## Part1- Pi-model component determination

Implement in Python the functions that allow to determine the values of the components of the π-model of integrated inductors, represented in Figure 1

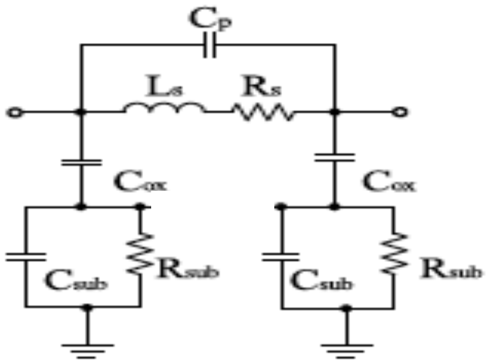


Figure 1:integrated inductor π-model

Consider the following technological parameters

```
% Tech file UMC130nm
miuR = 1;
miu = 4*pi*1e-7* miuR;
E0 = 8.854187817e-12;     // F/m
c =  299792458;           //  m/s
//Layer Oxide (Metal)
t = 2.8e-6;               //  Metal thickness (m)
Rsheet = 10*1e-3;       //  Sheet Resistance [Ohm/square] (= Ro/t)
Ro = Rsheet*t;            //  Metal Resistance [Ohm.m]
toxide = 5.42e-6;       //  Dielectric (Oxide) Thickness (from metal to substrate)
t_M_underpass = 0.4e-6;
toxide_Munderpass = toxide - t_M_underpass - 4.76e-6;
Erox = 4;               //  Oxide Er
Eox = E0* Erox;         //  Oxide permitivity  %Substrate
Ersub = 11.9;             //  substrate Er
Esub = E0*Ersub;          //  substrate permititvity
Tsub = 700e-6;             //  substrate thickness
Sub_resistiv = 2800;         // 28 ohm-cm ou 2800 Ohm-m
```

You should consider that the component values depend on geometric and technological parameters, according to the following expressions:

<u>Determination of Ls</u>

$$L_s = \frac{n^2 d_{avg} k_1 \mu_0}{\left(1 + k_2 \rho_x\right)}. \qquad (1)$$

$$\rho_x = \frac{\left(d_{out} - d_{in}\right)}{\left(d_{out} + d_{in}\right)}. \qquad (2)$$

$$d_{avg} = 0.5\left(d_{out} + d_{in}\right). \tag{3}$$

$$d_{out} = d_{in} + 2nw + 2\left(n-1\right)s. \tag{4}$$

The factors *K1* and *K2* depend on the shape of the inductor , taking the values indicated in table 1.

Table 1

| shape | K1 | K2 |
|---|---|---|
| square | 2.34 | 2.75 |
| Hexagonal | 2.33 | 3.82 |
| Octagonal | 2.25 | 3.55 |

<u>Determination of Rs</u>

$$R_s = \frac{l \cdot \rho}{w \cdot \delta \cdot t_{eff}}. \tag{5}$$

$$t_{eff} = \left(1 - e^{-t/\delta}\right). \tag{6}$$

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}. \tag{7}$$

$$l = N_{side}\, d_{avg}\, n \tan\left(\pi / N_{side}\right). \tag{8}$$

<u>Determination of Cp</u>

Capacitance Cp may be obtained from

$$C_p = n_c w^2 \frac{\varepsilon_{ox}}{t_{oxM1-M2}} \tag{9}$$

where $nc$ is the number of metallic superpositions, i.e., number of turns-1, and $t_{oxM1-M2}$ is thickness of the oxide between the two levels of metal

<u>Determination of Cox</u>

The value for capacitance across the oxide may be obtained with

$$C_{ox} = 0.5\, l\, w \frac{\varepsilon_{ox}}{t_{ox}} \tag{10}$$

<u>Determination of Csub</u>

The value for capacitance across the substrate may be obtained with

$$C_{sub} = 0.5\, l\, w \frac{\varepsilon_{sub}}{t_{sub}} \tag{11}$$

Determination of Rsub

The value for resistance of the substrate may be obtained with

$$R_{sub} = 2t_{sub} \frac{\text{Sub\_resistiv}}{l\,w} \quad (12)$$

## Part 2- Integrated Inductor Characterization

Considering that the integrated inductor has one of the terminals connected to ground, implement a function in Python that allows determining the complex impedance of the circuit shown in Figure 1. Then proceed as follows:

1. Determine the inductor inductance value for a frequency of 1GHz.

For validation of the implemented model, consider the values represented in table 2

Table 2

| N_sides | W(μm) | Dout(μm) | N-turns | L (nH) |
|---|---|---|---|---|
| 4 | 10 | 340 | 3 | 5.8 |
| 6 | 10 | 340 | 3 | 5.24 |
| 8 | 10 | 340 | 3 | 5.28 |

1. Determine the inductor quality factor for a frequency of 1GHz
2. Plot the inductance graph as a function of frequency, for a frequency between 1e3 Hz and 1e11 Hz
3. Plot the inductor quality factor as a function of frequency, for a frequency between 1e3 Hz and 1e11 Hz.
4. Determine the resonance frequency of the inductor.

## Part 3- Electrical Simulation Validation

In Ltspice edit the schematic of the circuit shown in Figure 1. Considering the values of the components obtained in Python, obtain the inductance and quality factor plots as a function of frequency, for a frequency between 1 and 3 Hz and 1 and 11 Hz.

## Part 4- Inductor project

In Python, using optimization functions, determine the geometric parameter values for a 6.5nH square inductor operating at a frequency of 2.4 GHz.

For the solution obtained, indicate the quality factor of the inductor, in that frequency, as well as the value of the respective resonance frequency.