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DETERMINATION OF MICROWAVE LUMPED ELEMENTS PARAMETERS FROM FREQUENCY DOMAIN IMPEDANCE MEASUREMENTS

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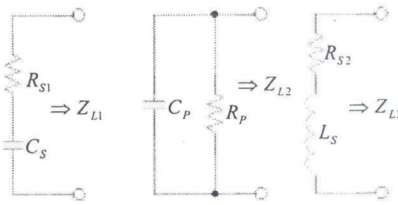
Abstract: **This article deals with identification of microwave lumped element equivalent circuits from high frequency reflection coefficient measurements using impedance method. Attention was focused mainly to characterization of inductors and capacitors with high quality. Precision of basic model parameter determination very closely depends on vector network analyzer (VNA) measurement accuracy as well as on measurement frequency band. The influence of magnitude and phase VNA error to final capacitance and inductance determination was investigated.**

INTRODUCTION

Lumped elements are basic devices in electronic circuits. However it could be not easy to measure their parameters on high frequencies. One of several possibilities is to utilize vector network analyzer for reflection coefficient measurement. In most simple case lumped element equivalent circuit could be calculated from reflection coefficient by impedance method. Unfortunately VNA measures amplitude and phase of scattering (S) parameters with finite accuracy given by manufacturer. In addition S-parameters are related to characteristic impedance of the test set, in most cases 50Ω. Wrong selected frequency band for reflection coefficient measurement can cause high deviation in final inductance and capacitance value calculations in comparison to their actual value. The influence of rectangular VNA error distribution to final inductance and capacitance measurement was simulated. It is shown, that impedance method is applicable to inductance and capacitance measurement in precisely defined frequency band, which depends on device under test (DUT) and VNA parameters.

INDUCTOR AND CAPACITOR MEASUREMENT USING IMPEDANCE METHOD

Basic simple models of capacitance and inductance, which corresponds to their real physical parameters are shown in Fig. 1, where ω is angular frequency we want to calculate load impedance for.



$$Z_{L1} = R_{S1} - \frac{j}{\omega C_S} \qquad (1)$$

$$Z_{L2} = \frac{1}{\frac{1}{R_P} + j\omega C_P} \qquad (2)$$

$$Z_{L3} = R_{S2} + j\omega L_S \qquad (3)$$

Fig.1: Simple capacitor and inductor equivalent circuits with equivalent load impedance equations.

Load impedance Z_L can be calculated from measured reflection coefficient S_{11} for appropriate frequency F using (4). Model parameters in Fig. 1 than could be very simply determined for appropriate frequency from load impedance by (5-7), where Z_0 is VNA characteristic impedance.

$$S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0} \Rightarrow Z_L = Z_0 \frac{(1+S_{11})}{(1-S_{11})} \quad (4)$$

$$Z_{L1} = R_{S1} - \frac{j}{2\pi F C_S}; \; Z_{L1} = x_1 + jy_1 \Rightarrow R_{S1} = x_1; \; \mathrm{C_S} = \frac{-1}{2\pi F y_1} \quad (5)$$

$$Z_{L2} = \frac{1}{\frac{1}{R_P} + j2\pi F C_P}; \; \frac{1}{Z_{L2}} = x_2 + jy_2 \Rightarrow R_P = \frac{1}{x_2}; \; \mathrm{C_P} = \frac{y_2}{2\pi F} \quad (6)$$

$$Z_{L3} = R_{S2} + j2\pi F L_S; \; Z_{L3} = x_3 + jy_3 \Rightarrow R_{S2} = x_3; \; \mathrm{L_S} = \frac{y_3}{2\pi F} \quad (7)$$

However, precision of such equivalent circuit parameters calculation is limited by VNA accuracy as well as device under test properties. It is wise to select measurement frequency bandwidth with respect to these conditions as will be shown in next section.

OPTIMAL MEASUREMENT FREQUENCY DETERMINATION FOR INDUCTOR AND CAPACITOR MODEL IDENTIFICATION

VNA used for characterization of microwave devices in high frequency range can measure amplitude and phase of S-parameters in tolerance specified by manufacturer. The non-ideality of VNA limits applicability of impedance method to specific frequency range only. Influence of measurement error was simulated for inductances and capacitances with different values. Firstly, simple inductor and capacitor model (Fig. 1) were chosen and ideal simulation values (in our example C_S=1pF, R_S=1Ω) were specified. Then load impedance Z_L and ideal reflection coefficient S_{11I} for investigated frequency was calculated. In fact data measured by ideal VNA was generated. Then magnitude and phase of ideal reflection coefficient was damaged in range of tolerances specified by manufacturer with very fine step (Fig. 2). It corresponds to rectangular VNA error distribution. At last an inverse progress was used to determine model parameters from damaged reflection coefficient and remember worst-case deviation from ideal values for each frequency. This simulation was done in frequency range 50 MHz up to 20 GHz with frequency step 50MHz. We suppose, that model parameters as well as instrument error are frequency independent in whole simulated frequency range. Maximal inaccuracy in magnitude and phase measurement was considered for HP4140B VNA with extension set for on-wafer measurements [1], [2] - $\Delta S_{11m} = \pm 0.2dB$ and $\Delta S_{11ph} = \pm 4^{\circ}$. Results for this test set are shown in Fig. 3, 4. Precision in capacitance or inductance identification strongly depends on properties of DUT as well as chosen measurement frequency range. There is possible to determine optimal measurement frequency for particular DUT and worst-case error of model parameters calculation. In example for 10pF capacitance is optimal measurement frequency F_{opt}=318 MHz as shown in Fig. 5. If the impedance method is used at frequency 8GHz with HP4140B, then final capacitance could be obtained with significant error.

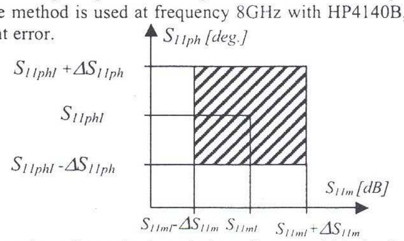
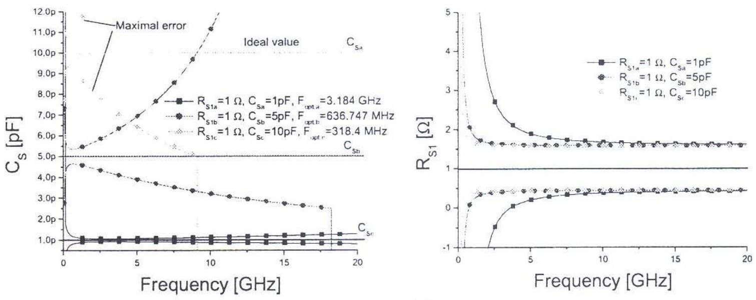
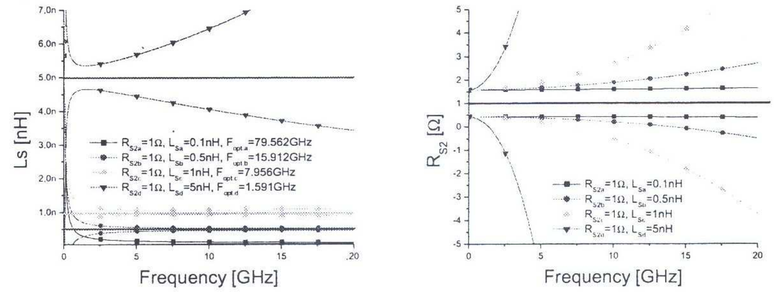


Fig. 2: Symbolic sweeping of magnitude and phase S_{11} around ideal value for single frequency point.



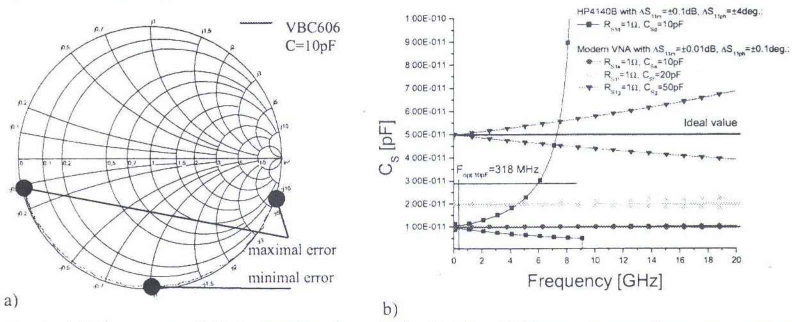
a) b)

Fig. 3: Worst-case error in capacitor measurement caused by limited VNA accuracy. a) capacitance C_S, b) serial resistance R_{S1}.



a) b)

Fig. 4: Worst-case error in inductance measurement caused by limited VNA accuracy. a) inductance L_S, b) serial resistance R_{S2}.



a) b)

Fig. 5: a) Measurement of 10pF capacitor shown in Smith chart. b) Worst case capacitance measurement errors for different VNA types.

EXPERIMENTAL RESULTS

Frequency limitation of impedance method was verified by measurement of capacitors VBC602-VBC607. Basic capacitor parameters are shown in tab. 1. All of capacitors have been realized as metal-insulator-semiconductor (MIS) type with gold electrodes deposited on Si_3N_4 dielectric material. Used dielectric material together with small dimensions ought to guarantee constant capacitor parameters in wide frequency range. However measured results show strong frequency dependency of capacitances above 2pF as shown in Fig. 6. These deviations were caused by non-optimal measurement frequency range chosen for high capacitances.

Tab. 1: Basic capacitor parameters given by manufacturer

Type	VBC602	VBC604	VBC605	VBC606	VBC607
C [pF]	0.5	2	5	10	20
F_C *[GHz]*	550	140	60	30	15
R_S *[Ω]*	0.57	0.56	0.53	0.53	0.53

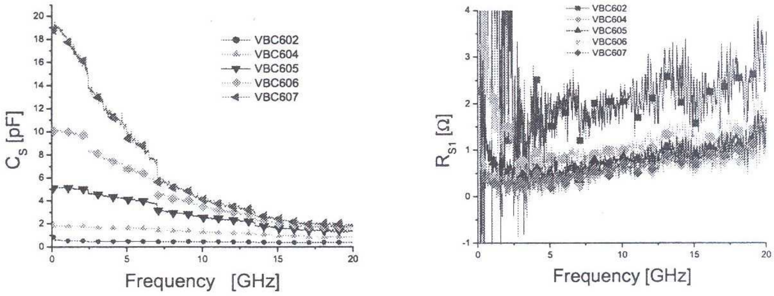


Fig. 6: Equivalent circuit parameters for capacitors VBC602-VBC607 calculated in frequency range 100MHz up to 20GHz from S_{11} measurement.

CONCLUSION

In this article limitations of impedance method for simple inductor and capacitor model identification were analyzed. Influence of VNA accuracy on calculated lumped elements model parameters was investigated. Simulations were verified by MIS capacitor measurements and model identifications. Lumped element models are most precise identified on frequencies, where magnitude of DUT impedance is most close to characteristic impedance of VNA. Practical measurements shows, that impedance method is very inaccurate out of optimal frequency range. Measurement of high capacitances with low precision VNA is frequency limited, otherwise it will cause significant errors. However, modern VNAs offer acceptable precision of capacitance or inductance estimation for elements obviously used in microwave frequencies.

Acknowledgement

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[2] *HP8408B Automatic Network Analyzer – System Reference Manual,* California, Hewlett Packard Company, 1979-1982.