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Evaluation of a Multi-line De-embedding Technique for Millimeter-Wave CMOS Circuit Design

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ABSTRACT — This paper presents the evaluation of a pad model which is made by using L-2L de-embedding method. The coplanar waveguide transmission line (CPWTL) is used to evaluate the de-embedding method. The pad circuit model is set up after obtaining the results of de-embedding. Two comparisons are carried out to accomplish the evaluation of the pad circuit model. The calculation error in quality factor of transmission line is less than 6% in experimental result. Employing the model to de-embed other DUTs, the process becomes simple and chip area can be saved.

Index Terms **—de-embedding, millimeter wave, transmission line, L-2L**

I. INTRODUCTION

Recently, many studies on millimeter-wave (MMW) CMOS circuit designs have been reported [1-2]. Due to the low fabrication cost and suitability for mass production, CMOS process is widely employed. Since the models provided by foundries are not accurate any more at MMW frequency, device modeling becomes very important. Test Elementary Group (TEG) of passive and active devices including text fixture such as pads and interconnects for measurement have been implemented before circuit design. In order to obtain the characteristic of the device under test (DUT), a proper de-embedding method is required to eliminate the parasitics. One commonly-used de-embedding method is open-short method proposed in [3]. However, it is difficult to realize ideal open, short or other patterns as the frequency is increased. Another way is to use through only pattern to calculate the pad parasitics [4]. It is a good method to save chip area. Nevertheless, it models the pad by using lumped component, the length of the through-line is required to be very short to match with the π-type lumped model. As the length of the through-line become longer the error becomes remarkable to treat it as a lumped model. Furthermore, when the through-line is shorted, the isolation between probes becomes very difficult due to the coupling of the probe at high frequency (MMW). In order to solve the problem, the L-2L de-embedding method is used to get the models of the pads [5]. As the proposed circuit models of the test fixture, the parastics can be subtracted from the measurement results easily, also can save the chip area. As is known, measurement results have error, which is caused by probing position in MMW frequency. As shown in Fig. 1, the pad has some area, and probing position is uncertain. Thus, the models created by using measurement results containing the error are not accurate.

In this paper, the pad model is made by using the L-2L method and the evaluation of the modeling error is investigated. Section II described the evaluation standard using transmission line. The common de-embedding methods for MMW are introduced in section III. The process of L-2L de-embedding methods and how to derive the models are described Section IV. The results of the de-embedding using the model are also shown. The conclusion is given in the final section.

II. EVALUATION USING TRANSMISSION LINE

According to transmission line theory [6], voltages and currents can vary in magnitude and phase over the line length. It has some characteristics which do not change as the length changed. In this paper, the transmission line is chosen to evaluate the de-embedding method. Fig.2 shows the lumped-element equivalent circuit of a segment of a transmission line.

The general expression for the complex propagation constant is

$$\gamma = \sqrt{(R + j\omega L) \times (G + j\omega C)} = \alpha + j\beta \tag{1}$$

And as frequency increased, $R \ll \omega L$ and $G \ll \omega C$, the attenuation constant α and the phase constant β can be expressed as

$$\alpha \approx \frac{1}{2}\left(\frac{R}{Z_0} + GZ_0\right) \tag{2}$$

$$\beta \approx \omega\sqrt{LC} \tag{3}$$

The characteristic impedance Z_0 can be expressed as

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \approx \sqrt{\frac{L}{C}} \tag{4}$$

And the quality factor is shown as

$$Q = \frac{\beta}{2\alpha}\,. \tag{5}$$

As shown in (1) ~ (5), the attenuation constant, the phase constant, the characteristic impedance and the quality factor are not raised with the length. In this paper, the coplanar waveguide transmission line (CPWTL) is used. Fig. 3 shows the structure of the CPWTL.

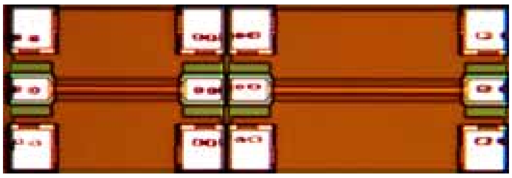


Fig.1. Chip photo of pad.

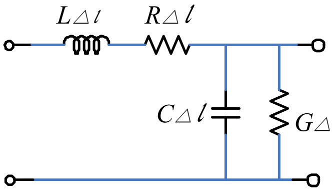


Fig.2. Lumped-element equivalent circuit of a segment of a transmission line.

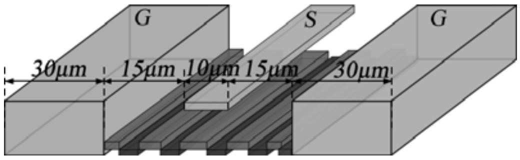
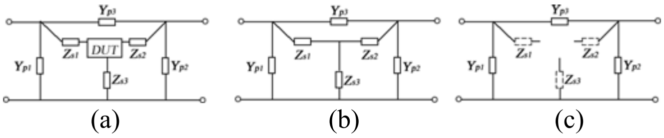


Fig.3. Structure of the coplanar waveguide transmission line.



(a) (b) (c)

Fig.4. Equivalent circuit diagram used in open-short de-embedding.

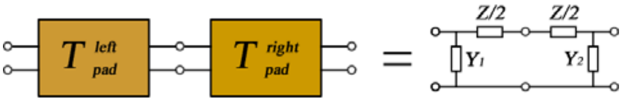


Fig.5. Through-only de-embedding method and its equivalent circuit.

III. THE COMMON DE-EMBEDDING METHODS FOR MMW

Open-short de-embedding method [3]

The equivalent circuit diagram is modeled as shown in Fig. 4(a). The DUT is surrounded by the parallel parasitics Y_{p1}, Y_{p2}, Y_{p3} and the series parasitics Z_{s1}, Z_{s2} and Z_{s3}. An open pattern and a short pattern are fabricated on the same wafer with the DUT as shown in Fig.4(b) and Fig.4(c). The series impedances can be easily derived from the short measurement by assuming a T-network model with impedances Z_{s1}, Z_{s2} and Z_{s3}, as shown in Fig. 4(c). The short pattern Y-parameters are first calculated to obtain parallel parasitics from the open-pattern measurement and transformed to Z-parameters.

$$\begin{pmatrix} Z_{s1}+Z_{s3} & Z_{s3} \\ Z_{s3} & Z_{s2}+Z_{s3} \end{pmatrix} = (Y_{short}-Y_{open})^{-1} \qquad (6)$$

Similarly, the Y-parameters of the DUT with the impedances Z_{s1}, Z_{s2} and Z_{s3} can be obtained by subtracting the Y parameters of the open pattern from that of the DUT measurement. Finally, the actual Z-parameters of the DUT can be obtained from:

$$Z_{DUT} = (Y_{meas}-Y_{open})^{-1} - (Y_{short}-Y_{open})^{-1} \qquad (7)$$

where Y_{meas} is the measured Y-parameters of the DUT with parasitics.

In this method, two or more patterns are required for each DUT with different size and topology, which consumes large chip area. In addition, it is difficult to realize the ideal open and short patterns as the frequency increased.

Thru-only de-embedding method [4]

In this method, the series and shunt impedances are considered. As shown in Fig.5, the thru is approximately described as a π -type equivalent circuit. Y-parameter matrix of the thru is

$$Y_{thru} = \begin{pmatrix} Y_1+\frac{1}{Z} & -\frac{1}{Z} \\ -\frac{1}{Z} & Y_2+\frac{1}{Z} \end{pmatrix}. \qquad (8)$$

The thru line is property symmetrical, so the left pad and the right pad are

$$Y_{pad}^{left} = \begin{pmatrix} Y_1+\frac{2}{Z} & -\frac{2}{Z} \\ -\frac{2}{Z} & \frac{2}{Z} \end{pmatrix} \qquad (9)$$

$$Y_{pad}^{right} = \begin{pmatrix} \frac{2}{Z} & -\frac{2}{Z} \\ -\frac{2}{Z} & Y_2+\frac{2}{Z} \end{pmatrix}. \qquad (10)$$

Then the Y-parameter is transformed to T-parameter. Thus, the device-under-test (DUT) can be de-embedded as

$$\begin{aligned} T_{DUT} &= (T_{pad}^{left})^{-1} T_{meas} (T_{pad}^{right})^{-1} \\ &= (T_{pad}^{left})^{-1}(T_{pad}^{left}) T_{DUT} (T_{pad}^{right})(T_{pad}^{right})^{-1} \end{aligned} \qquad (11)$$

IV L-2L DE-EMBEDDING METHOD AND THE MODE EVALUATION

As introduced in section II, transmission line is used to evaluate the de-embedding methods. The ground-signal-ground (GSG) pad is used. The impedance can be summarized as the shunt conductance and the series impedance. The equivalent circuit model is shown in Fig.6. The structure can be treated as a five parts cascade connection. The shunt conductance is $Y_p = G + 2j\pi\omega C$ and the series impedance is $Z_s = R + 2j\pi\omega L$. The transmission matrix of the test structure can be represented as the following product:

$$T_{mi} = T_{pad}^{left} T_{li} T_{pad}^{right} \tag{12}$$

$$T_{pad}^{left} = T_p T_s \tag{13}$$

$$T_{pad}^{right} = T_s T_p \tag{14}$$

where T_p and T_s is the T-parameter transformed from Y_p and Z_s.

In L-2L de-embedding method, two transmission lines are employed, the length of one is twice longer than the other. The de-embedding process is shown in Fig.7.

$$T_{pad}^{left} T_{pad}^{right} = T_{l1} T_{l2}^{-1} T_{l1} = T_{thru} \tag{15}$$

By transforming T-parameter of thru to Y-parameter, Y_L and Z_s can be expressed as:

$$Y_L = Y_{thru}(1,1) + Y_{thru}(1,2) \tag{16}$$

$$Z_S = \frac{-1}{2Y_{thru}(1,2)} \tag{17}$$

As the shunt conductance and the series impedance are obtained, the model of the pad can be made.

For L-2L de-embedding method, a 200μm CPWTL and 400μm CPWTL (Fig.8) are employed to derive pad model. Fig.9. shows de-embedding results of the two transmission lines. From the graphs, the characteristic impedances, the attenuation constants, the phase constants and the quality factors of the 200μm and 400μm CPWTL are matched very well.

Using calculated results, the parameters of pad which is shown in Fig.10 are obtained. Thus, the T-parameter of DUT can be calculated as:

$$T_{DUT} = (T_{\mathrm{mod}}^{left})^{-1} T_{meas} (T_{\mathrm{mod}}^{right})^{-1} \tag{18}$$

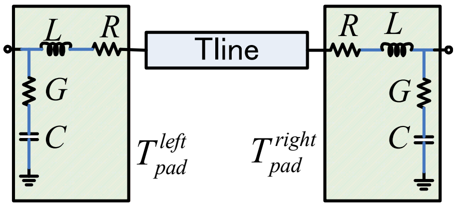


Fig.6. Equivalent circuit model of pad.

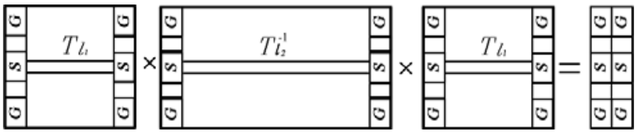


Fig.7. Process of L-2L de-embedding method.

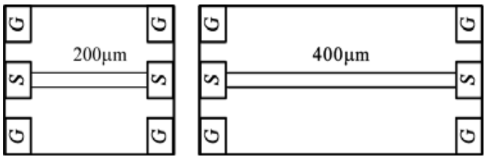


Fig.8. 200μm and 400μm CPWTL.

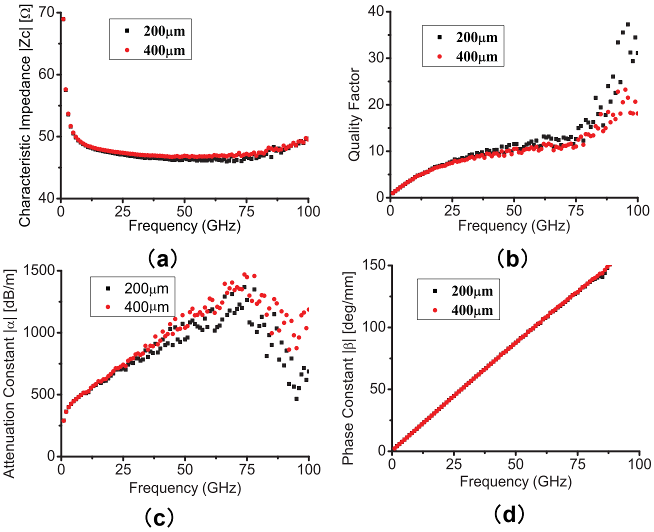
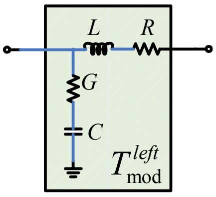


Fig.9. Measurement results of CPWTL using L-2L de-embedding method. (a) Characteristic Impedance. (b) Attenuation Constant. (c) Phase Constant. (d) Quality Factor.



$$L = 8.3\times10^{-12} + 2.14\times10^{-23} f \ \ (\mathrm{H})$$

$$R = 0.1 + 0.01\times10^{-9} f \ \ (\Omega)$$

$$1/G = 0.5 + 0.19\times10^{-9} f \ \ (\Omega)$$

$$C = 1.67\times10^{-14} - 6\times10^{-27} f \ \ (F)$$

Fig.10. Model of pad.

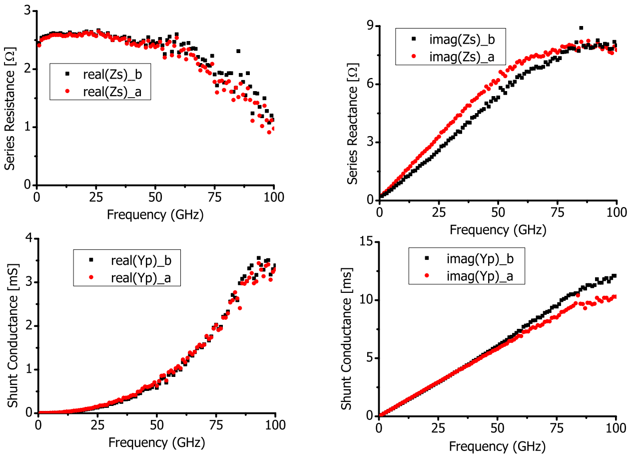
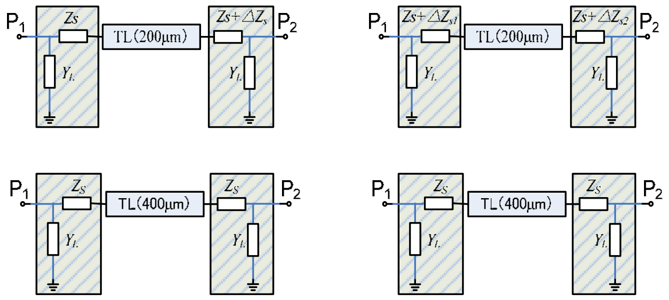


Fig.11. Impedance and conductance.



(a) Case I (b) Case II

Fig.12. Pad models containing errors.

As mentioned previously, measurement error causes modeling error. Even if the same model is used, the de-embedded results may be inaccuracy when the probe is contacted at different locations on the pad due to the difference of the series impedance. In order to evaluate the modeling error, the influence of probed position is investigated by using the measurement results using different probing position as shown in Fig.1. The series impedance and the shunt conductance are calculated by using L-2L method. As the results shown in Fig.11, the series reactance changes a lot while the series resistance and shunt conductance varies little. For the evaluation, an artificial parasitic impedance is assumed as shown in Fig.12, which is defined by using the following equation.

$$\Delta Zs = (-4\times 10^{-22} f^2 + 4\times 10^{-11} f + 0.0359) j \qquad (19)$$

In order to estimate the modeling error, the model shown in Fig.12 is assumed. Fig.12(a) contains error at one side, and Fig.12(b) contains error at both sides, which is simulated by using additional series impedance $\triangle Zs$. The 200µm and 400µm CPWTLs are used in the structure. Case I assumes that: $\triangle Zs1=0$, $\triangle Zs2=\triangle Zs$, and case II assumes that: $\triangle Zs1=\triangle Zs2=\triangle Zs$. The results of case I and II are shown in Fig.13 and the Fig.14, respectively.

From these two comparisons, the de-embedding error can be estimated. The case I has errors in the characteristic impedance and quality factor about 1% and 2% at 60GHz, while the case II has errors about 2% and 6% at 60GHz. In both cases, attenuation and phase constants are matched very well.

V. CONCLUSION

In this paper, the de-embedding accuracy of L-2L method is evaluated to consider difference in pad probing position. By using 200µm and 400µm CPW transmission lines, the evaluation is accomplished. In two cases, the error in quality factor of transmission line is less than 6%. Thus, the model of pad can be used in any other DUTs which use the same pad.

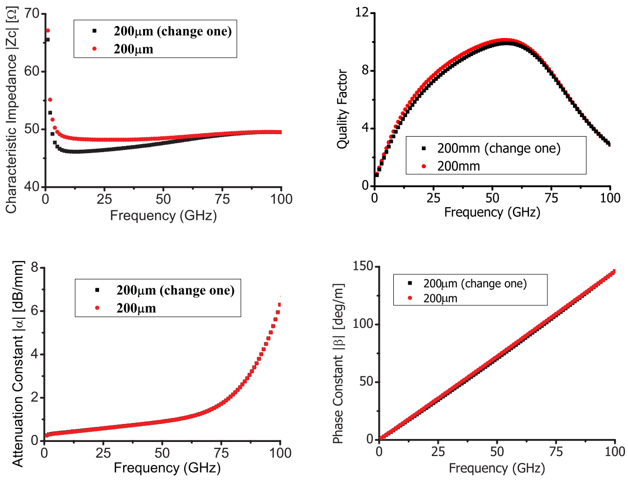


Fig.13. Parameters of 200µm CPWTL in case I.

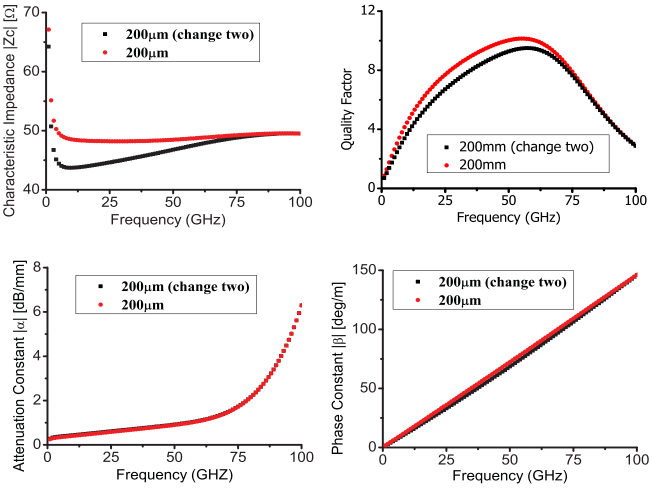


Fig.14. Parameters of 200µm CPWTL in case II.

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REFERENCES

[1] T. Suzuki, Y. Kawano, M. Sato, T. Hirose, and K. Joshin, “60 and 77GHz Power Amplifiers in Standard 90nm CMOS,” *IEEE ISSCC,* pp. 562-563, February, 2008.

[2] B. Razavi, “Design of Millimeter-Wave CMOS Radio: A Tutorial,” *2003 IEEE Trans. CAS-I,* vol. 56, no.1, pp. 4-16, January, 2009.

[3] M. Koolen, J. Geelen, and M. Versleijen, “An Improve De-embedding Technique for on-wafer High-frequency Characterization,” *BCTM,* vol. 19, no. 1, pp. 188-191, June, 1991.

[4] H. Ito, and K. Masu, “A Simple Through-only De-embedding Method for on-wafer S-parameter Measurements up to 110GHz,” *IEEE MTT-S IMS,* pp. 383-386, June, 2008.

[5] J. Song, F. Ling, G. Flynn, W. Blood, and E. Demircan, “A De-embedding Technique for Interconnects,” *EPEP,* pp. 129-132, October, 2001.

[6] D. M. Pozar, *Microwave Engineering*, 2nd ed. Willey, 2005, ISBN: 0-471-44878-8