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Pulse Sharpening Effects in Ferrites

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Abstract—Pulse sharpening effects were investigated both experimentally and theoretically in a coaxial transmission line filled with commercially available magnesium manganese ferrite. Measurements of rise-time reduction as a function of pulse voltage, magnetic field bias, and line length were obtained. Output rise times were reduced to values as low as 2.0 ns, with incident rise times as high as 30 ns, operating at a source voltage of 10 kV. The experimental results agree with a model in which the ferrite line is treated as an equivalent transmission line in which the series inductance and resistance depend on the magnetization reversal. A potential application for the ferrite pulse sharpener is the combination of this device with a commercially available slower switch, which will provide kilovolt pulses with nanosecond rise times, operating at high pulse repetition rates.

I. INTRODUCTION

PULSE SHARPENING effects in ferrite transmission lines may be described using complex shock wave analysis [1]. Recently, an approximate but useful model describing this phenomena was reported [2]. Although some experimental work also was reported, there was insufficient data for a meaningful comparison between model and experiment. In this paper the pulse rise time emerging from the output of a ferrite coaxial line was obtained as a function of voltage, line length, and magnetic field bias, and the results were compared with the model. Results show that the model is essentially correct, although a precise comparison is difficult because of the numerous factors (several of which are not well understood) which influence the pulse sharpening effect.

The motivation for this work is the need for pulsers which simultaneously satisfy pulser requirements for fast rise time (≈ 1.0 ns) and high pulse repetition rates (≥ 20 kHz) at kilovolt levels (≥ 15.0 kV). Switches now available do not simultaneously satisfy these requirements. One possible solution is the use of the ferrite transmission line in combination with a slower rise time switch, for example, a thyatron. There are disadvantages, however, and these are added circuit complexity, bulk, as well as lowered circuit efficiency caused by pulse dissipation and bias current. Nevertheless, the ferrite pulse sharpener has potential in an area where there are few technological alternatives.

II. OUTLINE OF MODEL

Before describing the experimental results, it is worthwhile to summarize the model [2]. Toward this goal we consider

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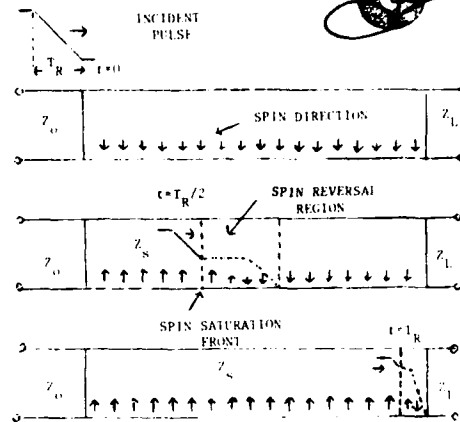


Fig. 1. Energy contained in rise time portion of pulse is used to reverse spins in ferrite transmission line. Magnetic field profile (dashed curve) in spin reversal region, as it emerges from output of line, represents residual, sharpened rise time.

a ferrite transmission line which is uniformly magnetized in the direction transverse to the direction of propagation (Fig. 1). A transmission line without ferrite, with impedance Z_0 , is connected to the input terminals of the ferrite line. A pulse with risetime T_R is incident upon the ferrite line. The polarity of the magnetic field of the pulse is opposite to that of the magnetization. As a consequence, a spin reversal process will be initiated, and the pulse will see a large RF impedance Z_f consisting of an inductance as well as a resistive component caused by dissipation in the ferrite. The ferrite line will not continually appear as a large impedance, however. Eventually, the initial portion of the ferrite line will reach saturation. When this happens the large impedance will suddenly decrease to the saturated impedance Z_s , which by design is chosen equal to Z_0 , the input impedance. As shown in Fig. 1, this process continues, so that a "spin saturation front" propagates along the length of the ferrite. The incident signal will be both reflected from and transmitted beyond the front. The velocity of this front will increase as the pulse amplitude is increased. The ferrite line is designed such that when the front reaches the end of the ferrite line (i.e., the entire length of the ferrite is magnetized opposite to its original direction) the pulse is near or at its plateau value. This will occur at $t = T_R$, ignoring transit time effects, i.e., assuming the velocity in the saturated region is much larger than the velocity of the spin saturation front.

Because of the finite time needed for the spins to reverse direction, a spin reversal region is set up beyond the front. When the pulse is introduced at the start of the line the spin reversal region will be relatively large since the field in the fer-

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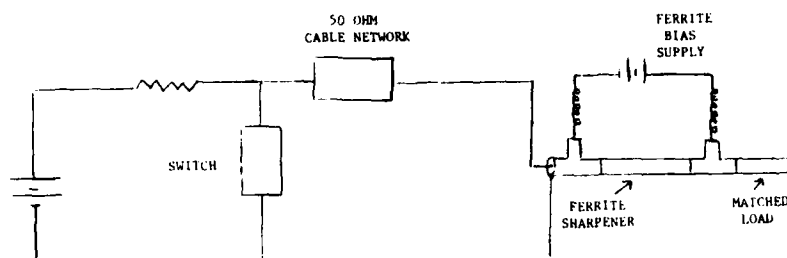


Fig. 2. Pulse sharpener test circuit.

rite is small. As the pulse increases in amplitude the spin saturation front velocity increases and will catch up to the field in the spin reversal region. The residual field penetration at the end of the line will have a time duration T_o which represents the rise time limitation. T_o also represents the time interval necessary for the magnetization to rotate direction, starting from its initial position and completing its motion when saturation in the direction of the applied field is attained. T_o is inversely proportional to the magnetic field in the spin reversal region, and the constant for this relationship is the "switching coefficient" [3], [4].

It should be remarked that, although Fig. 1 shows the magnetization undergoing complete reversal, this is actually not necessary for sharpening to occur. In fact, experimental results indicate that the minimum rise time orientation for the initial magnetization is intermediate between the two oppositely saturated states.

III. TEST CIRCUIT

The circuit for testing the sharpener is shown in Fig. 2. The input switch is a thyatron, JAN 8613, which operates up to 20-kV peak. The PFN cable has a 50- Ω impedance, and the pulsewidth was typically 100 ns. When the thyatron is triggered the PFN delivers a pulse to the input of the ferrite line, with an incident rise time of 15-30 ns, depending on the circuit inductance and the thyatron properties. The bias circuit provides current to "set" the ferrite. RF chokes are included to prevent pulse interaction between the bias circuit and the ferrite line. Current in the low inductance load is measured with a Tektronix CT-1 transformer.

The pulse sharpener consisted of a 120-cm long coaxial line with ferrite sleeves surrounding the center inductor. Each ferrite sleeve was 1.25 cm long with an outer diameter (OD) of 0.5 cm and an inner diameter (ID) of 0.25 cm. The ID and OD of the coaxial line were 0.24 cm and 0.64 cm, respectively. Space between the OD of the ferrite and the OD of the coax tubing was partially filled with plastic shrinkable tubing, which covered the ferrite. This aided in preventing breakdown and also helped to center the ferrite.

The ferrite was a magnesium manganese type, obtained from Trans-Tech Corporation (type TT1-3000). The saturation magnetization is 3000 G, the remanence is 2000 G, and the measured coercive force is 0.75 Oe.

IV. EXPERIMENTAL RESULTS

A. Variation of Source Voltage

Fig. 3 shows the observed rise time of the pulse emerging from the ferrite transmission line, together with the predic-

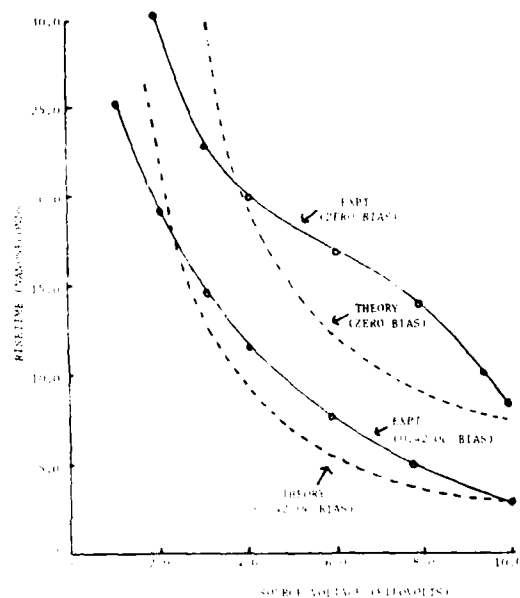


Fig. 3. Variation of output rise time with source voltage.

tions of the model, as a function of source voltage. Input rise time is 24 ns, i.e., the rise time delivered by the PFN to a 50- Ω load. Two cases are discussed. In the first the magnetic field bias is 0.42 Oe (referred to the mean diameter), and in the second case there is no bias.

The output rise time is seen to decrease as the source voltage is increased. For the biased case, in particular, the rise time is roughly proportional to the inverse of the source voltage. This behavior is related to a similar inverse relationship between the switching time and the magnetic field [4]. Appealing solely to this relationship for an explanation of pulse sharpening is misleading, however, since certain critical factors are omitted, such as the motion of the spin saturation front, and the reflections from this front (which are taken into account by the present model).

It may seem surprising at first that pulse sharpening is obtained at all for the case of zero bias. It should be borne in mind, however, that from the pulse point of view the abrupt change in permeability (needed for pulse sharpening) occurs not at the remanence point, but at the saturation magnetization point. In this regard it is useful to remember that the change in magnetization, produced by a fast rise time high level magnetic field pulse, will not follow the hysteresis curve (which is a low frequency phenomenon) but will be governed

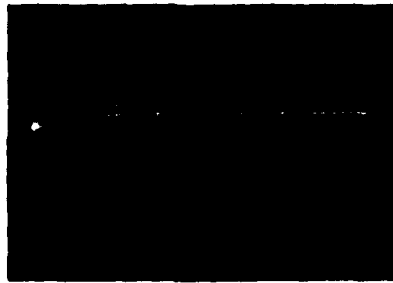


Fig. 4. Minor hysteresis loop utilizing positive pulses and bias of 0.42 Oe. Horizontal: 0.63 Oe/cm. Vertical: 2500 G/cm.

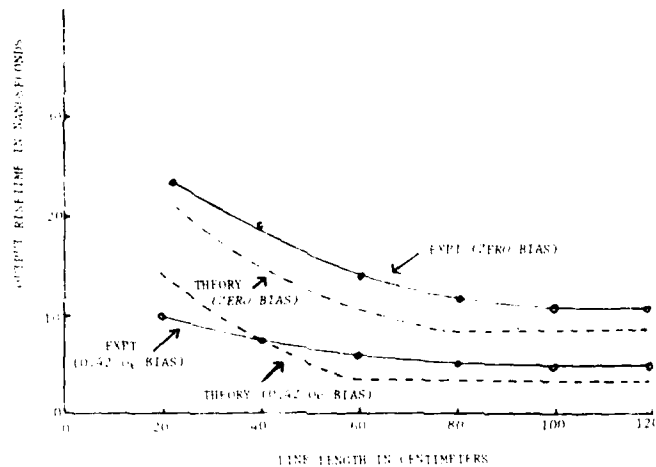


Fig. 5. Variation of output rise time with line length.

by the equation of motion for the magnetization which includes a dissipation term such as that given by Gilbert [3], [4].

The hysteresis curves are useful, however, for estimating the net change in the total flux brought about by the motion of the magnetization. This information is needed to compare the experimental results with the theory. In the case of zero bias the flux change is ≈ 1000 G, i.e., the difference between the saturation magnetization (3000 G) and the remanence (2000 G). In the case of the fully biased ferrite, the flux change is ordinarily twice the saturation magnetization less the zero bias flux change, or about 5000 G. In this experiment, however, the best results were obtained with a partial bias (less than coercive force), so that the flux change was less than its maximum. For example, at the bias level of 0.42 Oe used in Fig. 3, the flux change was taken to be ≈ 1800 G. This was estimated from the minor hysteresis loop obtained with unidirectional half sine wave pulses while the sample was oppositely biased at 0.42 Oe (Fig. 4). The flux change may be underestimated slightly because of pulse overshoot which may occur when ferrite sharpener is in actual operation.

For convenience of calculation, the impedance of the ferrite line is assumed to be 50Ω in the region where it is saturated. This, of course, is equivalent to assuming a constant saturated permeability, independent of the incident field. Measurements show, however, this is not completely true, and the effect of this assumption is to underestimate somewhat the mag-

netic field strength during the earlier portion of the incident rise time.

The theoretical curves shown in Fig. 3 were calculated from the model equations given in the Appendix. The rise time is given by 4, where the magnetic field h is obtained by solving (1)–(3). Over the voltage range shown the optimum length l_o (discussed in the next section) was always smaller than the line length of 120 cm. Discussion of the RF circuit and the equations representing the network parameters are given in [2]. In order to obtain reasonable agreement between the experimental results and the model, it was necessary to assign differing values of the switching coefficient to the two cases shown: approximately $0.4 \text{ Oe}\cdot\mu\text{s}$ for zero bias, and $0.1 \text{ Oe}\cdot\mu\text{s}$ for the biased ferrite. The apparent change in the switching coefficient for different bias levels is not well understood at the present time.

B. Variation of Output Rise Time with Ferrite Length

Fig. 5 shows results obtained by reducing the ferrite line length, starting with the original 120 cm. The results are for a fixed source voltage of 8 kV and an input rise time of 18 ns. Again, the results are shown for the cases of zero bias and 0.42 Oe. In both instances, during the initial reduction in line length, there is little change in output rise time. With further reduction in length, however, a gradual degradation in rise time occurs. This variation in rise time is not surprising and

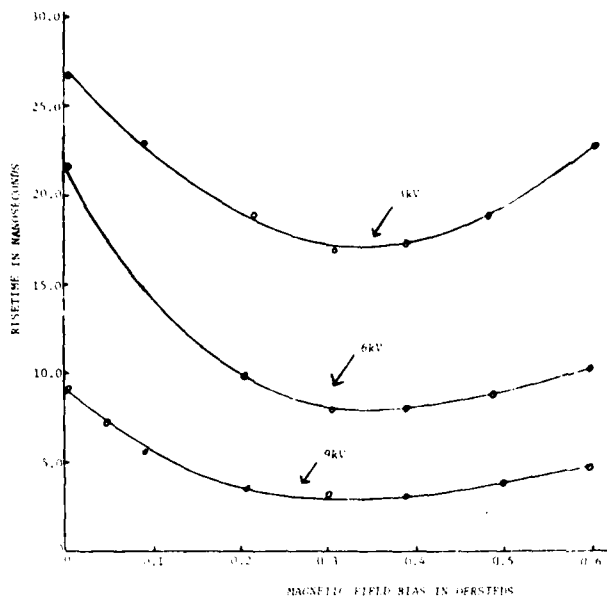


Fig. 6. Variation of output rise time with bias.

may be explained qualitatively. If the ferrite line is too small, there will be insufficient magnetic moment, so that only the initial portion of the rise time will be sharpened. If the line is increased, an optimum length will be achieved wherein the sharpening will occur over the entire rise time portion of the pulse, but the plateau portion will be unaffected. For a given voltage, the rise time is a minimum when the line length is optimum. If the line length exceeds the optimum length a portion of the pulse plateau will be "chewed off." When this happens, one should expect roughly the same rise time, with perhaps a slight degradation caused by residual dispersion and attenuation effects during saturation, particularly if the line far exceeds the optimum length.

The theoretical curves for the rise time also are shown in Fig. 5. The rise times were determined by first finding the optimum length l_o , which was obtained by solving (1)–(3). The rise time was then calculated from either (4) or (8). If l_o was less than or equal to the line length, (4) applied. If l_o exceeded the line length, (8) gave the rise time, after first solving (5)–(7). As shown in the figure l_o is 78.4 cm at zero bias and 58.6 cm for 0.42-Oe bias. It should be noted that the theoretical rise time is constant when the line exceeds l_o , in approximate agreement with the experimental curves. This effect is anticipated based on our previous discussion. When the voltage incident on the spin saturation front attains its plateau value, the front is located at some point along the line, and beyond this point the incident voltage is constant. Within the limits of the present model, this means a constant rise time. Just as in Fig. 3, we assume differing switching coefficients, depending on bias: 0.4 Oe- μ s at zero bias and 0.1 Oe- μ s at 0.42-Oe bias.

C. Variation of Rise Time with Bias

Fig. 6 shows the experimental results obtained by varying the magnetic field bias for various source voltages. The line

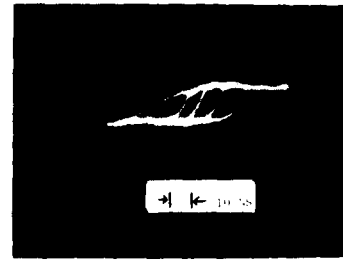


Fig. 7. Waveforms of output rise time for several bias levels (from left to right, 0–0.5 Oe in steps of 0.1 Oe). Source voltage is 6.0 kV.

length is 120 cm and the input rise time is 24 ns. As expected, the lower source voltages have larger rise times over the entire range of bias. For all values of source voltages the rise time is maximum at zero bias and proceeds to decrease until a fairly broad range (at least for 6 and 9 kV) of optimum bias level is attained, after which the rise time increases slowly. Explanation of the experimental curves is obtained if, as stated previously, the switching coefficient is allowed to vary as a function of bias level. At zero bias the switching coefficient is estimated at ≈ 0.4 Oe- μ s. With bias the value is ≈ 0.1 in the region of minimum rise time. With further increase in bias the rise time increased slowly, and this is attributed to two possible factors. One factor is the aforementioned change in the switching coefficient. A second factor is associated with residual dispersion and attenuation in the saturated line, particularly when the ferrite line is much longer than the optimum length.

Fig. 7 shows the emergent rise time for several values of bias at 6-kV source voltage and with a longer incident rise time (≈ 40 ns). The rise time waveforms, obtained on a single shot basis, were superimposed using a storage scope. The rise time appears to be optimized at about 0.3 Oe. Note that by increasing the bias a progressive delay is introduced, which tends to "trim off" the initially long rise time at zero bias.

V. CONCLUSION

Measurements of output rise time in ferrite transmission lines have been obtained as a function of voltage, line length, and magnetic field bias. Reasonable agreement with a pulse sharpening model is attained if the switching coefficient is allowed to vary appropriately with bias magnetic field. Independent measurement of the switching coefficient as a function of bias, for various pulse magnetic fields, is planned in order to further check the validity of the model. Other factors also have been omitted from the model, which make comparison with experiment tentative. These factors include the dependence of saturated ferrite impedance on pulse voltage, the impact of ferrite sleeve thickness, as well as factors discussed in previous work [2] such as field accumulation and transient effects.

For applications, one wishes to choose a ferrite with material properties which will enhance the pulse sharpening effect. Two such properties are the switching coefficient and the saturated permeability. Based on the previous discussion, the switching coefficient should be as small as possible, since this implies a faster rise time. A small saturated permeability is also desired, by virtue of the fact that this allows design of

lower impedance transmission lines with relatively large space between the center and outer conductors. For such a design, greater magnetic fields can be produced, and one should then expect faster rise times.

The results have shown that the ferrite pulse sharpener is worth exploring as a possible means for obtaining nanosecond, kilovolt pulses at high pulse repetition rates. Rise times as low as 2 ns have been obtained at 10 kV, and further sharpening is foreseen by operating at higher voltages and by optimizing the design of the ferrite transmission line.

VI. NOMENCLATURE

a	Inner radius of ferrite sleeve (meters).
C	Linear capacitance of transmission line (farads/meter).
d	Outer radius of ferrite sleeve (meters).
D	Outer radius of dielectric sleeve (meters).
ϵ_{eo}	Effective dielectric constant of combined ferrite and dielectric sleeves (farads/meter).
h	Peak magnetic field in spin reversal region (Oersteds).
l_m	Mean magnetic length: $\pi(d+a)$ (meters).
L	Linear inductance in spin reversal region (henries/meter).
L_o	Linear inductance in line after ferrite permeability has saturated (henries/meter).
l_G	Length of ferrite line (meters).
l_o	Optimum ferrite length (meters).
$4\pi\Delta M_z$	Flux change arising from motion of magnetization (gauss).
R	Linear resistance in spin reversal region (ohms/meter).
S	Switching coefficient (oersted-seconds).
T_o	Rise time of field in spin reversal region at end of line; equated to output rise time (seconds).
T'_o	Output rise time when line length is smaller than optimum (seconds).
T_R	Rise time of incident pulse (seconds).
t	Time (second).
μ_{eo}	Effective permeability of combined ferrite and dielectric sleeves after saturation (henries/meter).
V	Voltage incident on spin saturation front (volts).
V_M	Plateau voltage incident on spin saturation front (volts).
V_G	Voltage incident on spin saturation front at end of line (volts).
ω_o	Dominant frequency component of time needed for spin saturation front to traverse ferrite (radians/second).
Z_f	Impedance in spin reversal region (ohms).
Z_o	Characteristic impedance of input to ferrite line (ohms).
Z_s	Characteristic impedance of ferrite line after saturation. Set equal to Z_o (ohms).
Z_L	Load impedance (ohms).
Γ	Reflection coefficient at spin saturation front.

APPENDIX

DISCUSSION OF MODEL EQUATIONS

To simplify matters, the rise time T_R is represented by a linear ramp function. In order to ease the calculation, the

dominant frequency is taken to be the inverse of the time needed for the spin saturation to traverse the ferrite, $2\pi/\omega_o$. As mentioned previously, transient pulse effects are ignored. Using standard transmission line theory with steady-state frequency ω_o , the extent of mismatch at the front, represented by Γ , satisfies

$$h^2 \text{Re } Z_f = \left[\frac{4\pi V_M}{l_m} \right]^2 \frac{(1 - \Gamma^2)}{Z_o} \times 10^{-6} \quad (1)$$

where

$$1 - \Gamma^2 = \frac{E^2 - A^2}{E^2 + B^2}$$

$$A^2 = \left[\left(\frac{1}{2} \right)^{1/2} \left[\left(\frac{L^2}{C^2} + \frac{R^2}{\omega_o^2 C^2} \right)^{1/2} + \frac{L}{C} \right]^{1/2} - Z_o \right]^2$$

$$E^2 = \left[\left(\frac{1}{2} \right)^{1/2} \left[\left(\frac{L^2}{C^2} + \frac{R^2}{\omega_o^2 C^2} \right)^{1/2} + \frac{L}{C} \right]^{1/2} + Z_o \right]^2$$

$$B^2 = \frac{1}{2} \left[\left(\frac{L^2}{C^2} + \frac{R^2}{\omega_o^2 C^2} \right)^{1/2} - \frac{L}{C} \right]^2$$

$$\text{Re } Z_f = \left(\frac{1}{2} \right)^{1/2} \left[\left(\frac{L^2}{C^2} + \frac{R^2}{\omega_o^2 C^2} \right)^{1/2} + \frac{L}{C} \right]^{1/2}$$

and the circuit elements R , L , and C , representing the spin reversal region, are given by

$$R = \frac{16\pi^3(d^2 - a^2)\Delta M_z}{l_m^2 S} \times 10^{-7}$$

$$L = \frac{16\pi^2(d-a)\Delta M_z}{l_m h} \times 10^{-7}$$

$$C = \frac{2\pi\epsilon_{eo}}{\ln(D/a)}$$

and

$$Z_o = \frac{\ln(D/a)}{2\pi} \left(\frac{\mu_{eo}}{\epsilon_{eo}} \right)^{1/2}$$

The next two equations determine the optimal length l_o for the transmission line. l_o is obtained by equating two quantities. The first is the distance covered by the spin saturation front velocity (2). The second is the distance covered by the propagation velocity in the saturated medium, calculated at the point when the pulse incident on the front just reaches its plateau value (3):

$$l_o = \frac{l_m V_M (1 - \Gamma^2)^{1/2} \text{Re } Z_f}{4\pi\Delta M_z (d^2 - a^2) Z_o^{1/2} \omega_o} \times 10^3 \quad (2)$$

$$l_o = \left(\frac{1}{L_o C} \right)^{1/2} \left(\frac{2\pi}{\omega_o} - T_R \right) \quad (3)$$

Equations (1)-(3) are solved to yield ω_o , h , and l_o . It is then determined whether l_o satisfies the condition $l_o < l_G$. If $l_o \leq l_G$ then the emergent rise time is

$$T_o = S/h. \quad (4)$$

If $l_o > l_G$, then the following modified set of equations are utilized to obtain the rise time. Equation (1) becomes

$$h^2 \operatorname{Re} Z_f = \left[\frac{4\pi V_G}{l_m} \right]^2 \frac{(1 - \Gamma^2)}{Z_o} \times 10^{-6} \quad (5)$$

and $(1 - \Gamma^2)$, R , L , C , and Z_o are identical to the expressions in (1). Note that V_M is now replaced by V_G . The modified equations for (2) and (3) are

$$l_G = \frac{l_m V_G (1 - \Gamma^2)^{1/2} \operatorname{Re} Z_f}{4\pi \Delta M_2 (d^2 - a^2) Z_o^{1/2} \omega_o} \times 10^3 \quad (6)$$

$$l_G = \left(\frac{1}{L_o C} \right)^{1/2} \left[\frac{2\pi}{\omega_o} - \frac{V_G}{V_M} T_R \right] \quad (7)$$

Equations (5)-(7) are solved for h , V_G , and ω_o . The emergent

rise time is then given by

$$T'_o = \left(1 - \frac{V_G}{V_M} \right) T_R + T_o \quad (8)$$

where T_o is given by (4). Equations (4) and (8) (depending on whether $l_G \geq l_o$ or $l_G < l_o$) are the theoretical rise times given in Fig. 3 and 5.

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