Frequency Domain Cross Talk Measurements Using Twinax Cable

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1. OBJECTIVE

The experimental procedures described below are based on the assumption that the twinax cable can be regarded as a symmetric lossless three-conductor transmission line. Starting with a known length of twinax (three-conductor) cable, a set of experimental procedures for determining the phase propagation velocities, v_{EM} and v_{OM}, for the even and odd modes are described. Then additional procedures are provided for determining the characteristic impedances, Z_{EM} and Z_{OM}, of the even and odd modes respectively. Knowing these four parameters (Z_{EM}, Z_{OM}, v_{EM}, and v_{OM}) allows the near end cross talk coefficient to be calculated. This calculated value could then be compared with experimental measurements of the cross talk coefficient.

2. EQUIPMENT

- Signal generator capable of 10 dBm output over a bandwidth of 1 to 15 MHz. (HP 8647A)
- Dual Channel Oscilloscope (TDS 520A). The input impedance of each channel should be at least several hundred kilohms.
- Five short 50 ohm coaxial cables (no more than 2 meters long) terminated at each end with BNC connectors
- 4 BNC T-connectors
- 0 Ohm BNC terminations (two of them)
- 50 Ohm BNC Terminations (three of them)
- Twinax cable assembly (see Appendix 1)
- Toroid source assembly (see Appendix 1)

3. PROCEDURE

Part 1: Measuring Propagation Velocities

Referring to the individual on the left side of Figure 1 and going from the top of the figure to the bottom, the signal generator is connected via a 50-Ohm coax cable to one of the three toroidal windings.

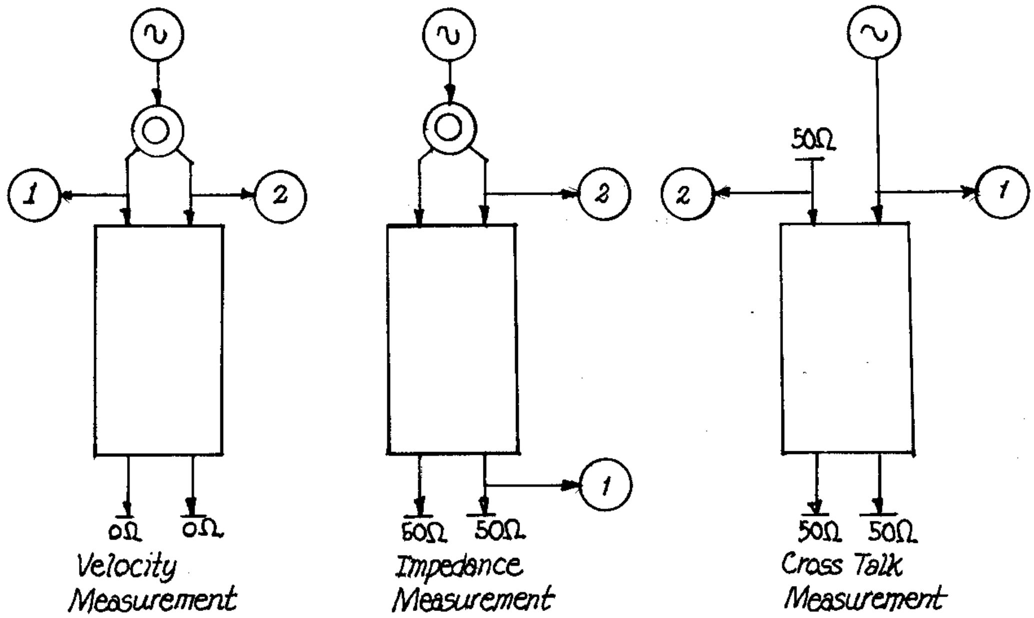

Figure 1: Measurement Configurations for: Velocity Measurements (Left); Impedance Measurements (Center); and Cross Talk Measurements (Right)

The other two toroidal windings are each connected, again through a 50-Ohm coax cable, to one arm of a BNC T connector at the input end of the twinax assembly. The other arm of each BNC T connector is connected to an oscilloscope input channel. The two oscilloscope channels are denoted here as "1" and "2". Starting with the signal generator at a very low frequency the signals displayed on the scope should be very small because an electrically short transmission line terminated in a short circuit has a very low input impedance. Increase the frequency gradually and note whether the voltages in channels 1 and 2 are in phase, indicating that the toroid is producing common (even) mode excitation or out of phase, indicating that the toroid is producing differential (odd) mode excitation. As the frequency is increased you should notice that the magnitudes of the voltages in Channels 1 and 2 track each other closely and initially tend to increase with increasing frequency (as long as the toroid is functioning properly and as long as the circuit remains reasonably well balanced). Keep increasing the frequency until the voltages shown in Channels 1 and 2 attain their maximum magnitude and start decreasing. Continue to increase the frequency until both voltages reach their minimum values. Both channels should reach their minimum values at the same frequency. At this frequency the transmission line is one-half wavelength long. To find the phase velocity let the value of the frequency be denoted by $f_{\min}$ and let the physical length of the twinax be ℓ_0. Since the transmission line is one half wavelength long at this frequency, the propagation velocity is

$$v_{xy} = f_{\min}\lambda = 2 f_{\min}\ell_0 \ .$$

In this case the xy subscript on the velocity becomes EM (even mode) if the toroid was producing common mode excitation and OM (odd mode) if the toroid was producing differential mode excitation. The excitation mode can be changed, from common mode to differential mode or vice versa, by interchanging the connections leading to either one of the toroid's two output BNC connectors (see Appendix 1). Therefore, change the excitation mode and repeat the procedure described above to determine the propagation velocity of the other excitation mode. For each of the two excitation modes note the frequency at which the minimum voltage occurs and also note the propagation velocity associated with each mode. These quantities will be needed in the following two parts of this experiment.

<u>Part 2: Measuring Characteristic Impedances</u>

Change the connections shown on the left side of Figure 1 by replacing each of the short circuit terminations with a 50-Ohm termination. Then move the lead to scope channel 1 from the BNC T connector on the input end of the twinax to either of the BNC T connectors on the output end of the twinax. The result should be the configuration shown in the center of Figure 1.

Assuming that the toroid provides common mode excitation, for example, set the frequency equal to one half of the value of $f_{\min}$ found for common mode excitation in the previous part of the experiment. For common mode excitation at this new and lower frequency, the transmission line should now be one quarter wavelength (or, equivalently, $\pi/2$ radians) long. At this frequency

$$V_1\big|_{\text{rms}} \propto \left|1+\frac{50-Z_{\text{EM}}}{50+Z_{\text{EM}}}\right| = 1+\frac{50-Z_{\text{EM}}}{50+Z_{\text{EM}}}$$

$$V_2\big|_{\text{rms}} \propto \left|1e^{j\pi/2}+\frac{50-Z_{\text{EM}}}{50+Z_{\text{EM}}}e^{-j\pi/2}\right| = 1-\frac{50-Z_{\text{EM}}}{50+Z_{\text{EM}}}$$

Therefore, the numerical value of Z_{EM} can be obtained from

$$\frac{V_2\big|_{\text{rms}}}{V_1\big|_{\text{rms}}} = \frac{1-\dfrac{50-Z_{\text{EM}}}{50+Z_{\text{EM}}}}{1+\dfrac{50-Z_{\text{EM}}}{50+Z_{\text{EM}}}} \times \frac{50+Z_{\text{EM}}}{50+Z_{\text{EM}}} = \frac{2Z_{\text{EM}}}{100} = \frac{Z_{\text{EM}}}{50}$$

so that

$$Z_{\text{EM}} = 50\times\frac{V_2\big|_{\text{rms}}}{V_1\big|_{\text{rms}}}$$

where $V_2\big|_{\text{rms}}$ is the rms voltage of the signal on scope channel 2 while $V_1\big|_{\text{rms}}$ is the rms voltage of the signal on scope channel 1.

To obtain the odd mode impedance, set the toroid to produce differential mode excitation; and change the frequency, if necessary, so that the transmission line will be one-quarter wavelength long for differential mode excitation. Note the new values of $V_2\big|_{\text{rms}}$ and $V_1\big|_{\text{rms}}$ and calculate the odd mode characteristic impedance according to

$$Z_{OM} = 50 \times \frac{V_2|_{rms}}{V_1|_{rms}}$$

Part 3: Measuring the Near End Cross Talk Coefficient

To measure the near end cross talk coefficient at a given frequency, connect the signal generator directly to one arm of a BNC T connector at the input end of the twinax assembly. Connect the other arm of this T connector to oscilloscope channel 1. The other input end T connector should be connected to oscilloscope channel 2 on one arm and to a 50 Ohm termination on the other arm. The output end BNC T connectors should remain connected to 50 Ohm terminations. The configuration of this circuit is shown on the right side of Figure 1.

With the signal generator set at frequency f_1, for example, the near end cross talk coefficient is

$$20\log_{10}\left(\frac{V_2|_{rms}}{V_1|_{rms}}\right)$$

The measured near end cross talk coefficient can then be plotted on semi-log graph paper as a function of frequency. An example of this type of plot can be found on page 223 of Clayton Paul's text on electromagnetic compatibility [1].

4. THEORY & DISCUSSION

Consider a lossless two-conductor transmission line such as the one shown below in Figure 2.

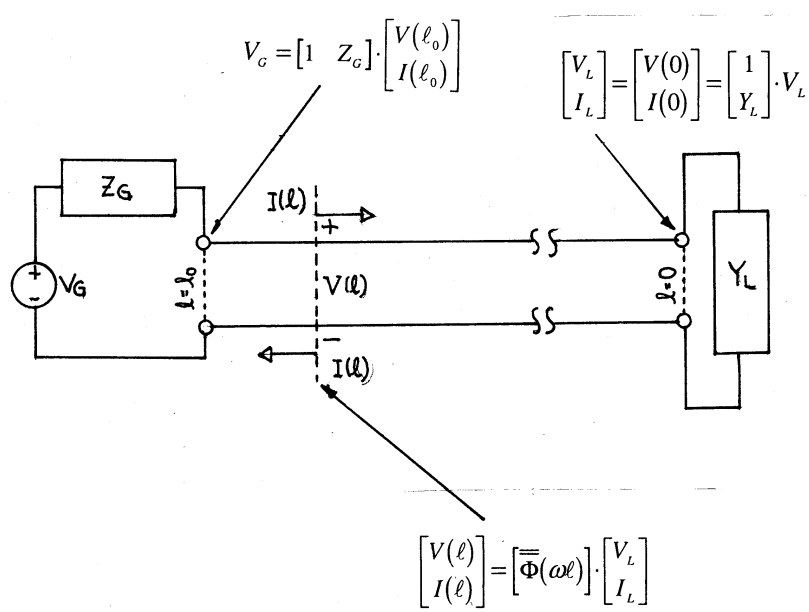

Figure 2: A Two-Conductor Transmission Line

The voltage $V(\ell)$ and current $I(\ell)$ at any point on the transmission line can be regarded as the superposition of the voltages and currents associated with two waves--a forward wave propagating from the generator end to the load end and a reflected wave propagating in the opposite direction. Formally, this superposition of waves can be written as:

$$\begin{bmatrix} V(\ell) \\ I(\ell) \end{bmatrix} = \alpha^{+} \begin{bmatrix} Z_0 \\ 1 \end{bmatrix} \exp\left(j \frac{\omega \ell}{v_0} \right) + \alpha^{-} \begin{bmatrix} -Z_0 \\ 1 \end{bmatrix} \exp\left(-j \frac{\omega \ell}{v_0} \right)$$

where α^{+} and α^{-} are linear combination coefficients and, in this case, α^{+} is equal to the phasor current associated with the forward propagating wave while α^{-} is equal to the phasor current associated with the reflected wave. In matrix form, this linear superposition can be written as:

$$\begin{bmatrix} V(\ell) \\ I(\ell) \end{bmatrix} = \begin{bmatrix} Z_0 & -Z_0 \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \exp\left(\frac{j\omega\ell}{v_0} \right) & 0 \\ 0 & \exp\left(\frac{-j\omega\ell}{v_0} \right) \end{bmatrix} \cdot \begin{bmatrix} \alpha^{+} \\ \alpha^{-} \end{bmatrix}$$

$$= \left[\overline{\overline{T}} \right] \cdot \left[\overline{\overline{E}}(\omega\ell) \right] \cdot [\vec{\alpha}]$$

where

$$\left[\overline{\overline{T}} \right] = \begin{bmatrix} Z_0 & -Z_0 \\ 1 & 1 \end{bmatrix} \qquad \left[\overline{\overline{E}}(\omega\ell) \right] = \begin{bmatrix} \exp\left(\frac{j\omega\ell}{v_0} \right) & 0 \\ 0 & \exp\left(\frac{-j\omega\ell}{v_0} \right) \end{bmatrix} \qquad \text{and } [\vec{\alpha}] = \begin{bmatrix} \alpha^{+} \\ \alpha^{-} \end{bmatrix}$$

For the special case of $\ell = 0$ (at the load end of the transmission line)

$$\begin{bmatrix} V(0) \\ I(0) \end{bmatrix} = \begin{bmatrix} Z_0 & -Z_0 \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} e^{j(0)} & 0 \\ 0 & e^{-j(0)} \end{bmatrix} \cdot \begin{bmatrix} \alpha^{+} \\ \alpha^{-} \end{bmatrix} = \left[\overline{\overline{T}} \right] \cdot [\vec{\alpha}]$$

Then solving for $[\vec{\alpha}]$ in terms of the load end voltages and currents (V_L and I_L)

$$[\vec{\alpha}] = \left[\overline{\overline{T}} \right]^{-1} \cdot \begin{bmatrix} V(0) \\ I(0) \end{bmatrix} = \left[\overline{\overline{T}} \right]^{-1} \cdot \begin{bmatrix} V_L \\ I_L \end{bmatrix}$$

Substituting this expression into the expression for the voltage and current at a general point on the transmission line

$$\begin{bmatrix} V(\ell) \\ I(\ell) \end{bmatrix} = \left[\overline{\overline{T}}\right] \cdot \left[\overline{\overline{E}}(\omega\ell)\right] \cdot [\vec{\alpha}]$$

$$= \left[\overline{\overline{T}}\right] \cdot \left[\overline{\overline{E}}(\omega\ell)\right] \cdot \left[\overline{\overline{T}}\right]^{-1} \cdot \begin{bmatrix} V_L \\ I_L \end{bmatrix}$$

$$= \left[\overline{\overline{\Phi}}(\omega\ell)\right] \cdot \begin{bmatrix} V_L \\ I_L \end{bmatrix}$$

where

$$\left[\overline{\overline{\Phi}}(\omega\ell)\right] \equiv \left[\overline{\overline{T}}\right] \cdot \left[\overline{\overline{E}}(\omega\ell)\right] \cdot \left[\overline{\overline{T}}\right]^{-1}$$

The matrix $\left[\overline{\overline{\Phi}}(\omega\ell)\right]$ relates the transmission line voltages and currents at an arbitrary point to the voltages and currents at the load. Furthermore, note that this matrix only depends upon the transmission line properties (v_0 and Z_0); the source frequency (ω); and position along the transmission line (ℓ). It does not depend upon the terminations of the transmission line.

The termination conditions are contained within the values of the load end voltage and current (V_L and I_L) and the generator end voltage and current ($V(\ell_0)$ and $I(\ell_0)$). For example, at the load end $I_L = Y_L V_L$ where $Y_L = 1/Z_L$ is the load admittance. Then the voltage and current at a general point along the transmission line can be written in terms of V_L alone through

$$\begin{bmatrix} V(\ell) \\ I(\ell) \end{bmatrix} = \left[\overline{\overline{\Phi}}(\omega\ell)\right] \cdot \begin{bmatrix} V_L \\ I_L \end{bmatrix}$$

$$= \left[\overline{\overline{\Phi}}(\omega\ell)\right] \cdot \begin{bmatrix} 1 \\ Y_L \end{bmatrix} V_L$$

$$= \left[\overline{\overline{\Phi}}(\omega\ell)\right] \cdot \left[\overline{\overline{Y}}_L\right] \cdot \left[\overline{\overline{V}}_L\right]$$

Even though V_L is simply a scalar, it is written here in the form of a 1 by 1 matrix to facilitate extending the two-conductor transmission line case treated here to the three-conductor transmission line case.

At the generator end of the transmission line, $\ell = \ell_0$, the generator voltage, V_0, is assumed to be known and is related to the generator end voltages and currents through

$$V_G = V(\ell_0) + Z_G I(\ell_0)$$

$$= \begin{bmatrix} 1 & Z_G \end{bmatrix} \cdot \begin{bmatrix} V(\ell_0) \\ I(\ell_0) \end{bmatrix}$$

$$= \left[\overline{\overline{Z}}_G\right] \cdot \left[\overline{\overline{\Phi}}(\omega\ell_0)\right] \cdot \left[\overline{\overline{Y}}_L\right] \cdot \left[\overline{\overline{V}}_L\right]$$

Writing the known source voltage in the form of a 1 by 1 matrix

$$\left[\overline{\overline{V}}_G\right] = \left[\overline{\overline{Z}}_G\right]\cdot\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]\cdot\left[\overline{\overline{Y}}_L\right]\cdot\left[\overline{\overline{V}}_L\right]$$

This can be inverted to solve for the unknown load end voltage in which case

$$\left[\overline{\overline{V}}_L\right] = \left\{\left[\overline{\overline{Z}}_G\right]\cdot\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]\cdot\left[\overline{\overline{Y}}_L\right]\right\}^{-1}\cdot\left[\overline{\overline{V}}_G\right]$$

Finally substituting this last unknown quantity into the expression for the voltage and current at a general point on the two-conductor transmission line

$$\begin{bmatrix} V(\ell) \\ I(\ell) \end{bmatrix} = \left[\overline{\overline{\Phi}}(\omega\ell)\right]_{(2\times 2)}\cdot\left[\overline{\overline{Y}}_L\right]_{(2\times 1)}\cdot\left\{\left[\overline{\overline{Z}}_G\right]_{(1\times 2)}\cdot\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]_{(2\times 2)}\cdot\left[\overline{\overline{Y}}_L\right]_{(2\times 1)}\right\}^{-1}\cdot\left[\overline{\overline{V}}_G\right]_{(1\times 1)}$$

Small subscripts have been appended to the matrices in order to show their sizes and also to facilitate comparison with the three-conductor transmission line.

Referring to the definitions for the transmission line voltages and currents on a three conductor transmission line as shown in Figure 3, a similar development leads to an expression for the voltages and currents at a general point on the three-conductor transmission line.

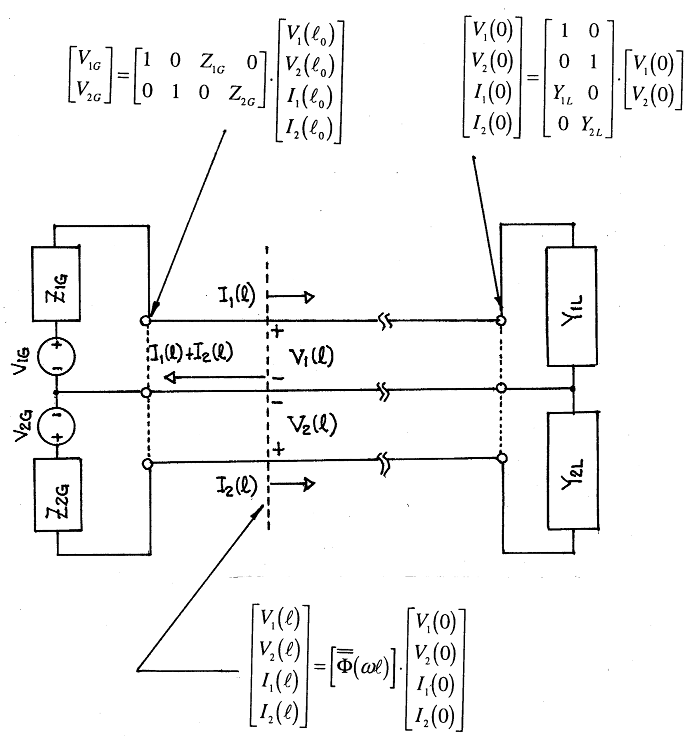

Figure 3: A Three-Conductor Transmission Line

In the case of the three-conductor transmission line as shown in this figure, there are two possible modes. In the even mode $V_1(\ell) = V_2(\ell)$ and $I_1(\ell) = I_2(\ell)$ at every point along the transmission line. Furthermore the even mode voltages and currents result from a superposition of a forward propagating even mode wave and a backward propagating even mode wave. In the odd mode $V_1(\ell) = -V_2(\ell)$ and $I_1(\ell) = -I_2(\ell)$ at every point along the transmission line. As in the even mode case, the odd mode voltages and currents can generally be regarded as the superposition of a forward propagating odd mode wave and a backward propagating odd mode wave. In short, the voltages and currents at any point on the three-conductor transmission line can be regarded as a linear superposition of the voltages and currents produced by forward and backward propagating odd and even mode waves. Then following a procedure similar to the one previously described for the two-conductor transmission line, the general expression for the voltages and currents at any point along the three-conductor transmission line is given by:

$$\begin{bmatrix} V_1(\ell) \\ V_2(\ell) \\ I_1(\ell) \\ I_2(\ell) \end{bmatrix} = \left[\overline{\overline{\Phi}}(\omega\ell)\right]_{(4\times4)} \cdot \left[\overline{\overline{Y}}_L\right]_{(4\times4)} \cdot \left\{\left[\overline{\overline{Z}}_G\right]_{(2\times4)} \cdot \left[\overline{\overline{\Phi}}(\omega\ell_0)\right]_{(4\times4)} \cdot \left[\overline{\overline{Y}}_L\right]_{(4\times2)}\right\}^{-1} \cdot \left[\overline{\overline{V}}_G\right]_{(2\times1)}$$

where

$$\left[\overline{\overline{V}}_G\right] = \begin{bmatrix} V_{1G} \\ V_{2G} \end{bmatrix}$$

$$\left[\overline{\overline{Y}}_L\right] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ Y_{1L} & 0 \\ 0 & Y_{2L} \end{bmatrix}$$

$$\left[\overline{\overline{Z}}_G\right] = \begin{bmatrix} 1 & 0 & Z_{1G} & 0 \\ 0 & 1 & 0 & Z_{2G} \end{bmatrix}$$

$$\left[\overline{\overline{T}}\right] = \begin{bmatrix} Z_{EM} & -Z_{EM} & -Z_{OM} & Z_{OM} \\ Z_{EM} & -Z_{EM} & Z_{OM} & -Z_{OM} \\ 1 & 1 & -1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

and

$$\left[\overline{\overline{\Phi}}(\omega\ell)\right] = \left[\overline{\overline{T}}\right]\cdot\left[\overline{\overline{E}}(\omega\ell)\right]\cdot\left[\overline{\overline{T}}\right]^{-1}$$

$$= \left[\overline{\overline{T}}\right]\cdot\begin{bmatrix} \exp\left(j\dfrac{\omega\ell}{v_{EM}}\right) & 0 & 0 & 0 \\ 0 & \exp\left(-j\dfrac{\omega\ell}{v_{EM}}\right) & 0 & 0 \\ 0 & 0 & \exp\left(j\dfrac{\omega\ell}{v_{OM}}\right) & 0 \\ 0 & 0 & 0 & \exp\left(-j\dfrac{\omega\ell}{v_{OM}}\right) \end{bmatrix}\cdot\left[\overline{\overline{T}}\right]^{-1}$$

This expression may be used to write the near end cross talk coefficient by noting that the cross talk measurement corresponds to setting $V_{2G} = 0$ and taking the ratio of $V_2(\ell_0)$ to $V_1(\ell_0)$. The impedance Z_{1G} is the internal impedance of the signal generator. The exact value of the signal generator voltage source is not important because it cancels out when evaluating the ratio of $V_2(\ell_0)$ to $V_1(\ell_0)$. Therefore, V_{1G} can be considered to be 1 Volt for the purpose of calculating the cross talk coefficient. The calculated near end cross talk coefficient in dB can then be written as

$$20\log_{10}\left(\frac{V_2(\ell_0)\big|_{\text{rms}}}{V_1(\ell_0)\big|_{\text{rms}}}\right)\Bigg|_{\substack{V_{1G}=1\\V_{2G}=0}}$$

$$= 20\log_{10}\left(\frac{\left|\text{Second Row of }\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]\cdot\left[\overline{\overline{Y}}_L\right]\cdot\left\{\left[\overline{\overline{Z}}_G\right]\cdot\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]\cdot\left[\overline{\overline{Y}}_L\right]\right\}^{-1}\cdot\begin{bmatrix}1\\0\end{bmatrix}\right|}{\left|\text{First Row of }\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]\cdot\left[\overline{\overline{Y}}_L\right]\cdot\left\{\left[\overline{\overline{Z}}_G\right]\cdot\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]\cdot\left[\overline{\overline{Y}}_L\right]\right\}^{-1}\cdot\begin{bmatrix}1\\0\end{bmatrix}\right|}\right)$$

$$= 20\log_{10}\left(\frac{\left|\begin{bmatrix}0 & 1 & 0 & 0\end{bmatrix}\cdot\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]\cdot\left[\overline{\overline{Y}}_L\right]\cdot\left\{\left[\overline{\overline{Z}}_G\right]\cdot\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]\cdot\left[\overline{\overline{Y}}_L\right]\right\}^{-1}\cdot\begin{bmatrix}1\\0\end{bmatrix}\right|}{\left|\begin{bmatrix}1 & 0 & 0 & 0\end{bmatrix}\cdot\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]\cdot\left[\overline{\overline{Y}}_L\right]\cdot\left\{\left[\overline{\overline{Z}}_G\right]\cdot\left[\overline{\overline{\Phi}}(\omega\ell_0)\right]\cdot\left[\overline{\overline{Y}}_L\right]\right\}^{-1}\cdot\begin{bmatrix}1\\0\end{bmatrix}\right|}\right)$$

The following figure shows the calculated near end cross talk coefficient when $Z_{EM} = 39\Omega$, $Z_{OM} = 30\Omega$, and $v_{EM} = v_{OM} = 1.95\times10^8$ meters per second. The twinax cable in this case was 13 meters long. These values for Z_{EM}, Z_{OM}, v_{EM}, and v_{OM} were obtained from parts 1 and 2 of this experiment.

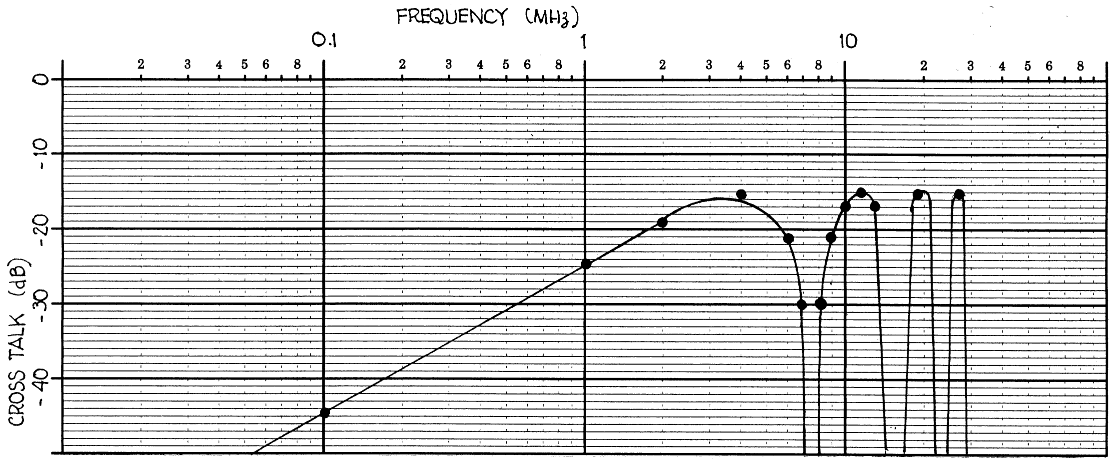

Figure 4: Calculated Near-End Cross Talk Coefficient

When the even and odd mode propagation velocities are the same (as in this case), the matrix $\left[\overline{\overline{\Phi}}(\omega\ell)\right]$ is periodic in frequency with a period of $f_0 = \frac{v_{EM}}{\ell_0} = \frac{v_{OM}}{\ell_0}$. For the values of used in this figure, the frequency f_0 is approximately 15 MHz. However, the cross talk coefficient as defined above only involves the absolute value of the ratio of two voltages and hence the cross talk coefficient should be periodic with a period of one-half of f_0, or 7.5 MHz. This frequency can be seen to correspond to the spacing between the "nulls" in Figure 4.

5. SUMMARY AND CONCLUSIONS

The purpose of this experiment is to use relatively simple low frequency measurements to characterize a length of twinax cable and then to use this characterization to predict the near end cross talk coefficient. The calculated value of the near end cross talk coefficient can then be compared with the value based on the ratio of measured voltages at the generator end of the twinax. Although a dual channel oscilloscope is not absolutely necessary to perform this experiment, it is very helpful to be able to simultaneously compare the displays of the two channels. Also having some math capabilities on the oscilloscope is useful for having the oscilloscope calculate the rms or peak values of the voltages on the two channels.

The toroid assembly was built on a breadboard. A more rugged assembly where one or more toroid windings is connected to a switch would have been an improvement.

Occasionally, erratic oscilloscope readings can make it difficult or impossible to obtain reasonable propagation velocities and/or even and odd mode impedances. Aside from "wiring errors" such as connecting a scope channel to the wrong end of the twinax, the most common cause of difficulties seems to be the BNC connectors on the twinax assembly. **Lightly** pressing or wiggling any one of the T connectors on the twinax assembly should not cause a significant change in the voltage level displayed on either channel of the oscilloscope. When light pressure on one or more BNC T connectors does cause a significant change in the voltage, it is probably an appropriate time to replace the T connectors. Also make sure that the female BNC connectors (Part G in Figure 5) are still tightly bolted to the aluminum angle plates (part E in Figure 5).

6. REFERENCES

[1] Clayton Paul, *Introduction to Electromagnetic Compatibility,* John Wiley & Sons, Inc., New York, 1992.

APPENDIX 1: TWINAX ASSEMBLY

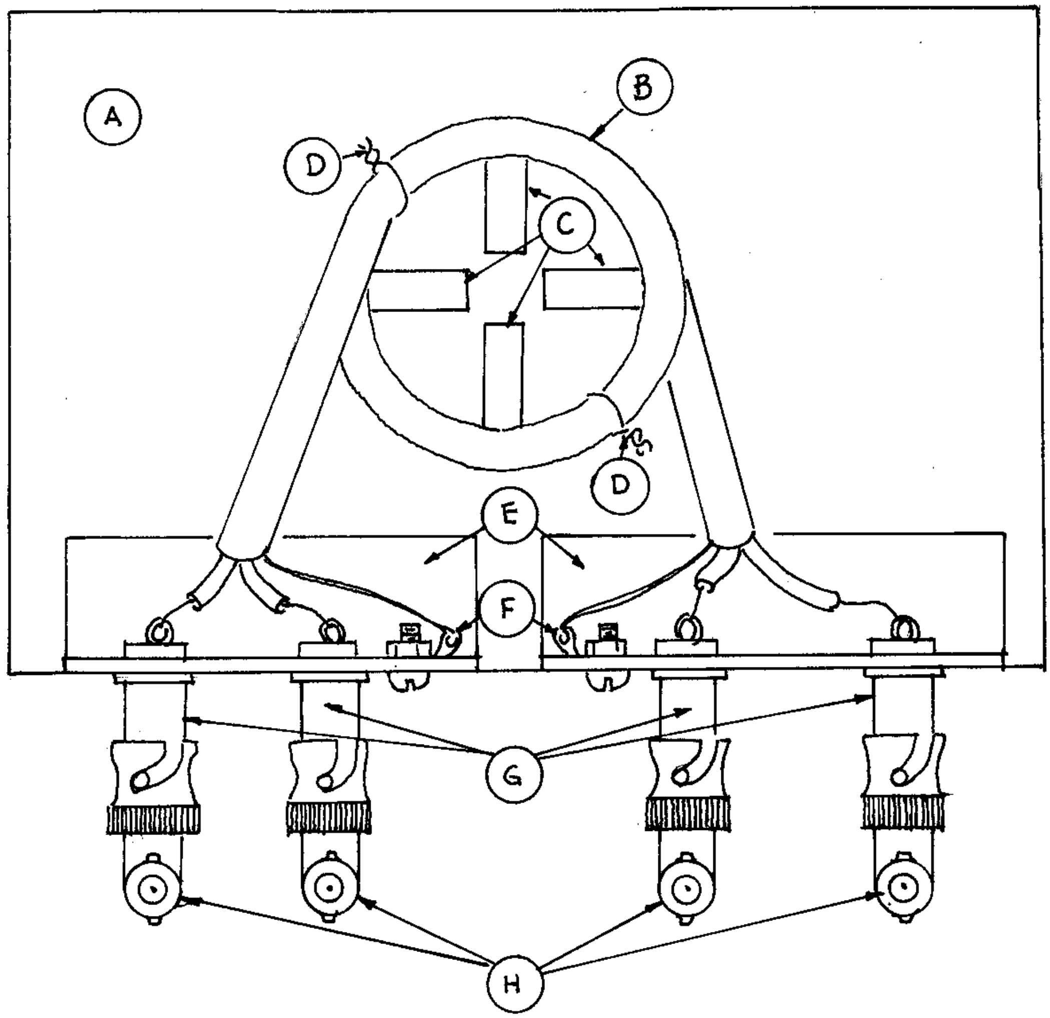

Figure 5: Twinax Cable Assembly (Top View)

Parts list:

A. Wooden Base
B. Spool of Twinax Cable (approximately 13 meters long)
C. Wooden Pegs to Hold Spool of Cable
D. Cable Ties
E. Aluminum Angle Plates
F. Solder Lugs Connected to Braid Conductor of Twinax Cable
G. BNC Connectors (Female)
H. BNC T Connectors (Female-Male-Female)

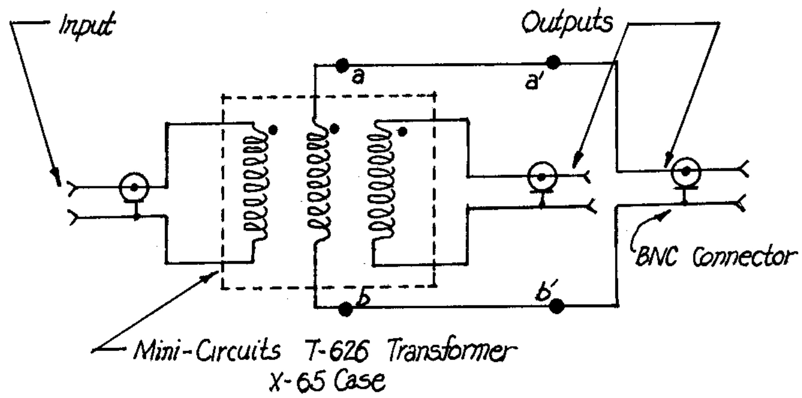

Figure 6: Toroid Assembly Set Up for Common Mode Excitation

Connections:
Common Mode: Connect a to a′ and b to b′
Differential Mode: Connect a to b′ and b to a′