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# In-Circuit Impedance Measurement Based on a Two-Probe Approach

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*Abstract*— **Most impedance measurement instruments usually measure the impedance of a component or device under no-load condition. Therefore, any non-linear behaviour and other on-board circuit components or parasitic are not detected or taken into consideration. Based on a novel two-probe measurement technique, the impedance of any in-circuit component can be measured with ease. Using the resistor characterization as a preliminary study, the proposed technique is able to accurately determine the impedance of the in-circuit resistor at the intended operating condition up to 1 GHz.**

## I. INTRODUCTION

Signal Integrity (SI) is a high-speed design practice that ensures the transmitted signals, is received correctly at the receiver [1, 2]. In the last decade, the data rates and device speed have already pushed the digital design to a new era into the RF arena. In many of the commonly found consumer products in the market, on-chip speed are easily above 500 MHz and board buses speed including the onboard interface signals are well above hundreds of MHz. The topic of SI [3, 4] is now becoming one of the most important design issues in the high-speed digital design.

The fundamental of SI evolves around the concept of impedance matching. A well-matched device to the transmission line provides good signal performance with minimum reflection, reduction in EM emission and ground fluctuations. The driving device impedances can be obtained from manufacturer supplied information, EDA IBIS model or datasheets. The remaining crucial factor affecting the circuit signal integrity performance is the matching termination. Various termination techniques in interconnect interface are available but resistive termination is still by far most commonly adopted because of its simplicity and effectiveness. However, when a resistive termination is added on for transmission line termination, the in-circuit impedance behaviour of the resistor could be affected by other components that are also mounted on the same PCB, especially at high frequency, the parasitic effects of these components and the board may affect the matching performance. In this paper, we attempt to explore the used of a novel measurement technique to characterize in-circuit impedance of any component that mounted on PCB and under powered up condition. As a preliminary study, in this paper, only the resistor under in-circuit operating environment is measured.

## II. MEASUREMENT TECHNIQUE AND THEORY

The dual current probe measurement techniques for characterizing unknown devices has long been utilized since mid 60s and reported by various researchers [5-9]. However most of the work mainly focuses on power related fields such as power line impedance and common mode choke characterization, which are at frequency range less than 100 MHz. With the advancement in current probe technology extending beyond 1 GHz, this paper explores the feasibility of in-circuit impedance characterization up to 1 GHz. The key advantages of current probe measurement are the non contact impedance isolation which minimizes loading effect and disturbances to the circuit under test and the ability to eliminate any error due to measurement setup.
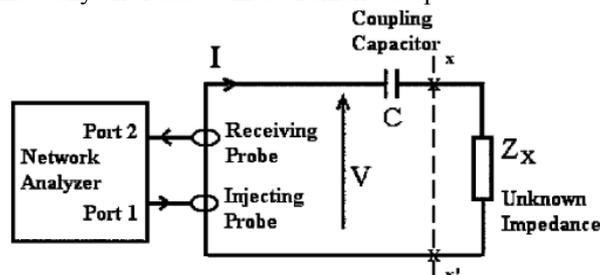


Fig 1 Basic Circuit Setup of Two Probe Measurement

The concept of measuring unknown impedance using two probes approach can be illustrated with Fig 1. The basic setup consists of an injecting current probe, a receiving current probe and a network analyzer. The two probes and the coupling capacitor C form a coupling circuit to avoid direct connection to the unknown impedance $Z_x$. By reflecting the primary circuits of the injecting and receiving probes in the coupling circuit loop, the equivalent circuit of the measurement setup can be represented as Fig. 2. $Z_{m1}$ and $Z_{m2}$

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are the reflected impedances of the injecting and receiving probe to the coupling loop, respectively; and $V_{M1}$, is the reflected signal voltage in the coupling loop due to port 1 of the network analyser. L is the effective loop inductance.
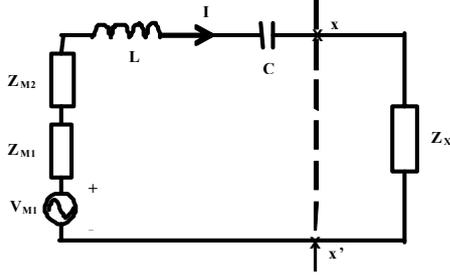


Fig. 2  Equivalent Circuit of the Two-Probe Measurement Setup

The resultant current flowing in the coupling loop due to the injecting signal is given by:

$$I = \frac{V_{M1}}{Z_{M1} + Z_{M2} + j\omega L + \frac{1}{j\omega C} + Z_X} \qquad (1)$$

By letting $Z_{setup} = Z_{M1} + Z_{M2} + j\omega L + \frac{1}{j\omega C}$, equation (1) can be simplified as follows:

$$I = \frac{V_{M1}}{Z_{setup} + Z_X} \qquad (2)$$

The induced voltage in the loop is given by:

$$V_{M1} = j\omega M_1 \left( \frac{V_1}{Z_{p1} + Z_1} \right) \qquad (3)$$

where $M_1$ is the mutual inductance between the injecting probe and the coupling loop, $V_1$ is the output source of port 1, $Z_1$ is the output impedance of port 1 and $Z_{p1}$ is the impedance of injecting probe seen by port 1.

The current I measured by the receiving probe is:

$$I = \frac{V_2}{Z_{T2}} \qquad (4)$$

where $V_2$ is the received signal at port 2 and $Z_{T2}$ is the transfer impedance of receiving probe.

By substituting equations (3) and (4) into (2), the unknown impedance $Z_x$ can now be determined as follows:

$$Z_x = \frac{kV_1}{V_2} - Z_{setup} \qquad (5)$$

where $k = \frac{j\omega M_1 Z_{T2}}{Z_{p2} + Z_1}$ is a frequency dependent coefficient.

By replacing $Z_x$ with a known precision resistor $R_{std}$ and then with a short during the calibration process, $Z_{setup}$ can be found as follows:

$$Z_{setup} = \frac{V_2 \big|_{Z_X = R_{std}}}{V_2 \big|_{Z_X = 0} - V_2 \big|_{Z_X = R_{std}}} R_{std} \qquad (6)$$

Once the whole setup is calibrated, the two-probe measurement is ready to measure any in-circuit unknown impedance $Z_x$ as follows:

$$Z_X = \frac{(R_{std} + Z_{setup})V_2 \big|_{Z_X = R_{std}}}{V_2 \big|_{Z_X = unknown}} - Z_{setup} \qquad (7)$$

III. MEASUREMENT RESULTS

To emulate an in-circuit test condition, the circuit shown in Fig. 3(a) is employed. The two probes used in the measurement are Tektronix CT-6 [10] (5mV/mA, bandwidth of 250 kHz to 2 GHz) current probes. The Rohde & Schwarz ZVB Vector Network Analyser with a bandwidth of 8.5 GHz is used for the measurement with the two probes.

The actual fabricated test jig is shown in Fig. 3 (b). The jig consists of two coupling capacitors $C_1$ and $C_2$ to form a coupling measurement loop that enables the in-circuit component-under-test (CUT) to be measured. Both capacitors are 47 nF that provide high-frequency coupling closed loop to the CUT without affecting the DC basing condition of the CUT. The external DC power supply and the load resistor R provide the DC biasing current for the CUT. For the measurement, the value of R is chosen as 100 Ω.



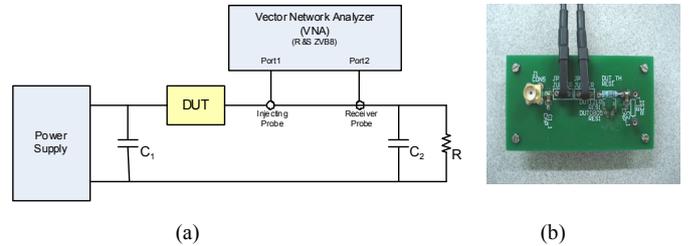(a)                                    (b)

Fig. 3  (a) Two Probe Measurement Setup Circuit and (b) Actual Test Jig

Several resistors are carefully characterised using the Agilent HP4396B (1.8GHz) Impedance Analyser together 43961A RF Impedance Test Kit and the HP16194A Component Test Fixture for axial leaded devices. The integrated instrumentation setup is shown in Fig.4.
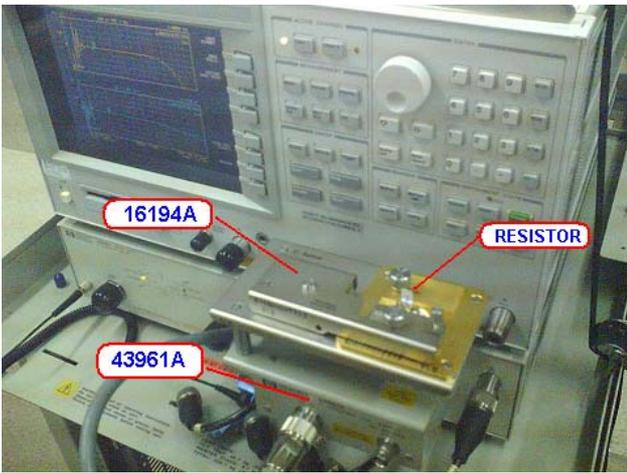
Fig. 4 Instrumentation Characterisation of Resistor using Agilent 4396B

The measured resistance at 1 MHz using the two-probe approach and that using the HP4191A LF Impedance Analyzer are compared and given in Table 1. The discrepancy is less than 4%.

TABLE 1
LOW FREQUENCY ACCURACY MEASUREMENT

| s/n | Ref | Measured with HP4191A | Measured with Two probe | Accuracy |
|-----|------|------|------|------|
| 1 | R30 | 30.35 | 30.31 | 0.1% |
| 2 | R51 | 50.89 | 50.24 | 0.7% |
| 3 | R100 | 100.5 | 96.85 | 3.4% |
| 4 | R220 | 222.0 | 227.15 | 2.3% |
| 5 | R510 | 512.0 | 504.24 | 1.5% |
| 6 | R1K | 1002.0 | 1030.3 | 2.8% |
| 7 | R2K | 2007.0 | 1954.8 | 2.5% |

Using the two-probe technique, setup impedance due to the test jig ($Z_{setup}$) is determined with Equation (6) and shown in Fig. 5 in comparison to the actual resistor under test (30 Ω). It shows that $Z_{setup}$ is very low below 100 MHz but becomes significant as frequency increases.
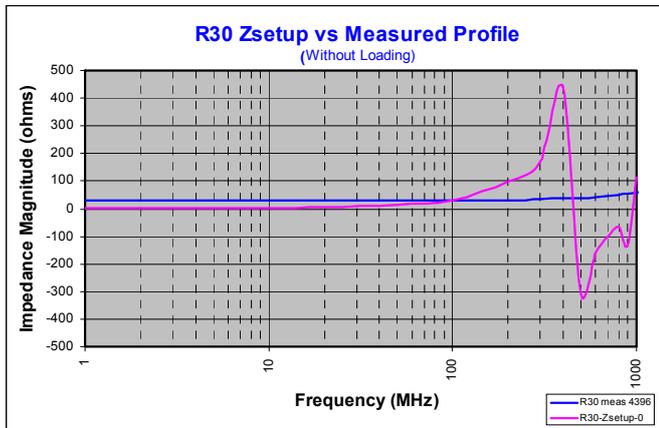


Fig. 5 Axial 30ohms Zsetup vs. component measurements results

Figs. 6 and 7 compare the measurement results using the two-probe approach and Agilent HP4396B Impedance Analyzer for 30 Ω and 100 Ω resistors, respectively. The setup impedance $Z_{setup}$ is now eliminated using equation (7). The comparison shows that the two-probe approach matches very well with the measured results using the impedance analyzer. For small resistor value, high frequency behaviour is dominated by the equivalent series inductance (~10 nH). For higher resistor value, the parasitic capacitance (~0.35pF) dominates instead causing the impedance to reduced at high frequency. The measurement results using both approaches correlate well with each other up to 1 GHz. Hence, the two-probe in-circuit measurement technique has been validated.
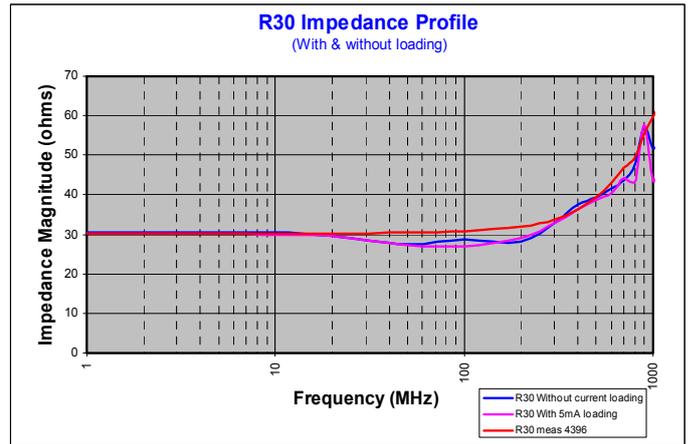


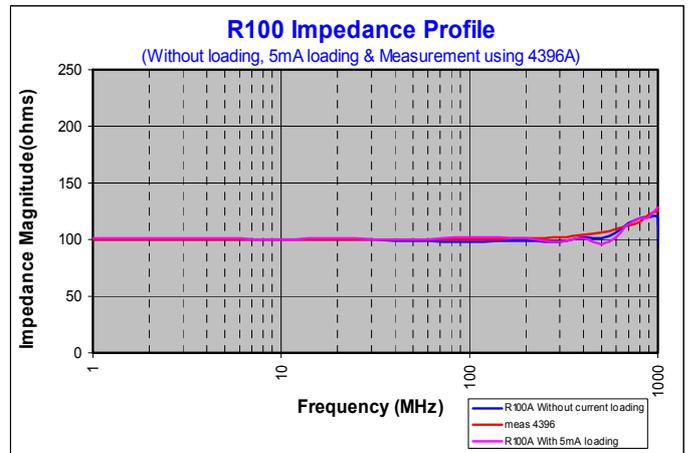Fig. 6 Axial 30ohms resistance measurements results



Fig. 7 Axial 100ohms resistance measurements results

Fig. 8 shows the measurement results of a wide range of resistor values, including 30 Ω, 51 Ω, 100 Ω, 220 Ω, 510 Ω, 1 kΩ and 2 kΩ over a frequency bandwidth from 1 MHz – 1 GHz under in-circuit loading condition.

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**Overall Resistor Impedance Profile Comparison**
**(With 5mA loading)**
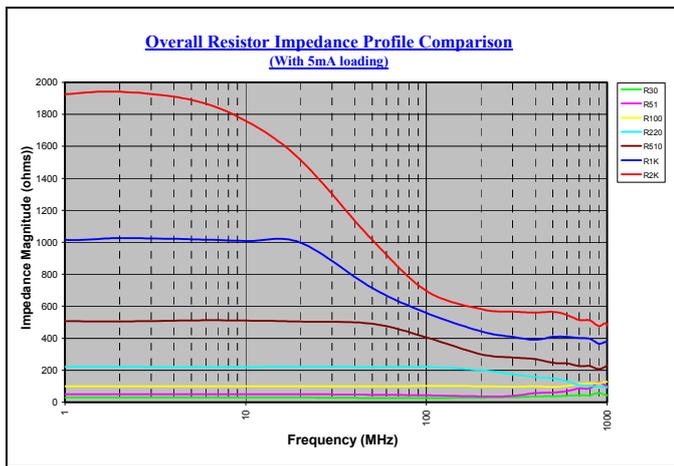
Fig. 8  Overall Resistors Impedance Profile Comparison (30ohms – 2Kohms)

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## IV. CONCLUSIONS

The proposed two-probe measurement technique for in-circuit impedance characterization has been described and validated. The measurement results show that it is able to measure a wide range of passive resistors with good accuracy up to 1 GHz. Without complex and elaborative setup, this technique allows characterization of component performance in its real working condition. Further work is on going to characterize component with non-linear behaviors.

## ACKNOWLEDGMENT

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