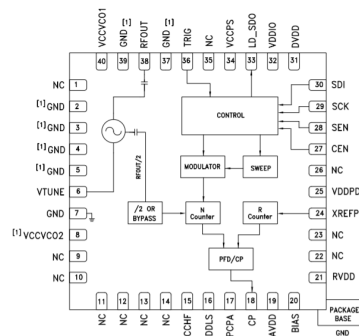
(a)  $L1 == 13\text{mm}$ ,  $L2 == 25\text{mm}$ ,  $R1 == 0\text{ Ohm}$ (b)  $L2 == 13\text{mm}$ ,  $L1 == 25\text{mm}$ ,  $R2 == 0\text{ Ohm}$ Figure 4.1: Relation between  $L0$  and magnitude of impedance  $Zin$ (a)  $L0 == 30\text{mm}$ ,  $L1 == 13\text{mm}$ ,  $L2 == 25\text{mm}$ ,  $\text{Ohm}$ Figure 4.2: Relation between  $R2$  (x-axis),  $R1$  (curves family) and magnitude of impedance  $Zin$ (a)  $L0 == 30\text{mm}$ ,  $L2 == 25\text{mm}$ (b)  $L0 = 30\text{mm}$ ,  $L1 == 13\text{mm}$ Figure 4.3: Relation between lengths  $L1$ ,  $L2$  and magnitude of impedance  $Zin$



# Chapter 5

## HMC778LP6CE – fractional–n PLL with integrated VCO

### Problem statement



### Circuit information

The HMC778LP6CE is a fully functioned Fractional-N Phase-Locked-Loop (PLL) Frequency Synthesizer with an integrated Voltage Controlled Oscillator (VCO).

The official datasheet is describing the input reference frequency range to be DC to 350 MHz. The manufacturer claims that it provide very good phase noise performance over temperature,

shock and process. The HMC778LP6CE offers frequency sweep and modulation features, external triggering, double-buffering, exact frequency control, phase modulation.

The HMC778LP6CE is packaged in a leadless QFN 6 x 6 mm surface mount package.

### PLL operation

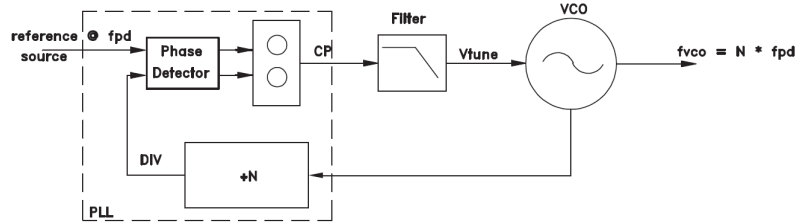
The assignment was to prepare a short summary of principles of PLLs operation of the HMC778 circuit and to describe the difference in operation between integer and fractional PLLs.

The basic application of PLL integrated circuit such as HMC778 is to form a control loop

to multiply low frequency source to a higher frequency.

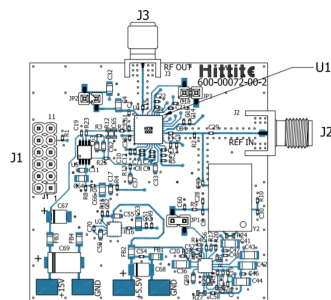
The phase detector and charge-pump drive the tuning signal of VCO (voltage controlled oscillator) to bring the phases (phases of both reference signal and tuning signal) at the detector input into alignment.

If the loop succeeds, then the phase detector inputs (reference and DIV at the diagram) are at the same frequency. As the frequency of DIV =  $f_{VCO}/N$ , then its equality means that control loop forced the frequency of VCO to be  $N \cdot f_{PD}$ . The difference between in-



teger and fractional PLL is that the fractional can bring N value at fractional level (1.6, 2.4, 3.7) while the integer can do it only with discrete value of N (2, 4, 10, 13 etc.).

## Designing PCB for HMC778



Guidelines to design a PCB board:

- The circuit board used in the application should use RF circuit design techniques.
- Signal lines should have 50 Ohm impedance while the package ground leads and exposed paddle should be connected directly to the ground plane.
- A sufficient number of via holes should be used to connect the top and bottom ground planes.



# Chapter 6

## Free-space path losses

### Problem statement

During the laboratory, we discussed the aspect of free-space losses and started the evaluation according to the distance.

This task was to finish the calculations we started and prepared the comparison in the tabular form.

Table. 6.1: The comparison of free-space losses in relation to used frequency and distance between transmitter and receiver

Frequency	Distance			
	500 km	20 000 km	37 000 km	400 000 km
100 MHz	126 dB	158 dB	163 dB	184 dB
900 MHz	145 dB	177 dB	182 dB	203 dB
2.5 GHz	154 dB	186 dB	191 dB	212 dB
5 GHz	160 dB	192 dB	197 dB	218 dB
10 GHz	166 dB	196 dB	203 dB	224 dB
20 GHz	172 dB	204 dB	209 dB	230 dB

The table observation leads to a clear conclusion – the free-space losses are increasing with the longer distance and when using high frequencies.





# Chapter 7

## Microwave low-noise amplifier operating at C-band

### Problem statement

The C-band is a portion of the electromagnetic spectrum in the microwave range of frequencies ranging from 4.0 to 8.0 GHz (according to IEEE designation).

To fulfill the given assignment, the packed low noise amplifier manufactured by Qorvo was chosen. It is **TGA2611-SM** model, operating at frequency range 2.0 - 6.0 GHz, so its range of operation covers C-band.

It is said, that the product is designed to commercial and military radars or communication.

Its noise figure is estimated to be 1.0 dB.

Product Features
<ul style="list-style-type: none"><li>• Frequency Range: 2–6 GHz</li><li>• NF: 1.0 dB</li><li>• OTOI: 30 dBm @ <math>P_{out}/Tone = 18</math> dBm</li><li>• Small Signal Gain: 22 dB</li><li>• Return Loss: &gt; 10 dB</li><li>• P1dB: 18 dBm; <math>P_{SAT} = 26</math> dBm @ <math>P_{IN} = 10</math> dBm</li><li>• Bias: <math>V_D = 10</math> V, <math>I_{DD} = 100</math> mA; <math>V_G = -2.3</math> V (Typical)</li><li>• Package Dimensions: 4.0 x 4.0 x 0.85 mm</li></ul>

Figure 7.1: Basic features of selected amplifier.

The \*.s2p file describing the scattering matrix of the plot was obtained from the Qorvo site. In the Ansoft Designer there was prepared a report:

The Scattering matrix describes the following aspects of the N-port element:

- S11 input return loss (blue plot)
- S12 reverse gain (red plot)
- S21 small signal gain (green plot)
- S22 output return loss (pink plot)

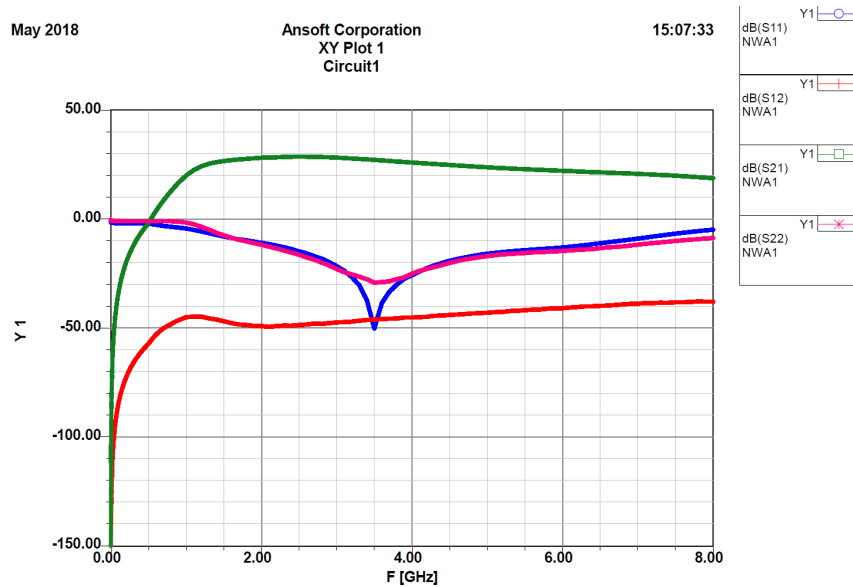


Figure 7.2: Plot of the scattering matrix.

## Noise Figure

The plot below presents the noise figure of the selected amplifier.

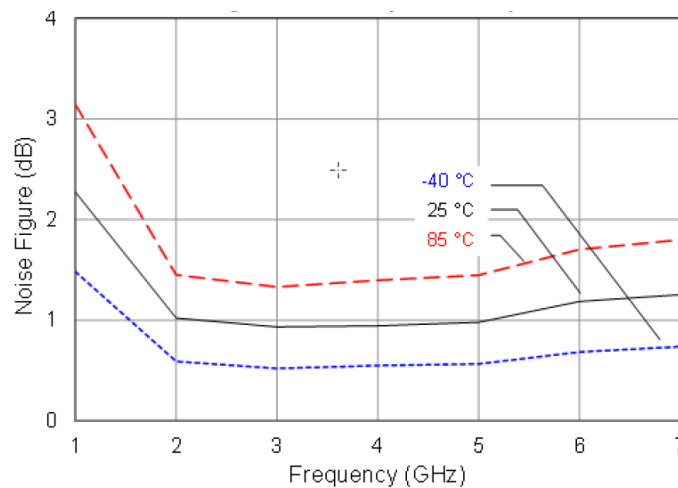


Figure 7.3: Noise figure vs frequency (at different temperatures).

Despite advertised 1dB noise figure in the operating range (reminder: 2 – 6 GHz), when approaching the upper limit of 6 GHz the NF increases. However, the change is very insignificant (more or less it is 1.25 dB).

Of course also the temperature is important, but also at 85 °C the NF in operating range is around 1.75 dB.

# Bibliography

- [1] Online Microwave Encyclopedia, <http://microwave101.com>, (27.02.2018)



# Bibliography

- [1] Online Microwave Encyclopedia, <http://microwave101.com>, (27.02.2018)