APPENDIX

The resistance, capacitances and inductances of circuit model are evaluated by the formulas available in the literature. They are given here for reference:

The capacitor C_i is equal to the average of C_{ia} and C_{ib} for a better approximation

$$C_i = \frac{1}{2}(C_{ia} + C_{ib}) \tag{1}$$

Where [8-10]:

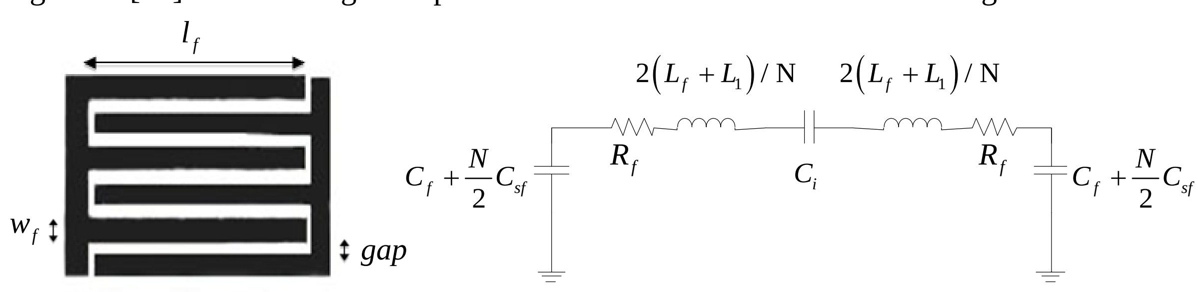
$$C_{ia} = (\varepsilon_r + 1) l_f [(N-3)A_1 + A_2)] \tag{2}$$

$$A_1 = 4.409 \tanh\left\{\left(0.55\left(\frac{h}{w_c}\right)^{0.45}\right)\right\}(F/\mu m),\ A_2 = 9.92 \tanh\left\{\left(0.52\left(\frac{h}{w_c}\right)^{0.5}\right)\right\}(F/\mu m) \tag{3}$$

$$C_{ib} = \frac{\varepsilon_{effc}(f)10^{-3}}{18\pi}\frac{K(k)}{K(k')}(N-1)l_f(pF),\ \frac{K(k)}{K(k')} = \begin{cases} \dfrac{1}{\pi}\ln\left(2\dfrac{1+\sqrt{k}}{1-\sqrt{k}}\right) & 0.707 \le k \le 1 \\ \dfrac{\pi}{\ln\left(2\dfrac{1+\sqrt{k'}}{1-\sqrt{k'}}\right)} & 0 \le k \le 0.0707 \end{cases} \tag{4}$$

$$k = \tan^2\left(\frac{\pi a}{4b}\right),\ a = \frac{w_f}{2},\ b = \frac{w_f + gap}{2},\ k' = \sqrt{1-k^2} \tag{5}$$

The interdigital capacitor is considered as a transmission line with width w_c and characteristic impedance Z_{oc} in order to determine its capacitance and inductance. Its magnetic behaviour is neglected [11]. The interdigital capacitor and its circuit modal is shown in Fig. 1.



(a) (b)

Fig. 1.Interdigital Capacitor. (a)Layout;(b)Circuit Model

$$L_f = \frac{1}{2}\frac{Z_{0c}(f)\sqrt{\varepsilon_{effc}(f)}}{c_0} l_f (H), C_f = \frac{1}{2}\frac{\sqrt{\varepsilon_{effc}(f)}}{Z_{0c}(f)C_0}(F) \tag{6}$$

The capacitance and inductance of step junctions are [8]:

$$C_{sf} = 1370 \times h^{(m)} \times \frac{\sqrt{\varepsilon_{eff_c}(f)}}{Z_{oc}}(1-\frac{w_f}{w_c})(\frac{\varepsilon_{eff_c}(f)+0.3}{\varepsilon_{eff_c}(f)-0.258}) \times (\frac{\frac{w_c}{h}+0.264}{\frac{w_c}{h}+0.8})(pF) \tag{7}$$

$$L_{sf} = h^{(m)}[1-\frac{Z_{oc}}{Z_{of}}\sqrt{\frac{\varepsilon_{eff_c}(f)}{\varepsilon_{eff_f}(f)}}]^2 (\mu H) \tag{8}$$

The shunt stub is modeled by a capacitor C_{st} parallel to a series combination of L_{st} and R_{st}. The via is modeled by L_{via} connected in series with R_{via} and the formulas are given in [8].The circuit model is shown in Fig. 2(a). The T- junction controls the right-handed part of the CRLH and its model is given by [16] which is shown in Fig. 2(b).

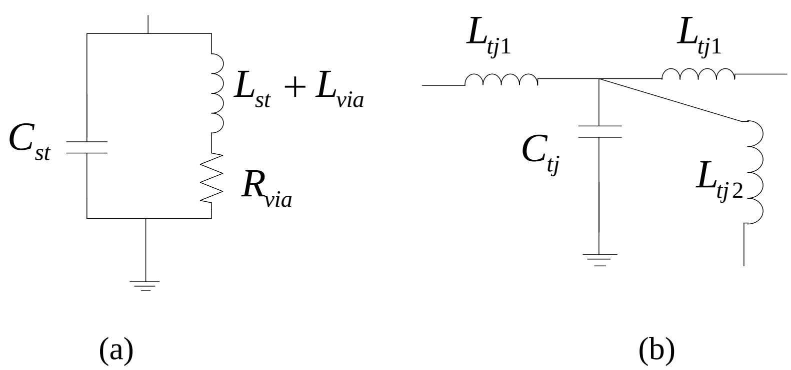


Fig. 2.(a)Shorted Stub Model (b)T-Junction Model.

$$C_{st} = \varepsilon_0 \varepsilon_r \frac{l_{st} w_{st}}{h}(F), L_{st} = \frac{Z_{0st}(f)\sqrt{\varepsilon_{effst}(f)}}{c_0} l_{st}(H), R_{st} = \frac{l_{st}}{\sigma_c w_{st} t}(\Omega) \tag{9}$$

$$L_{via} = \frac{\mu_0}{2\pi}\left[h \times \ln(\frac{h-\sqrt{r_{via}{}^2+h^2}}{r_{via}}) + \frac{3}{2}(r_{via} - \sqrt{r_{via}{}^2+h^2} \right](pH) \tag{10}$$

Where h is in μm and r_{via} is the radius of via.

$$R_{via} = R(f=0)\sqrt{1+\frac{f}{f_\delta}}(\Omega),\ f_\delta = \frac{1}{\pi\mu_0\sigma_c t^2} \tag{11}$$

The parameters of T-junction are [8]:

$$\frac{C_{tj}}{w_{tj1}} = \frac{100}{\tanh(0.0072Z_{02})} + 0.64Z_{02} - 261(pF/m) \tag{12}$$

$$L_{tj1} = -w_{tj2}\left(\frac{w_{tj2}}{h}\left(-0.016\frac{w_{tj1}}{h} - 0.064\right) + \frac{0.016}{w_{tj1}/h}\right)L_{w_1}(nH) \tag{13}$$

$$L_{tj2} = \left\{\left(0.12\frac{w_{tj1}}{h} - 0.47\right)\frac{w_{tj2}}{h} + 0.195\frac{w_{tj1}}{h} - 0.357 + 0.0283\sin\left(\pi\frac{w_{tj1}}{h} - 0.75\pi\right)\right\}L_{w2}(nH) \tag{14}$$

The microstrip line connecting the interdigital capacitor and meander inductor is [8,11]:

$$L_l = 2\times10^{-4}d_1\left(\ln\left(\frac{d_1}{w_m+t}\right) + 1.193 + 0.2235\frac{w_m+t}{d_1}\right)\times K_g(nH) \tag{15}$$

Where,

$$K_g = 0.57 - 0.145\ln\left(\frac{w_m}{h}\right) \tag{16}$$

And meander inductance is

$$L_m = 0.004l_m\left[\ln\left(\frac{d_2}{w_m+t}\right) + 1.5 + \ln k - \ln e\right] \tag{17}$$