

2008

Innovative Techniques in Instruction Technology, E-learning, E-assessment, and Education

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Recommended Citation

Iskander, Magued and Balaji, Uma, "Innovative Techniques in Instruction Technology, E-learning, E-assessment, and Education" (2008). *Engineering Faculty Book Gallery*. 36.

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Demonstrations of Transmission Line Effects

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Abstract – A set of experiments on transmission line effects at high frequency has been described in this paper. They are measurement of impedance characteristics of resistors and capacitors at high frequency, determination of characteristic impedance and velocity factor of transmission lines and crosstalk measurements. Issues in design of analog/digital circuits at high frequencies are better appreciated by students when these experiments are performed.

INTRODUCTION

Research has continued to advance the operating speed of computers. The digital circuits in the computers are connected by transmission lines. Impedance mismatch between the source, transmission lines and load while operating circuits at high frequencies can result in loss of energy transfer from source to load causing the circuits to function differently than expected. It is impossible to design circuits where source, transmission lines and load impedances are always matched at all frequencies of use. The effects due to mismatch of the load and characteristic impedance can be studied by time domain reflectometry measurements as in [1]. This is done by sending a pulse on the line with its load mismatched and watching the reflected pulse due to mismatch. This gives an idea of the insertion loss of the line, velocity of voltage wave on line, characteristic impedance and other parameters of the line. Signal integrity has become important topics in design of high speed circuits. There are many websites that provide information to students on effects due to transmission lines using java applets [2]. Crosstalk between two adjacent lines is also simulated with animations [2].

However, presently digital design at high frequency demands time domain and frequency domain analysis. Laboratory experiments have been described in this paper to study some of the characteristics in frequency domain which can complement those suggested in references. One of them is study of high frequency behavior of passive components. A resistors or a capacitors included in the circuits tend to behave differently from their normal behavior at high frequency. A measurement of their impedance values over a large frequency range can show how they differ from the expected characteristics. The measurement of frequency domain characteristic of these components using impedance analyzer is presented here. Measurement of the characteristic impedance of transmission lines using the impedance analyzer is also presented. Transmission lines transform impedances at the load end to different impedance at their input at high frequencies. This can affect the behavior of circuit designed to operate at high speeds. Demonstration of impedance

transformations through measurements is also presented here. This paper also discusses simple laboratory experiments to show effects due to capacitive and inductive coupling in transmission lines.

LABORATORY DESCRIPTIONS

A laboratory on high frequency behavior of resistors and capacitors requires impedance analyzer. An RF impedance analyzer, Hewlett Packard 4195A that measures component values from 10Hz to 500 MHz has been used here. Calibration of the equipment is required prior to these measurements. A standard short circuit and matched load are required for this. It is a good practice to calibrate before the experiment is performed as it affects accuracy of measurements. The frequency range of measurement is set on the equipment before calibration is begun. Impedance analyzers equipment provides a standard menu for calibration. A one port calibration is required and the equipment prompts to connect standard short, an open (realized by leaving the port open) and matched load. In order to connect resistors or capacitors, port extensions are used. The port extension transforms the coaxial line port to that with terminals for contacts where the resistor or capacitor can be connected. Since the calibration is performed at the coaxial port a correction factor for the length of the extensions of this port needs to be entered in the equipment

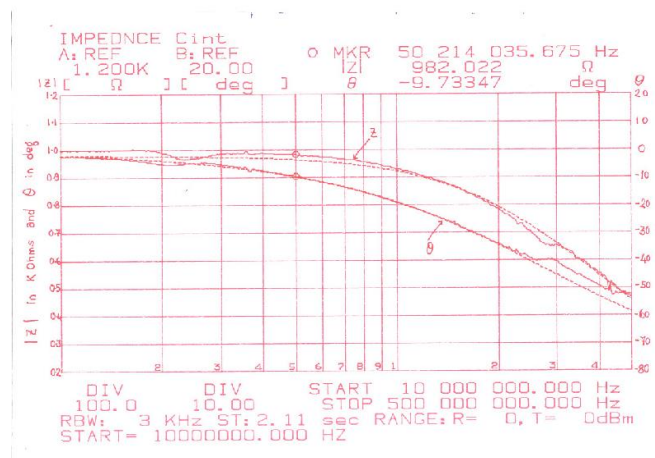


Fig. 1 High frequency behavior of Resistor (solid lines - measured, dotted lines – simulated)

After calibrations are performed and the corrections have been done the component is connected on the port extensions. Keeping the leads of the components unclipped exaggerates the high frequency effect and is useful in demonstrating concepts on high frequency effects. Based on the impedance characteristics the equivalent circuit of the component can be obtained from the equipment along with its simulations. The inductance and capacitance from leads and other sources inside the resistor show that it behaves reactively at high frequencies. Fig. 1 shows this behavior of a resistor. The simulation of the equivalent circuit is shown by dotted lines while the actual measurements are shown by solid lines. The lead inductance of a capacitor can be large causing it to resonate. Fig. 2 shows this impedance behavior of a capacitor. The resonance due to lead inductance takes place at about 250 MHz. As an addition to this, students can be asked to build air core inductors by winding wires and the theoretical and experimental behavior can be compared.

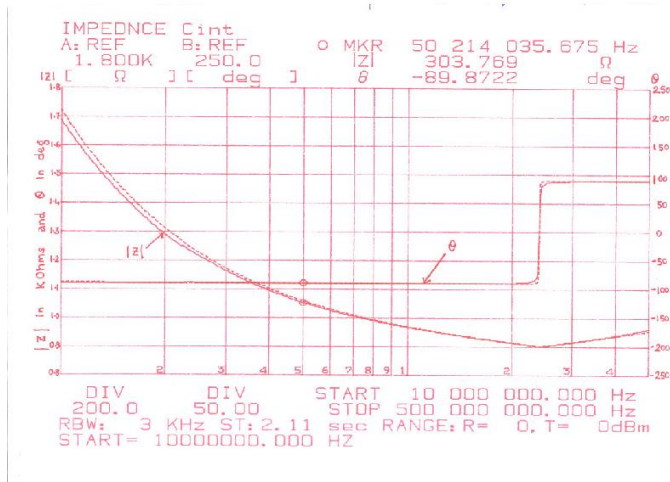


Fig. 2 High frequency behavior of Capacitor (solid lines - measured, dotted lines – simulated)

A measurement of characteristic impedance of a coaxial cable can also be done on the impedance analyzer. In order to do this the equipment is calibrated in the desired frequency range of measurement. After calibration is performed a short length (length \ll wavelength at the measurement frequency) of coaxial cable is connected to the port and terminated by short circuit. Measurement of input impedance is done at a single frequency point with short circuit termination on the far end of the line. It is called Z_{inSC} . Measurement of input impedance is repeated at the same frequency point with open circuit termination at the far end of the line and it is called Z_{inOC} . The characteristic impedance is obtained using the relation $Z_0 = (Z_{inSC} Z_{inOC})^{0.5}$. The inductance and capacitance per unit length of the line for a short length of line is obtained using the relations $L = \frac{|Z_{inSC}|}{2\pi f l}$ and $C = \frac{1}{2\pi f |Z_{inOC}|}$ where l is the length of the line. The velocity of the voltage wave on the line

is obtained from $1/(LC)^{0.5}$. Measurements of input impedance on RG58U cable at a frequency of 15 MHz gave a value of $Z_{inOC} = 169.6 \angle -90^\circ$ and $Z_{inSC} = 14.74 \angle 88.6^\circ$. A characteristic impedance of 50 ohms is obtained by approximating Z_{inSC} as purely reactive.



Fig. 3 Input impedance of a cable terminated in short circuit

The distributed inductance parameter L from these measurements was calculated as 246.22nH/m and capacitance of the line was 98.5pF/m. From the values of L and C the velocity of voltage wave, v was calculated as 2.03E8m/s. The measured input impedance of RG58U cable terminated by short circuit is shown in Fig. 3. The input impedance measured from 10 MHz to 100 MHz shows that it is very large and approximates that of open circuit around 80 MHz. The impedance analyzer plot shows both R and X . The value of R almost equals to zero (about 4 Ohms) at all frequencies except at 80MHz where the input impedance is that of open circuit with R approaching infinity along with X , meaning that the input impedance is infinity.

Analytically, input impedance of a line terminated by short circuit $Z_{inSC} = jZ_0 \tan(2\pi f l / v)$ is purely imaginary. The measurements in Fig. 3 are verified with a plot from a simple MATLAB code as shown in Fig. 4. The input impedance approaches infinity at 80MHz as in Fig. 3 of measured values. This study can be extended by terminating a coaxial line or any other type of transmission lines with other values of impedance and measuring the impedance at the input end of the line. Analytically, the input impedance Z_{in} when a line of characteristic impedance Z_0 is terminated by an impedance Z_L is obtained from,

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l}$$

where $\beta = 2\pi f / v$ is the propagation constant of the line and l is the length of the line.

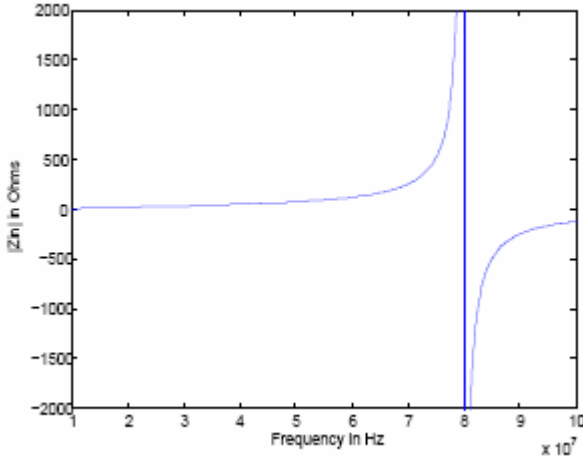


Fig. 4 The Input impedance (computed) of the cable in Fig. 3

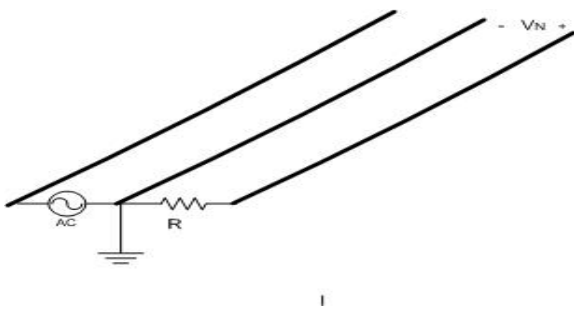


Fig. 5 Assembly of wires for determining capacitive coupling

Principles of crosstalk are fundamental to digital design at high speed and have been discussed in [3]. A simple experiment has been performed to gain knowledge on capacitive and inductive coupling in transmission lines. Capacitive coupling between lines is tested independently from inductive coupling. The set up consists of three wires of equal length laid parallel to each other at a known distance apart from each other as in Fig. 5. This layout can either be realized by laying small lengths of wires or easily obtained from three adjacent wires of a flat ribbon cable. The middle wire of the three wires in this set up is selected as the ground line although other lines can also be selected. The top and middle wire pairs are connected to source while the induced noise voltage between the bottom and middle wire pair is measured. The load ends of both pairs of wires are left open. While the top and middle pairs are connected to the source at the other end the bottom and middle wire pair is terminated in 1 KOhm resistor at this end. Capacitive coupling to the bottom and middle pair is tested by measuring the induced noise voltage at the open end while varying the frequency of sinusoidal excitation that is connected to the top and middle

wire pairs. Due to the fact that the load ends of both two wire transmission lines are kept open, the current flowing on the lines is close to zero. Hence the coupling is assumed to be primarily due to electric field between the lines which means coupling is capacitive. The equivalent circuit as given in Fig. 6 of this configuration is thus due to the capacitance of the two wire lines. It is obtained by multiplying the capacitance per unit length of line by the line lengths used in the set up. The capacitance per unit length for a two wire line is given by $C = \pi\epsilon / \cosh^{-1}(d/2a)$ where 'd' is distance of separation between the two wires and 'a' is the radius of the wires [4]. For $d/2a > 3$, C is given by $C = \pi\epsilon / \cosh^{-1}(d/a)$. The capacitance per unit length of line for this configuration can also be measured using the impedance analyzer by following the procedure described earlier for a coaxial line. For flat ribbon cables it is usually specified by the manufacturer. The noise voltage V_N induced at the open end of middle and bottom wire pair can be calculated from the equivalent circuit as,

$$V_N = \frac{j\omega[C_{12} / (C_{12} + C_{2G})]}{j\omega + 1/R(C_{12} + C_{2G})} V_1$$

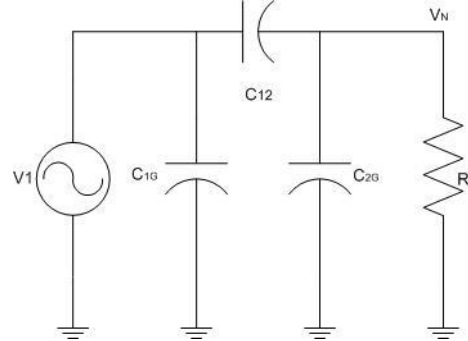


Fig. 6 Equivalent circuit of assembly in Fig. 5

In many practical applications $R \ll 1/[j\omega(C_{12} + C_{2G})]$ and the above equation is reduced to an approximate relation with $V_N = j\omega R C_{12} V_1$. From this relation it is observed that the noise voltage increases linearly with frequency.

Measurement was conducted using three parallel wires, about 15 cm long laid at a distance of 1.5 cm from each other. The induced noise voltage was measured from 100 KHz to 1 MHz. An oscilloscope was used in the measurement of induced voltage at the open end. It had an input capacitance of 25pF and resistance of 1MOhm. These two elements would be in parallel with the C_{2G} . This capacitance was also accounted for in the equation as it is of the order of the line capacitance. Hence C_{2G} is replaced with the parallel combination of C_{2G} with 25pF. The resistance R was a parallel combination of 1Kohm and 1MOhm. The theoretical and experimental values of induced voltage are shown in Fig. 7 and a reasonable agreement is found.

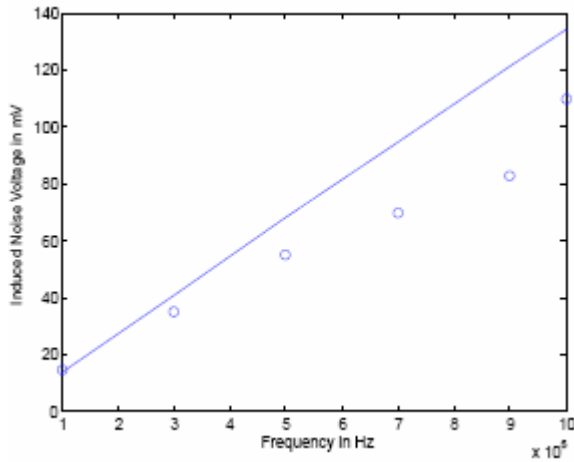


Fig. 7 Induced noise voltage due to capacitive coupling (solid lines - computed, dots - measured)

Inductive coupling can be studied by use of coplanar loop structures. Two loops of wires lying in the same plane are prepared with a certain radius. It is ensured that the loops are concentric and coplanar. One loop (loop 1) was terminated in a resistance and excited by sinusoidal excitation while the other loop (loop 2) was left open as shown in Fig. 8. Induced noise voltage in the loop that is not terminated or excited is measured.

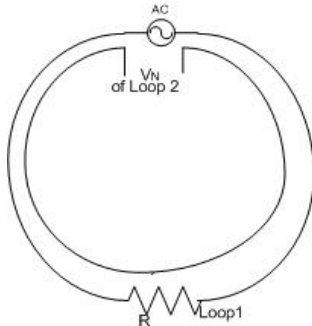


Fig. 8 Assembly of loops for determining inductive coupling

In this experiment circular loops are prepared although loops formed in a general PCB layout of circuits are rectangular. It is done so that the coupling is primarily due to inductance of the lines, rather than the capacitance between lines. The capacitive coupling can therefore be neglected. The inductive coupling to loop 2 from loop 1 can be obtained analytically from the mutual inductance between two loops $M_{12} = \phi_{12} / I_1$ where ϕ_{12} is the flux linking between loops 1 and 2 due to current I_1 loop 1. The voltage induced in a loop 2 is obtained from Faraday's law for a time varying current in loop 1 as $V_N = -\frac{d}{dt} \int_s B \cdot ds$ where B is the flux density in the plane of loop 2. A sinusoidal source is used to excite the loop. Using the Faraday's law and the definition of mutual inductance the

induced noise voltage is obtained., $V_N = j\omega M_{12} I_1$. The mutual inductance between the two loops 1 and 2 of inductances L_1 and L_2 can be obtained from $M_{12} = K\sqrt{L_1 L_2}$ where K is the coupling co-efficient between the two loops. Here the two loops are identical: $M_{12} = KL$. The constant K can be set to 1 for this configuration based on the approximation that all the flux links between the two loops. However K will vary for different orientation of the loops. The inductance of a loop (placed in air) can be obtained analytically from $L = \frac{\mu_o l}{2\pi} (\ln \frac{4l}{d} - 2.45)$ where l is the perimeter of the loop and d is the diameter of wire [4]. It can also be measured using the impedance analyzer.

A layout with two loops of radius about 12 cm was prepared and assembled concentric and coplanar. From 100 KHz to 1MHz the voltage induced at open end of loop 2 was measured. The inductance of loop 2 was measured using impedance analyzer and found to be 420nH at 1MHz. The current in loop I_1 was not measured but can be obtained analytically from the fact that it is the ratio of voltage excited in loop1 to its impedance. The impedance offered by the loop for a frequency of the excitation can be computed by treating the loop as a series combination of loop inductance (which is the same as that of loop 2 approximately) and resistance R (1K Ohm). A plot of analytical and measured induced voltage is shown in Fig. 9 and a reasonable agreement is found.

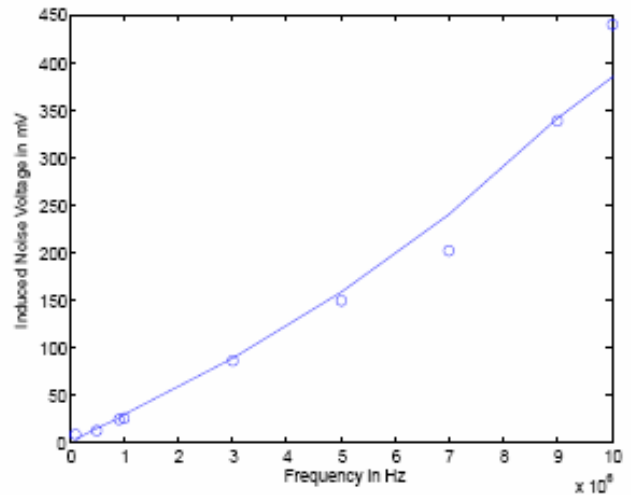


Fig. 9 Induced noise voltage due to inductive coupling (solid lines - computed, dots - measured)

This experiment demonstrates that noise voltages are induced in another loop lying on the same plane as that of another loop due to inductive coupling causing interference. In general in a PCB layout, the voltage induced is due the combined inductive and capacitive coupling. In such complex scenarios, transmission line model needs to be used in predicting crosstalk [5]. But a study of inductive and capacitive coupling

suggests that neglecting crosstalk can lead to problems in the proper functioning of systems operating at high frequencies.

CONCLUSIONS

This paper has presented a set of experiments for students to understand transmission line parameters, and their effects. The approaches used in these experiments are based on frequency domain techniques. Students of digital system design and/or electromagnetics and communication engineering have been able to understand these essential concepts related to transmission line effects.

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