Compact Modeling for Open and Short Structures in RF CMOS Technology over 0.25-110 GHz

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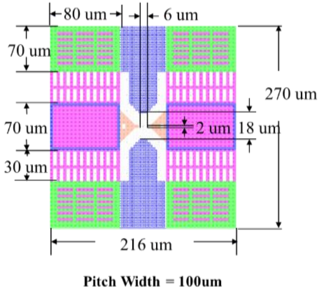
Outline

1、Introduction

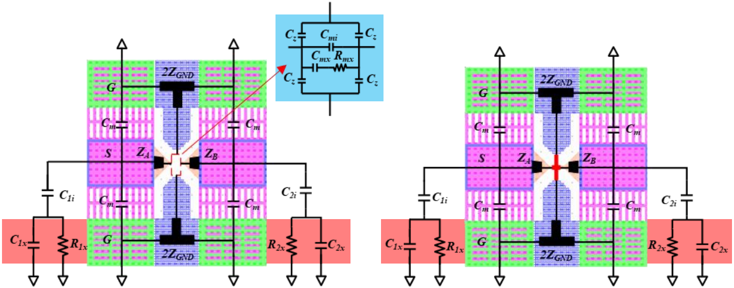
- The operation frequency of the RF-IC manufactured in CMOS technologies have reached well over 100 GHz
- GSG pads are commonly used in most of the integrated circuit design for on-wafer testing.
- A complete and accurate modeling method for open and short test structure with GSG pads are still lack.

2、Model Development and Extraction



Simplified layout of a GSG pad in RF CMOS technology.

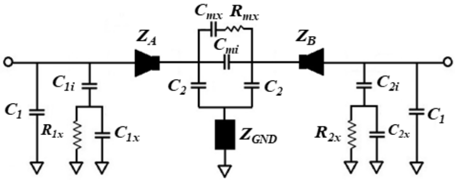
2、Model Development and Extraction



(a) (b)

The proposed equivalent circuit model for open and short structures.

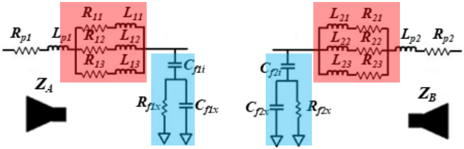
2、Model Development and Extraction



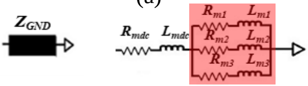
$C_1=2C_m$
$C_2=2C_z$

Simplified model topology for the open structure.

2、Model Development and Extraction



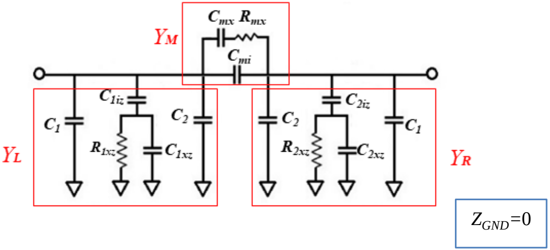
(a)



(b)

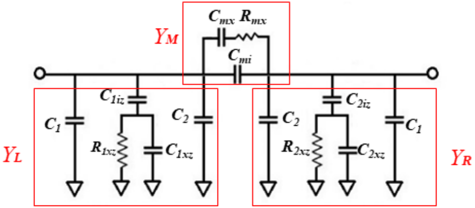
(a) Equivalent circuits for the metal feedlines at port 1 and port 2.
(b) Equivalent circuit for the metal ground plane.

2、Model Development and Extraction



Simplified model topology for the open test structure at low frequency. The relationships of model elements given as $C_{1iz}=C_{f1i}//C_{1i}$, $C_{1xz}=C_{f1x}//C_{1x}$ and $R_{1xz}=R_{f1x}//R_{1x}$.

2、Model Development and Extraction



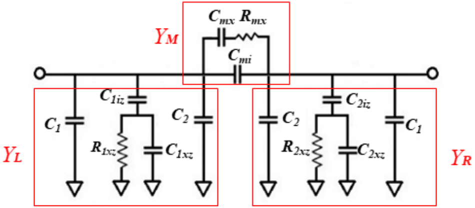
$$Y_M = j\omega C_{mi} + \left[R_{mx} + \left(j\omega C_{mx}\right)^{-1}\right]^{-1}$$

The real and imaginary parts of Y_M can be arranged as follows

$$\left[\mathrm{Re}\left(Y_M\right)\right]^{-1} = \left(C_{mx}^2 R_{mx}\right)^{-1}\omega^{-2} + R_{mx}$$

$$\mathrm{Im}\left(Y_M\right) = \omega C_{mi} + \omega C_{mx}\left(1 + \omega^2 C_{mx}^2 R_{mx}^2\right)^{-1}$$

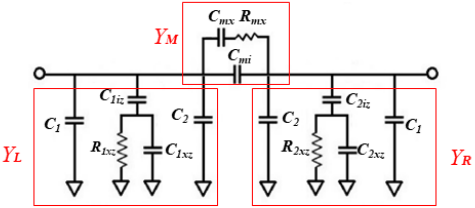
2、Model Development and Extraction



C_{mx} and R_{mx} can be determined from the intercept and slope of $[\mathrm{Re}(Y_M)]^{-1}$ versus ω^{-2}, respectively.
C_{mi} is that can be calculated from as

$$C_{mi} = \mathrm{Im}\left(Y_M\right)\omega^{-1} - C_{mx}\left(1+\omega^2 C_{mx}^2 R_{mx}^2\right)^{-1}$$

2、Model Development and Extraction



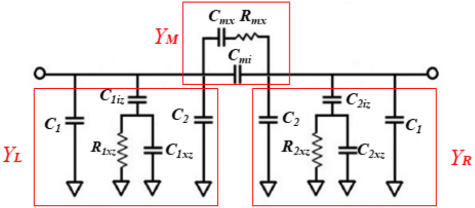
$$Y_L = j\omega\left(C_1 + C_2\right) + \left[\left(j\omega C_{1iz}\right)^{-1} + \left(j\omega C_{1xz} + R_{1xz}^{-1}\right)^{-1}\right]^{-1}$$

The real and imaginary parts of $[Y_L - j\omega(C_1+C_2)^{-1}]$ can be arranged as follows

$$\left\{\mathrm{Re}\left[Y_L - j\omega\left(C_1 + C_2\right)^{-1}\right]\right\}^{-1} = R_{1xz}^{-1} + C_{1xz}^2 R_{1xz}\omega^2$$

$$\mathrm{Im}\left[Y_L - j\omega\left(C_1 + C_2\right)^{-1}\right]^{-1} = -\left(\omega C_{1iz}\right)^{-1} - \omega C_{1xz} R_{1xz}^2 \,(1 + \omega^2 C_{1xz}^2 R_{1xz}^2)^{-1}$$

2、Model Development and Extraction

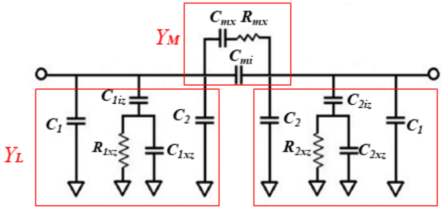


R_{1xz} and C_{1xz} can be determined from the intercept and slope of $\{\mathrm{Re}[Y_L - j\omega(C_1+C_2)^{-1}]\}^{-1}$ versus ω^2, respectively.

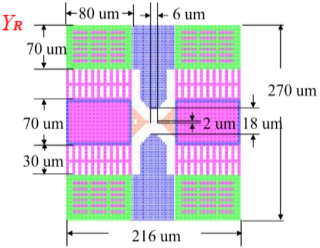
Once R_{1xz} and C_{1xz} are obtained, C_{1iz} can be calculated as

$$C_{1iz}^{-1} = -\omega\,\mathrm{Im}\left(Y_L - j\omega C_1\right)^{-1} - \omega^2 C_{1xz} R_{1xz}^2 (1+\omega^2 C_{1xz}^2 R_{1xz}^2)^{-1}$$

2、Model Development and Extraction

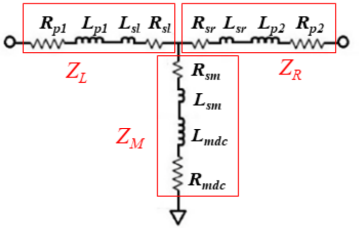


$$C_{1iz}=C_{f1i}//C_{1i}$$
$$C_{1xz}=C_{f1x}//C_{1x}$$
$$R_{1xz}=R_{f1x}//R_{1x}$$



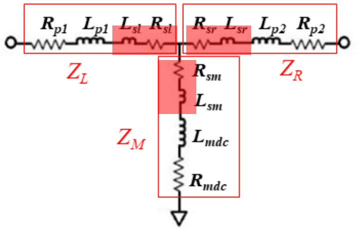
Pitch Width = 100um

2、Model Development and Extraction



The equivalent circuit of the short structure after open deembedded, e.g. Y_{short} - Y_{open}. The model topology is low frequency accurate.

2、Model Development and Extraction



$$Z_L = \left(R_{p1} + R_{sl}\right) + j\omega\left(L_{p1} + L_{sl}\right)$$

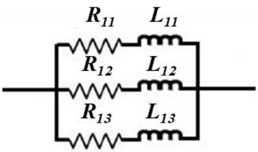
$$Z_R = \left(R_{p2} + R_{sr}\right) + j\omega\left(L_{p2} + L_{sr}\right)$$

$$Z_M = \left(R_{mdc} + R_{sm}\right) + j\omega\left(L_{mdc} + L_{sm}\right)$$

L_{sl}, R_{sl}, L_{sr}, R_{sr} and L_{sm}, R_{sm} are generally small and can be ignored.

R_{p1}, R_{p2}, R_{mdc} and L_{p1}, L_{p2}, L_{mdc} are that determined from the real and imaginary parts of Z_L, Z_R and Z_M as R_{p1} = Re(Z_L), R_{p2} = Re(Z_R), R_{mdc} = Re(Z_M) and L_{p1} = Imag(Z_L)/ω, L_{p2} = Imag(Z_R)/ω, L_{mdc} = Imag(Z_M)/ω, respectively.

2、Model Development and Extraction



The skin effect elements L_{11}, L_{12}, L_{13} and R_{11}, R_{12}, R_{13} can be determined by using empirical formula.

$$L_{1m} = K_1 \times 10^{-7} \times 2 \times l_{total} \times \left[\ln\left(\frac{2 \times l_{total}}{w_{ms} + h_{1s}} \right) + 0.50049 + \frac{w_{ms} + h_{ms}}{3 \times l_{total}} \right]$$

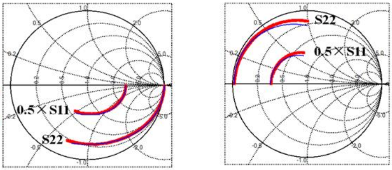
$$R_{1m} = K_2 \times l_{total} / \left(condtls \times h_{ms} \times w_{ms} \right) \qquad (m=1,2,3)$$

3、Model Verification

Table 1. Initially Extracted and Optimized Values of the Model Parameters RMS Error = |Extracted Value – Optimized Value| / Extracted Value ×100%

Parameter	Extracted	Optimized	Error(%)
$C_{1i}/C_{1x}(\times10^{-15}F)$	46.67/90.5	44.63/88.5	4.4/2.2
$C_{f1i}/C_{f1x}(\times10^{-15}F)$	0.83/1.62	0.83/1.616	0/0.24
C_{2i}/C_{2x} $(\times10^{-15}F)$	47.06/96.9	45.72/102.7	2.8/6
$C_{f2i}/C_{f2x}(\times10^{-15}F)$	0.84/1.73	0.83/1.7	1.2/1.7
R_{1x}/R_{2x} (Ω)	26.75/27.67	25.66/26.54	4.1/4.08
$R_{f1x}/R_{f2x}(\times10^{3}\Omega)$	1.498/1.55	1.5/1.548	0.13/0.13
$L_{p1}/L_{p2}(\times10^{-12}H)$	28.5/30	27.9/28.2	2.1/6
R_{p1}/R_{p2} $(\times10^{-3}\Omega)$	192/196	189.6/196.9	1.3/0.5
L_{mdc} $(\times10^{-12}H)$	1.8	1.65	8.3
R_{mdc} $(\times10^{-3}\Omega)$	244	248.9	2
$L_{11}/L_{12}/L_{13}(\times10^{-12}H)$	4/4.2/5.12	3.8/4.3/5.1	5/2.4/0.4
$R_{11}/R_{12}/R_{13}(\Omega)$	0.6/0.37/0.3	0.6/0.37/0.28	0.3/0/1
$L_{21}/L_{22}/L_{23}(\times10^{-12}H)$	4/4.2/5.12	4.1/4.1/5.1	2.5/2.4/0.4
$R_{21}/R_{22}/R_{23}(\Omega)$	0.6/0.37/0.3	0.6/0.36/0.29	0/1.1/0.7
C_{mi}/C_{mx} $(\times10^{-15}F)$	2/5.0	1.97/5.33	1.5/6.6
$R_{mx}(\Omega)$	344	322.6	6.2
C_1 $(\times10^{-15}F)$	1	1.05	5
C_2 $(\times10^{-15}F)$	4	4.1	2.5
$L_{m1}/L_{m2}/L_{m3}(\times10^{-12}H)$	3.4/3.4/4.54	3.3/3.3/4.6	2.9/2.9/1.3
$R_{m1}/R_{m2}/R_{m3}(\times10^{-3}\Omega)$	67/34/11	67/33/12	0/2.9/9
$L_{sl}/L_{sr}/L_{sm}(\times10^{-12}H)$	0.5/0.5/0.5	0.49/0.48/0.5	2/4/8
$R_{sl}/R_{sr}/R_{sm}(\times10^{-3}\Omega)$	35/35/35	36/35.2/37	2.86/0.6/6

3、Model Verification



(a) (b)

The measured and simulated *S* parameters.
(a) Open results between measured and simulated values.
(b) Short results between measured and simulated values.

4、Conclusion

- A new compact model for GSG pad structure in RF CMOS has been presented.
- A novel model parameter extraction method has been proposed.
- The model simulated results show excellent agreement with the measured results, verified the high accuracy of the proposed model.

Thank you!