Coursework 2

Microwave Low-pass Filter Design

The aim of the coursework is to learn how filters in printed circuit technology are designed. All design is done in the Advanced Design System (ADS) software. Instructions on how to download ADS software on your computer is given separately.

The coursework consists of two parts:

In part A you will familiarise yourself with fundamental principles on how lumped capacitance and inductance can be realised using high frequency transmission lines. For this part you will need to understand and apply the basics of Transmission Line Theory, in particular the concept of characteristic impedance, input impedance and electrical length of the transmission line.

In Part B you will apply the transformation techniques to map lumped circuit low-pass prototype filter into a low-pass microwave filter and produce the layout of the filter ready for fabrication.

Please note: For the lab session to be useful to you it is essential that you familiarise yourself in advance with the:

- ADS software and
- Programming script for Part A.

References

A specific reference for this project is:

David M. Pozar, Microwave Engineering, John Wiley & Sons.

Introduction

Filters are frequency selective devices that are used to select desirable band of frequency. As such, filters have low attenuation in the passband and high attenuation in the stopband. Depending on the position of the passband filters can be classified in low-pass (passband from 0 to ω_c), high pass (passband from ω_c to $\propto$) and bandpass (passband from ω_{c1} to ω_{c2}) filters, where ω_c denotes the cutoff frequency. Most popular filter characteristics are maximally flat filter (or Butterworth filter) and Chebyshev filter. In this coursework we will base our design on the Butterworth filter response.

Ideal filters cannot be realised so appropriate specification in terms of insertion loss in the passband and in the stopband needs to be given. For example, in the case of a maximally flat low-pass prototype filter specification includes defining the maximum insertion loss in the passband (IL_{max}), the minimum insertion loss in the stopband (IL_{min}), and the cut-off frequency ω_c as shown in Fig.1. Please note that x-axis is normalised with the cut-off frequency ω/ω_c. Fig.1 also shows that higher order filters (higher N) more closely approximate ideal filter characteristic.

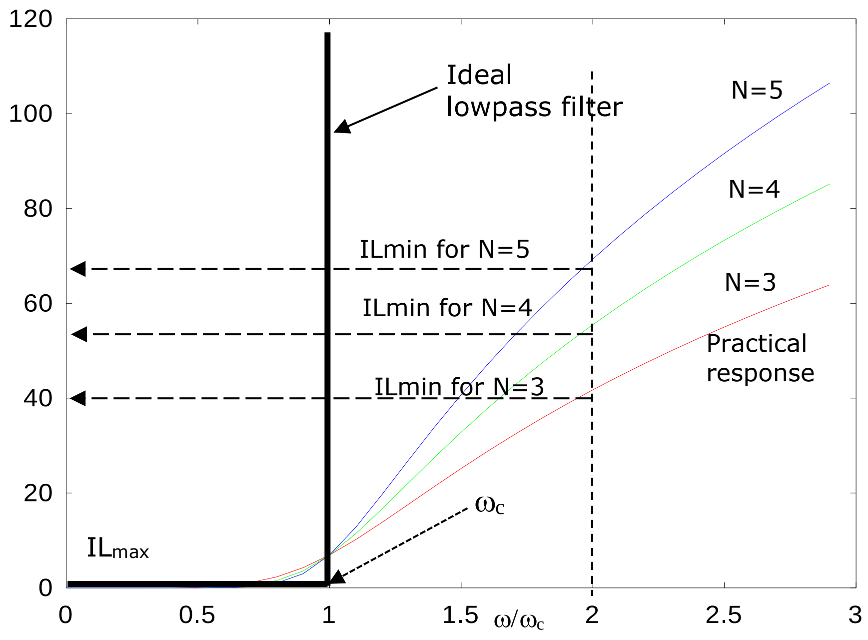

Fig.1. Maximally flat filter characteristics for a low pass prototype filter

This coursework will consider a simple approach in designing a low pass filter – stepped impedance filter. Stepped-impedance filters are popular as they are easy to design and take up less space than low-pass filters using stubs but their performance is not as good due to approximations used in the design process.

Design procedure of a stepped-impedance microwave filter goes through 5 steps and these are:

STEP1: Defining filter characteristics.

These parameters will be defined for you and they include:

a. Insertion loss (IL) in the passband. The passband is defined by a cutoff or pass-band frequency ω_c. In the case of a lowpass filter the passband is from 0- ω_c.
b. Minimal insertion loss at the frequency ω_s – this frequency characterizes the edge of the stopband. The insertion loss in the stopband is required to be greater than insertion loss at frequency ω_s.
c. Input and output impedance of the system. This is usually 50Ω impedance.

Not every filter will satisfy given filter characteristics, and therefore, based on given filter characteristics the order of the filter is first found. The appropriate order of the filter, *N*, is determined for given filter specifications. For the maximally flat filter characteristic the order of the filter that satisfies given filter characteristics is given by:

$$N \geq \frac{IL(\omega_c) + IL(\omega_s)}{20\,log\left(\frac{\omega_s}{\omega_c}\right)} \tag{1}$$

STEP 2: Select appropriate lowpass prototype filter

Lowpass prototype filter is a lumped element circuit operating at 1 Ω impedance system with a cut-off frequency of ω=1rad/s. The elements of the lowpass prototype filter are pre-calculated and are given in the Table 1 in Part B for filter orders N=1,..9. based on your calculation of eq(1) you will select appropriate filter order from Table 1 and determine normalised values for source impedance and load, and circuit capacitances and inductances (g_1, …g_{10}).

STEP 3: Transformation of the low-pass prototype network into the microwave LC filter network.

This includes scaling the lumped circuit elements to 50Ω load impedance system. The frequency of the prototype filter is also scaled from ω=1rad/s to a desired $\omega_c=2\pi f_c$. These transformations are called impedance and frequency scaling.

New values of *L′*, *C′* and the source and load impedances (R_S, R_L) are:

$$\begin{aligned} L' &= R_0 L / \omega_c \\ C' &= C / (R_0 \omega_c) \\ R'_S &= R_0 \\ R'_L &= R_0 R_L \end{aligned} \tag{2}$$

STEP4: Convert the LC microwave filter into transmission line filter.

Lumped element filters are not practical at high frequencies as their size is proportional to the wavelength of the signal and wave effects deteriorate characteristics of the component. Instead, L and C components are converted into equivalent transmission line stubs for which electrical length (βl) and characteristic impedance (Z_o) are defined. Transmission lines are idealised representation of practical lines (microstrip, stripline etc) and are characterised by characteristic impedance Zo and electrical length $\theta=\beta l$ at a specific frequency. Once we know Z_o and θ we can determine physical dimensions of transmission lines, in our case microstrip line.

a) Converting inductors into equivalent transmission lines

An inductor component can be approximated by a transmission line of high characteristic impedance. The transformation is shown in Fig.2 and is achieved by:

$$\omega_c L = Z_{oL}(\beta l) \qquad (3)$$

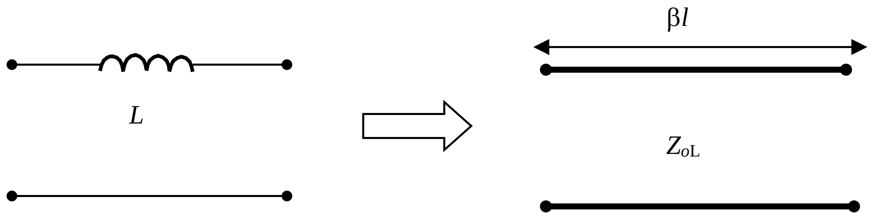

Fig.2. Lumped inductor and equivalent transmission line

For mapping to work we need to decide on 2 parameters: characteristic impedance of the line (Z_{oL}) and electrical length of the line (βl).
Typically, the value of the characteristic impedance Z_{oL} is chosen by a designer. The value of characteristic impedance depends on the technology in which filter is realised (microstrip line or stripline). In the case of microstrip line, high values of the characteristic impedance ensure better mapping. This is however limited by practical fabrication limits as high impedance implies very thin microstrip line. Typically impedance as high as $Z_{oL}=120\Omega$ can be realised in microstrip.
So it is safe to assume that characteristic impedance is 110 Ω. The electrical length can be obtained as

$$\theta = \beta l = \omega_c L / Z_{oL}$$

Please note that θ is calculated at cut-off frequency ω_c.

Note: As you increase the characteristic impedance of the transmission line the width of the practical miscrostrip line reduces, so there will be a point at which widths are too narrow and hence difficult to produce using lithography.

b) Converting capacitors into equivalent transmission lines

It can be shown that inductor can be approximated by a transmission line of low characteristic impedance. The transformation is shown in Fig.3 and is achieved by:

$$\omega_c C = (\beta l)/Z_{oC} \qquad (4)$$

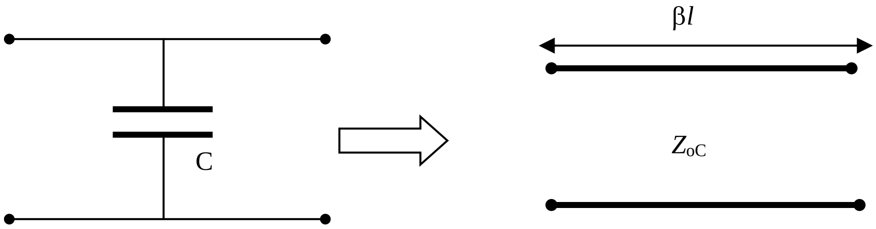

Fig.3. Lumped capacitor and equivalent transmission line

For mapping to work we need to decide on 2 parameters: characteristic impedance of the line (Z_{oC}) and electrical length of the line (βl).
Typically, the value of the characteristic impedance Z_{oC} is set to be low. In the case of microstrip technology, the choice is usually $Z_{oC}=30\Omega$.

STEP 5: Converting the transmission line filter into microstrip filter: producing a layout of the filter.

In this section you will use ADS software to obtain physical dimensions of the filter and produce a layout that is ready for fabrication. Based on known characteristic impedance and an electrical length the software outputs the width and the length of a microstrip line specified for a given substrate. The process in which the physical widths and lengths of microstrip lines are obtained is called synthesis. The inverse process, where the characteristic impedance and the electrical length of a physical microstrip transmission line are obtained from the width and length of the microstrip line is called microstrip line analysis.

The software for microstrip line synthesis is embedded within the Advanced Design System. For a given transmission line (characteristic impedance, electrical length at the cut-off frequency) and for given parameters of the substrate, the ADS software will return widths and lengths of a microstrip line.

PART A

In part A you will familiarise yourself with fundamental principles on how lumped capacitance and inductance can be realised using high frequency transmission lines. For this part you will need to understand and apply the basics of Transmission Line Theory in particular the concept of characteristic impedance, input impedance and electrical length of the transmission line.
To start you of with the Task 1a,b) you can use the prepared Matlab script. You can then develop your own scripts for other tasks in Part A and you can do that using a programming language/package of your choice (Matlab/C/C++/Excell). For the completion of this task only very basic programming skills are required. Programming skills are not assessed rather the results you obtain.

Task 1. Realising capacitance for high frequency circuits

You need to realise a capacitance of 4pF at 5 GHz in microstrip technology. To do that you need to find characteristic impedance and electrical length of the idealised transmission line so that input impedance of such a line is equivalent to the capacitor impedance. You have two options for line termination: short circuit or open circuit. Which one is better?
Which set of options (Z_{oC} and θ) will give you the best mapping?
In order to answer these question you will perform several tasks and use the outcomes to inform your answer.

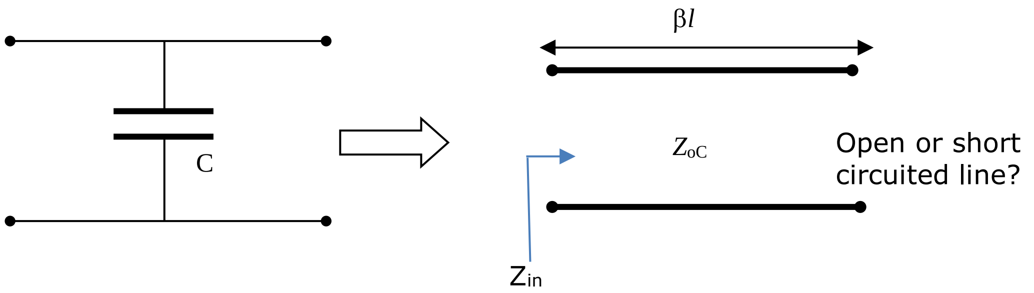

Fig.4

To obtain matching between the capacitance and transmission line, effective impedances have to match, ie.

$$Z_C = Z_{in} \tag{6}$$

The impedance of the capacitor is known and is frequency dependent. The input impedance of the transmission line is a function of line characteristic impedance, frequency and electrical length θ, ($\theta=\beta l$) and is also frequency dependent. We have 2 unknowns (Z_{oC} and θ) and one equation (6).

Task 1a.
Fix the characteristic impedance of the transmission line to be 30 Ohm and fix the frequency to 5GHz. Assume the transmission line is terminated with an open circuit.
Calculate and plot impedance Z_{in} for a range of electrical lengths ($0<\theta<2\pi$). Compare it with the value of the impedance of a capacitor Z_C at 5GHz where capacitance is 4pF.
For which value of electrical length there is a match between capacitor impedance and input impedance of the open circuited line?

Now find electrical length using eq(4). Compare it with the result you found above using accurate formula for input impedance.

Comment on the results.

Task 1b.
Reduce the characteristic impedance Z_{oC} to 10 Ohm. Repeat the exercise and compare it with Task 1a).

Task 1c.
Repeat the Task 1a,b) for the case of short circuited termination. Compare the results with those of Task1a,b) and discuss your results.

Summarise what is the best solution for Z_{oC} and electrical length?

Task 2 Realising inductance for high frequency circuits

You need to realise a capacitance of 1nH at 5GHz in microstrip technology. To do that you need to find characteristic impedance and electrical length of the idealised transmission line so that input impedance of such a line is equivalent to the capacitor impedance. You have two options for line termination: short circuit or open circuit. Which one is better? Which set of options will give you the best mapping? In order to answer these question you will perform several tasks and use the outcomes to inform your answer.

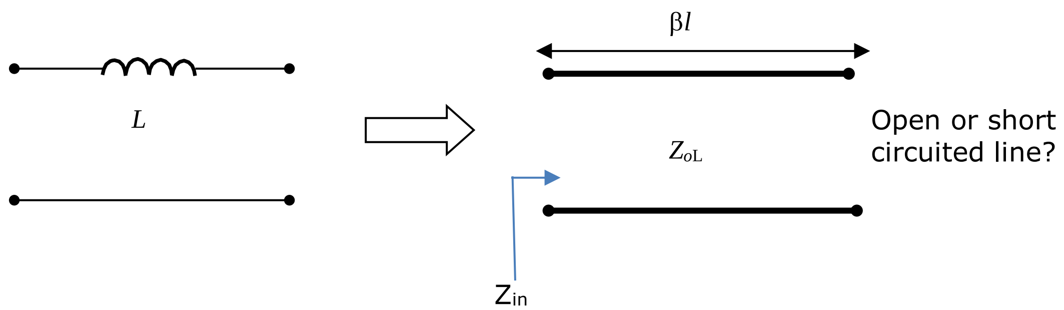

Fig. 5

Task 2a.
Fix the characteristic impedance of the transmission line to be 80 Ohm. Assume the transmission line is terminated with a short circuit.
Calculate and plot the impedance Z_{in} for a range of electrical lengths (0 rad to 2π rad).
Compare it with the value of the impedance of an inductor Z_L at 5GHz where inductor is 1nH.
Compare it with the value of the impedance of a inductor Z_L at 5GHz where inductance is 1nH.
For which value of electrical length there is a match between inductor impedance and input impedance of the short-circuited line?

Now find electrical length using eq(3). Compare it with the result you found above using accurate formula for input impedance.

Task 2b.
Increase the characteristic impedance Z_{oL} to 120 Ohm. Repeat the exercise and compare it with the Task 2a).

Task 2c.
Repeat the Task 2a,b) for the case of open-circuited line. Compare the results with those of Task 2a,b) and discuss.
Summarise what is the best solution for Z_{oL} and electrical length.

Part B

Following a design approach outlined in the introduction of the coursework, design a maximally flat low-pass filter that has the cut-off frequency at 4 GHz, maximum insertion loss in the passband of 0.5 dB, at least 14dB attenuation at 6 GHz and input and output impedance of 50Ω. Filter is to be realised in the microstrip circuit technology.

The normalised lowpass prototype filter parameters and the ladder circuit are given in Table 1 and Figure 4 respectively.
The input and output filter impedance is 50Ω. Microstrip line material parameters are:

Substrate thickness	H	2.5mm
Relative dielectric constant	ε_r	4.2
Relative permeability	Mur	1
Conductor conductivity	Cond	10^5
Cover height	Hu	10mm
Conductor thickness	T	0mm
Dielectric loss tangent	TanD	0
Conductor surface roughness	Rough	0mm

N	g1	g2	g3	g4	g5	g6	g7	g8	g9	g10
1	2.0	1.0								
2	1.4142	1.4142	1.0							
3	1.0	2.0	1.0	1.0						
4	0.7654	1.8478	1.8478	0.7654	1.0					
5	0.6180	1.6180	2.0	1.6180	0.6180	1.0				
6	0.5176	1.4242	1.9318	1.9318	1.4142	0.5176	1.0			
7	0.4450	1.2470	1.8019	2.0	1.8019	1.2470	0.4450	1.0		
8	0.3902	1.1111	1.6629	1.9615	1.9615	1.6629	1.1111	0.3902	1.0	
9	0.3473	1.0	1.5321	1.8794	2.0	1.8794	1.5321	1.0	0.3473	1.0

Table 1. Element values for maximally flat low pass Filter Prototypes ($g_0=1$, $\omega_c=1$, N=1 to 9)

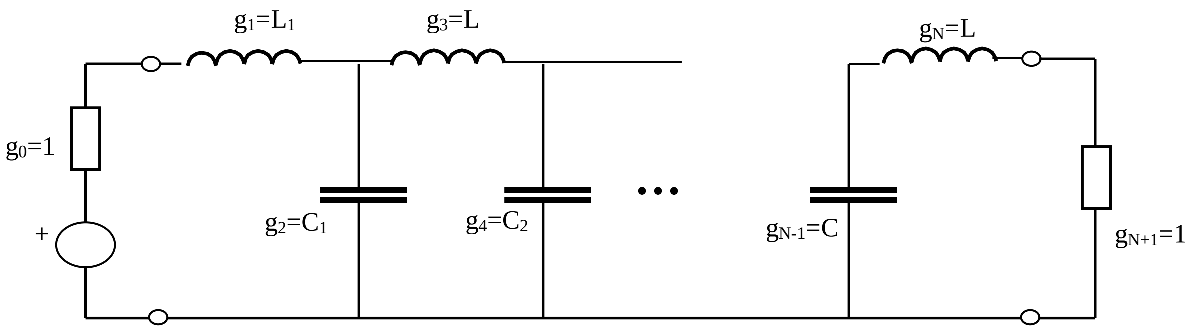

Fig.6. Ladder circuit for low pass prototype and their element definitions

In this task you need to:

- Apply the design process for the lowpass filter design using the ADS software outlined in the introduction.
- For the each design step (prototype, microwave LC filter, transmission line filter and microstrip filter) give schematic presentation of the filter and its parameters.
- Show the performance of each filter by plotting S parameters.
- Explore how you can optimise the filter response. The ADS software has an optimisation tool. You can opt to use this approach, however, I am also looking at some more intuitive and insightful approaches to filter optimisation that you can extract from the performance of non-optimised filter.
- Explore how conductor thickness and conductor conductivity can affect the response of the microstrip filter.
- In this design you will need to test a number of different filters in order to decide which one meets the specification. You need to justify your choice in terms of performance, size and cost.