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Advanced On-chip SOL Calibration Method for Unknown Fixture De-embedding

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***Abstract*—SOL (Short, Open and Load) calibration based on iterative error sensitivity is proposed in this paper. With advanced SOL calibration, unknown parasitic parameters at on-chip terminations are accurately estimated up to 20 GHz. Artificial terminations are designed on printed circuit board (PCB) to experiment the proposed method. On-chip SHORT, OPEN and LOAD fabricated inside silicon shows the accuracy of proposed calibration method through the comparison with known fixture S-parameter after de-embedding**

***Index Terms*—SOL calibration, iterative error sensitivity, de-embedding**

I. INTRODUCTION

While both a data-rate and number of massive channels from ICs dramatically has been increasing, an allowable jitter level has been decreasing in modern high-speed link. Therefore, the timing margin estimated right after IC buffer has become more important. However, the estimation of pure jitter number inside ICs is getting harder due to many unknown parameters caused by unknown parasitic form conventional fixtures such as not only connector, transmission line and via on PCB but very short package/IC channel ignored before. Thus, there are various calibration methods to characterize fixtures and de-embed fixture effect to remove unnecessary channel effect on timing error. Many researches regarding various calibration methods such as SOLT, TRL and LRRM are reported for de-embedding of the fixture [1-4]. SOLT calibration is widely known as the easiest calibration standards using SHORT, OPEN, LOAD termination including accurate parasitic information [5-10].

However, the commercial calibration kit has a couple of limitations to silicon fixture de-embedding. Since SMA connector or micro probes are usually used for calibration procedure, an ordinary SOLT calibration method is hard to characterize remaining fixture before the signal pad. If unexpected fixtures cannot be removed and all parasitic fixtures on package/ICs are remained, the timing error is still overestimated and it results in the cost increase. Thus, on-PCB or on-chip SOLT calibration kit is manually designed for more accurate characterization these days. Manual SOLT calibration kit provides a solution to de-embed all other parasitic fixtures where is not calibrated with commercial calibration kit. Moreover, since all terminations use same materials of fixture design, the fixture characteristic is very close to that of real channel which is desired to be removed. However, this manual calibration kit has a limitation to get parasitic parameters at terminations. The harder thing is that these parasitic vary with a small tolerance associated with a process variation or material properties. Therefore, a novel calibration method considering unknown parasitic are essentially necessary.

This paper analyzes the error amplification from small variation at each termination and proposes an advanced SOLT calibration method using iterative error sensitivity. In addition, the iterative error procedure make an easy way to find out correct parasitic values. Proposed

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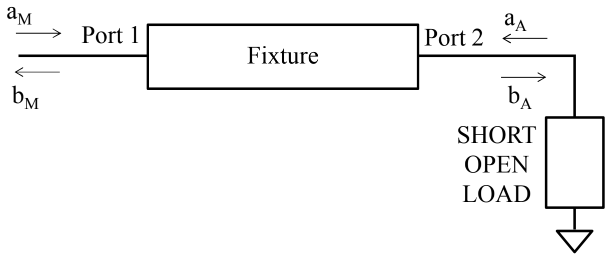


Fig. 1. Three different terminations, SHORT, OPEN and LOAD, are necessary to calibrate fixture.

procedure uses an error level between original S-parameter and calculated S-parameter and tunes parasitic to minimize this error level. To validate proposed iterative procedure with experimental measurement, artificial SHORT, OPEN, LOAD terminations and THRU line are fabricated on PCB and on-chip. Through fabricated manual calibration kit, all parasitic can be estimated and each parameter is validated with TDR. Finally, the proposed calibration method is applied to remove errors from parasitic values and characterize on-chip fixtures.

II. SOL CALIBRATION

To characterize the fixture with SOL calibration, actual terminations such as SHORT, OPEN and LOAD are necessary at the end of the fixture as shown in Fig. 1.

Additional THRU fixture is also necessary for multi-port calibration. While ratio of incident wave and reflected wave at Port1 is determined as a reflection coefficient [Γ_M], another ratio at Port2 is an actual reflection coefficient [Γ_A] as express in (1) and (2). If all terminations are ideal, the actual reflection coefficients at SHORT, OPEN, LOAD have -1,1, 0 respectively.

$$\Gamma_M = \frac{b_M}{a_M} \tag{1}$$

$$\Gamma_A = \frac{a_A}{b_A} \tag{2}$$

Transmission matrix is more comfortable to characterize the fixture with SOL calibration since transmission matrix can be cascaded in series directly. Transmission matrix can be transformed from S-parameter as expressed in (3) and each matrix parameter can be expressed in (4) if the fixture is reciprocal and passive.

$$T_M = \frac{1}{S_{M21}}\begin{bmatrix} -\det S_M & S_{M11} \\ -S_{M22} & 1 \end{bmatrix} = \frac{1}{S_{M21}}\begin{bmatrix} A & B \\ C & 1 \end{bmatrix} \tag{3}$$

$$S_{11} = B,\ S_{22} = -C,\ S_{12} = S_{21} = \sqrt{A - BC} \tag{4}$$

Two reflection coefficients are related with the fixture in between as express in (5). Since there are three unknown parameters A,B and C, three equations are necessary to specify individual parameter. That is why three different measurements are needed for 1-port SOL calibration.

$$\Gamma_A = \frac{\Gamma_M - B}{A - \Gamma_M C} \tag{5}$$

If two reflection coefficients at SHORT, OPEN and LOAD are known, three unknown parameters can be obtained as expressed in (6), (7), (8) and (9).

$$A = \frac{Q_2 M_1 - Q_1 M_2}{Q_2 P_1 - Q_1 P_2} \tag{6}$$

$$C = \frac{P_2 M_1 - P_1 M_2}{P_2 Q_1 - P_1 Q_2} \tag{7}$$

$$\begin{aligned} B &= \Gamma_{ML} + \Gamma_{AL}\Gamma_{ML} C - \Gamma_{AL} A \\ &= \Gamma_{ML} + \frac{\Gamma_{AL}\Gamma_{ML}(P_1 M_2 - P_2 M_1) - \Gamma_{AL}(Q_2 M_1 - Q_1 M_2)}{Q_2 P_1 - Q_1 P_2} \end{aligned} \tag{8}$$

$$\begin{array}{lll} Q_1 = \Gamma_{AO}\Gamma_{MO} - \Gamma_{AS}\Gamma_{MS} & P_1 = \Gamma_{AS} - \Gamma_{AO} & M_1 = \Gamma_{MS} - \Gamma_{MO} \\ Q_2 = \Gamma_{AL}\Gamma_{ML} - \Gamma_{AO}\Gamma_{MO} & P_2 = \Gamma_{AO} - \Gamma_{AL} & M_2 = \Gamma_{MO} - \Gamma_{ML} \end{array} \tag{9}$$

As seen by equations of unknown parameters, the S-parameter matrix for the fixture from SOL calibration consists of three measured reflection coefficients and actual reflection coefficients. Thus, obtained S-parameter vary if one of three actual reflection coefficients have a very small error caused by unknown parasitic at the end of each termination. An error sensitivity of reflection coefficient is shown as expressed in (10), (11) and (12). Three error sensitivity expressions show similar formula and have a common error term [E] consisting of reflection coefficients as shown in (13). Other error terms [E_{S1}, E_{S2}, E_{O1}, E_{O2}, E_{L1}, E_{L2}] have different formula but are composed of reflection coefficients as expressed in (14), (15), (16), (17), (18), and (19).

$$dE_{SHORT,RL} = \frac{dS_{11}}{d\Gamma_{AS}} = E_{S1} - EE_{S2} \tag{10}$$

$$dE_{OPEN,RL} = \frac{dS_{11}}{d\Gamma_{AO}} = E_{O1} - EE_{O2} \tag{11}$$

$$dE_{LOAD,RL} = \frac{dS_{11}}{d\Gamma_{AL}} = E_{L1} - EE_{L2} \tag{12}$$

$$E = \frac{\Gamma_{AL}\Gamma_{ML}(P_1M_2 - P_2M_1) - \Gamma_{AL}(Q_2M_1 - Q_1M_2)}{Q_2P_1 - Q_1P_2} \tag{13}$$

$$E_{S1} = \frac{\Gamma_{AL}M_2(\Gamma_{ML} - \Gamma_{MS})}{Q_2P_1 - Q_1P_2} \tag{14}$$

$$E_{S2} = \frac{(\Gamma_{MS}P_2 + \Gamma_{AL}\Gamma_{ML} - \Gamma_{AO}\Gamma_{MO})}{Q_2P_1 - Q_1P_2} \tag{15}$$

$$E_{L1} = \frac{\Gamma_{AL}(P_1M_2 - P_2M_1) - (Q_2M_1 - Q_1M_2)}{Q_2P_1 - Q_1P_2} \tag{16}$$

$$E_{O1} = \frac{\Gamma_{AL}(M_1 + M_2)(\Gamma_{MO} - \Gamma_{ML})}{Q_2P_1 - Q_1P_2} \tag{17}$$

$$E_{O2} = \frac{(-\Gamma_{MO}(P_1 + P_2) - \Gamma_{AL}\Gamma_{ML} + \Gamma_{AS}\Gamma_{MS})}{Q_2P_1 - Q_1P_2} \tag{18}$$

$$E_{L2} = \frac{(\Gamma_{ML}P_1 + \Gamma_{AO}\Gamma_{MO} - \Gamma_{AS}\Gamma_{MS})}{Q_2P_1 - Q_1P_2} \tag{19}$$

$$dE_{SHORT,IL} = \frac{dS_{21}}{d\Gamma_{AS}} = \frac{1}{Q_2P_1 - Q_1P_2}\left(-M_2(\Gamma_{ML} - \Gamma_{MS} + E) - (Q_2M_1 - Q_1M_2)E_{S2} - (P_1M_2 - P_2M_1)(E_{S1} - 2EE_{S2} - \Gamma_{ML}E_{S2})\right)\frac{1}{E_d} \tag{20}$$

$$dE_{OPEN,IL} = \frac{dS_{21}}{d\Gamma_{AO}} = \frac{1}{Q_2P_1 - Q_1P_2}\left((M_1 + M_1)(\Gamma_{ML} - \Gamma_{MO} + E) - (Q_2M_1 - Q_1M_2)E_{O2} - (P_1M_2 - P_2M_1)(E_{O1} - 2EE_{O2} - \Gamma_{ML}E_{O2})\right)\frac{1}{E_d} \tag{21}$$

$$dE_{LOAD,IL} = \frac{dS_{21}}{d\Gamma_{AL}} = \frac{1}{Q_2P_1 - Q_1P}\left(-M_1E - (Q_2M_1 - Q_1M_2)E_{L2} - (P_1M_2 - P_2M_1)(E_{L0} - 2EE_{L2} - \Gamma_{ML}E_{L2})\right)\frac{1}{E_d} \tag{22}$$

$$E_d = 2\sqrt{\frac{Q_2M_1 - Q_1M_2}{Q_2P_1 - Q_1P_2} - \frac{(\Gamma_{ML} + E)(M_2P_1 - M_1P_2)}{Q_2P_1 - Q_1P_2}} \tag{23}$$

Another error sensitivity of insertion loss in S-parameter from three end terminations can be obtained but these equations are much complicated than that of return loss as expressed in (20), (21) and (22). Three sensitivity equations for insertion loss also has similar formula construction with six reflection coefficients and have common denominator error term [E_d] as expressed in (23). The check of error sensitivity is important to see the variation in S-parameter due to unknown parasitic at actual terminations.

III. ITERATIVE ERROR CHECK

If the equivalent model of actual termination and parasitic parameters on calibration kit are known, S-parameter of the fixture for the de-embedding is accurately characterized based on three actual gammas [Γ_{AS}, Γ_{AO} ,Γ_{AL}] as shown in the previous chapter. However, there is no way to find out accurate parasitic parameters for artificial calibration kit. This chapter introduces an iterative method to find out all unknown parasitic parameters and minimize the error sensitivity. The proposed method basically adopts an error minimization between two S-parameters from the measurement and the estimation as shown in Fig. 2.

The first step is to follow a general calibration procedure and measure reflection coefficient at Port1 and Port2. THRU fixture on manual calibration kit is also measured to know S-parameter of 2x-fixture [S_{2xF}^{M}] which is one of two S-parameters for the comparison. Another S-parameter for the comparison can be obtained from two different 1x-fixture [S_{1xF1}^{e}, S_{1xF2}^{e}] Each 1x-fixture S-parameter is calculated with measured gamma [Γ_{MS}, Γ_{MO}, Γ_{ML}] at each Port and actual gamma [Γ_{AS}, Γ_{AO}, Γ_{AL}] at the end of terminations. At the first turn of iterative procedure, all actual gamma starts at approximated values. However, this calculated 2x-fixture [S_{2xF}^{C}] has a certain amount of error due to inaccurate actual gamma values. Thus, the difference between

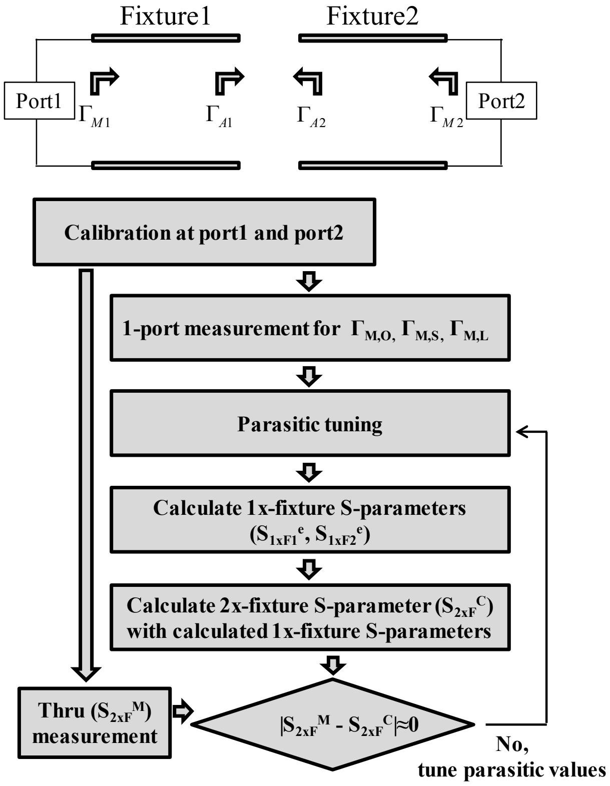


Fig. 2. A flow chart of iterative error sensitivity to find out correct parasitic parameters in manual calibration kit. Proposed procedures use an error minimization between measurement and estimation.

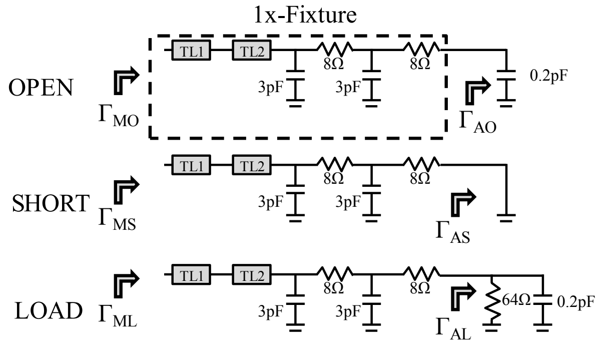


Fig. 3. Manually designed calibration kit with ideal lumped elements. OPEN and LOAD termination includes 0.2 pF of parasitic capacitor value in parallel but SHORT termination is ideal.

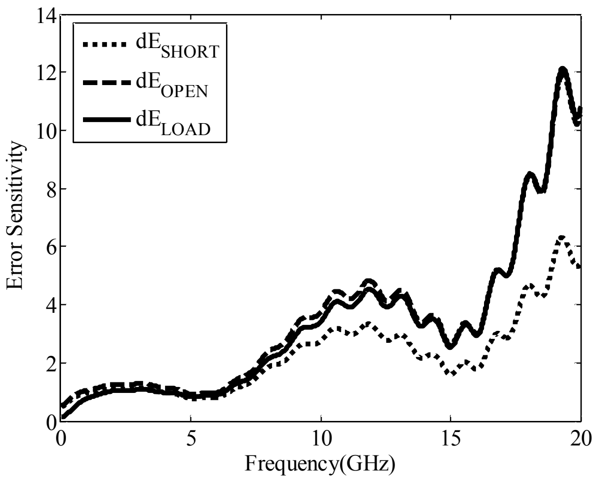


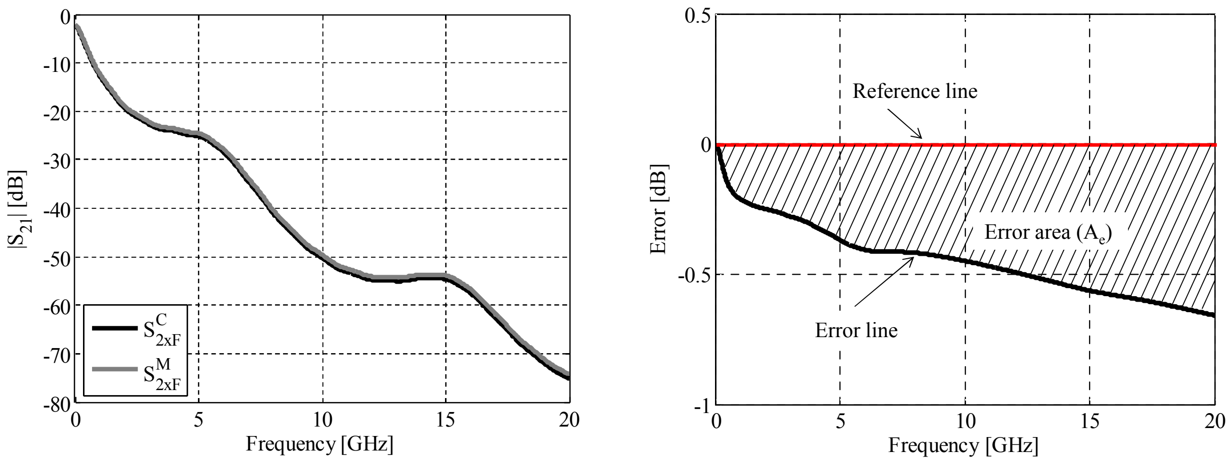
Fig. 4. Error sensitivity at SHORT, OPEN and LOAT termination, SHORT termination is less sensitive to the common error than OPEN or LOAD termination.

measured 2x-fixture and calculated one has an error. If so, re-calculation is necessary with different actual gamma based on a little bit tuned parameter from the first turn. As parasitic parameters close to original values, the difference between two 2x-fixtures ideally approaches to zero.

In order to validate the proposed iterative method, a manual calibration kit is designed as shown in Fig. 3. 1x-Fixture consists of two transmission lines with different characteristic impedances and lumped elements such as capacitors and resistors before the termination. While LOAD and OPEN termination includes 0.2 pF of parasitic capacitor value in parallel, SHORT termination is ideal for ideal actual gamma.

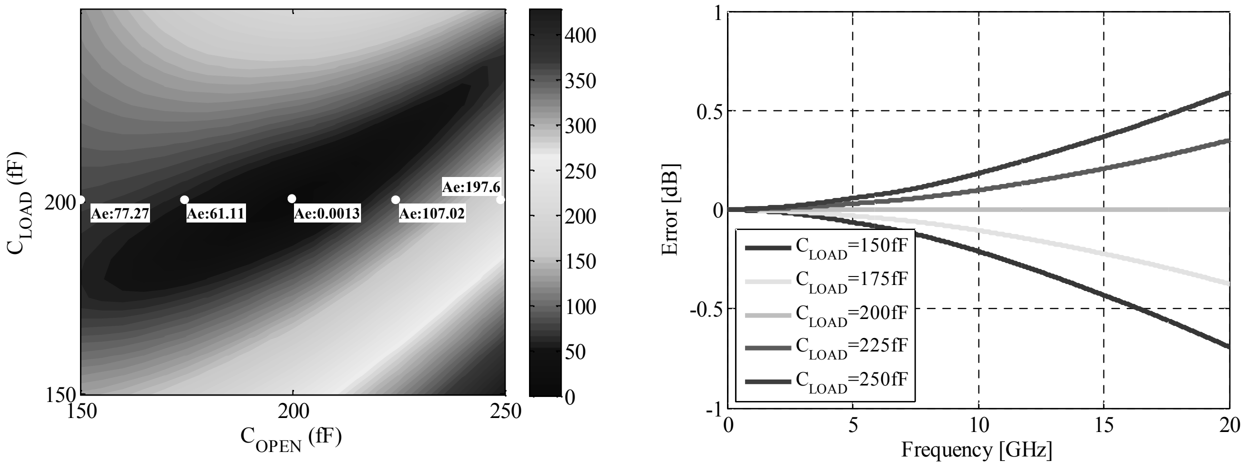
At the first step of iterative procedure, error sensitivity is shown in Fig. 4. SHORT termination has a half sensitivity of OPEN or LOAD termination from the common error due to no parasitic model. Fig. 4 shows that a small error at OPEN, SHORT and LOAD termination eventually makes a big error in pure DUT S-parameter after fixture de-embedding as frequency goes higher. Fig. 5(a) shows two DUT S-parameters, one from measured DUT [S_{2xF}^M] for the reference and the other from calculated DUT with error [S_{2xF}^C]. Two S-parameters look similar but has a small difference in between as shown in Fig. 5(b). To quantify the error magnitude depending on parasitic parameters, a new error level to show an amount of error is necessary during iterative procedure. The total error area [A_e] between an error line and the reference line can become a standard to show how accurate selected parasitic parameter is. As the parasitic is far away from original value, the error area becomes larger. However, the error area is gradually reduced if parasitic are approaching to the original value.

If two parasitic values at LOAD and OPEN termination vary, the error level based on parasitic parameters are shown in Fig. 6(a). The parasitic is



(a) (b)

Fig. 5. Two DUT S-parameters after de-embedding look similar but has small difference in between (a). Difference in error would be close to 0 as parasitic values are approaching to original values and then the error area become smaller (b).



(a) (b)

Fig. 6. Error level plot (a) depending on two parasitic values and error level converge on optimized one pairs to get the smallest error level. The error line is close to 0dB line as parasitic value approaches to original parasitic value (b).

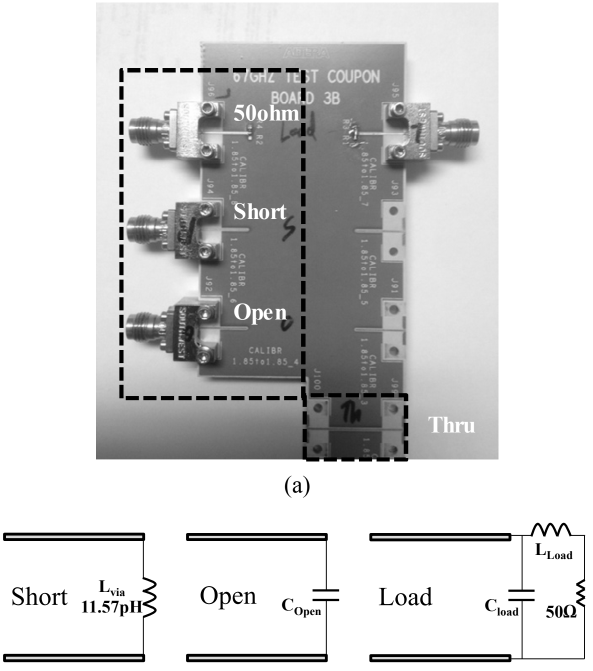
converging on the original values as the iterative method is applied more and more. Fig. 6(b) shows multi error lines depending on different parasitic at LOAD termination. Either of two parameters changes a little bit and then the error level dramatically increases.

IV. EXPERIMENTAL MEASUREMENT

1. SOLT Calibration on PCB

The customized calibration kit is designed for the experimental validation and fabricated on extremely low-loss material of 0.0013 (TanD) as shown in Fig. 7(a).

Each fixture for the calibration has 1 cm of 50 ohm transmission line in common but different terminations, SHORT, OEPN and LOAD. While OPEN termination is just open without any connection, SHORT termination uses via between transmission line and ground. LOAD termination uses 50 ohm resistor on two pads and one of pads is connected to ground through via. Equivalent circuit model describes each termination with lumped elements such as resistor, inductor and capacitor as shown in Fig. 7(b). OPEN has only single capacitor but its capacitance is not easy to estimate. At SHORT termination, 11.75 pH is put as an inductor. A parasitic resistor in series with inductor is negligible due to very short via length. LOAD termination is a bit more complicated due to commercial resistor at the pad.



(a)

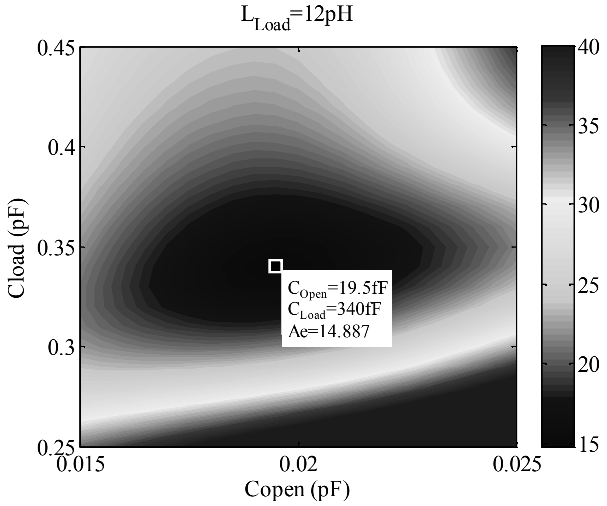
(b)

Fig. 7. Customized calibration kit on low-loss material, SHORT, OPEN, LOAD and THRU (a) equivalent circuit model for each termination (b).

Capacitor at LOAD is from in between pads and pad-to-ground. In LOAD model, attached resistor is assumed as an ideal 50ohm and via resistor is also neglected. THRU is used for the direct 2x-fixture measurement for the validation of de-embedding accuracy after proposed calibration method.

$$L_{via} = \frac{\mu_0}{2\pi}\left[h\cdot\ln\left(\frac{h+\sqrt{r^2+h^2}}{r}\right)+\frac{3}{2}\left(r-\sqrt{r^2+h^2}\right)\right] \qquad (24)$$

There are three unknown parameters at each termination, C_{Load}, L_{Load} and C_{Open}. The proposed iterative method optimizes three parameters to minimize the error area (Ae). Since via geometry at LOAD has same with via at SHORT termination, L_{Load} shows 12 pH which is the calculated inductor at SHORT termination. At 12 pH, the error plot shows the best combination of C_{Load} and C_{Open}. C_{Load} is larger than C_{Open} due to wider area from the resistor pad as shown in Fig. 8



L_{Load} [pH]	C_{Open} [fF]	C_{Load} [fF]	Error
12	19.5	340	14.8870

Fig. 8. Error level plot at 12 pH of L_{Load} and best combination of C_{Load} and C_{Open} to get the minimum error area.

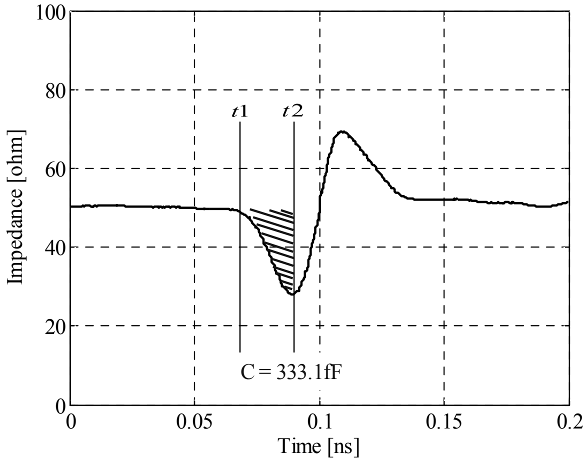


Fig. 9. TDR waveform of LOAD Termination for C_{Load} estimation and anti-resonance is caused by load capacitor. Calculated capacitance is 333.1 fF which is optimized capacitance from proposed method.

The optimized C_{Load} is estimated through another way with TDR measurement as shown in Fig. 9. While the flat region shows 50 ohm transmission line, the anti-resonance peak comes from load capacitor at LOAD termination. Since depth of the peak is linear proportional to the capacitance, the half of anti-resonance peak area is same with load capacitance based on (25).

$$C = \frac{1}{2}\int_{t1}^{t2}\frac{1}{Z(t)}dt \qquad (25)$$

The calculated capacitance is 333.1 fF and this has only 2% difference with optimized load capacitance from proposed iterative error sensitivity.

Fig. 10 shows the improvement in DUT S-parameter

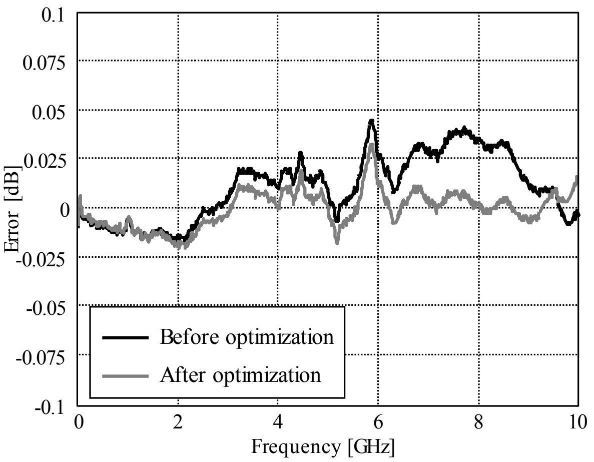
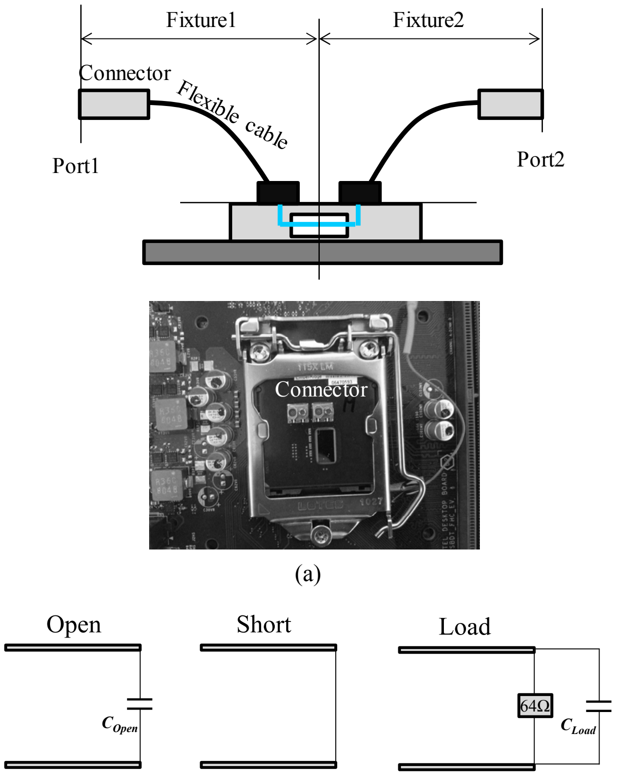


Fig. 10. Error in DUT S-parameter after de-embedding and the error is getting improved as frequency goes higher.

after de-embedding with proposed calibration method. Since capacitor and inductor are not dominant at low frequency, there is no big difference less than 2 GHz between measurement and estimation. However, S-parameter error is dramatically reduced as it goes higher frequency. Since capacitor impedance becomes smaller at higher frequency, parasitic capacitor dominantly affects an impedance summation in parallel with resistor at LOAD and OPEN. With proposed error sensitivity analysis, the error in S-parameter after de-embedding is closing to 0 up to 10 GHz. The proposed method is well validated with unknown calibration kit on PCB.



(a)

(b)

Fig. 11. On-die SOLT calibration kit and its measurement setup (a) Three equivalent circuit models for SHORT, OEPN and LOAD termination (b).

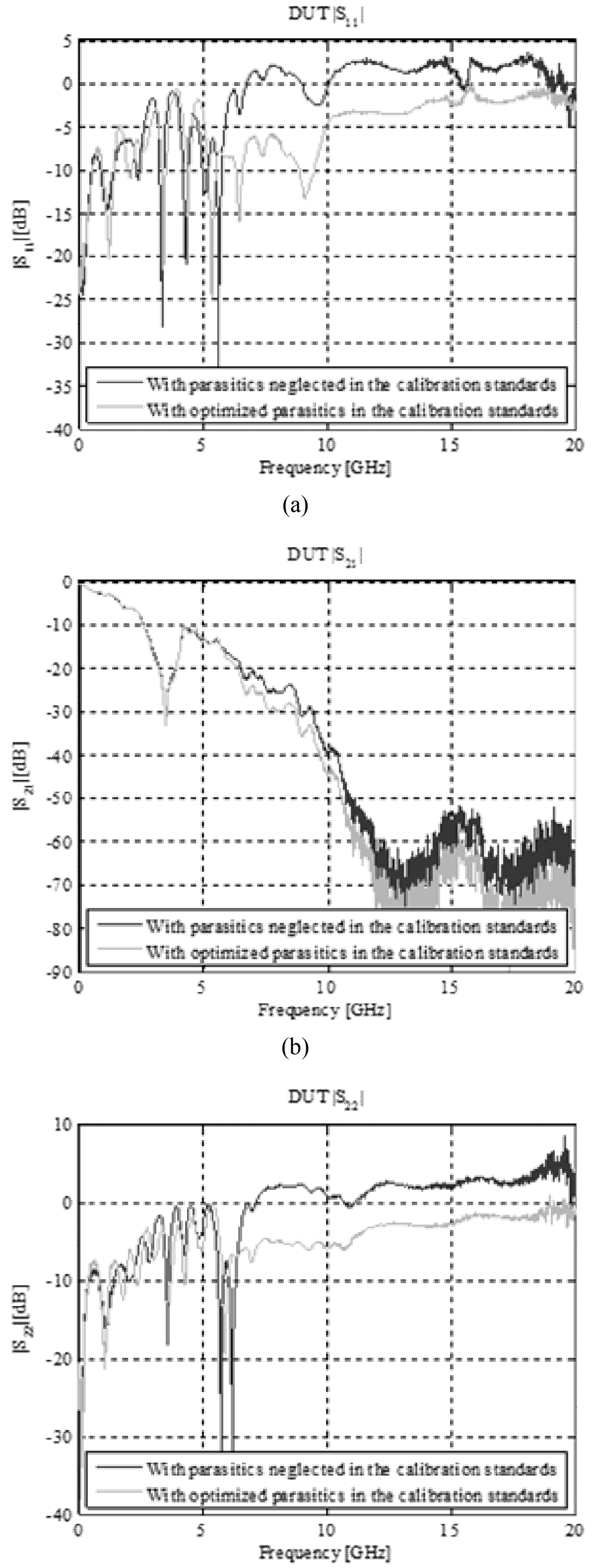
2. On-chip SOL Calibration

Proposed calibration method is working at PCB level and it is easy to validate accuracy of optimized parasitic values from TDR measurement. 330 pF at LOAD termination is big enough to be seen after long 50 transmission line in time-domain. To see more accuracy of proposed calibration method, on-chip SOL termination is designed as shown in Fig. 11(a). SHORT, OPEN and LOAD termination are designed inside silicon and all terminations are fabricated right after 50ohm connector. Thus, 1x-fixture for de-embedding includes SMA connectors, cables and micro-connector before terminations. An equivalent circuit models for each termination is simpler than PCB termination due to chip-scale dimension inside silicon as shown in Fig. 11(b). While LOAD termination is designed to get 64 ohm instead of 50 ohm, SHORT and OPEN termination is same as usual. Inductors from via in on-die terminations are negligible due to chip-scaled via length.

Based on equivalent circuit models at terminations, optimized S-parameter of on-chip DUT channel is calculated as shown in Fig. 12. There is no reference for comparison since pure on-die channel is impossible to measure. However, S-parameter from ideal actual gamma [Γ_{AS}, Γ_{AO}, Γ_{AL}] shows a wrong reflection after 6 GHz which region is more than 0 dB. Reflection from passive channel is always less than 0 dB. Ideal actual gamma is not appropriate to be used for de-embedding but need to consider parasitic values. With proposed calibration method, while insertion loss is not changed a lot, reflection is always less than 0 dB within overall frequency range from 0 dB to 20 GHz. The optimized C_{Load} and C_{Open} are 420 fF and 140 fF respectively.

V. CONCLUSION

A new SOLT calibration method with the error sensitivity is proposed to optimize unknown parasitic



(a)

(b)

(c)

Fig. 12. On-chip SOLT calibration kit and its measurement setup (a) Three equivalent circuit models for SHORT, OEPN and LOAD termination (b).

parameters at SHORT, OPEN and LOAD termination. A quantitative error area is adopted to find out optimization point and verified with known SOL calibration kit. Also, the proposed method is validated with customized SOL calibration kit on PCB and applied to on-chip SOL terminations. With proposed iterative error procedure, on-chip fixture S-parameter is successfully calibrated.

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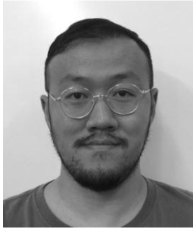

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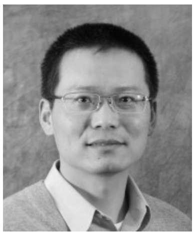

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