Distortion of Fast Pulses by Non-TEM Effects in Coaxial Cables

Jon Barth and John Richner

INTRODUCTION

While designing fast pulse low distortion coaxial components we have found limitations that must be observed when using large, low loss coax lines for Ultra Wide Band (UWB) pulse transmission. These effects seem to be unreported in the time domain literature. The purpose of this paper is to make others in this industry aware of these problems and also to detail some of the types of coax constructions that will avoid distortions of pulse transmission.

The generation of high amplitude, ultra fast pulses is so difficult and costly that the transportation of those pulses should be done with minimal degradation of amplitude or risetime from all causes. The following information will outline some of the effects of Time Delay Distortion of pulses that can be generated in coaxial transmission lines.

LARGE COAXIAL TRANSMISSION LINES USED BEYOND "CUTOFF"

Large coaxial transmission lines can be used to minimize losses for fast UWB pulses. They are usually not used in Radio Frequency/Microwave (RF/MW) at frequencies above where they support higher order waveguide propagation modes. Information on the excess loss from these real but very narrow band width resonances is well known and published in the RF/MW literature. Large coax can be used in the time domain at risetimes that contain frequencies far higher than would be used in the frequency domain. The definition of CUTOFF frequency for coaxial lines in the frequency domain is defined by the location of the first higher order mode. Any noticeable amounts of this effect can be avoided in time domain UWB because energy is spread across tremendously wide bandwidths. Large coaxial lines that would support many narrow bandwidth higher order modes can be used because an UWB pulse has so little energy in the frequency band of each of these higher order modes. The higher order mode shock excitation of these narrow resonances by a step function (typically 2MHz at 8GHz) can be prevented.

We have been able to avoid these TE and TM mode generation problems in large coaxial cable when using a step risetime as fast as 20 ps. For reflection or transmission measurements. An example of the possibilities for large diameter coaxial transmission lines, is a straight six foot long air insulated pulse transformer which we have designed and built. It uses a three inch diameter outer conductor to transform a 50 ohm impedance pulse with 50 picosecond risetime down to 0.5 ohms. We were careful to observe some basic rules listed below, and there was no evidence of any resonances at the highest sensitivities. Therefore, any resonances were below 0.1* of the amplitude of the time domain pulse.

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TEST METHOD

We use a Hewlett Packard Model 54120 sampling oscilloscope. This scope provides on-screen digital measurements and normalization. A calibration procedure records a step function through a coaxial system path. The scope then adds or subtracts to the pulse what is needed to form that step function into a perfect gaussian step function. This calibrated addition or subtraction to the pulse becomes the basis for "normalization". The internal mathematical procedure also provides a perfect reference pulse for a range of input risetimes. This "normalized" input pulse can be passed through a Device Under Test (OUT) to determine the exact distortion produced by that component at the desired risetime.

Normalization provides two benefits. First, it eliminates the 'system' from the measurement, by mathematically factoring out the system losses. Second, it allows the pulse to be Gaussian filtered to any rise time, which is the equivalent of using a slower or slightly faster rise pulse into the OUT and displaying the resultant output pulse. We have compared the HP scope normalization results with other methods of risetime spoiling, and have found the scope to be very accurate, as long as the calibration practices are carefully followed. This feature of the scope has been invaluable to us as a perfect and adjustable risetime reference.

DISTORTION OF FAST PULSES TRAVERSING A BEND IN TEN LINES

The risetime degradation and extra ringing from a single half turn of two feet of 1/2 inch dia. coax is only slightly noticeable with risetimes as fast as 30 ps. Risetime degradation can however become very troublesome in large coax, used for minimal loss, when formed in tight bends. The amount of this effect at any affected risetime depends on the diameter of the coaxial conductors and the radius of the cable bend.

Most of our work requires type N connectors so we use precision 3.5 mm to type APC-N adapters on the head of the sampling scope. To compare the risetime pulse out of channel #1 to the terminating channel #4 of our HP 54120 sampling scope, we built a very low loss coaxial jumper. See Fig. 1.

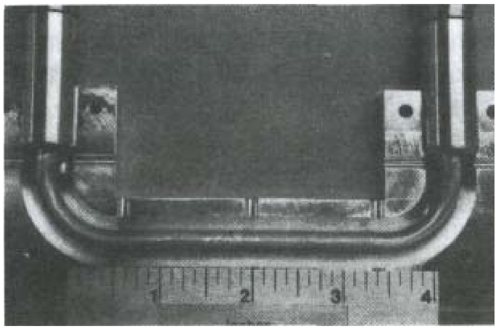

Fig. 1

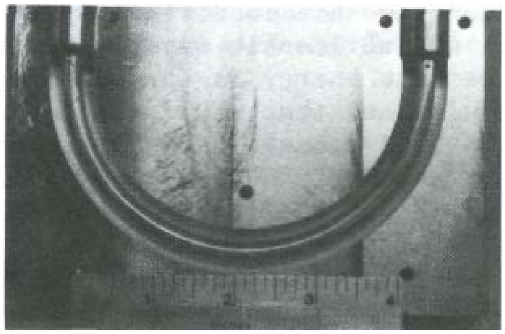

Fig. 2

It had a 0.250 inch diameter copper tube inner conductor with a 90 degree 0.750 inch radii on either end to line up with the 4.500 inch center to center spacing between the two sampling head connectors.

The ends of the 0.250 inch dia. copper inner conductor and 0.575 dia. aluminum outer conductor 50 ohm line, had a 3 degree inner conductor and a 7 degree outer conductor taper down to the 7 mm. APC-N connectors. The Time Domain Reflection coefficient (TDK) was less than 3* from the N connector through the taper, the 0.250 in. dia. bent line and the other taper section and N connector. The pulse risetime into this low loss jumper was 36.8ps. with a 2.6% overshoot. The output pulse was very distorted with 14.7* overshoot after a significantly slowed risetime of 59.4 ps. We have seen slowed risetimes for unknown reasons many times before, but the response of this jumper finally helped in our understanding of previous problems.

Desiring more coax bend distortion information, we built another low loss 50 ohm single 180 degree bend with a 2.250 inch radius and the same 0.250 inch dia. copper inner conductor. See Fig 2. This coaxial line bend produced a faster risetime of 47.8 ps. with 12.1% overshoot, with the same 36.8 ps input risetime.

This information made us suspicious of the output risetime and overshoot of our model 732 pulse generator. The output of the coaxial reed switch was 50 ps. with a small amount of overshoot. To provide the shortest output pulse width, the charge line was a straight short connection to one end of the reed switch. The output of the switch fed into a 0.188 inch dia copper inner conductor that immediately makes a 180 degree bend with a 0.750 inch radius. It then travels by a straight line to the output connector. This relatively large diameter inner conductor provides low loss and withstands the 6kv DC charge voltage. See Fig. 3.

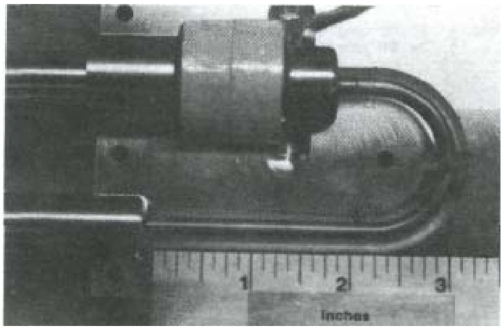

Fig. 3

From the information learned about curved coaxial lines, we tested the output of the switch by simply reversing the output and the charge line connectors. This arrangement allows the output pulse to travel straight out to the connector labeled "Charge Line" without a bend in the output line. The risetime improved from 50 ps. to slightly less than 40 ps. with almost no overshoot.

The only theoretical analysis of curved coaxial transmission lines has been done by Krempasky in the frequency domain for lines small enough to avoid higher order modes. [1]

PROPOSED TINE/DIMENSION RATIO

For rule of thumb information on the potential problems described, we would like to propose a concept of Rise Time Length, (RTL). This is an empirical formula that provides an electrical dimensional to relate to the physical dimensions of the coaxial transmission line.

RTL= c*RT/v/eT~

Rise Time Length = velocity of light times the 10% to 90% risetime divided by the square root of the dielectric constant of the medium.

This is similar to the wavelength calculation for RF/MW; but it should be different to avoid confusion and multiple conversions in the different characteristics of the time domain.

COILED DELAY LINES

The same causes of short radius coax bend time distortions have similar but smaller effects with longer lengths of larger bend radius coiled delay lines.

Figure 4 shows the gaussian step response of a 20 ns. long 1/2 inch foam delay line in the form of one large 6 foot loop with a 50 ps input risetime. The slower pulse response with overshoot is the pulse response through this same coax, coiled into a 13 inch diameter with four turns. The slower rise time of Fig 4 is 55.2 ps. with 2.4% overshoot.

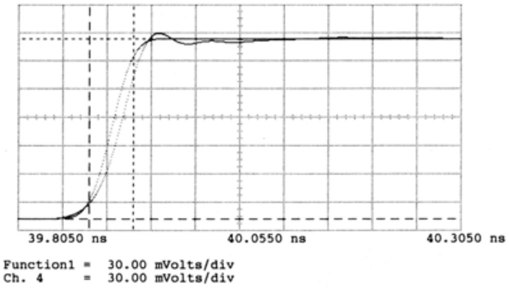

Fig. 4

Notice that the bottom 14% of the pulse has has been affected with a slower rate of rise which will cause problems if this coax were to be equalized. This time distortion occurs in any type of coax construction and can be reduced by using a figure 8 pattern when packing up a long delay line.

We uncoiled this delay line and then wound it into a three section figure 8 with six tighter loops. This form produced a faster risetime of 52.6 ps. with an overshoot of the same 2.4%; but with the same slower rate of rise at the bottom 14% of the pulse.

COAXIAL CABLE MEASUREMENTS

Over the years we have acquired and tested the risetime of a number of different types of coaxial cables. The results we present are for different cable constructions that are very close to a nominal 1/2 inch size. The cables used for risetime comparisons had inner conductors that had a diameter range of .161 to .189 inch with the outer conductor inner diameter range of .432 to .481 inch. These cables would therefore be expected to have about the same losses and risetimes for equal lengths.

Most of the skin effect loss is in the inner conductor, and solid copper or copper clad aluminum is used for the lowest loss. Copper for the outer conductor and inner conductors has the lowest losses from skin effect. Straight soft tubular aluminum outer conductor has only slightly higher losses, is less expensive and is flexible. The slightly higher resistivity of an aluminum outer conductor adds very little risetime degradation.

Although many of these types of coax were not designed for fast risetime use, they perform well if coaxial connectors can be made with reduced reflections. Major reflections of most connectors supplied for these cables can degrade the risetime through the cable. We modified the existing connectors or made completely new connectors to achieve accurate risetime measurements.

Several cable samples of various constructions all with about 20 ns delay length were tested for risetime, associated overshoot and pulse risetime degradation. The system reference for normalization was done using 1/2" alumifoam coax as the standard for comparative measurements with the other coaxial cables. Therefore when "normalization" is performed on the test samples for other input pulse risetime, the waveshape yielded is the theoretical pulse waveshape for the indicated input pulse risetime minus the losses of the calibration cable.

The calibration cable risetime losses are assumed to be typical for non-distorting 20 ns 1/2" copper/aluminum/polyethylene delay lines. This enabled measurements to be taken that show the time delay distortions in the cable without the resistive risetime losses. The output pulse waveshape for the 1/2" alumifoam (System), the 1/2" corrugated outer jacket type, and the 1/2" helical dielectric support type are shown in Figures 5, 6, and 7 respectively.

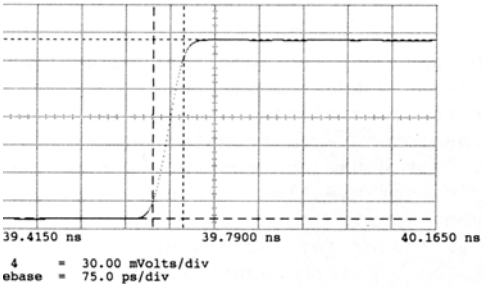

Fig. 5 1/2" Alumifoam

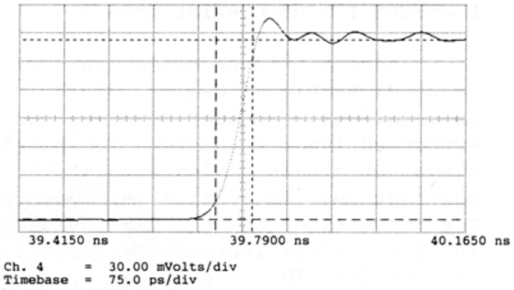

Fig.6 1/2" Corrugated

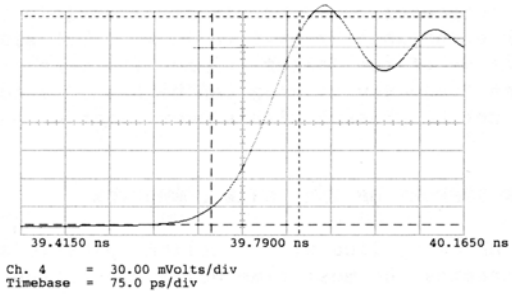

Fig. 7 1/2" Helical insulator

All three waveforms were normalized to the alumifoam at 50 ps. risetime, and were recorded at 75 ps. per division. The results of the measurements of all of the 1/2" diameter range coax samples are shown in Table 1.

Table 1

Coax Cable Comparison

20 ns Nominal Length Cables

	Normalized 50 ps input		Normalized 75 ps input		Normalized 100 ps input		Normalized 200 ps input	
Coax Type	Rise Time (ps)	Over-Shoot (%)	Rise Time (ps)	Over-Shoot (%)	Rise Time (ps)	Over-Shoot (%)	Rise Time (ps)	Over-Shoot (%)
RF-44 ½” Alumifoam *(1)	49.6	0.98	73.8	0.49	99.0	0.49	198.8	0.00
½” Alumifoam *(2)	50.4	0.00	75.4	0.00	100.4	0.00	200.4	0.00
Times LMR-600	51.2	2.48	76.2	0.49	101.1	0.49	202.0	0.00
Prodelin	58.0	7.84	76.6	1.96	100.4	0.49	200.0	0.00
6 PE Tube Dielectric Cablewave FLC 12-50 ½”	60.4	11.88	78.8	3.92	100.2	1.46	199.0	0.00
Corrugated Outer Jacket Helical Dielectric Support From HP Delay Line *(3)	148.0	23.30	149.2	20.00	156.0	15.10	205.0	4.40

*(1) Low loss gas blocked cable used at the Nevada Test Site.
*(2) System calibration done with this coax, see explanation in report body.
*(3) Normalized to 375ps input rise, Rise Time = 367.0ps, Overshoot = 0.00%.

TIME DELAY DISTORTIONS BY NON UNIFORM CONSTRUCTION OF COAXIAL CABLES

There are three basic non-uniform coax constructions that cause time delay distortions: Helical dielectric inner conductor support. Corrugations in copper outer conductor for flexibility, and Spline supported inner conductor. The helix insulator and corrugated outer conductor create a slow wave structure that cause non-absorptive risetime degradations. These time delay distortions of risetime, are caused by the faster parts of the risetime being slowed in time more than slower parts. The time delays increase in a continuous manner for increasing frequencies. The longest delays are at the highest frequencies. If the ringing continues for more than a few observable cycles, the frequency of the ringing will be seen to increase past the front rise of the pulse. This is an obvious result of the higher frequencies having more delay. Of course if a long enough cable is used and the losses at the ringing frequencies are high, the ringing will be much attenuated, but the excess risetime loss from time distortion will remain.

These pulse responses would be almost impossible to equalize. This is not due to series or shunt resistive losses, but simply due to additional time delay of the faster (higher frequencies) parts of the risetime. The high frequency ringing can be highly attenuated in longer lengths, and may not be present with slower risetime pulses.

HELICAL INSULATOR SUPPORT OF THE INNER CONDUCTOR

Coax from a HP delay line with a helical plastic support of the inner conductor creates the most time delay distortion. This cable slows the risetime by time delay distortions of the faster parts of the risetime. It also creates ringing at the top of the pulse from the delayed faster parts of the risetime.

This construction is also used in "Spirafil" and "Flexwell" which are registered trademarks of Cablewave Systems in 3/8, 1/2, 7/8, 1 5/8 inch and larger cable sizes, and "Heliax" which is a registered trademark of Andrew Corporation in ½, 7/8, 1 5/8 inch dia. & larger cable sizes. Some of these constructions also have a corrugated outer conductor. This coax construction was originally produced by Phelps Dodge under the name of "Styroflex". A very thorough frequency donain analysis of the complex characteristics of its operation (in the exact 1/2 inch size that we measured) was done by J. Griemsmann of Microwave Res. Inst., Polytechnic Intst. of Brooklyn, N.Y. [2]

His analysis identified an attenuation band between 13.3 and 14.4 GHz. Our time domain measurements identified large amplitude ringing that started at 3.1 GHz and increased to 7 GHz. There are probably some nonlinear phase delays beginning in this frequency range; but Griemsmann does not identify it.

CORRUGATED OUTER CONDUCTOR COAX

Time domain pulse fidelity in coax cables is also distorted by corrugated outer conductors. Corrugated outer conductor construction distortions do not have as much time delay distortion as the above described helical insulated inner conductors. The copper outer conductor is corrugated to allow flexing without metal fatigue. Outer conductor periodicity in a 1/2" size has a slow wave characteristic that begins to create time delay distortions with risetimes faster than 100 ps.

"Heliax" is the registered trademark of Andrew and "Flexwell" is the registered trademark of Cablewave. Both types of coax have very low loss for RF/MW and use a solid inner conductor and a corrugated copper outer conductor with foamed polyethylene inner conductor support. The foam dielectric provides low dielectric losses and the relatively large diameter copper or copper clad aluminum inner conductor provides low series resistance losses.

SPLINE DIELECTRIC INNER CONDUCTOR SUPPORT

Spline dielectric inner conductor supports seem to have the least excess pulse distortion of those cables that exhibit time delay distortions. By comparison they could be classified as minor. We have not tested a true molded Spline supported inner conductor coaxial cable; but we have the pulse response through a coax with the inner conductor supported by six polyethylene tubes. This dielectric support should be close enough to a spline dielectric construction of a 1/2 inch size to provide a similar pulse response. But as with the other non-uniform coax constructions its time domain pulse response would probably suffer more at high RTL/dia. ratios.

There is a simple HP 41C calculator program that will predict the risetime from RF losses at three or more frequencies. [3]. These calculations are only accurate for uniform coax constructions that do not have the time delay distortions previous described.

CONCLUSION

The basic rule-of-thumb from all of this information, is that if overshoot is created by the coax lines of a system, the risetime is slowed as a consequence. There is also a direct correlation between overshoot amplitude and excess risetime time distortion for similar sizes of coax. This is most noticeable in shorter lengths of cables that do not have significant resistive losses in the conductors and dielectric.

Our information is not thorough for all sizes and construction types of coax; but it does provide some information to warn time domain users of some of the pitfalls of blindly transposing frequency domain cable loss to the time domain.

Coax is made less lossy by reducing the amount of dielectric material between the inner and outer conductors for two reasons. One, the dielectric material is more lossy than an air dielectric. Two, with less dielectric material and a lower dielectric constant, the inner conductor for the same impedance is larger and provides less series resistance losses. Both of these methods create desirable low RF/MW loss and time domain losses. Large coax for time domain should only use dielectric material uniformly distributed to support the inner conductor.

The use of cables with helical supported inner conductor should be avoided when 0.500 inch diameter coaxial cables are used for risetimes faster than 200 ps. The best coax for use in wide band pulse applications is one that has a solid center conductor and a uniform outer conductor. A uniform dielectric axially and circumfrentially, solid or foamed, avoids the above mentioned time distortions. With the possible variation in foam density, variations in length can cause slight time distortions; but this can be easily found with TDR testing. Foil with over-braid outer conductors in place of the solid outer conductor for cables allows more flexibility and also perform quite well. Non uniform construction or cables that have a periodic conductor axial variations or dielectric constant variations in the axial or circumference should be avoided for RTL/diameter ratios near one.

"Foamflex" which is a registered trade mark of Cablewave Systems has a solid copper clad inner conductor, polyethylene foam dielectric and a solid aluminum outer conductor and is available in 1/2 and 7/8 inch sizes. "Alumifoam" is a registered trademark of Times Microwave Systems and has the same construction and is available in 1/4, 3/8, 1/2, 3/4 and 7/8 inch dia. sizes. These cables have uniform construction with minimal time delay distortions.

Unexpected results in large systems can be avoided if samples of the coax are first tested at the voltages and risetimes to be transported.

Lower loss in ultra wide bandwidth time domain can use much larger coaxial line sizes. Minor higher order narrow resonances of coax in UWB can be ignored as long as a few basic rules for the use of large coaxial lines are observed.

1. Be careful of the bend radius in large (coax) TEM Lines with fast pulses.
2. Use TEM Lines with constructions that do not create non-TEM modes.
    A. Avoid corrugated or non uniform conductors in the direction of propagation SP Line.
    B. Avoid non uniform dielectric insulation around the circumference of coax lines.
    C. Use tapered lines when changing TEM Line sizes, and avoid abrupt dielectric constant changes.

REFERENCES

[1] J.J. Krempasky, "Analysis of TEM Mode on a Curved Coaxial Transmission Line," IEEE Transactions on Microwave Theory and Techniques, Vol. 38, No. 6, June 1990
[2] J. Griemsmann, "An Approximate analysis of Coaxial line with a Helical Dielectric Support" IRE Transactions-Microwave Theory and Techniques. Jan, 1956 pp 13-23
[3]. HP 41C program # 03153D "Coaxial Cable Rise Time"

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