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RISE TIME TO FREQUENCY CORRELATION
OF CROSSTALK IN COUPLED MICROSTRIP LINES

BY

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B.S.E., University of Central Florida, 1987

THESIS

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ABSTRACT

An examination of forward crosstalk in microstrip transmission lines is presented through a computer simulation using SPICE. A non-resistive lumped L-C transmission line model is modified to include capacitive and inductive coupling from adjacent lines. Two adjacent microstrip transmission lines are modeled, and simulation results in both the time and frequency domains are shown.

The time domain or transient analysis looks at the effect of rise times on crosstalk. Rise times in the range of 100 to 1000 nanoseconds (ns) are considered. The frequency analysis shows the crosstalk frequency response over the range of 100 to 1600 kilohertz (kHz). The effects of line spacing to dielectric height ratios, line width to dielectric height ratios, and line terminations are shown.

A correlation of rise time to equivalent crosstalk frequency using crosstalk magnitude as a common point of reference is performed, and the line geometry and termination effects upon the correlation are explored.

ACKNOWLEDGEMENTS

I would like to thank Mr. Robert Canright for his helpful suggestions. Many thanks also go to Dr. Parveen Wahid for her advice and recommendations. Special thanks go to my advisor, Dr. Madjid Belkerdid, for his help and guidance with the research and writing of this thesis.

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CHAPTER I
INTRODUCTION

When two parallel lines are placed in close proximity, crosstalk can occur between them due to capacitive and inductive coupling. The problem of crosstalk noise in digital circuitry interconnections becomes significant with high density circuit packaging and short rise time pulses used in high speed circuits. Predicting the amount of crosstalk is complicated by the need to know characteristic impedances, coupling coefficients, and types of line terminations.

Work producing analytical predictions of crosstalk in the time domain has been done by many, such as DeFalco [1,2], Jarvis [3], and Feller et al. [4], in which differential equations describing the coupling between transmission lines are developed and then solved using the various line terminations as boundary conditions. This straightforward method can become quite complicated when the lines are driving non-linear loads (which can be distributed along the length of the line). Computer simulation can provide a convenient alternative to analytically obtaining crosstalk predictions.

In actual crosstalk measurements, the convenience and accuracy of automatic network analyzers make them an attractive test instrument. However, using test results from network analyzers to determine crosstalk for digital design engineers presents a problem. Network analyzers present crosstalk data as noise versus frequency. This is preferred by radio frequency engineers. Digital engineers prefer results in the time domain as crosstalk versus rise time.

The objective of this work is to provide a simple method to predict forward crosstalk due to signal rise time using crosstalk versus frequency information.

CHAPTER II

TRANSMISSION LINE THEORY

The work presented in this paper involves an investigation into transmission line behavior; therefore, a short derivation of transmission line equations is in order. This will show from where the transmission line model originates and that the model will support traveling waves. A transverse electromagnetic (TEM) propagation mode is assumed.

The electromagnetic properties of a microstrip transmission line are the self inductance per unit length (L), self capacitance per unit length (C), line resistance per unit length (R), and dielectric conductance from the line to the ground plane per unit length (G). The currents and voltages in the transmission line are expressed as functions of space (z) and time (t). The equivalent circuit model of a small, finite, transmission line section of length Δz and the corresponding voltages and currents are shown in Figure 1. The change in voltage and current, at one instant in time, across the model is expressed as

$$v(z,t) - v(z+\Delta z,t) = \left[R \Delta z + L \Delta z \frac{\partial}{\partial t} \right] i(z,t) \quad (2-1)$$

$$i(z,t) - i(z+\Delta z,t) = \left[G \Delta z + C \Delta z \frac{\partial}{\partial t} \right] v(z+\Delta z,t) \quad (2-2)$$

Or, with some rearranging, as

$$\frac{v(z,t) - v(z+\Delta z,t)}{\Delta z} = R i(z,t) + L \frac{\partial i(z,t)}{\partial t} \quad (2-3)$$

$$\frac{i(z,t) - i(z+\Delta z,t)}{\Delta z} = G v(z+\Delta z,t) + C \frac{\partial v(z+\Delta z,t)}{\partial t} \quad (2-4)$$

Letting the model length approach zero and using the definition of the partial derivative,

$$\lim_{\Delta z \rightarrow 0} \frac{f(z+\Delta z,t) - f(z,t)}{\Delta z} = \frac{\partial f(z,t)}{\partial z} \quad (2-5)$$

allows Equations 2-3 and 2-4 to be written as

$$\frac{\partial v(z,t)}{\partial z} = - R i(z,t) - L \frac{\partial i(z,t)}{\partial t} \quad (2-6)$$

$$\frac{\partial i(z,t)}{\partial z} = - G v(z,t) - C \frac{\partial v(z,t)}{\partial t} \quad (2-7)$$

Most microstrip lines can be considered approximately lossless. Hence, the resistive terms R and G can be safely neglected from the model and equations without losing much in the way of accuracy. This yields

$$\frac{\partial v(z,t)}{\partial z} = - L \frac{\partial i(z,t)}{\partial t} \quad (2-8)$$

$$\frac{\partial i(z,t)}{\partial z} = - C \frac{\partial v(z,t)}{\partial t} \quad (2-9)$$

Taking the partial derivative of 2-8 with respect to z , and 2-9 with respect to t ,

$$\frac{\partial^2 v(z,t)}{\partial z^2} = - L \frac{\partial^2 i(z,t)}{\partial t \partial z} \quad (2-10)$$

$$\frac{\partial^2 i(z,t)}{\partial t \partial z} = -C \frac{\partial^2 v(z,t)}{\partial t^2} \quad (2-11)$$

and combining these to solve for the voltage gives,

$$\frac{\partial^2 v(z,t)}{\partial z^2} = LC \frac{\partial^2 v(z,t)}{\partial t^2} \quad (2-12)$$

$$\frac{\partial^2 v(z,t)}{\partial z^2} - LC \frac{\partial^2 v(z,t)}{\partial t^2} = 0 \quad (2-13)$$

This is in the form of the one-dimensional wave equation

$$\frac{\partial^2 f(z,t)}{\partial z^2} - \frac{1}{V_P^2} \frac{\partial^2 f(z,t)}{\partial t^2} = 0 \quad (2-14)$$

which has a solution of the form

$$v(z,t) = F_1\left(t - \frac{z}{V_P}\right) + F_2\left(t + \frac{z}{V_P}\right) \quad (2-15)$$

where V_P is the velocity of propagation $[(LC)^{-1/2}]$.

This indicates the total voltage is composed of arbitrary forward (F_1) and backward (F_2) traveling waveforms. Although this result assumes the transmission line is composed of an infinite number of incremental models of infinitesimal length dz , the line can be approximated with a finite number of models of length Δz . The required number of models for a close approximation is discussed in Chapter III.

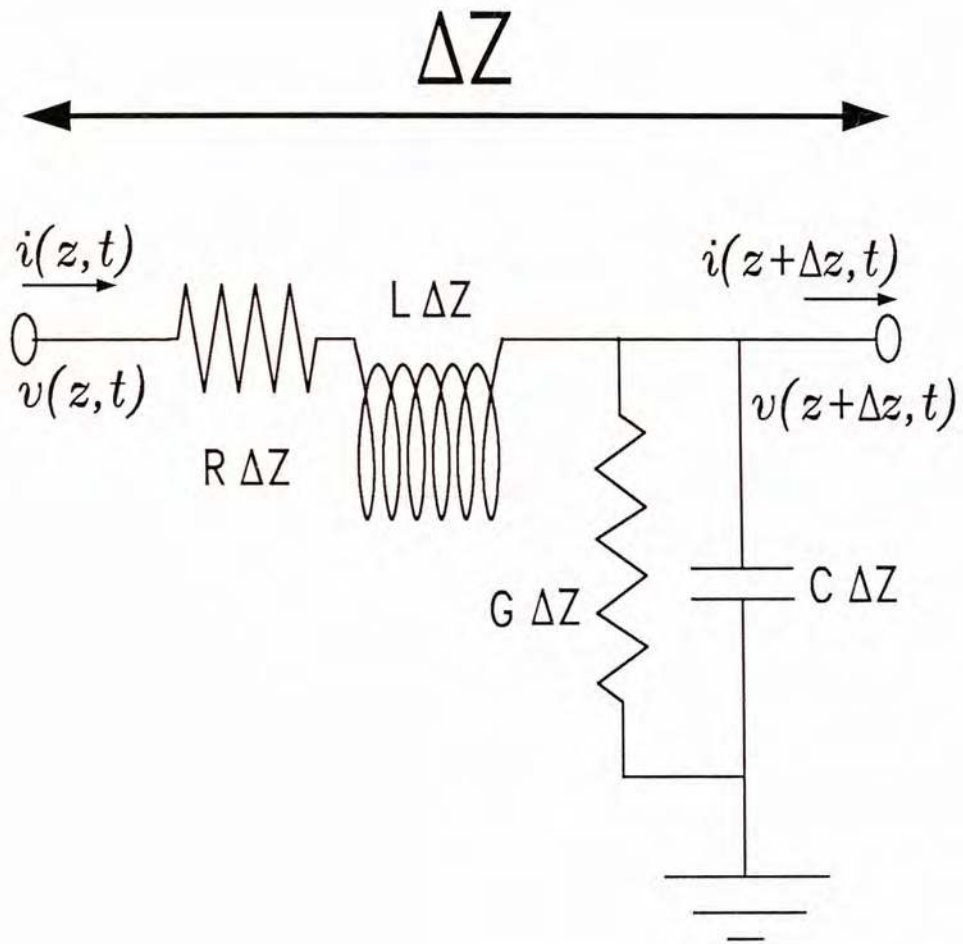


Figure 1. Equivalent Circuit Model of a Microstrip Transmission Line Section.

CHAPTER III
TRANSMISSION LINE MODELING

Model Development

The geometry of two adjacent microstrip transmission lines is shown in Figure 2a. The lines are assumed to be lossless and of zero thickness (T). The items of interest are the line width (W), line spacing (S), height above the ground plane (H), and relative dielectric constant of the substrate board (ϵ_r). Using the S/H and W/H ratios and ϵ_r , values for the self inductance per unit length (L), self capacitance per unit length (C), mutual capacitance per unit length (C_M), inductive coupling constant (K_L), and characteristic impedance (Z_0) can be found via a numerical method used by Okugawa [5]. A FORTRAN program using this method is shown in Appendix A. These line parameters can then be used in two, coupled, incremental transmission line models [6] shown in Figure 2b.

When modeling a line of length y with lumped L-C elements, the line is divided into N discrete blocks of length Δz . As a rule of thumb, the propagation delay (T_d) caused by the element representing the length Δz should never be larger than one fifth the shortest rise time (tr_{MIN}) expected; a value of one twentieth the minimum rise

time, or less, allows the model to closely approximate the actual line [6]. The propagation delay is found by dividing the distance traveled, Δz , by the velocity of propagation as follows

$$T_d = \frac{\Delta z}{v_p} \quad (3-1)$$

$$v_p = (LC)^{-1/2} \quad (3-2)$$

$$T_d = \Delta z (LC)^{1/2} \quad (3-3)$$

using the previous condition of

$$T_d \leq \frac{tr_{MIN}}{20} \quad (3-4)$$

the required N can be determined as

$$\Delta z \leq \frac{tr_{MIN}}{20 (LC)^{1/2}} \quad (3-5)$$

$$\Delta z = \frac{y}{N} \quad (3-6)$$

$$N \cong \frac{20 y (LC)^{1/2}}{tr_{MIN}} \quad (3-7)$$

When N is found from Equation 3-7, it can be used in Equation 3-6 to find Δz . The values of L , C , and C_M are then multiplied by Δz to obtain the values of the inductance, capacitance, and mutual capacitance, respectively, for use in each of the N incremental models.

Model Parameter Calculations

Eleven sets of 40 centimeter transmission lines were modeled. The S/H and W/H ratios were unique for each set so as to cover a range of layout geometries. Both S/H and W/H values ranged from 0.67 to 2.00. The values for S/H and W/H for each set, numbered 1 through 11, are listed in Table 1. Values of 5.3 and zero were used for ϵ_r and T , respectively. Using this information, the FORTRAN program in Appendix A calculated the line parameters which are compiled in Table 2. Using L and C values in Table 2, 0.4 meters for y , and tr_{MIN} of 100 ns in Equation 3-7, minimum values of N were found to be 5 or 6. A value of 8 was chosen for greater accuracy. Next, Δz was found, using Equation 3-6, to be 50×10^{-3} meters or 5 centimeters. From Δz , the element values for each incremental model for each set were calculated and are listed in Table 3.

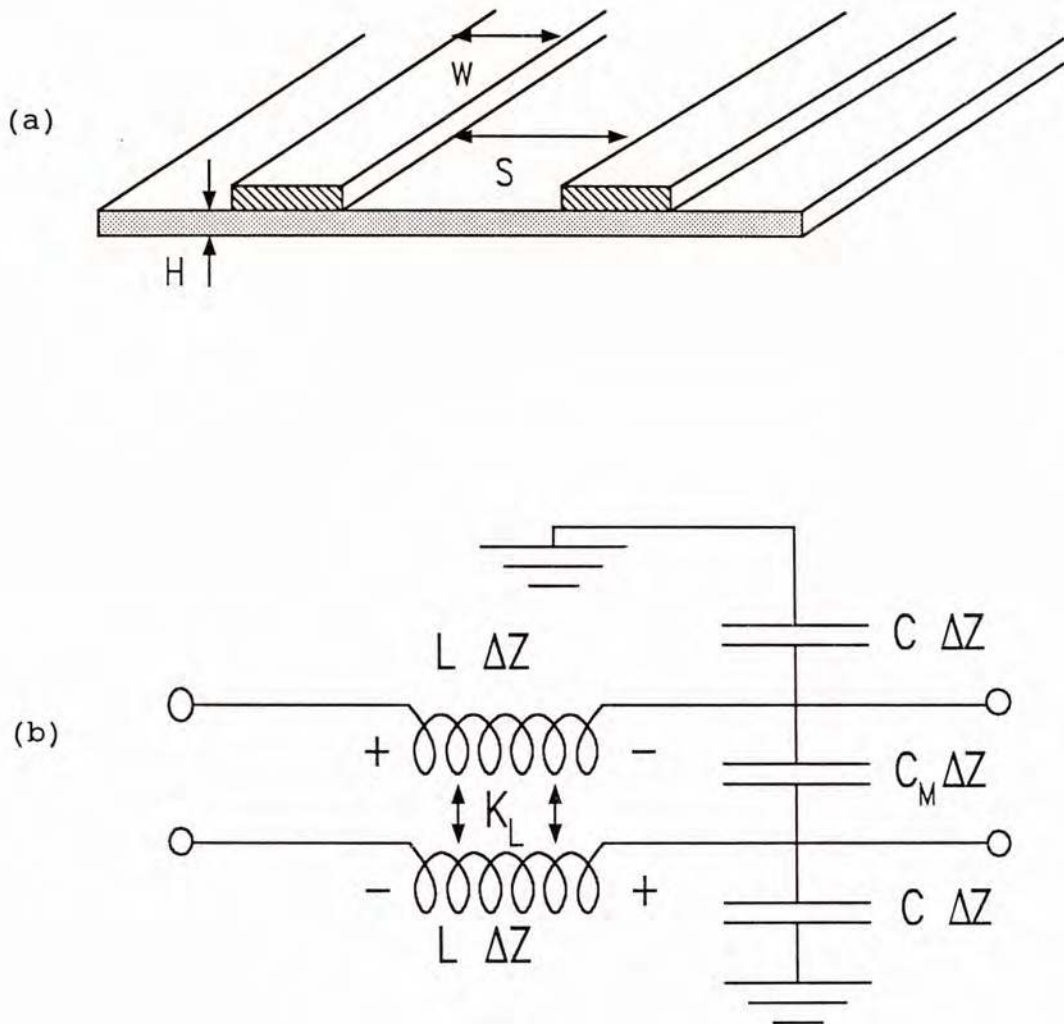


Figure 2. (a) Geometry of Two Adjacent Microstrip Transmission Lines. (b) Two, Coupled, Incremental Transmission Line Models of Length Δz .

Model Implementation

A physical conceptualization of the computer simulation setup is shown in Figure 3. A voltage source at $z=0$ with an internal resistance matched to the coupling influenced Z_0 of the set being simulated is driving what will be called hereafter the active line. The active line is terminated with a resistance of Z_0 at $z=y$. The adjacent line, hereafter called the passive line, is terminated at $z=0$ with a resistance of Z_0 and at $z=y$ with a resistance Z_T . The simulations are conducted with Z_T being set to a value of Z_0 and infinity (open).

An item worth noting is that the impedance of the source is an external resistor above it. This resistor, and the one at the opposite end of the line, form a voltage divider of one half. Therefore, when a voltage value for the source is hereafter mentioned, the actual SPICE source is double this value.

SPICE Circuit Description

The above setup was translated into a SPICE circuit description. The main body of the circuit description includes the source, the terminations, and a call to a subcircuit in place of the lines. This subcircuit contains 8 calls to a second subcircuit which contains a circuit description of the coupled incremental model. Thus, 8 incremental models are, in effect, placed in the main body

of the circuit description. A sample of the circuit descriptions can be found in Appendices B and C.

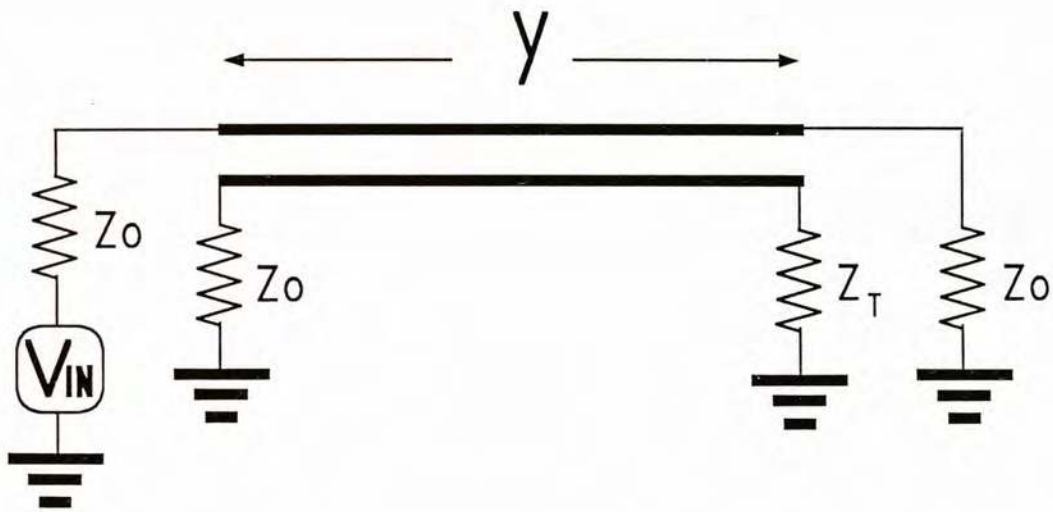


Figure 3. Physical Conceptualization of Computer Simulation Setup.

TABLE 1
LIST OF S/H AND W/H VALUES FOR ALL SETS

SET NUMBER	S/H	W/H
1	0.67	0.67
2	1.33	0.67
3	2.00	0.67
4	1.33	1.00
5	1.33	1.33
6	0.67	1.67
7	1.00	1.67
8	1.33	1.67
9	1.67	1.67
10	2.00	1.67
11	1.33	2.00

TABLE 2
 LINE PARAMETERS FOR ALL SETS
 (CALCULATED BY PROGRAM IN APPENDIX A)

SET NUMBER	Z_0 (ohms)	L (nH/m)	C (pF/m)	C_M (pF/m)	K_L
1	74.998	486.54	84.049	14.895	0.28774
2	76.783	488.04	81.460	7.2828	0.19112
3	77.437	490.10	80.882	4.0043	0.14180
4	64.279	412.80	98.403	8.4377	0.18495
5	55.636	360.76	114.90	9.2434	0.17729
6	48.147	319.05	134.41	17.874	0.24569
7	48.746	320.33	132.51	12.964	0.20078
8	49.095	321.39	131.57	9.8820	0.16992
9	49.318	322.29	131.10	7.7554	0.14680
10	49.457	323.01	130.90	6.3024	0.12977
11	41.794	289.05	163.50	11.560	0.16027

TABLE 3

COUPLED INCREMENTAL MODEL ELEMENT VALUES FOR ALL SETS
(CALCULATED FROM TABLE 2)

SET NUMBER	L (nH)	C (pF)	C _M (pF)	K _L
1	24.327	4.2025	0.74475	0.28774
2	24.402	4.0730	0.36414	0.19112
3	24.505	4.0441	0.20022	0.14180
4	20.640	4.9202	0.42189	0.18495
5	18.038	5.7450	0.46217	0.17729
6	15.953	6.7205	0.89370	0.24569
7	16.017	6.6255	0.64820	0.20078
8	16.070	6.5785	0.49410	0.16992
9	16.115	6.5550	0.38777	0.14680
10	16.151	6.5450	0.31512	0.12977
11	14.453	8.1750	0.57800	0.16027

CHAPTER IV
ANALYTICAL PREDICTIONS OF CROSSTALK

The general expression [4] for the instantaneous forward crosstalk voltage induced anywhere on the passive line in Figure 3, when the active line is driven by the voltage $V_{in}(t)$, is

$$V(z,t) = K_f z \frac{d}{dt} \left[V_{in} \left(t - T_d \frac{z}{y} \right) \right] \quad (4-1)$$

where K_f is the forward crosstalk constant, z is the distance along the line and y is the physical length of the coupled region (the entire length in this case). For forward crosstalk, the point of interest is at $z=y$. Therefore,

$$V_C(t) = K_f y \frac{d}{dt} \left[V_{in} (t - T_d) \right] \quad (4-2)$$

When $V_{in}(t)$ is a ramped pulse going from 0 to V_1 volts in a rise time of t_r seconds, the prediction for the forward crosstalk voltage is a rectangular pulse, of duration t_r and

value V_2 , whose appearance lags the source start time by T_d [1,2]. V_2 is expressed as

$$V_2 = - \left[K_L - \frac{C_M}{C} \right] (LC)^{1/2} \frac{Y}{2} \frac{V_1}{tr} \quad (Z_T=Z_O) \quad (4-3)$$

$$V_2 = - \left[K_L - \frac{C_M}{C} \right] (LC)^{1/2} Y \frac{V_1}{tr} \quad (Z_T=open) \quad (4-4)$$

where V_1/tr is the derivative of $V_{in}(t)$ with respect to time. Therefore,

$$K_f = - \frac{1}{2} \left[K_L - \frac{C_M}{C} \right] (LC)^{1/2} \quad (Z_T=Z_O) \quad (4-5)$$

$$K_f = - \left[K_L - \frac{C_M}{C} \right] (LC)^{1/2} \quad (Z_T=open) \quad (4-6)$$

Using the above definitions, Equation 4-2 can be written as

$$V_C = K_f \gamma \frac{V_1}{tr} \quad (4-7)$$

A graphical representation of this case can be seen in Figure 4. When solving for these equations, it is assumed that the coupling can be considered "weak" (the active line signal is not appreciably degraded by the passive line crosstalk waveform - one way coupling).

For the case of a sinusoidal input to the active line [$V_{in}(t) = V_1 \sin(\omega t)$], the solution of Equation 4-2 is

$$V_C = - K_f \gamma V_1 \omega \cos(\omega t) \quad (4-8)$$

The peak crosstalk voltage value for the sinusoidal case is

$$|V_C| = |K_f| \gamma V_1 2\pi f \quad (4-9)$$

where $f = \omega/2\pi$.

Rise Time to Equivalent Crosstalk Frequency Correlation

Given a rise time, an equivalent forward crosstalk frequency can be found by setting the magnitudes of the crosstalk values in Equations 4-7 and 4-8 to be equal. The result is

$$|K_f| \cdot \frac{V_1}{tr} = |K_f| \cdot V_1 \cdot 2\pi f \quad (4-10)$$

Thus,

$$f = \frac{1}{2\pi tr} \quad (4-11)$$

or

$$tr = \frac{1}{2\pi f} \quad (4-12)$$

This shows that the rise time to equivalent crosstalk frequency correlation should have no dependency on line characteristics or the termination value of Z_T . This correlation should allow a designer to predict crosstalk due to rise times by using noise versus frequency data obtained from measurements on a network analyzer.

Equation 4-12 is based on the assumption that the peak sinusoidal and transient pulse voltages are equal. Although most network analyzers have a low maximum peak sinusoidal voltage value, scaling can be performed to relate the results to a different transient pulse voltage by modifying Equation 4-12 to be

$$tr = \frac{V_t}{V_f 2 \pi f} \quad (4-13)$$

where V_t is the peak pulse voltage and V_f is the peak sinusoidal voltage.

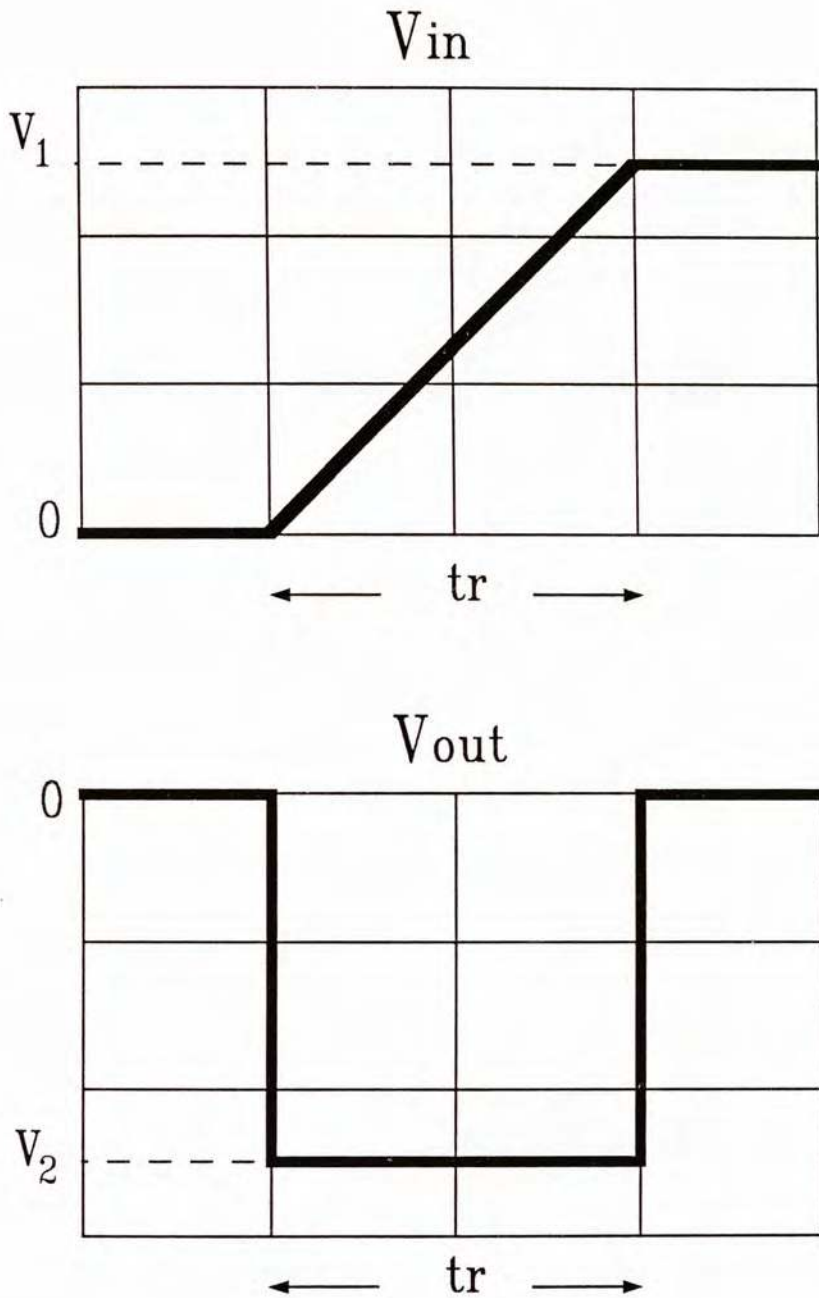


Figure 4. Graphical Representation of Crosstalk.

CHAPTER V
COMPUTER SIMULATION OF CROSSTALK

A computer simulation of crosstalk was executed on a Microsoft Disk Operating System (MS-DOS) based computer (Intel 80286 microprocessor) equipped with a math co-processor (Intel 80287). A SPICE software package entitled "IS_SPICE" (from Intusoft Corporation, San Pedro, CA) was used to run transient and frequency response simulations on the coupled lines.

Transient Analysis

In the transient analysis, a programmable rise time voltage source going from 0 to 4 volts was used to drive the active line. Ten cases of rise times were simulated with t_r ranging from 100 to 1000 ns in 100 ns steps. A 500 ns rise time input waveform is shown in Figure 5. This was done for each case of Z_T in each of the eleven sets; thus, a total of 220 transient simulations were performed. Samples of the SPICE transient analysis circuit descriptions can be found in Appendix B.

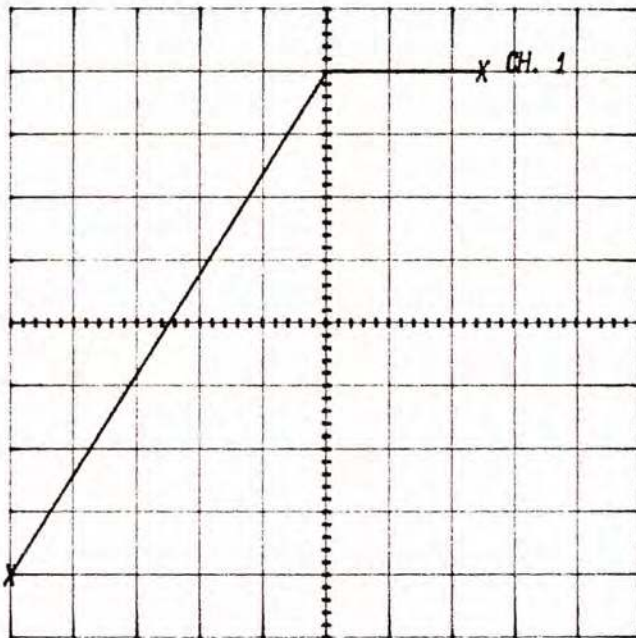
Frequency Analysis

In the frequency analysis, a sinusoidal voltage source of 4 volts peak was used to drive the active line. This was done for each case of Z_T in each of the eleven sets. This produced a total of 22 frequency analysis simulations. A sample of the SPICE frequency analysis circuit descriptions can be found in Appendix C.

Transient Analysis Results

The forward crosstalk voltage results obtained from the transient simulation closely agreed with the analytical predictions. The crosstalk waveforms were negative going rectangular shaped pulses of t_r in duration. However, for many of the sets, a sharp spike or overshoot appeared at the transitions of the rectangle and some sets had some ripple superimposed upon the pulse. This was due to ringing in the passive line model, since the rise time of the rectangular shaped waveform propagating through the model was violating the propagation delay to rise time relationship requirement from Chapter II; nevertheless, the overshoot quickly subsided. Samples of the crosstalk waveforms can be found in Appendix D. When taking voltage readings, the overshoots, when present, were neglected and the average value of the ripple, when present, was used. Examples of the overshoot and ripple can be seen in Figures 6a and 6b. The crosstalk amplitudes are shown in Tables 4 and 5. These amplitudes

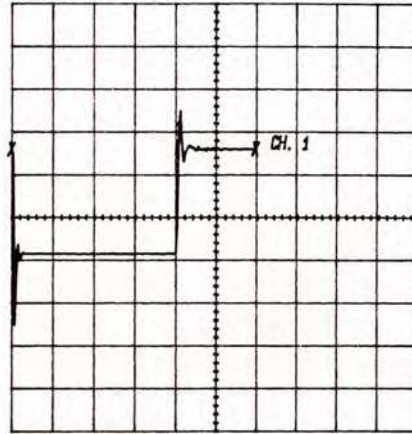
consistently reached approximately 87% of the analytically predicted values. Plots of predicted values and simulation results for one simulation are shown in Figure 7. As predicted, the crosstalk amplitudes doubled when Z_T went from Z_0 to open as can be seen in Figure 8. The change in the crosstalk, due to variations in S/H and W/H ratios, is shown in Figures 9 and 10.



CH 1 V (2) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500MV/DIV				
YZERO 2.00 V	VER	-0.00E0V	4.00 V	4.00 V
XSCALE 100NSEC/DIV				
XZERO 500NSEC	HOR	-10.7FSEC	747NSEC	747NSEC

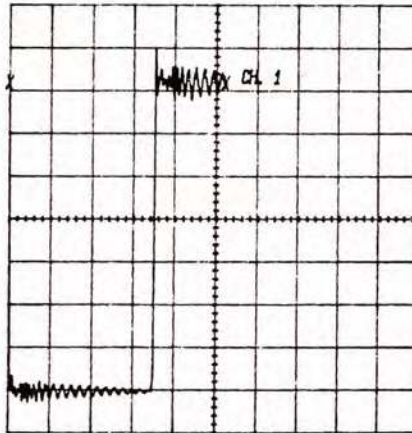
Figure 5. 500 ns Rise Time Input Waveform for Active Line.

(a)



CH 1 V (5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO -1.60MV	VER	-0.00E0V	6.25UV	6.25UV
XSCALE 50NSEC/DIV				
XZERO 250NSEC	HOR	-5.33FSEC	299NSEC	299NSEC

(b)



CH 1 V (5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 100UV/DIV				
YZERO -320UV	VER	-0.00E0V	-1.06UV	-1.06UV
XSCALE 200NSEC/DIV				
XZERO 1.00USEC	HOR	-21.3FSEC	1.04USEC	1.04USEC

Figure 6. (a) Example of Overshoot (Set 1, $t_r=200\text{ns}$, $Z_T=Z_O$). (b) Example of ripple (Set 7, $t_r=700\text{ns}$, $Z_T=Z_O$).

TABLE 4
 FORWARD CROSSTALK AMPLITUDES FOR $Z_T=Z_O$

SET	RISE TIME (ns)									
	100	200	300	400	500	600	700	800	900	1000
					(mv)					
1	-4.89	-2.45	-1.63	-1.22	-.977	-.815	-.699	-.611	-.544	-.489
2	-4.92	-2.46	-1.64	-1.23	-.984	-.820	-.703	-.615	-.546	-.492
3	-4.56	-2.28	-1.52	-1.14	-.912	-.760	-.651	-.570	-.506	-.456
4	-4.88	-2.44	-1.63	-1.22	-.976	-.813	-.697	-.610	-.542	-.488
5	-4.81	-2.41	-1.60	-1.20	-.963	-.802	-.686	-.602	-.535	-.481
6	-5.33	-2.66	-1.78	-1.33	-1.07	-.888	-.761	-.666	-.592	-.533
7	-5.05	-2.53	-1.68	-1.26	-1.01	-.842	-.722	-.632	-.562	-.505
8	-4.74	-2.37	-1.58	-1.19	-.949	-.791	-.678	-.592	-.527	-.474
9	-4.43	-2.22	-1.48	-1.11	-.887	-.739	-.633	-.554	-.493	-.443
10	-4.16	-2.08	-1.39	-1.04	-.831	-.693	-.594	-.519	-.462	-.416
11	-4.31	-2.15	-1.44	-1.08	-.862	-.718	-.615	-.538	-.479	-.431

TABLE 5

FORWARD CROSSTALK AMPLITUDES FOR $Z_T = \text{OPEN}$

SET	RISE TIME (ns)									
	100	200	300	400	500	600	700	800	900	1000
					(mv)					
1	-9.78	-4.89	-3.26	-2.45	-1.96	-1.63	-1.40	-1.22	-1.09	-.979
2	-9.84	-4.92	-3.28	-2.46	-1.97	-1.64	-1.41	-1.23	-1.09	-.984
3	-9.12	-4.56	-3.04	-2.28	-1.82	-1.52	-1.30	-1.14	-1.01	-.912
4	-9.76	-4.88	-3.25	-2.44	-1.95	-1.63	-1.39	-1.22	-1.08	-.946
5	-9.63	-4.81	-3.21	-2.41	-1.92	-1.60	-1.38	-1.20	-1.07	-.962
6	-10.7	-5.33	-3.55	-2.66	-2.13	-1.78	-1.52	-1.33	-1.18	-1.07
7	-10.1	-5.05	-3.37	-2.53	-2.02	-1.68	-1.44	-1.26	-1.12	-1.01
8	-9.49	-4.74	-3.16	-2.37	-1.90	-1.58	-1.35	-1.19	-1.05	-.948
9	-8.87	-4.43	-2.96	-2.22	-1.77	-1.48	-1.27	-1.11	-.985	-.887
10	-8.31	-4.16	-2.77	-2.08	-1.66	-1.39	-1.19	-1.04	-.923	-.831
11	-8.61	-4.31	-2.87	-2.15	-1.72	-1.44	-1.23	-1.08	-.957	-.861

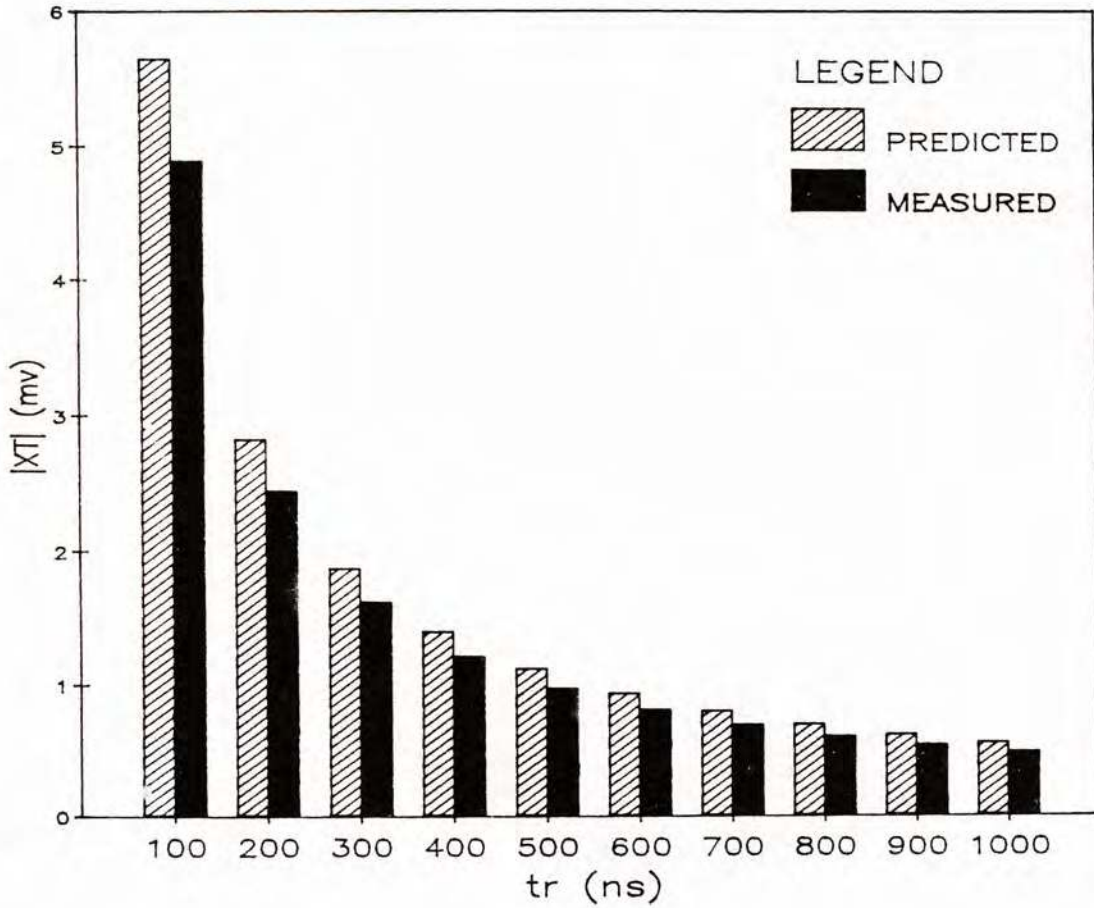


Figure 7. Plot of Theoretical and Simulated Crosstalk Magnitude for Set 1 with $Z_T=Z_0$.

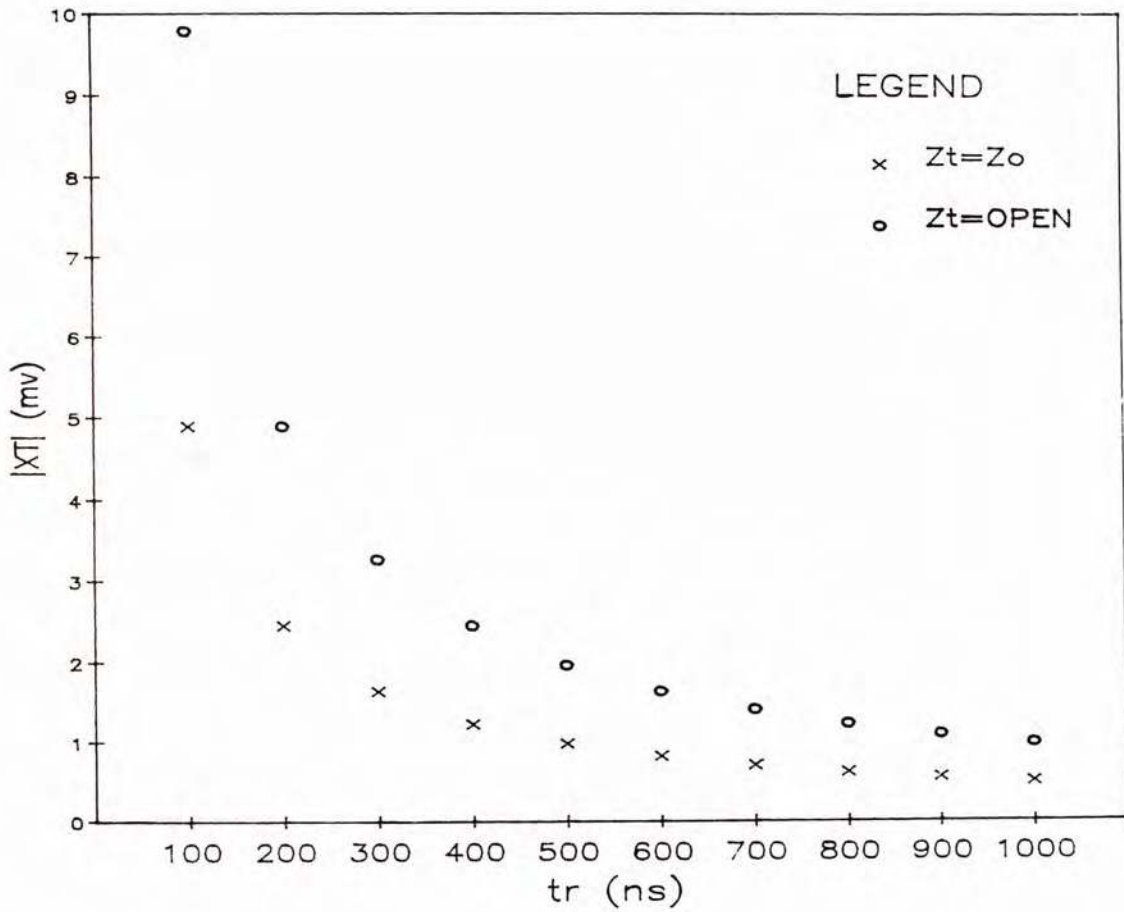


Figure 8. Plot of Simulated Crosstalk Magnitude for Set 1 with $Z_T=Z_O$ and $Z_T=Open$.

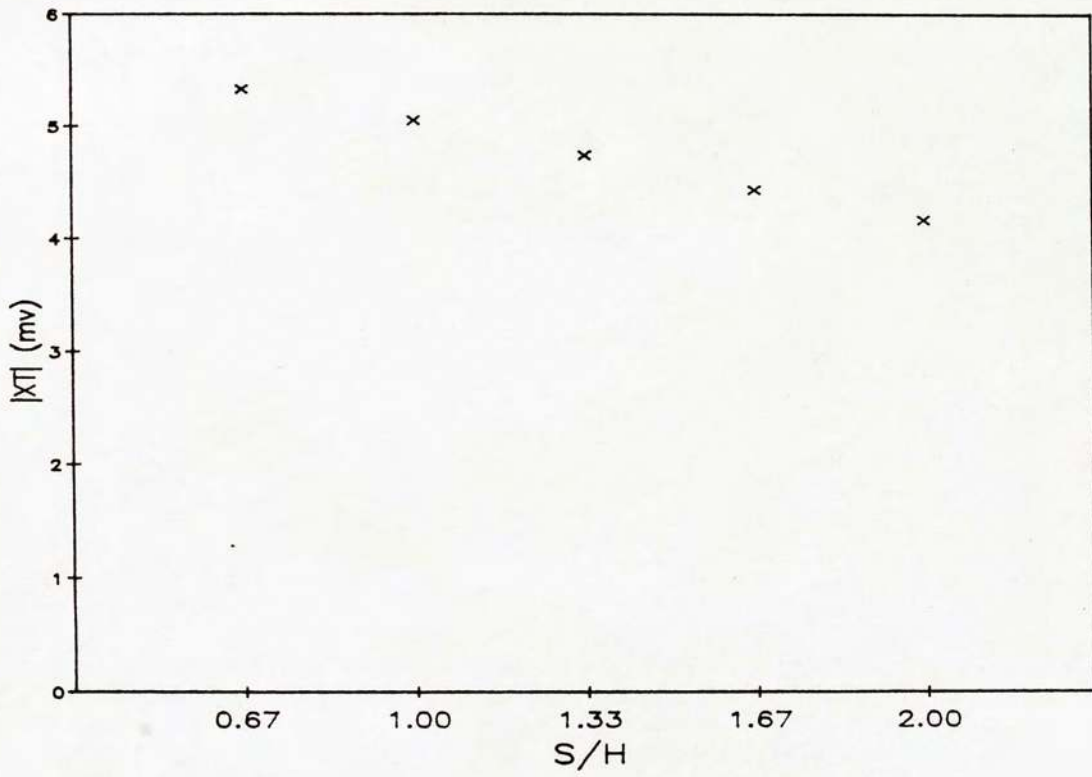


Figure 9. Plot of Simulated Crosstalk Magnitude vs S/H.

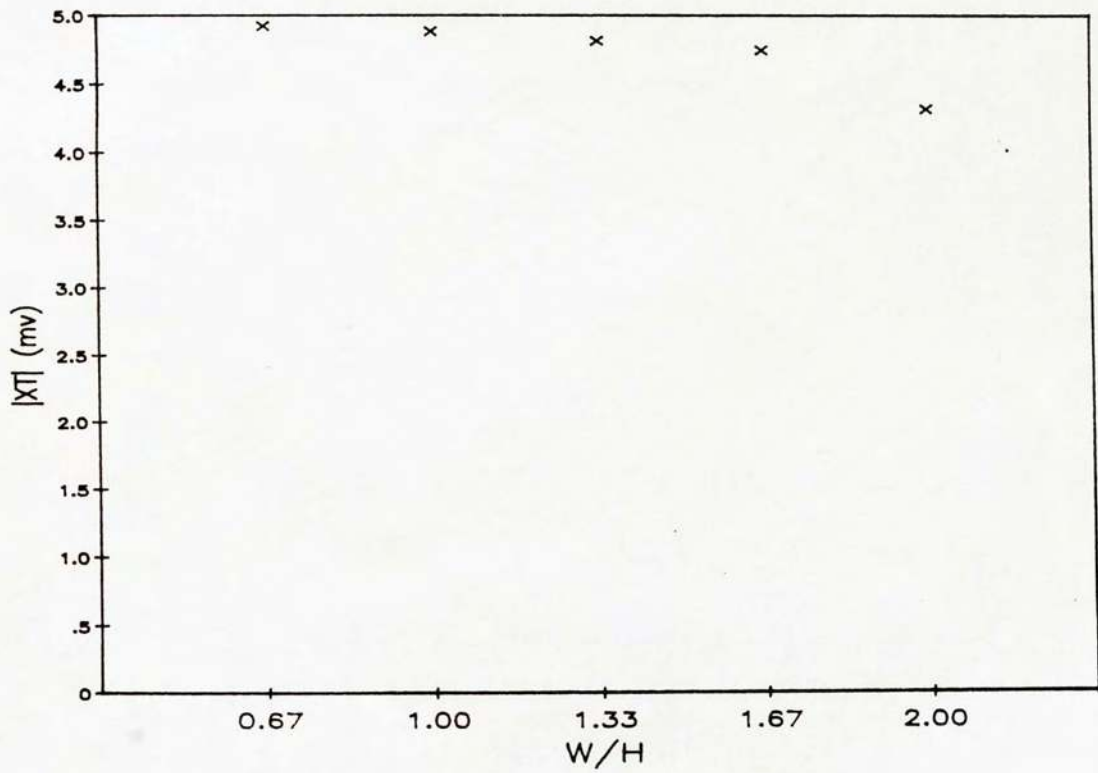


Figure 10. Plot of Simulated Crosstalk Magnitude vs W/H.

Frequency Analysis Results

The forward crosstalk voltage frequency response showed a linear dependency on frequency which agrees with the analytical predictions. However, the crosstalk voltage magnitudes consistently reached only 87% of the predicted values as in the transient analysis. The frequency response curves can be found in Appendix E.

CHAPTER VI

RISE TIME TO EQUIVALENT CROSSTALK FREQUENCY CORRELATION

The rise time to equivalent crosstalk frequency correlation was performed by finding the frequency which gives the same crosstalk voltage magnitude as a particular rise time. This was done for each case of Z_T in all eleven sets and all ten values of t_r . The results, listed in Tables 6 and 7, are in agreement with the analytical correlation predictions of Equations 4-11 and 4-12 as can be seen in Figure 11. The frequency versus rise time values predicted by Equation 4-11 are shown in Table 8.

TABLE 6
EQUIVALENT CROSSTALK FREQUENCIES FOR $Z_T=Z_O$

SET	RISE TIME (ns)									
	100	200	300	400	500	600	700	800	900	1000
					(kHz)					
1	15,900	796	530	398	318	265	228	199	177	159
2	15,900	795	530	398	318	265	228	199	177	159
3	15,900	795	530	398	319	265	227	199	177	159
4	15,900	796	530	398	318	265	227	199	177	159
5	15,900	796	529	398	319	265	227	199	177	159
6	15,900	795	533	398	319	265	227	199	177	159
7	15,900	796	530	398	318	265	227	199	177	159
8	15,900	795	530	399	319	265	228	199	177	159
9	15,900	796	531	398	319	265	227	199	177	159
10	15,900	795	531	398	318	265	228	199	177	159
11	15,900	795	533	398	319	265	227	199	177	159

TABLE 7
EQUIVALENT CROSSTALK FREQUENCIES FOR $Z_T=OPEN$

SET	RISE TIME (ns)									
	100	200	300	400	500	600	700	800	900	1000
					(kHz)					
1	15,900	795	530	399	319	265	228	199	177	159
2	15,900	795	530	398	318	265	228	199	177	159
3	15,900	795	530	398	318	265	228	199	177	159
4	15,900	795	530	398	318	266	227	199	176	159
5	15,900	795	530	399	318	265	228	199	177	159
6	15,900	796	530	398	318	266	227	199	177	160
7	15,900	795	530	399	318	265	227	199	176	159
8	15,900	795	530	398	319	265	227	200	176	159
9	15,900	795	531	399	318	265	228	199	177	159
10	15,900	795	530	398	318	266	228	199	177	159
11	15,900	795	530	398	318	266	228	199	177	159

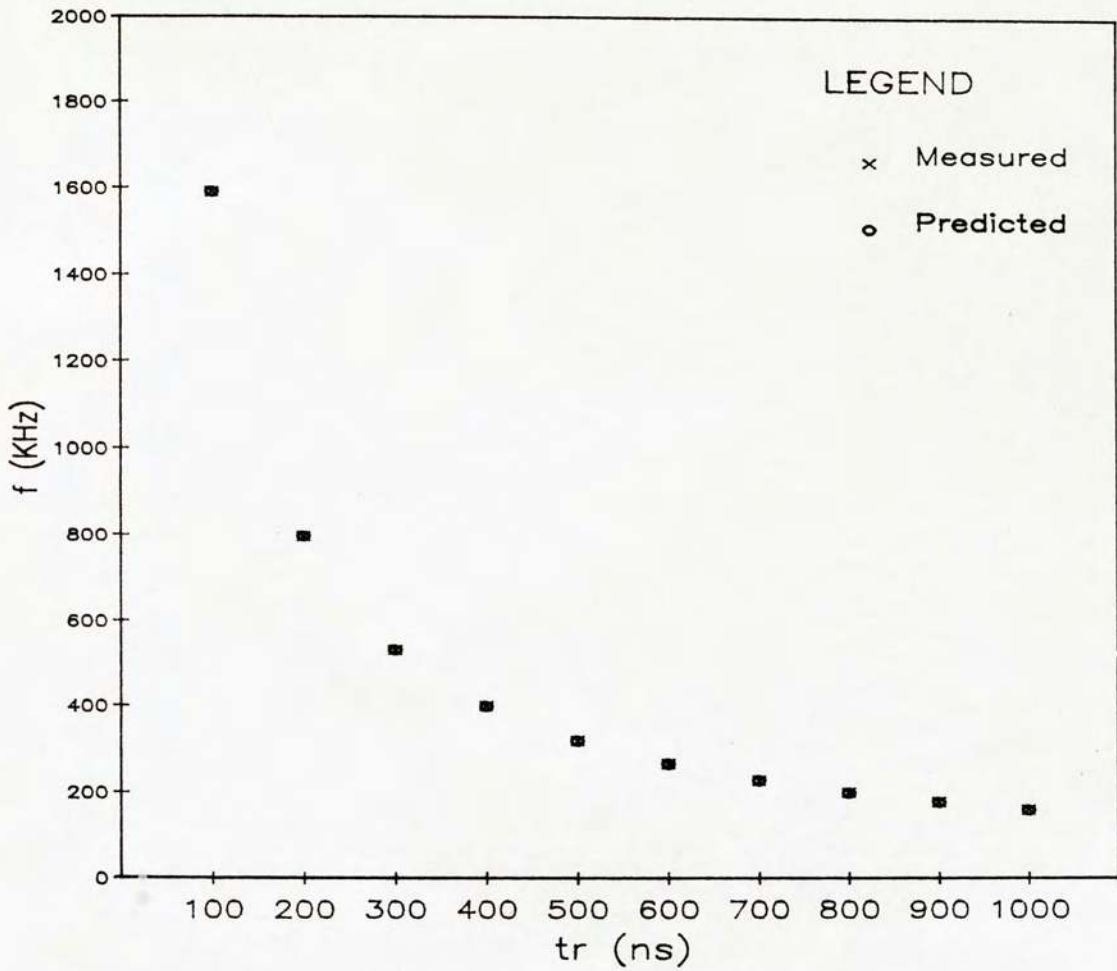


Figure 11. Plots of Correlated Simulation Measurements and Analytical Predictions of Frequency vs Equivalent Crosstalk Rise Time.

TABLE 8

PREDICTED EQUIVALENT CROSSTALK FREQUENCIES

RISE TIME (ns)	FREQUENCY (KHz)
100	15,900
200	796
300	531
400	398
500	318
600	265
700	227
800	199
900	177
1000	159

CHAPTER VII

CONCLUSIONS

Both frequency and transient response crosstalk values were consistently 13% lower than the analytical predictions. This was due to the discrete nature of the simulation model. In this model, energy exchange between the active and passive lines was allowed at only 8 discrete points. In reality, energy is continuously being absorbed by the passive line over the entire length of the coupled region. This discretization error, which lowers the apparent forward crosstalk constant, can be reduced by increasing the number of incremental models at the expense of increasing the simulation time and, eventually, running out of computer memory. However, the forward crosstalk constant, K_f , is equally common to both the transient and frequency response. Therefore, as can be seen in the effects of Z_T , that which affects K_f , affects both responses equally. Equations 4-11 and 4-12 show that the forward crosstalk constant cancels out in the rise time to equivalent crosstalk frequency correlation; hence, the discretization error serves to point out the immunity of the correlation predictions against variances in coupling strength.

Reduction of crosstalk in the setup under consideration can be accomplished by the modification of three items: the rise time, the line parameters, and the line termination. Reducing the rise time will reduce the crosstalk; however, the thrust of modern digital circuit design is to increase the speed of operation leading to shorter data pulses and, consequently, shorter rise times. Therefore, in most cases, this is an unfeasible option. Increasing the W/H ratio tends to concentrate the electric and magnetic fields between the microstrip line and the ground plane, thereby reducing coupling somewhat. The S/H ratio controls the proximity coupling effect which is analogous to the near field region of an antenna. Here, the field strength is inversely proportional to various powers of the spacing. Increasing S and/or W , however, is contrary to the desire for denser packaging to meet the constant demand for more compact designs. The decreasing of the dielectric height would help, but this is limited by manufacturing techniques. In any case, the decrease in crosstalk due to varying S/H and W/H is small compared to the effect of line termination. Designing device input impedances to closely match the characteristic impedance of the microstrip lines appears to be a feasible option. This can reduce crosstalk values by as much as one half and also avoid reflections.

The rise time to equivalent crosstalk frequency correlation results show that it is possible to use forward

crosstalk noise versus frequency data obtained from a network analyzer to predict forward crosstalk versus rise time in a simple and accurate manner. This allows one to avoid tedious and error prone time domain tests where oscilloscope capacitive loading and bandwidth restriction can present considerable measurement problems when using short rise times.

There is an upper limit on the frequency range over which this correlation can be considered valid. A TEM propagation mode was assumed when developing the equations and model used in this study of crosstalk. This is a safe assumption up to a frequency of several gigahertz for most microstrip lines. At higher frequencies, however, the lines become dispersive due to the different dielectric constants of the air and the substrate board. The coupling to the passive line should still remain proportional to the derivative of the signal on the active line due to the nature of inductive and capacitive coupling. However, the ramped pulse signal on the active line is subject to distortion as it propagates when the rise times become very small and the derivative of this distorted signal will determine the resultant crosstalk waveform. Further work studying the effects of dispersive propagation on forward crosstalk may determine the upper frequency limit at which the correlation may be considered valid.

APPENDICES

APPENDIX A

FORTRAN PROGRAM FOR CALCULATING
MICROSTRIP TRANSMISSION LINE CHARACTERISTICS

```

C      COUPLED MICROSTRIP LINES
C
C      S - DISTANCE BETWEEN STRIPS
C      W - WIDTH OF STRIP
C      T - THICKNESS OF STRIP
C      H - THICKNESS OF DIELECTRIC
C      LT - LOSS TANGENT
C      ER - PERMITTIVITY OF DIELECTRIC
C      ERE - EFFECTIVE PERMITTIVITY
C      CE - EVEN MODE CAPACITANCE
C      CO - ODD MODE CAPACITANCE
C      CF - FRINGE CAPACITANCE
C      CP - CAPACITANCE BETWEEN STRIP AND GROUND PLANE
C      CFM - MODIFICATION OF CF DUE TO PRESENCE OF
C           ANOTHER LINE
C      CGA - GAP CAPACITANCE IN AIR
C      CGD - GAP CAPACITANCE IN DIELECTRIC
C      CEA - EVEN MODE CAPACITANCE FOR AIR DIELECTRIC
C      COA - ODD MODE CAPACITANCE FOR AIR DIELECTRIC
C      L1S - SELF INDUCTANCE OF LINE
C      C1S - SELF CAPACITANCE OF LINE
C      LOM - MUTUAL INDUCTANCE OF COUPLED LINES
C      COM - MUTUAL CAPACITANCE OF COUPLED LINES
C      KL,KC - COUPLING COEFFICIENTS
C      ZOEM,ZOOM - CHARACTERISTIC IMPEDANCES OF COUPLED
C                  EVEN AND MODES
C      ZO - CHARACTERISTIC IMPEDANCE OF COUPLED LINE
C      FREQ - FREQUENCY AT WHICH ANALYSIS IS PERFORMED
C
C      CALCULATION OF EVEN AND ODD ORDER CAPACITANCES.
C      REF: GUPTA,GARG & BAHL -- MICROSTRIP LINES AND
C           SLOT LINES. PG 337
C      CE=CP+CF+CFM  CO=CF+CP+CGA+CGD
C
C      100  FORMAT(E11.1,4(F7.3))
C      102  FORMAT(2X,'FREQ=',E9.1,2X,'SBH=',F5.3,2X,'WBH=',
C           *F5.3,2X,'T=',F5.3,12X,'ER=',F5.3/)
C      105  FORMAT(/5X,'WIDE STRIP ---- ER')
C      110  FORMAT(5X,'WIDE STRIP ---- AIR')
C      115  FORMAT(/5X,'NARROW STRIP ---- ER')
C      120  FORMAT(5X,'NARROW STRIP ---- AIR')
C      125  FORMAT(/5X,'ERE=',E12.5,2X,'ZOS=',E12.5/)
C      130  FORMAT(5X,'CP=',E12.5,2X,'CF=',E12.5,2X,'CFM=',E12.5)
C      135  FORMAT(/5X,'EVEN MODE CAPACITANCE CEF=',E12.5/)
C      140  FORMAT(5X,'CGA=',E12.5,2X,'CGD=',E12.5)
C      145  FORMAT(/5X,'ODD MODE CAPACITANCE COA=',E12.5/)
C      150  FORMAT(/5X,'L1S=',E12.5,2X,'LOM=',E12.5/)
C      155  FORMAT(5X,'C1S=',E12.5,2X,'COM=',E12.5/)
C      160  FORMAT(5X,'KL=',E12.5,2X,'KC=',E12.5/)
C      165  FORMAT(5X,'ZOEM=',E12.5,2X,'ZOOM=',E12.5,2X,

```



```

*'ZO=' ,E12.6/)
REAL LT,K,K2,KP,KL,KC,L1S,LOM,MUO,KP2,KLCP
DIMENSION Y(30)
PI=3.142
EO=8.854E-12
MUO=PI*4E-07

```

C

```

OPEN(9,FILE='INPUT.DAT',STATUS='OLD')
READ(9,100)FREQ,SBH,WBH,T,ER
CLOSE(9)
OPEN(11,FILE='OUT.DAT',STATUS='UNKNOWN')
WRITE(11,102)FREQ,SBH,WBH,T,ER
GO TO 80

```

C RATIO OF W/H > 2 -WIDE STRIP; W/H < 2 -NARROW STRIP

```

SBHI=1.0/SBH
WBHI=1.0/WBH
DO 30 I=1,2
IF(I.EQ.2)ER=1.0
ERP1=ER+1.0
ERM1=ER-1.0
IF(WBH.LT.2.0)GO TO 10

```

C WIDE STRIP

```

IF(I.EQ.1)WRITE(11,105)
IF(I.EQ.2)WRITE(11,110)
CALL CDR(X,WBH)
D=1.0+SQRT(1.0+X**2)
A1=ALOG((D+X)/(D-X))
A21=0.358*D+0.595
A2=ALOG(A21+SQRT(A21**2-1.0))
A3=D*ER
Q=1.0-A1/D+0.732*(A1-A2)/A3+ERM1/A3*(0.386-0.5/(D-1))
ERE=1.0-Q+Q*ER
ZOS=377.0/SQRT(ER)*((WBH+0.883+ERP1/(PI*ER))*
*(ALOG(0.5*WBH+0.94)+1.451)+0.165*ERM1/ER**2)**(-1))
WRITE(11,125)ERE,ZOS
GO TO 15

```

10 CONTINUE

C NARROW STRIP

```

IF(I.EQ.1)WRITE(11,115)
IF(I.EQ.2)WRITE(11,120)
ERE=0.5*ERP1+0.5*ERM1*(ALOG(0.5*PI)+ALOG(4.0/PI)
*/ER)/ALOG(8.0*WBHI)
ZOS=377.0/(2.0*PI*SQRT(0.5*ERP1))*(ALOG(8.0*WBHI)
*+(0.5*WBH)**2/8.0-0.5*ERM1/ERP1*(ALOG(0.5*PI)+
*ALOG(4.0/PI)/ER))
WRITE(11,125)ERE,ZOS

```

15

```

CONTINUE
VEL=3.0E+08
CP=EO*ER*WBH
A=EXP(-0.1*EXP(2.33-2.53*WBH))
CF=0.5*((SQRT(ERE))/(VEL*ZOS)-CP)

```

```

X=10.0*SBH
ATX=(EXP(X)-EXP(-X))/(EXP(X)+EXP(-X))
DEN=1.0+A*SBHI*ATX
CFM=CF/DEN*SQRT(ER/ERE)
WRITE(11,130)CP,CF,CFM
CEF=CP+CF+CFM
WRITE(11,135)CEF
IF(I.EQ.2)THEN
  CEA=CEF
ELSE
  CE=CEF
ENDIF
K=SBH/(SBH+2.0*WBH)
K2=K**2
KP2=SQRT(1.0-K2)
KP=SQRT(KP2)
IF((0.5.LE.K2).AND.(K2.LE.1.0))GO TO 20
C  FOR 0.0 <= K2 <= 0.5
  CGA=(EO/PI)*ALOG(2.0*(1.0+SQRT(KP))/(1.0-SQRT(KP)))
  GO TO 25
20  CONTINUE
  CGA=PI*EO/ALOG(2.0*(1.0+SQRT(K))/(1.0-SQRT(K)))
25  CONTINUE
  X=PI*SBH/4.0
  ACX=(EXP(X)+EXP(-X))/(EXP(X)-EXP(-X))
  CGD=EO*ER/PI*ALOG(ACX)+0.65*CF*(0.02*SQRT(ER)/SBH
  *(1.0-1.0/ER**2))
  WRITE(11,140)CGA,CGD
  COF=CP+CF+CGA+CGD
  WRITE(11,145)COF
  IF(I.EQ.2)THEN
    COA=COF
  ELSE
    CO=COF
  ENDIF
30  CONTINUE
  L1S = MUO*EO*(1.0/COA+1.0/CEA)/2.0
  LOM = MUO*EO*(1.0/CEA-1.0/COA)/2.0
  WRITE(11,150)L1S,LOM
  C1S = 0.5*(CO+CE)
  COM = 0.5*(CO-CE)
  WRITE(11,155)C1S,COM
  KL = LOM/L1S
  KC = COM/C1S
  WRITE(11,160)KL,KC
  ZOEM = 1.0/(VEL*SQRT(CEA*CE))
  ZOOM = 1.0/(VEL*SQRT(COA*CO))
  ZO=SQRT(ZOEM*ZOOM)
  WRITE(11,165)ZOEM,ZOOM,ZO
80  CONTINUE
  CLOSE(11)

```

STOP
END

C
C
C

SUBROUTINE CDR(XX,WBH)

DIMENSION Y(30)

PI=3.142

X=0.0

DO 100 I=1,10

F=X-ALOG(X+SQRT(X*X+1.0))-PI*WBH/2.0

FP=1.0-((1.0+X/SQRT(1.0+X*X))/(X+SQRT(X*X+1.0)))

IF(FP.EQ.0.0)FP=1.0E-05

Y(I)=X-F/FP

X=Y(I)

IF(F.EQ.0.01) GO TO 200

100 CONTINUE

200 X=XX

RETURN

END

APPENDIX B

SAMPLES OF SPICE TRANSIENT ANALYSIS CIRCUIT DESCRIPTIONS


```

*****
* Model of 40 cm coupled lines constructed of 8
* cascaded 5 cm segments.
* INDUCTIVE AND CAPACITIVE COUPLING
* SET 1, tr=100 ns, ZT=Zo.
*****
*
.OPTIONS ACCT LIST LIMPTS=1000
.TRAN 1.0E-9 1.5E-7
.PRINT TRAN V(5) V(4) V(2)
VIN 1 0 PULSE 0 8 0 1.0E-7 1.0E-7 3.0E-7
RIN 1 2 74.998
X1 2 3 4 5 TWOLINE1
RLOAD1 3 0 74.998
RLOAD2 4 0 74.998
RLOAD3 5 0 74.998
*
*****
.SUBCKT TWOLINE1 1 3 2 4
X1 1 3 5 6 TWOLINE2
X2 5 6 7 8 TWOLINE2
X3 7 8 9 10 TWOLINE2
X4 9 10 11 12 TWOLINE2
X5 11 12 13 14 TWOLINE2
X6 13 14 15 16 TWOLINE2
X7 15 16 17 18 TWOLINE2
X8 17 18 2 4 TWOLINE2
.ENDS
*****
*
*****
.SUBCKT TWOLINE2 1 3 2 4
* IN OUT
L1 1 2 2.432699979960813E-008
C1 2 0 4.202449909067959E-012
*
L2 3 4 2.432699979960813E-008
C2 4 0 4.202449909067959E-012
*
CM2 2 4 7.447500192890482E-013
K12 L1 L2 .2877399921417236
*
.ENDS
*****
*****
.END

```



```

*****
* Model of 40 cm coupled lines constructed of 8
* cascaded 5 cm segments.
* INDUCTIVE AND CAPACITIVE COUPLING
* SET 2, tr=100 ns, ZT=OPEN.
*****
*
.OPTIONS ACCT LIST LIMPTS=1000
.TRAN 1.0E-9 1.5E-7
.PRINT TRAN V(5) V(4) V(2)
VIN 1 0 PULSE 0 8 0 1.0E-7 1.0E-7 3.0E-7
RIN 1 2 76.783
X1 2 3 4 5 TWOLINE1
RLOAD1 3 0 76.783
RLOAD2 4 0 76.783
*
*****
.SUBCKT TWOLINE1 1 3 2 4
X1 1 3 5 6 TWOLINE2
X2 5 6 7 8 TWOLINE2
X3 7 8 9 10 TWOLINE2
X4 9 10 11 12 TWOLINE2
X5 11 12 13 14 TWOLINE2
X6 13 14 15 16 TWOLINE2
X7 15 16 17 18 TWOLINE2
X8 17 18 2 4 TWOLINE2
.ENDS
*****
*
*****
.SUBCKT TWOLINE2 1 3 2 4
* IN OUT
L1 1 2 2.440199900757065E-008
C1 2 0 4.072999984135883E-012
*
L2 3 4 2.440199900757065E-008
C2 4 0 4.072999984135883E-012
*
CM2 2 4 3.641400169728298E-013
K12 L1 L2 .1911199986934662
*
.ENDS
*****
*****
.END

```

APPENDIX C

SAMPLES OF SPICE FREQUENCY ANALYSIS CIRCUIT DESCRIPTIONS

```

*****
* Model of 40 cm coupled lines constructed of 8
* cascaded 5 cm segments.
* INDUCTIVE AND CAPACITIVE COUPLING
* SET 1, ZT=Zo.
*****
*
.OPTIONS LIMPTS=1000
.AC LIN 512 100KHZ 1600KHZ
.PRINT AC VM(5) VM(4) VM(2)
VIN      1      0      AC 8
RIN      1      2      74.998
X1       2 3    4 5    TWOLINE1
RLOAD1   3      0      74.998
RLOAD2   4      0      74.998
RLOAD3   5      0      74.998
*
*****
.SUBCKT TWOLINE1 1 3      2 4
X1       1 3    5 6    TWOLINE2
X2       5 6    7 8    TWOLINE2
X3       7 8    9 10   TWOLINE2
X4       9 10   11 12  TWOLINE2
X5       11 12  13 14  TWOLINE2
X6       13 14  15 16  TWOLINE2
X7       15 16  17 18  TWOLINE2
X8       17 18  2 4    TWOLINE2
.ENDS
*****
*
*****
.SUBCKT TWOLINE2 1 3      2 4
*                IN      OUT
L1       1      2      2.432699979960813E-008
C1       2      0      4.202449909067959E-012
*
L2       3      4      2.432699979960813E-008
C2       4      0      4.202449909067959E-012
*
CM2      2      4      7.447500192890482E-013
K12      L1     L2     .2877399921417236
*
.ENDS
*****
*****
.END

```

```

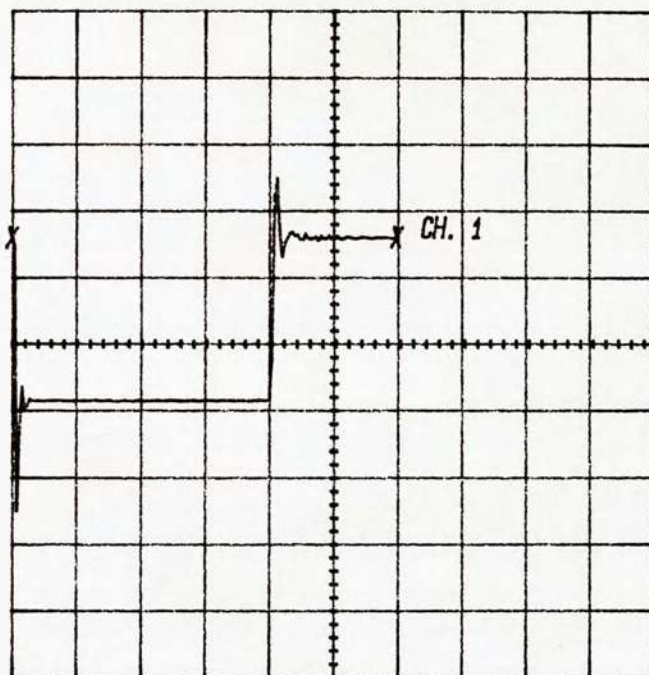
*****
* Model of 40 cm coupled lines constructed of 8
* cascaded 5 cm segments.
* INDUCTIVE AND CAPACITIVE COUPLING
* SET 2, ZT=OPEN.
*****
*
.OPTIONS LIMPTS=1000
.AC LIN 512 100KHZ 1600KHZ
.PRINT AC VM(5) VM(4) VM(2)
VIN      1      0      AC 8
RIN      1      2      76.783
X1       2 3    4 5    TWOLINE1
RLOAD1   3      0      76.783
RLOAD2   4      0      76.783
*
*****
.SUBCKT TWOLINE1 1 3      2 4
X1       1 3    5 6    TWOLINE2
X2       5 6    7 8    TWOLINE2
X3       7 8    9 10   TWOLINE2
X4       9 10   11 12  TWOLINE2
X5       11 12  13 14  TWOLINE2
X6       13 14  15 16  TWOLINE2
X7       15 16  17 18  TWOLINE2
X8       17 18  2 4    TWOLINE2
.ENDS
*****
*
*****
.SUBCKT TWOLINE2 1 3      2 4
*                IN      OUT
L1       1      2      2.440199900757065E-008
C1       2      0      4.072999984135883E-012
*
L2       3      4      2.440199900757065E-008
C2       4      0      4.072999984135883E-012
*
CM2      2      4      3.641400169728298E-013
K12      L1     L2     .1911199986934662
*
.ENDS
*****
*****
.END

```


APPENDIX D

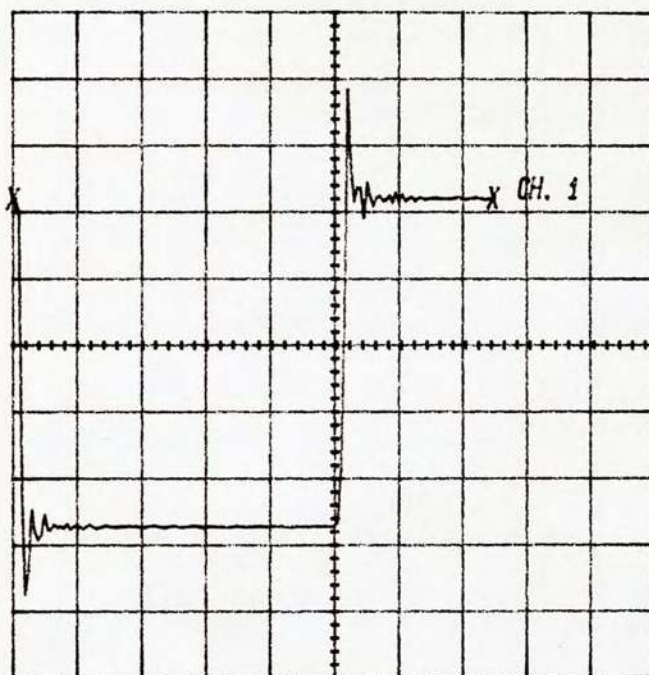
SAMPLES OF TRANSIENT SIMULATION RESULTS

SET 1, $Z_T = Z_O$, $t_r = 200$ ns.



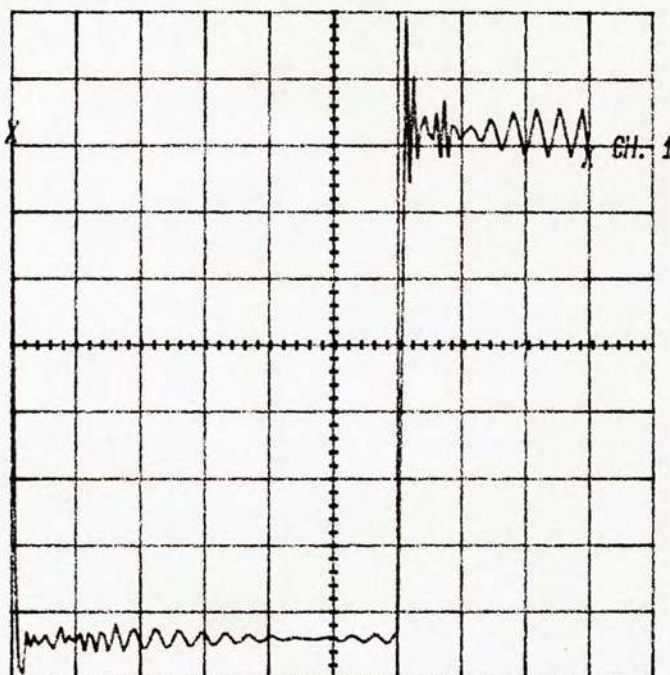
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO -1.60MV	VER	-0.00E0V	6.25UV	6.25UV
XSCALE 50NSEC/DIV				
XZERO 250NSEC	HOR	-5.33FSEC	299NSEC	299NSEC

SET 2, $Z_T = Z_O$, $t_r = 100$ ns.



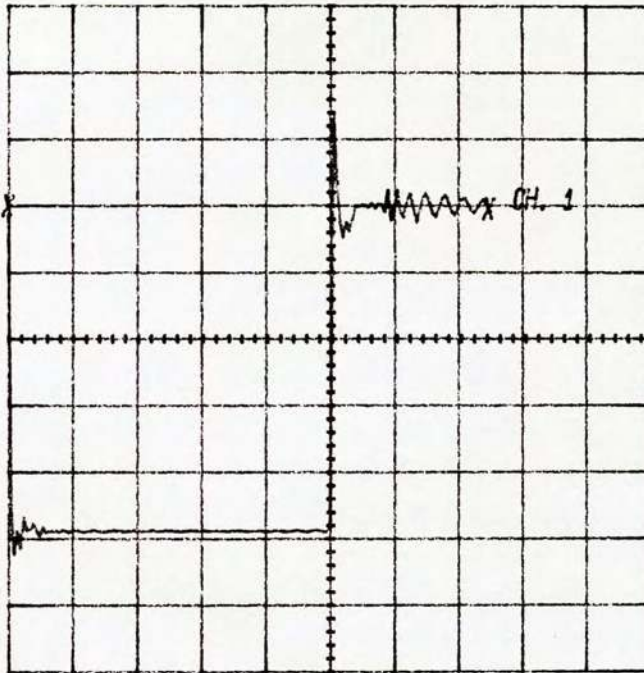
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO -2.20MV	VER	305PV	7.50UV	7.50UV
XSCALE 20NSEC/DIV				
XZERO 100NSEC	HOR	4.00FSEC	150NSEC	150NSEC

SET 3, $Z_T = Z_O$, $t_r = 300$ ns.



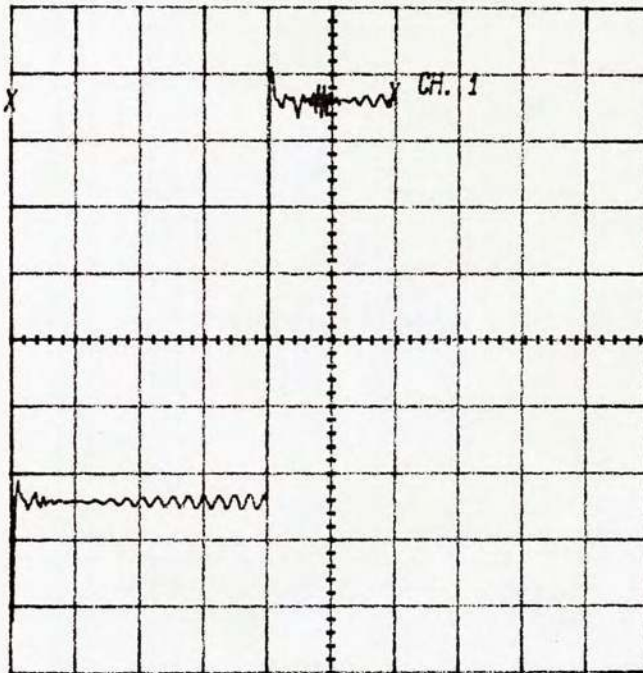
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 200UV/DIV				
YZERO -640UV	VER	-0.00E0V	-72.4UV	-72.4UV
XSCALE 50NSEC/DIV				
XZERO 250NSEC	HOR	-5.33FSEC	449NSEC	449NSEC

SET 4, $Z_T = Z_O$, $t_r = 500$ ns.



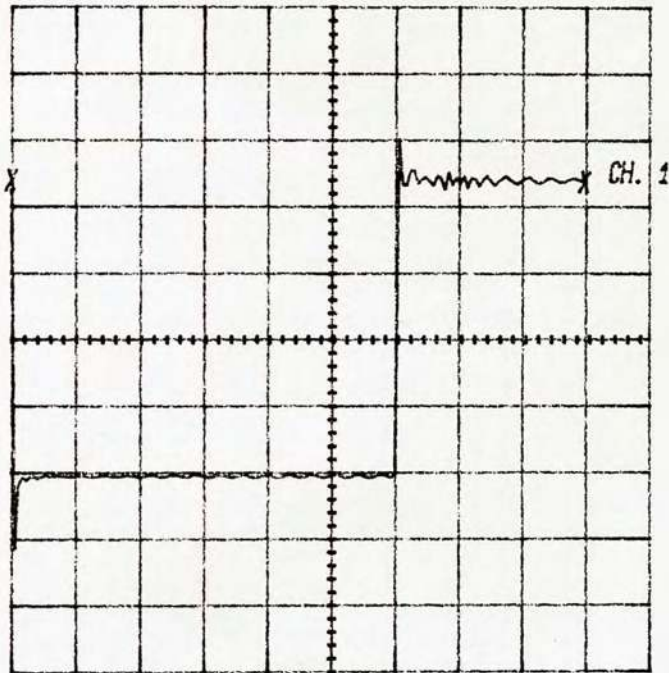
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 200UV/DIV				
YZERO -400UV	VER	-0.00E0V	-9.00UV	-9.00UV
XSCALE 100NSEC/DIV				
XZERO 500NSEC	HOR	-10.7FSEC	747NSEC	747NSEC

SET 5, $Z_T = Z_O$, $t_r = 400$ ns.



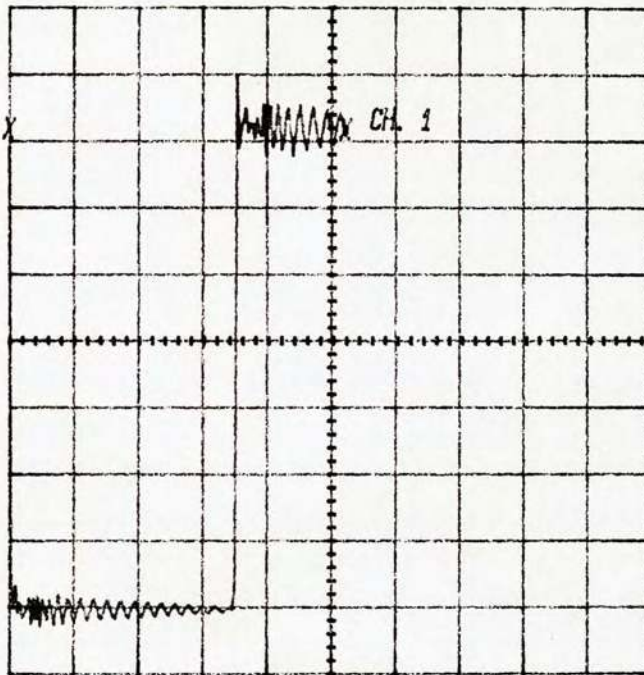
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 200UV/DIV				
YZERO -720UV	VER	-0.00E0V	23.8UV	23.8UV
XSCALE 100NSEC/DIV				
XZERO 500NSEC	HOR	-10.7FSEC	597NSEC	597NSEC

SET 6, $Z_T = Z_O$, $t_r = 600$ ns.



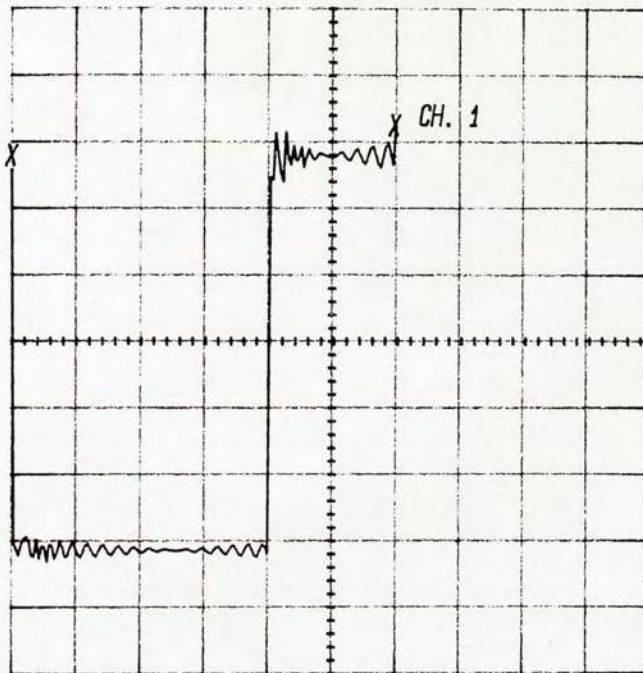
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 200UV/DIV				
YZERO -480UV	VER	-0.00E0V	-4.25UV	-4.25UV
XSCALE 100NSEC/DIV				
XZERO 500NSEC	HOR	-10.7FSEC	897NSEC	897NSEC

SET 7, $Z_T = Z_O$, $t_r = 700$ ns.



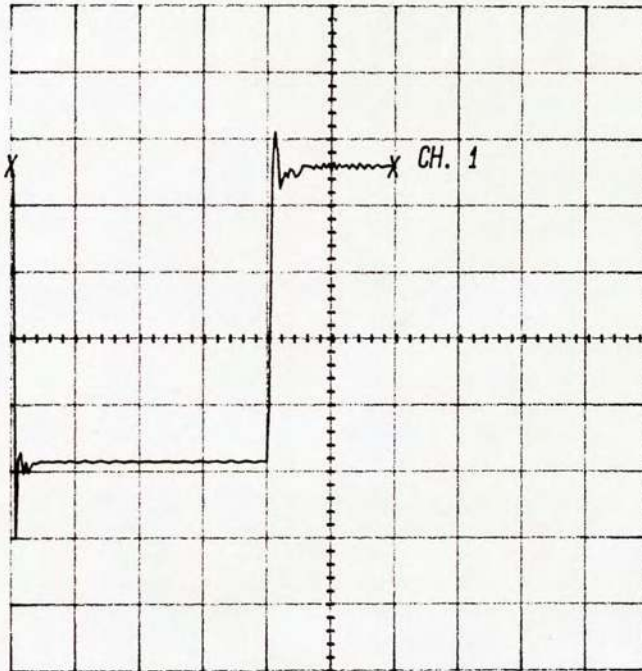
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 100UV/DIV				
YZERO -320UV	VER	-0.00E0V	-1.06UV	-1.06UV
XSCALE 200NSEC/DIV				
XZERO 1.00USEC	HOR	-21.3FSEC	1.04USEC	1.04USEC

SET 8, $Z_T = Z_O$, $t_r = 800$ ns.



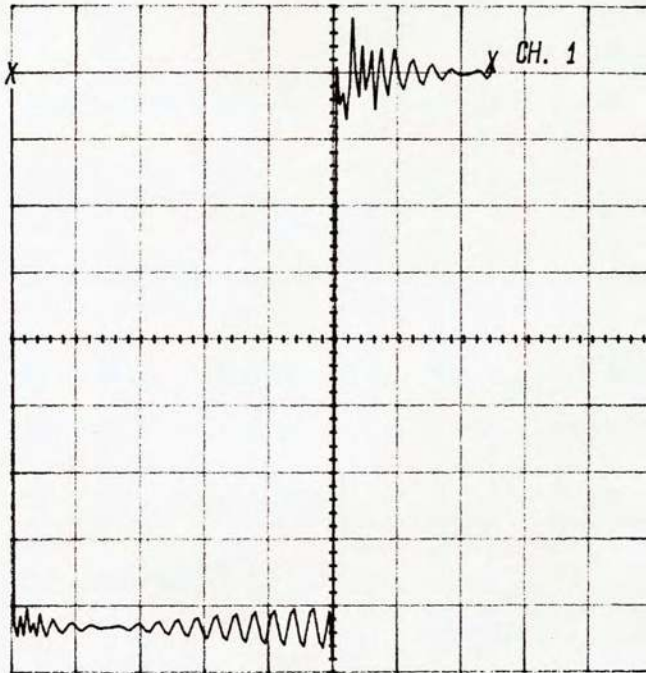
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 100UV/DIV				
YZERO -280UV	VER	30.5PV	45.8UV	45.8UV
XSCALE 200NSEC/DIV				
XZERO 1.00USEC	HOR	-21.3FSEC	1.19USEC	1.19USEC

SET 9, $Z_T = Z_O$, $t_r = 200$ ns.



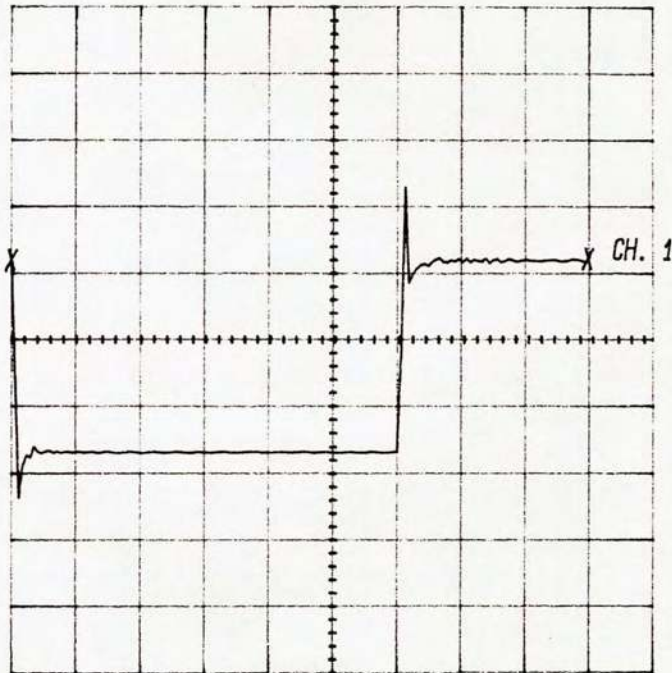
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO -1.30MV	VER	-0.00E0V	-4.69UV	-4.69UV
XSCALE 50NSEC/DIV				
XZERO 250NSEC	HOR	-5.33FSEC	299NSEC	299NSEC

SET 10, $Z_T = Z_O$, $tr = 1000$ ns.



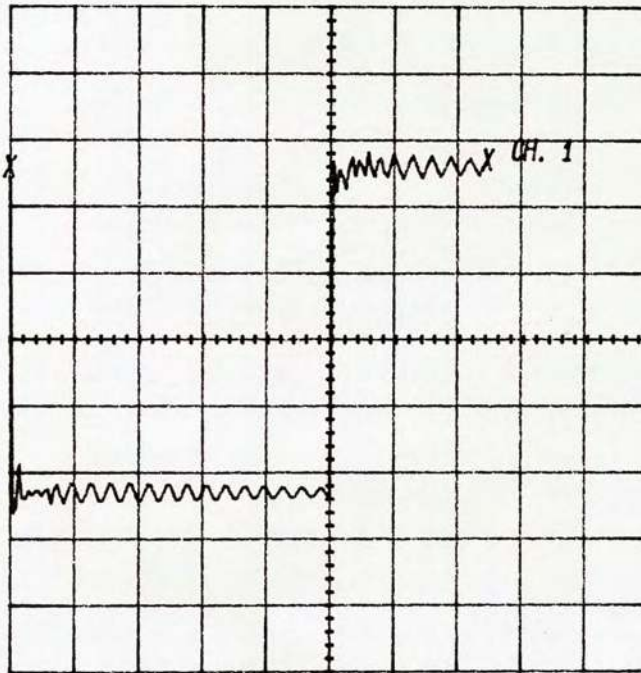
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 50UV/DIV				
YZERO -200UV	VER	-0.00E0V	8.69UV	8.69UV
XSCALE 200NSEC/DIV				
XZERO 1.00USEC	HOR	-21.3FSEC	1.49USEC	1.49USEC

SET 11, $Z_T = Z_O$, $tr = 300$ ns.



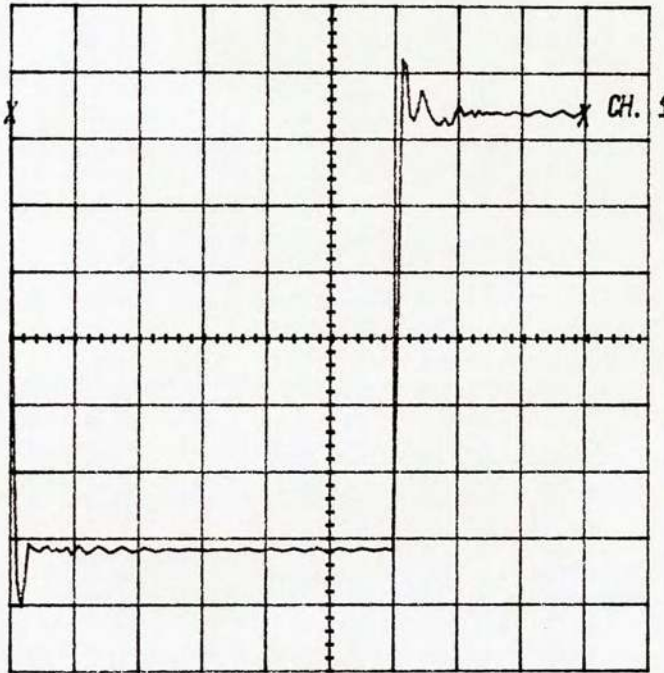
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO -600UV	VER	-0.00E0V	11.9UV	11.9UV
XSCALE 50NSEC/DIV				
XZERO 250NSEC	HOR	-5.33FSEC	449NSEC	449NSEC

SET 1, $Z_T = \text{OPEN}$, $t_r = 1000 \text{ ns}$.



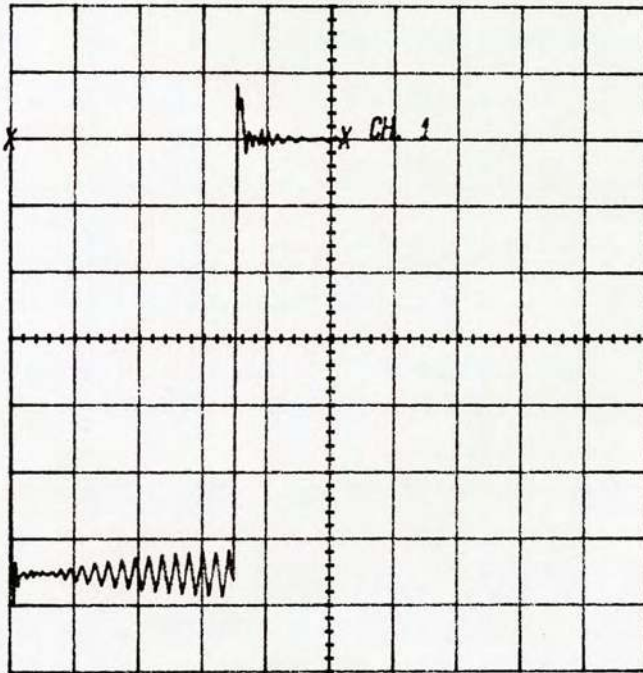
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 200UV/DIV				
YZERO -520UV	VER	-0.00E0V	23.0UV	23.0UV
XSCALE 200NSEC/DIV				
XZERO 1.00USEC	HOR	-21.3FSEC	1.49USEC	1.49USEC

SET 2, $Z_T = \text{OPEN}$, $t_r = 300 \text{ ns}$.



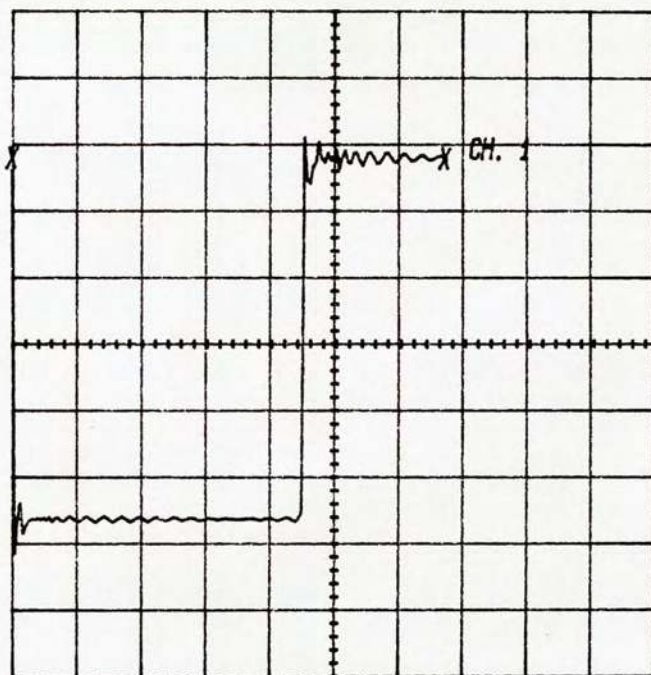
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO -1.70MV	VER	-0.00E0V	-11.9UV	-11.9UV
XSCALE 50NSEC/DIV				
XZERO 250NSEC	HOR	-5.33FSEC	449NSEC	449NSEC

SET 3, $Z_T = \text{OPEN}$, $t_r = 700 \text{ ns}$.



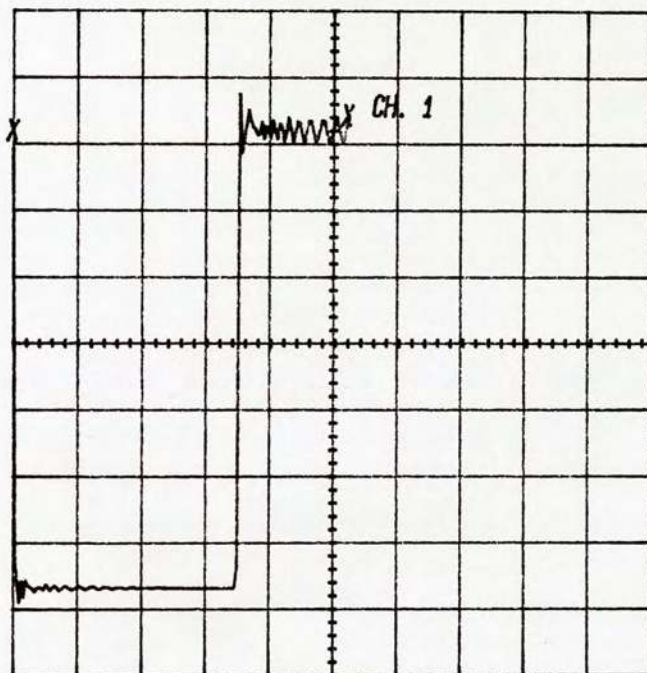
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 200UV/DIV				
YZERO -600UV	VER	-0.00E0V	6.37UV	6.37UV
XSCALE 200NSEC/DIV				
XZERO 1.00USEC	HOR	-21.3FSEC	1.04USEC	1.04USEC

SET 4, $Z_T = \text{OPEN}$, $t_r = 900 \text{ ns}$.



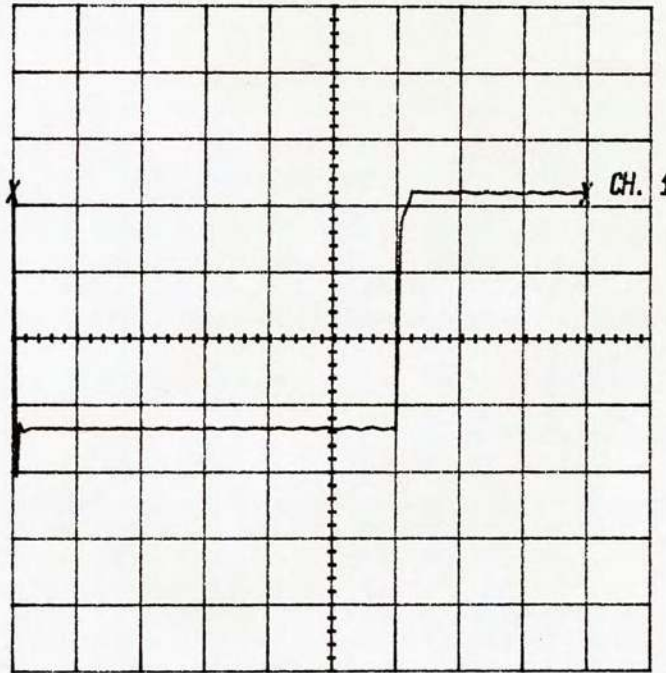
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 200UV/DIV				
YZERO -560UV	VER	61.0PV	-1.50UV	-1.50UV
XSCALE 200NSEC/DIV				
XZERO 1.00USEC	HOR	-21.3FSEC	1.34USEC	1.34USEC

SET 5, $Z_T = \text{OPEN}$, $t_r = 700 \text{ ns}$.



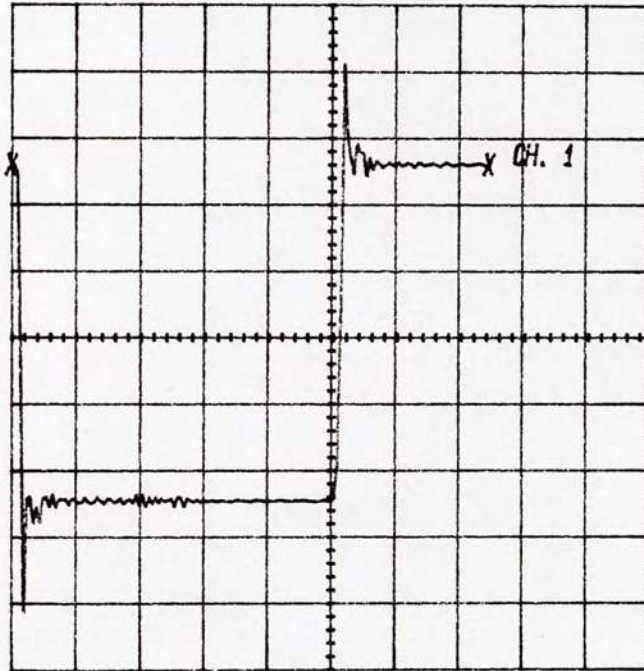
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 200UV/DIV				
YZERO -640UV	VER	-0.00E0V	45.4UV	45.4UV
XSCALE 200NSEC/DIV				
XZERO 1.00USEC	HOR	-21.3FSEC	1.04USEC	1.04USEC

SET 6, $Z_T = \text{OPEN}$, $t_r = 600 \text{ ns}$.



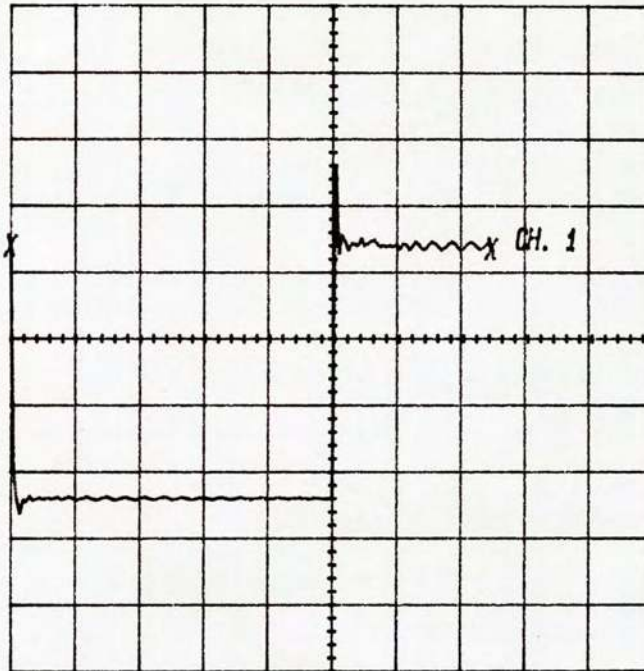
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO -1.10MV	VER	153PV	-3.44UV	-3.44UV
XSCALE 100NSEC/DIV				
XZERO 500NSEC	HOR	-10.7FSEC	897NSEC	897NSEC

SET 7, $Z_T = \text{OPEN}$, $t_r = 100 \text{ ns}$.



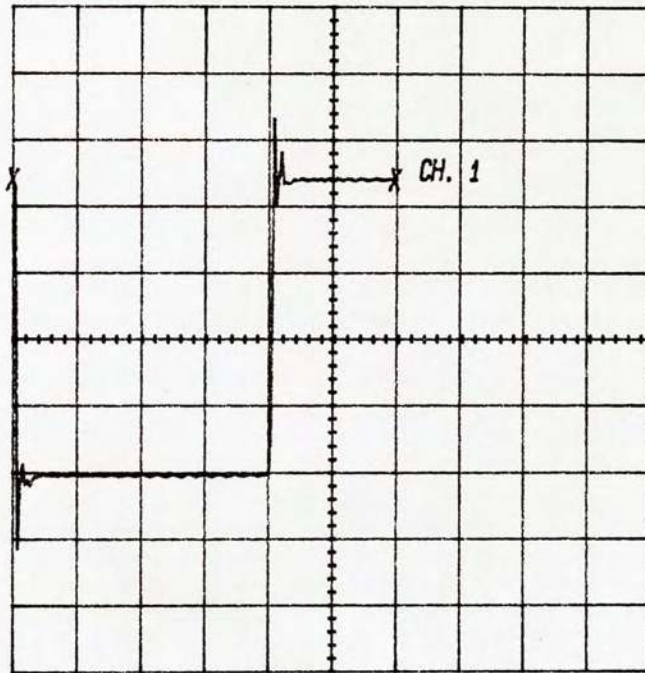
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 2MV/DIV				
YZERO -5.20MV	VER	-0.00E0V	15.00V	15.00V
XSCALE 20NSEC/DIV				
XZERO 100NSEC	HOR	4.00FSEC	150NSEC	150NSEC

SET 8, $Z_T=OPEN$, $t_r=500$ ns.



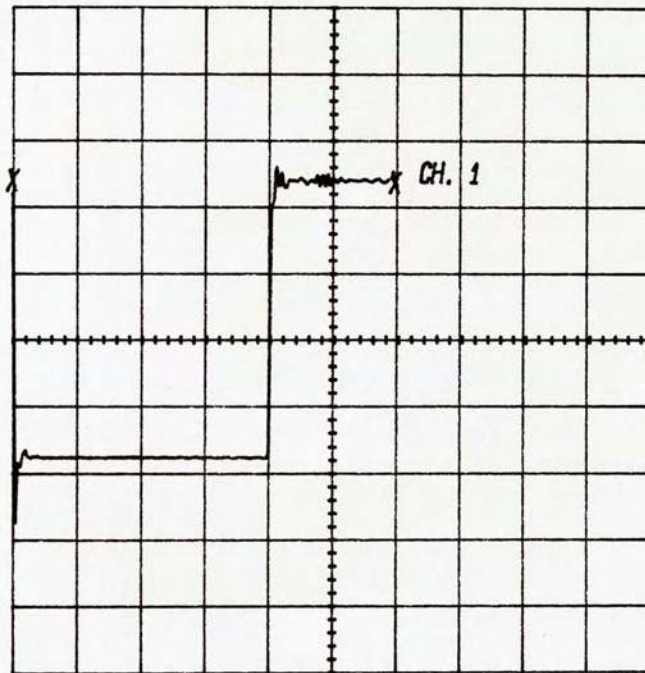
CH 1 V (5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO -700UV	VER	-0.00E0V	-22.2UV	-22.2UV
XSCALE 100NSEC/DIV				
XZERO 500NSEC	HOR	-10.7FSEC	747NSEC	747NSEC

SET 9, $Z_T=OPEN$, $tr=200$ ns.



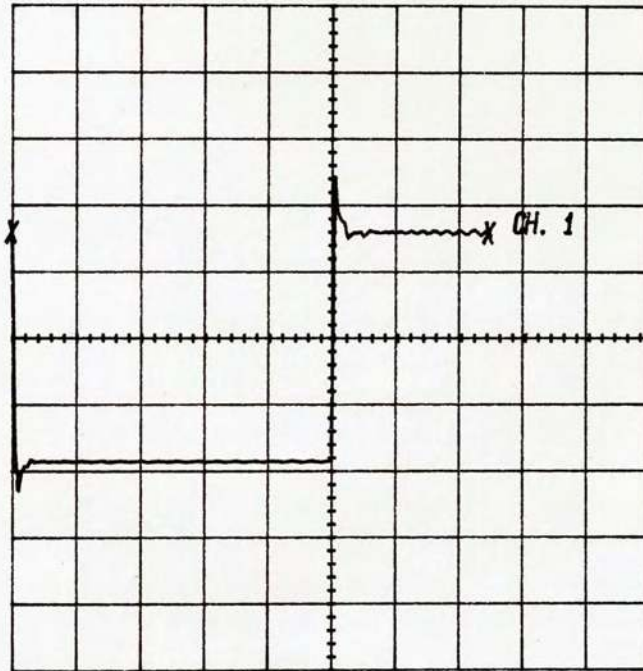
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO -2.40MV	VER	-0.00E0V	1.25UV	1.25UV
XSCALE 50NSEC/DIV				
XZERO 250NSEC	HOR	-5.33FSEC	299NSEC	299NSEC

SET 10, $Z_T=OPEN$, $tr=400$ ns.



CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO -1.20MV	VER	-0.00E0V	-14.7UV	-14.7UV
XSCALE 100NSEC/DIV				
XZERO 500NSEC	HOR	-10.7FSEC	597NSEC	597NSEC

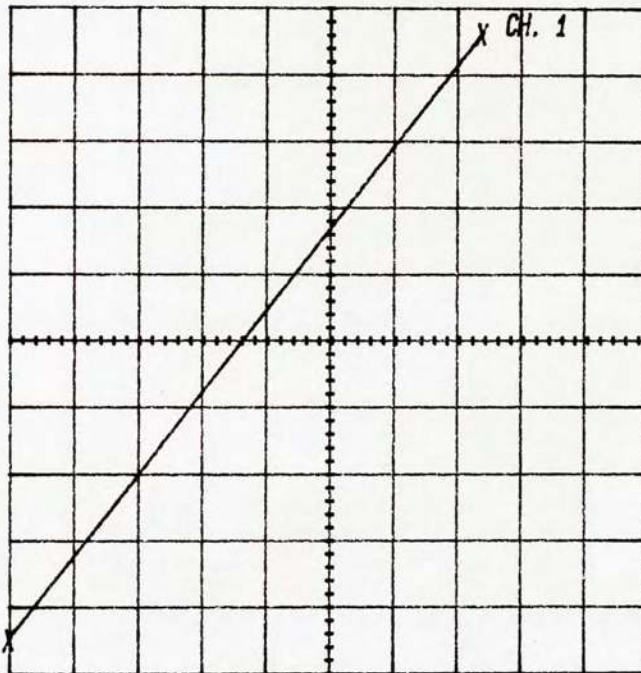
SET 11, $Z_T = \text{OPEN}$, $t_r = 500 \text{ ns}$.



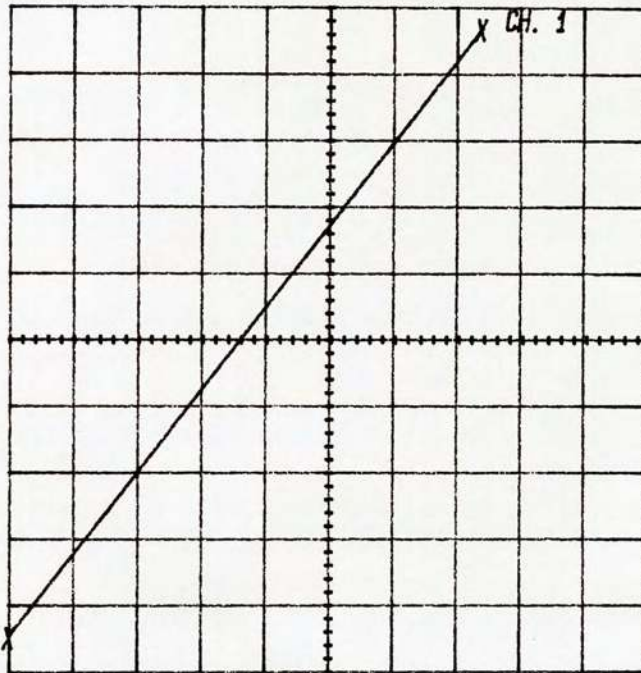
CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO -800UV	VER	-0.00E0V	-3.75UV	-3.75UV
XSCALE 100NSEC/DIV				
XZERO 500NSEC	HOR	-10.7FSEC	747NSEC	747NSEC

APPENDIX E

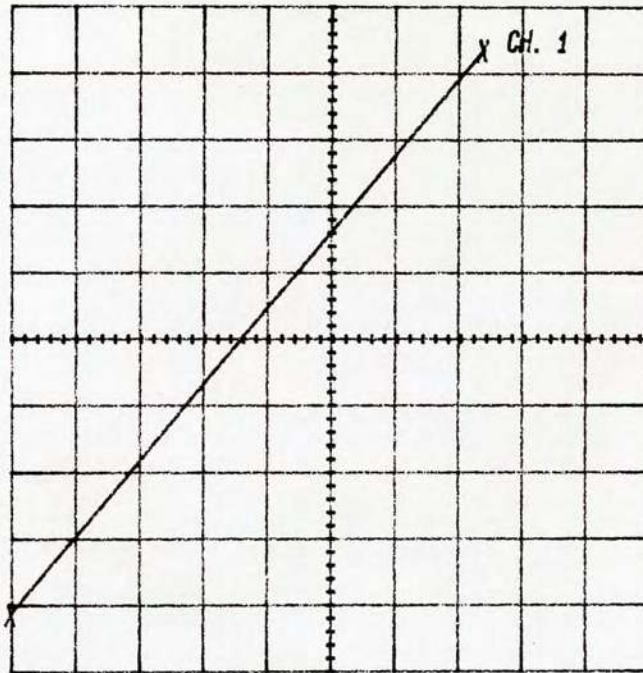
FREQUENCY SIMULATION RESULTS

SET 1, $Z_T = Z_O$.

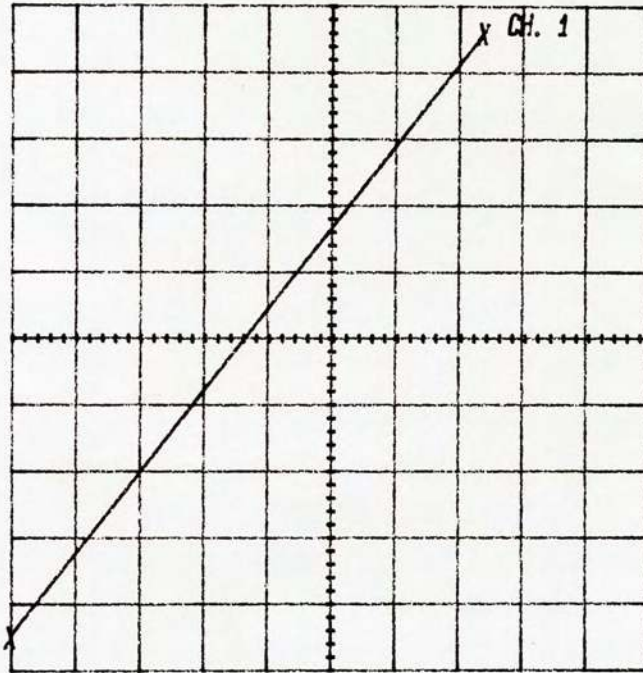
CH 1 VM (5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO 2.60MV	VER	353UV	4.91MV	4.55MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 2, $Z_T = Z_O$.

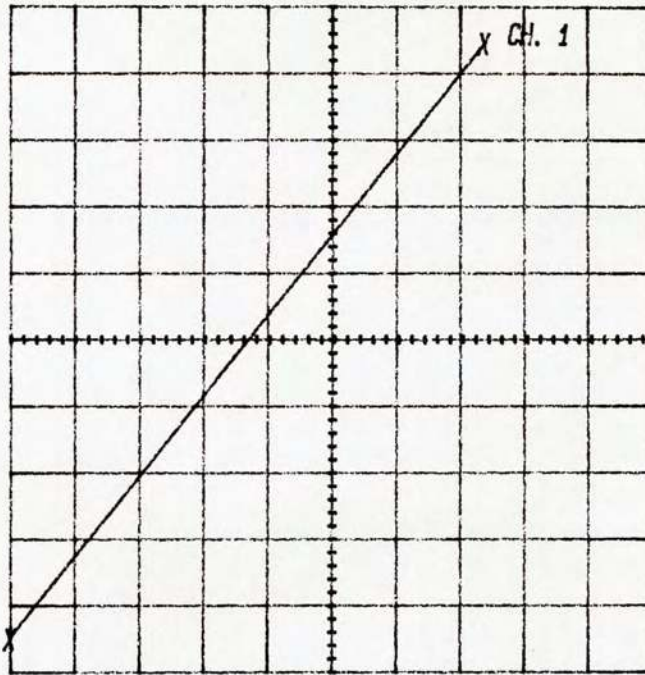
CH 1 VM (5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO 2.60MV	VER	354UV	4.93MV	4.58MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 3, $Z_T = Z_O$.

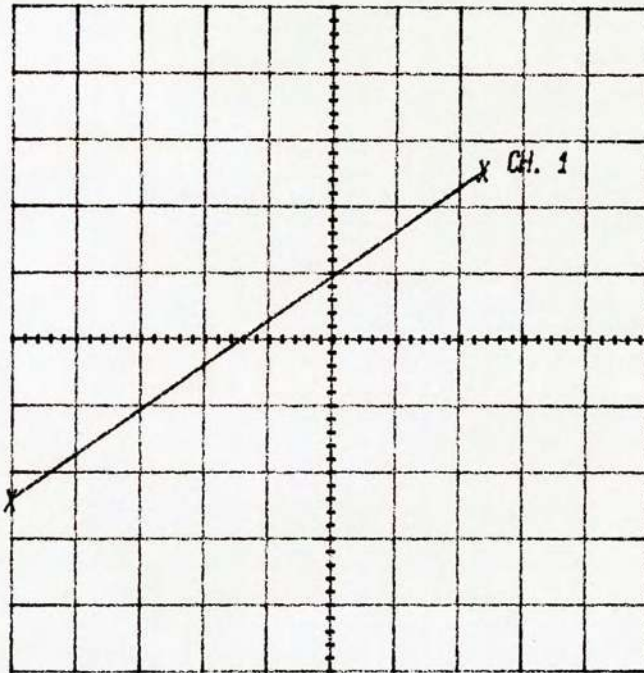
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO 2.40MV	VER	328UV	4.57MV	4.24MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 4, $Z_T = Z_O$.

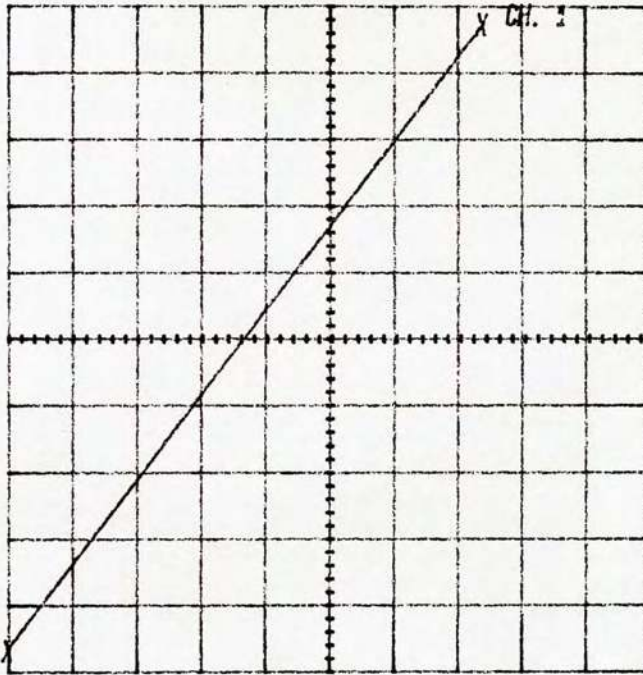
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO 2.60MV	VER	352UV	4.89MV	4.54MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 5, $Z_T = Z_O$.

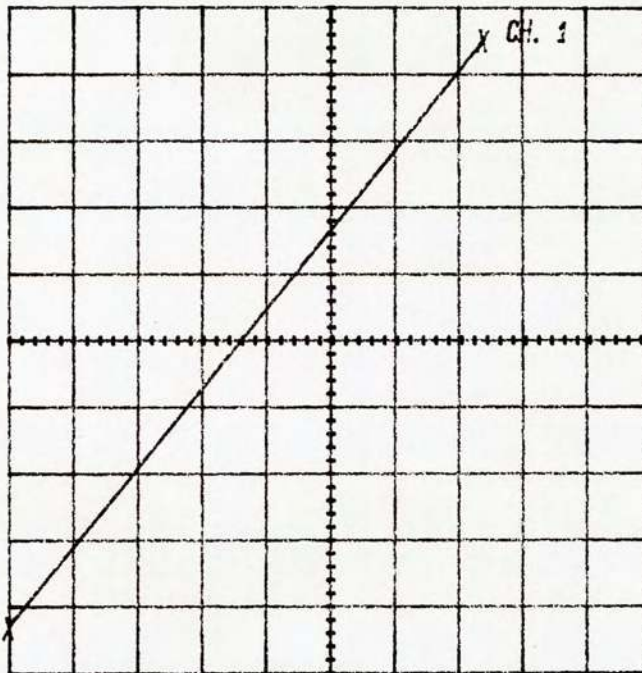
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO 2.60MV	VER	347UV	4.82MV	4.48MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 6, $Z_T = Z_O$.

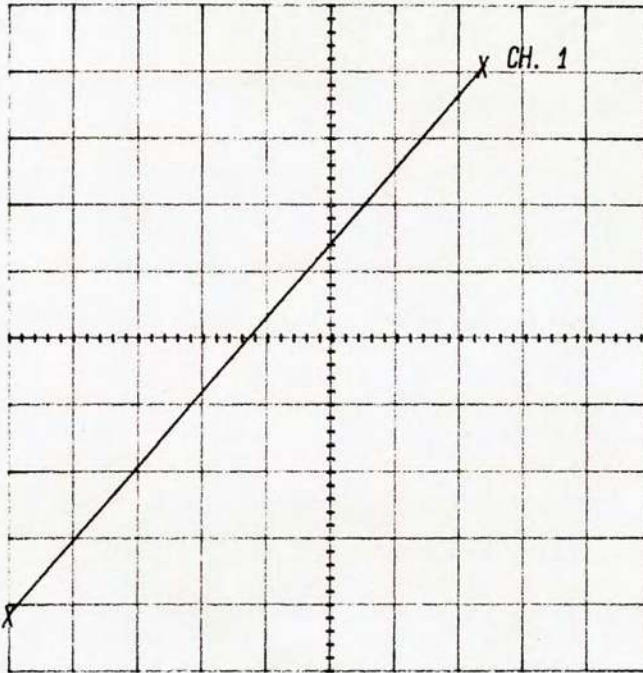
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 2.80MV	VER	384UV	5.34MV	4.96MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 7, $Z_T = Z_O$.

CH 1 VM (5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO 2.70MV	VER	364UV	5.07MV	4.70MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

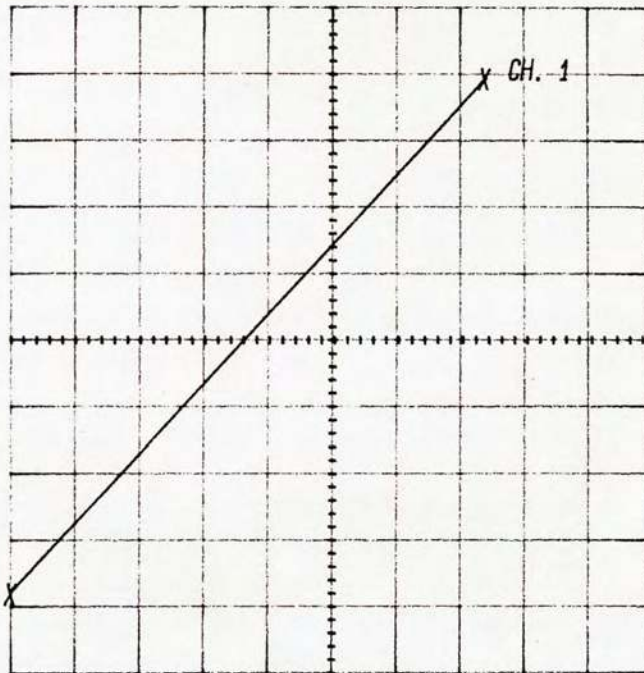
SET 8, $Z_T = Z_O$.

CH 1 VM (5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO 2.50MV	VER	342UV	4.75MV	4.41MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

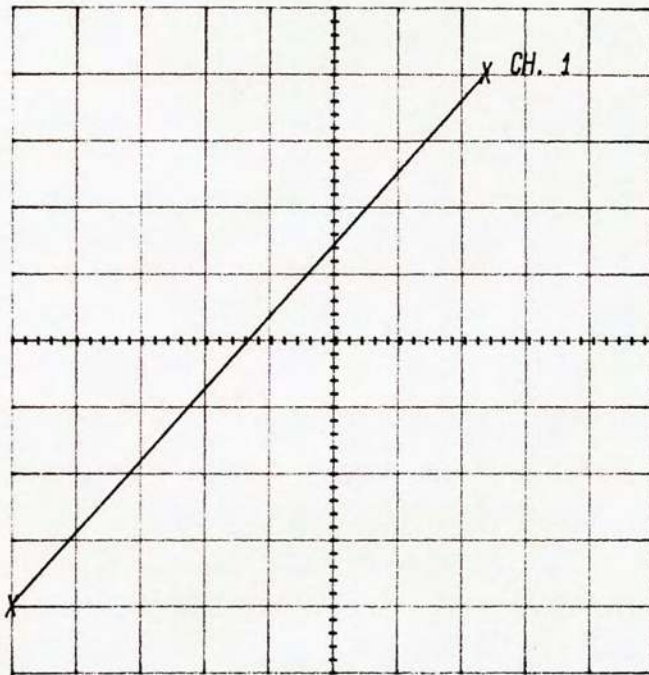
SET 9, $Z_T = Z_O$.

CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO 2.40MV	VER	319UV	4.44MV	4.12MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

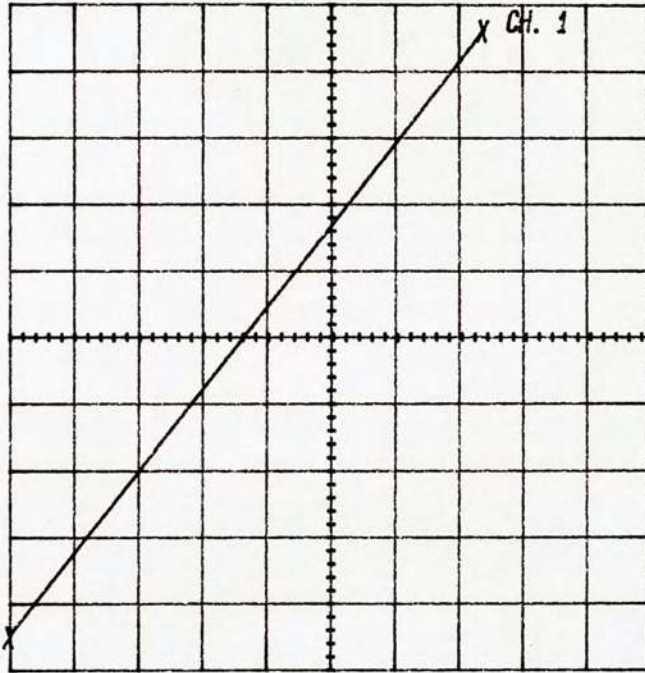
SET 10, $Z_T = Z_O$.



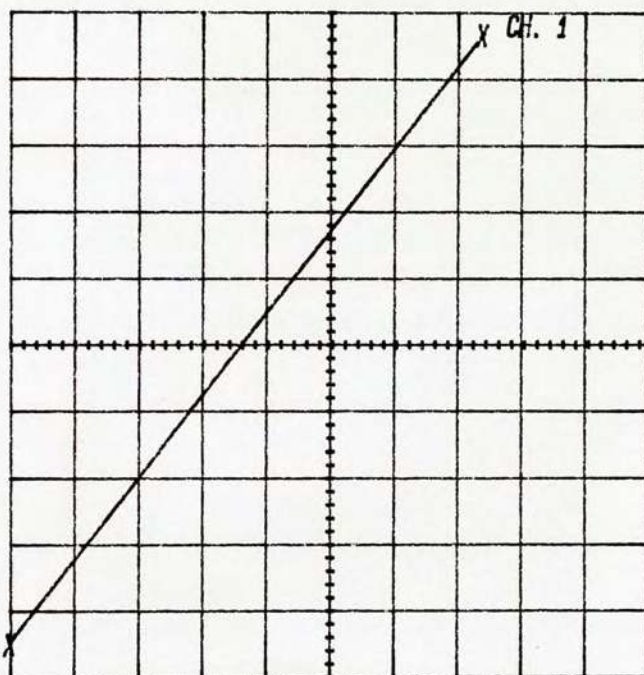
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO 2.20MV	VER	299UV	4.16MV	3.87MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 11, $Z_T = Z_O$.

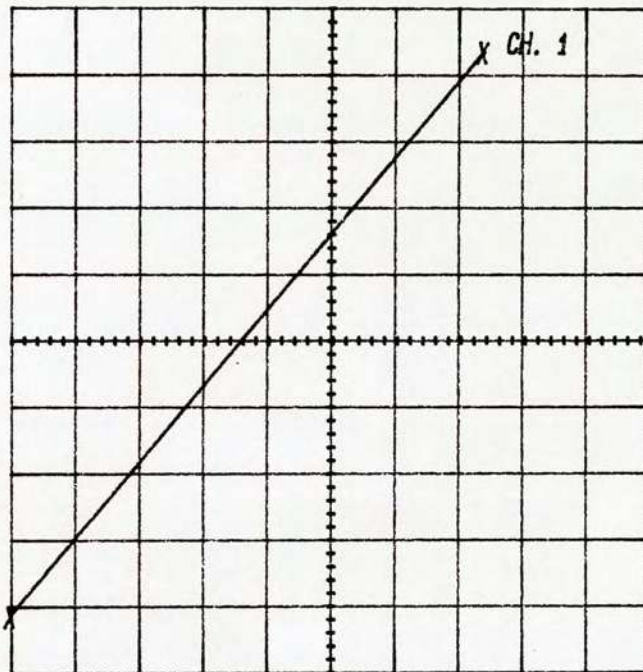
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500UV/DIV				
YZERO 2.30MV	VER	310UV	4.32MV	4.01MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 1, $Z_T = \text{OPEN}$.

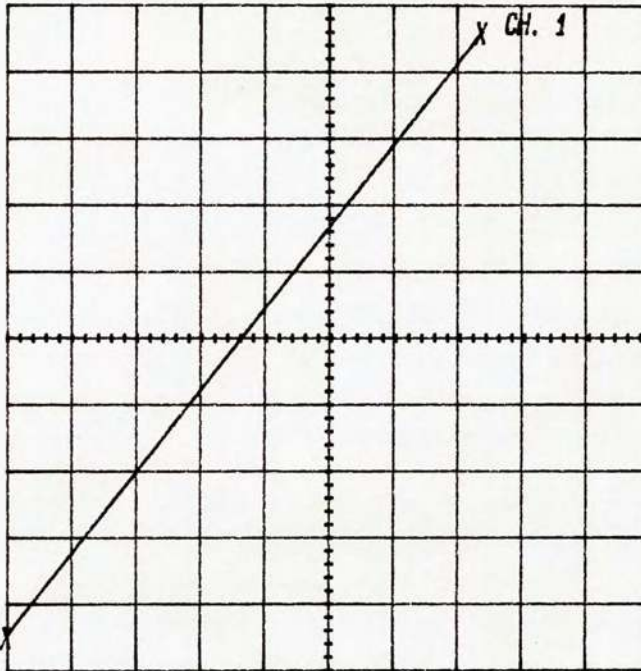
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 5.20MV	VER	705UV	9.81MV	9.11MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 2, $Z_T = \text{OPEN}$.

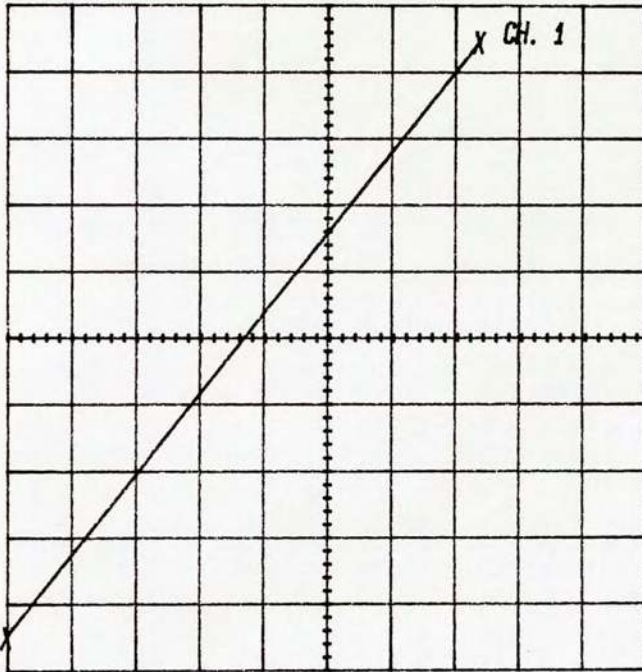
CH 1 VM (5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 5.20MV	VER	709UV	9.86MV	9.15MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 3, $Z_T = \text{OPEN}$.

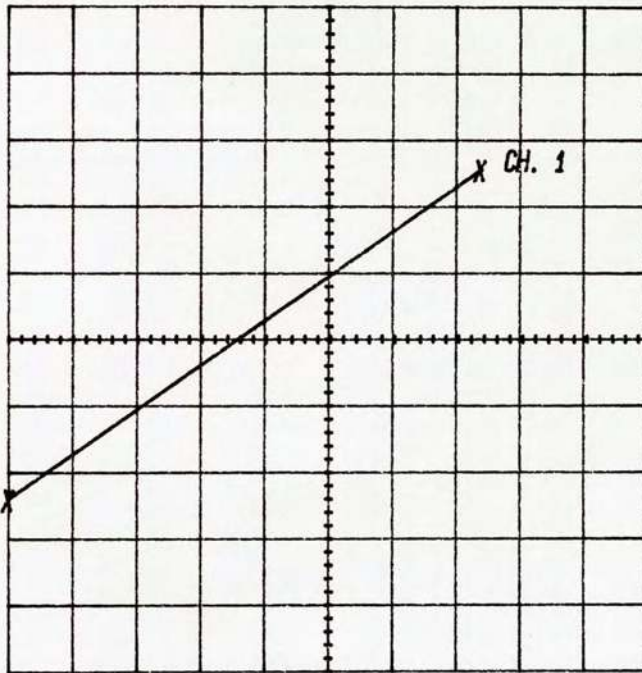
CH 1 VM (5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 4.80MV	VER	657UV	9.14MV	8.48MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 4, $Z_T = \text{OPEN}$.

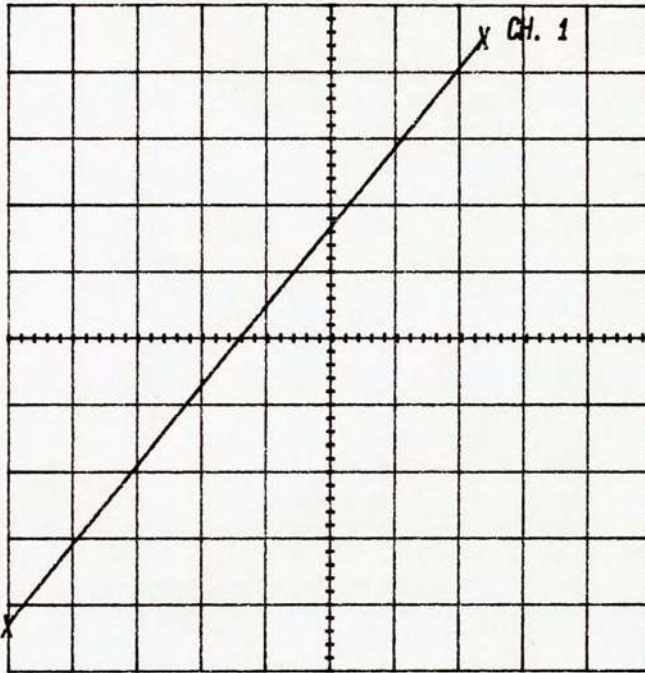
CH 1 VM (5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 5.20MV	VER	703UV	9.78MV	9.08MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 5, $Z_T = \text{OPEN}$.

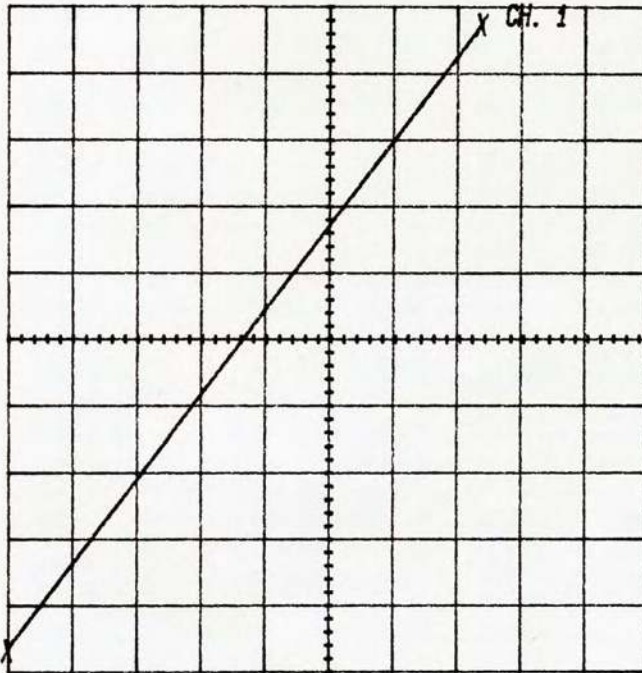
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 5.20MV	VER	694UV	9.65MV	8.95MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 6, $Z_T = \text{OPEN}$.

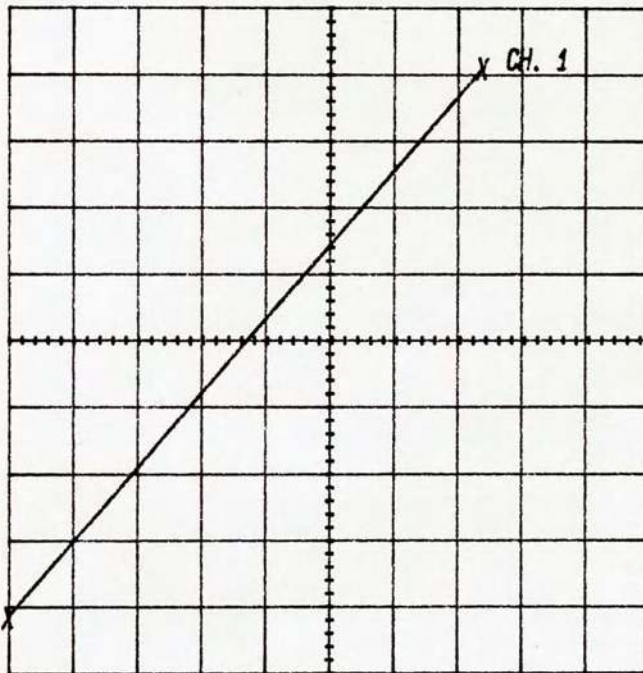
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 2MV/DIV				
YZERO 5.60MV	VER	768UV	10.7MV	9.91MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 7, $Z_T = \text{OPEN}$.

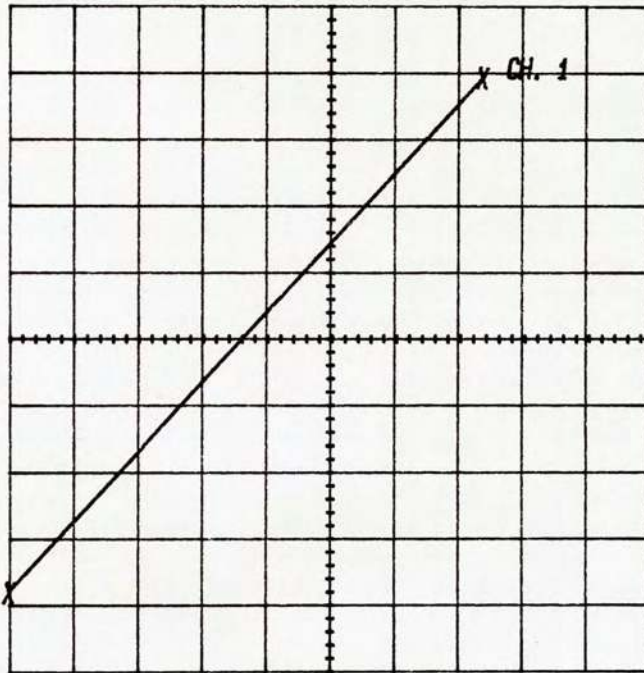
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 5.00MV	VER	684UV	9.51MV	8.82MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 8, $Z_T = \text{OPEN}$.

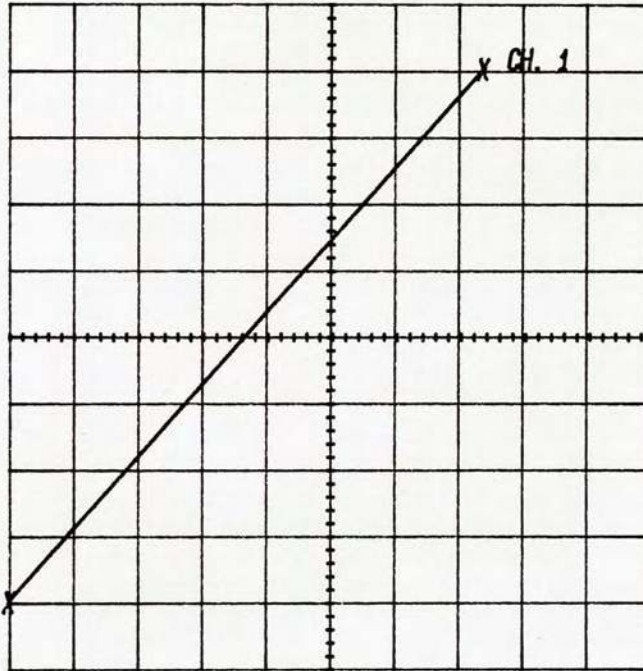
CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 5.40MV	VER	728UV	10.1MV	9.41MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 9, $Z_T = \text{OPEN}$.

CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 4.80MV	VER	639UV	8.89MV	8.25MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 10, $Z_T = \text{OPEN}$.

CH 1 VM (5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 4.40MV	VER	599UV	8.33MV	7.73MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

SET 11, $Z_T = \text{OPEN}$.

CH 1 VM(5) vs FREQ	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MV/DIV				
YZERO 4.60MV	VER	621UV	8.63MV	8.01MV
XSCALE 200KHZ/DIV				
XZERO 1.12MEGHZ	HOR	120KHZ	1.59MEGHZ	1.48MEGHZ

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