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# Multiple Reflection of Metallic Time Domain Reflectometry

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Abstract

Metallic Time Domain Reflectometry(MTDR) is an electromagnetic pulse testing technique using metallic coaxial cable as the conducting and sensing device. This technique can be applied to monitor fracture within concrete structure. While the coaxial cable is embedded in the concrete structure, it works like a continuous fracture and relative movement monitoring sensor which can detect any major change along its length. By sending an electromagnetic pulse down the cable, reflection can be seen from the receiving Oscilloscope. Points of discontinuity can be located precisely.Type and magnitude of discontinuity can then be studied.

TDR monitoring provides a very powerful tool when fracture locations are not known in advance. Technique of Multiple reflection analysis proved to be a better solution to the data acquired. The technique developed can be applied to analyze reflection in multiple mode. Result shows the applicability in building and analyzing a multiple points monitoring system for concrete structure in infrastructure.

## Introduction

Time Domain Reflectometry (TDR) employed in this study was developed initially by Electrical Engineers as a method to locate discontinuities in coaxial transmission cables [1]. The concept has been extended to measurement of the properties of materials in which conductors are embedded, such as soil water content [2], and the evaluation of material dielectric behaviour [3]. In rock mechanics, the technique has been employed to identify zones of rock mass deformation corresponding to locations of cable failure [4,5], and blast effects [6]. This technique can be applied to monitor fracture within concrete structure [7]. While the coaxial cable is embedded in the concrete structure, it works like a continuous fracture and relative movement monitoring sensor which can detect any major change along its length. By sending an electromagnetic pulse down the cable, reflection can be seen from the receiving Oscilloscope. Points of discontinuity can be located precisely. By using the special fast rise electromagnetic wave, TDR fracture monitoring provide a viable tool when fracture locations are not known in advance. This is the major advantage for TDR system compared with other monitoring system. In this paper, possibility of quantifying multiple reflection signature is studied. Tests result together with explanation are presented to verify the proposed methodology.

## Time-Domain Reflectometry

TDR is a special type of time-domain measurement, its measurements are made of signal reflections from impedance discontinuities. The value of this type of measurement is that specific discontinuities have readily identifiable characteristic signatures. Also, the location of the discontinuity on a transmission system can be accurately measured by its propagation time of the incident signal and then reflection.

A simplified schematic of a TDR system is shown in Fig. 1. A pulse generator produces the signal that is directed to the system under test. A step waveform is usually employed. A pickoff probe is used to sample the incident and reflected waveforms. A low-level repetitive pulse generator is used so that equivalent time sampling systems can be used, allowing measurement of risetimes of less than 50 ps. Reflections of traveling waves at impedance discontinuities are measured and analyzed.

The coaxial transmission line employed in a TDR monitoring system provides a one-dimensional propagation path for an electromagnetic wave. Equations governing such coaxial wave propagation can be derived either from circuit theory or from Maxwell's equations and both approaches lead to the same result. Details of the derivation can be found in texts on transmission line theory (e.g. Dworsky[8]).

A coaxial cable such as shown in Fig.2 is composed of an outer conductor and an inner conductor. In longitudinal cross-section, the coaxial cable may be represented by an ideal two-wire transmission line where the two conoductors in Fig. 2 represent the outer and inner conductors. Current, $I$, flowing in the two-wire transmission line produces a voltage, , which is the potential difference between the two conductors at some distance, $x$, along the cable.

Time domain analysis is performed on the motion of transverse electromagnetic (TEM) waves [8] and is the simplest mode of electromagnetic wave fields by restriction to the transverse plane, i.e. normal to the wave propagation direction. By assuming the coaxial cable to be a lossless line, i.e. no transmission loss. Voltage and current along the system can be presented as

$$\partial V / \partial x = -L \cdot \partial I / \partial t \quad (1)$$

and

$$\partial I / \partial x = -C \cdot \partial V / \partial t \quad (2)$$

Differentiating equation (1) with respect to $x$ and equation (2) with respect to $t$

$$\partial^2 V / \partial x^2 = -L \cdot \partial^2 I / \partial t \, \partial x \quad (3)$$

and

$$\partial^2 I / \partial x \, \partial t = -C \cdot \partial^2 V / \partial t^2 \quad (4)$$

Then substituting equation (4) into equation (3)

$$\partial^2 V / \partial x^2 = L \cdot C \cdot \partial^2 V / \partial t^2 \quad (5)$$

Equation (5) can be recognized as the basic wave equation for voltage pulse as a function of distance $X$ and time $t$. The reflected electrical signal can be analyzed in the time domain , i.e. at a given instant of time.

The propagation function (or propagation constant) is the voltage pulse propagation velocity, $\gamma$, which is

$$\gamma = (L \cdot C)^{1/2} = v_p \quad (6)$$

for lossless cable.

Another cable parameter is the characteristic impedance, $Z_0$, which is

$$Z_0 = (L/C)^{1/2} \quad (7)$$

for a lossless cable.

**Type of Voltage Reflections**

Coaxial cable deformities produce electrical circuit discontinuities that can be divided into two categories: a change in characteristic impedance $Z_0$(type Ⅰ), or a change in reactive lumped circuit elements (type Ⅱ).[9] Either type Ⅰ or Ⅱ discontinuities produce a reflected voltage pulse. Travel time between initiation and reflection of the pulse allows calculating discontinuity location, while the slope and amplitude of the reflection can be related to specific changes in cable properties. Since individual discontinuities are separated in space, they are also separated in time and thus can be analyzed separately. This relation between location and travel time forms the basis of time domain reflectometry.

Ⅰ. Cable Extension

Extended cable decreases its diameter because of the necking effect. Smaller cross-section maked its characteristic impedance change to $Z_1$, different than the remainder, $Z_0$. At the interface, the reflection coefficient can be defined in terms of characteristic impedances as shown in Fig. 3g[10]

$$\rho = (Z_1 - Z_0)/(Z_1 + Z_0) \quad (8)$$

expressed in terms of its characteristic.

Ⅱ. Cable shear

When the cable is sheared, the deformation and resultant reflection is localized and can be modelled by adding an equivalent capacitance to the lumped circuit system. Then, the reflection, $\rho$, cannot be expressed simply in terms of impedance, but must be idealized by a localized change in capacitance. A plot of voltage vs time for a capacitive discontinuity circuit is presented in Fig. 3f (type Ⅱ) as obtained analytically [11]

$$(0,t) = 1/2[V(t) - V(t - 2l/v_p) \times \exp(-2/Z_0C)(t - 2l/v_p)] \quad (9)$$

where $(0,t)$ is the reflected voltage at point 0 (the origin) as a function of time $t$. The time delay $2l/v_p$ is the time for the signal to travel from the origin to the discontinuity and back. The distance from the origin to the discontinuity is $l$ and $v_p$ is the wave propagation velocity in the coaxial cable. Characteristic impedance and the shunted equivalent capacitance are denoted as $Z_0$ and $C$ respectively.

For the ideal shunted capacitance case (Fig. 3f), the reflection coefficient, $\rho$, can be approximated by [10]

$$\rho = \Delta C \cdot Z_0 / 2 \cdot t_r \quad (10)$$

where

$\Delta C$ = magnitude of the equivalent shunted capacitance,
$Z_0$ =the cable characteristic impedance, and
$t_r$ =the rise time

rather than utilizing equation (9), which requires calculation of the voltage waveform.

**Multiple Reflection**

In a practical TDR measurement, the TDR risetime is finite and the measurement is thus limited in bandwidth. Typical circuit discontinuities along a transmission line have time constants much faster than the TDR risetime. Thus changing the ideal response to an impulse response. This is shown in Fig.4 and the eqivalent capacitance can then be calculated using the following equation.[12]

$$C = \left| \frac{Z}{m \cdot Z_0} \right| \times \left[ E_{r,\max} \right] \quad (11)$$

in above equation, $m = \left. \frac{dE_i}{dt} \right|_{\max} \quad in\ \mathrm{mv/sec}$ (12)

Capacitance is equivalent to the reflection coefficient both in eq.(11) and (12). It means same equivalent capacitance doesn't produce the same drop of voltage, $E_{r,\max}$, if the incident waveform's risetime is different.

The amplitude of small discontinuities will be decreased by the system risetime, which acts as a pulse stretcher. Multiple discontinuities on a transmission line create effects that complicate TDR analysis by virtue of the multiple reflections occurring between them. If the cable of interest is composed of several sections, each with its own distinct characteristic impedance, a part of the incident signal is reflected at each of these impedance discontinuities. Part of each reflected signal will then be again reflected at each subsequent discontinuity so that the amplitudes of the TDR signals beyond the second discontinuity are reduced.

For many practical measuring situations, the discontinuities are small. When they are, the magnitude of the multiple reflections rapidly approaches zero, and many small discontinuities can be analyzed without significant perturbation to each other.

A new approach is proposed to overcome the effect of pulse risetime to the magnitude of drop of voltage as describe in eq. (11). The area method, as shown in Fig. 4, is applied to calculate the equivalent capacitance by integrating the voltage drop overtime.

$$C = \int_{t_1}^{t_2} V(t)dt \quad (13)$$

$t_1$,is the starting point of voltage drop. The lowering section of waveform stands for the drawing of voltage to fill the capacitance. When the waveform returns to its reference level, it means the equivalent capacitance is filled up. On time scale, it is $t_2$.

Verification test

A semi-rigid coaxial cable is used to verify above mentioned procedure. The effect of shunted capacitance is produced by crimping the cable at different locations. Testing cable measures one meter long and can be connected to the TDR machine at both end. The purpose of this test setup is twofold. One is to show the effect of cable deformation can be equivalented to a shunted capacitance without directional consideration. The other is to test the effect of multiple reflection. As shown in fig (5), the cable can be connected to the TDR machine at both end, labelled L and R. One crimp is made at point A, measurements are taken from both end seperately . Then add another crimp at point B , measurements are taken again.

Data reduction and discussion

Testing results reduced from recorded waveform are put together in Table 1. Small and large deformations are used to represent different effect of crimping and to represent different magnitude of reflected voltage change. Number of crimp is used to distinguish cable's discontinuity, when there are two crimps on the testing cable, waveform measurement are taken for both crimps. Connection at L and R are used to represent measurement direction on the cable, And on the last row, % of differences are used to calculate deviation of $E_{r,\max}$ and Area for measuring from different connection individually. Measured waveform presented as graph Fig. 6 and 7 are waveform record for two different conditions, Fig. 6 is for one crimp on the cable and Fig. 7 is for two crimps on it. Fig. 8 and there after are records that have waveforms enlarged for each measurement. Fig. 8 is for a small crimp and Fig. 9 is for a larger one at the location. (L) and (R) are used to label the connecting point. Fig. 10 and 11 are waveform records for the cable having two crimps on it, in which Fig. 10 is for crimp A and Fig. 11 for crimp B. As can be seen from figures, shape of reflected waveform are not the same. It means that the connection shows certain effect on pulse risetime.

On table 1 , data for different connection should be the same because there should be no directional effect for equivalent capacitance. Data for measure point A should be the same for one and two crimps situation because there is no interaction. The result for $E_{r,\max}$ comparison is not acceptable, its difference(in %) could be as large as 17.39% for the two crimps case. But, if the reduction is made using the area concept, the differences(in %) are all controlled within 1%.

Conclusions

TDR technique can be used as the fracture monitoring system for concrete structure. The coaxial cable embedded in the concrete structure works like a continuous fracture and relative movement monitoring sensor which can detect any deformation occurred along its length.

Analysis of multiple reflection using integrated area method to calculate its equivalent capacitance are proved theoretically and experimentally. This analysis technique expand the capability of MTDR monitoring system especially in large concrete structure which may have multiple deformation location to be monitored but not known in advance.

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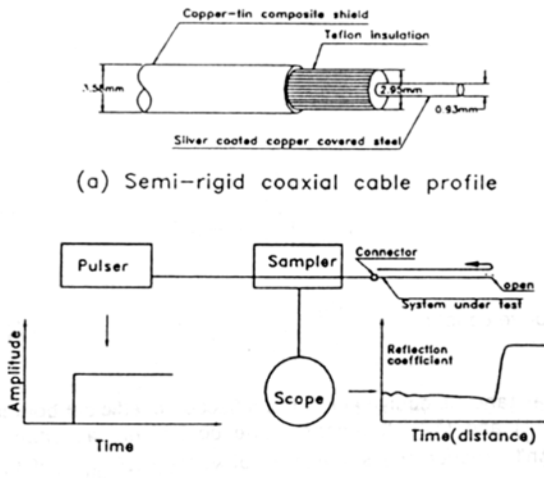
Table 1. Complete lists of test result

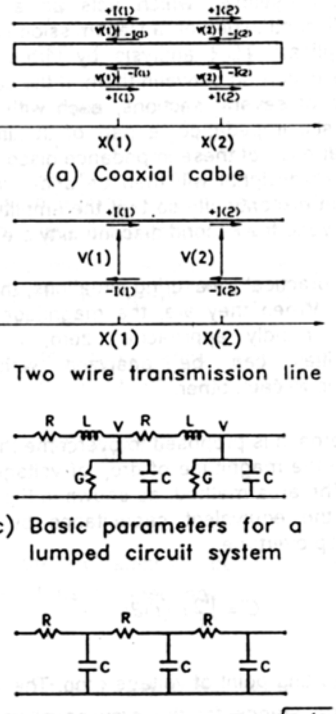
| Deformation type | Small deformation | | Large deformation | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cable crimp | One crimp at A | | One crimp at A | | Two crimps | | | |
| Measure pt. | A | | A | | A | | B | |
| Measure item | $E_r$, max (mρ) | Area (mρ - μs) | $E_r$, max (mρ) | Area (mρ - μs) | $E_r$, max (mρ) | Area (mρ - μs) | $E_r$, max (mρ) | Area (mρ - μs) |
| Connection at L | 28.90 | 1499 | 118.71 | 6743 | 129.03 | 6754 | 110.97 | 6568 |
| Connection at R | 28.65 | 1507 | 116.13 | 6702 | 106.39 | 6718 | 122.32 | 6610 |
| Difference (%) | 0.87 | 0.53 | 2.20 | 0.61 | 17.39 | 0.53 | 9.73 | 0.64 |



(a) Semi-rigid coaxial cable profile

(b) Operating principle

Fig.1. Components of TDR monitoring system



(a) Coaxial cable

(b) Two wire transmission line

(c) Basic parameters for a lumped circuit system

(d) Loss-less system $Zo=\sqrt{R/C}$

Fig.2. Idealizaton of a coaxial cable as lumped circuit system

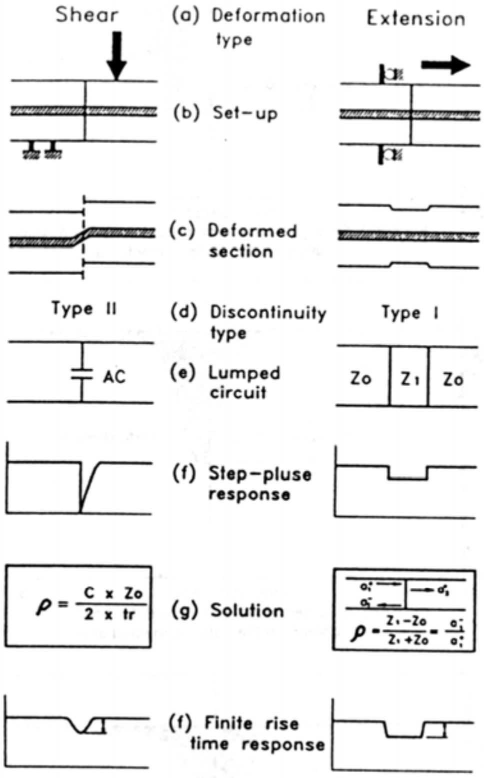



Fig.3.Relationship between cable deformation, type of reflected signal and idealization for analysis (Dowding et. al. 1989)

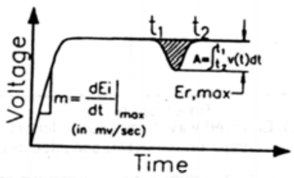



Fig4. Capacitance calculated as integration of voltage drop over time

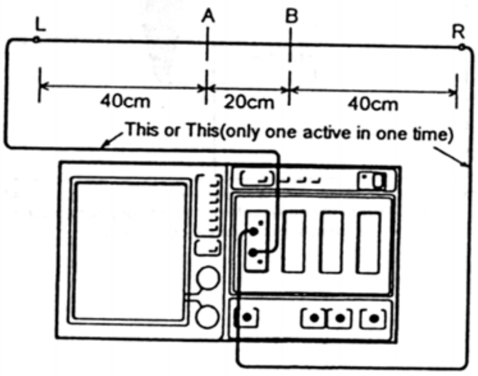



Fig5. Set-up for Verification test

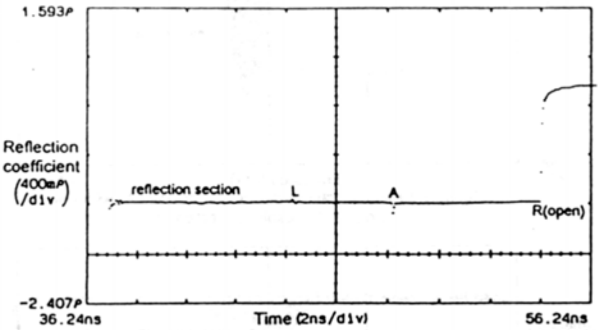



Fig.6(L). Waveform record with one crimp at point A, connected at L

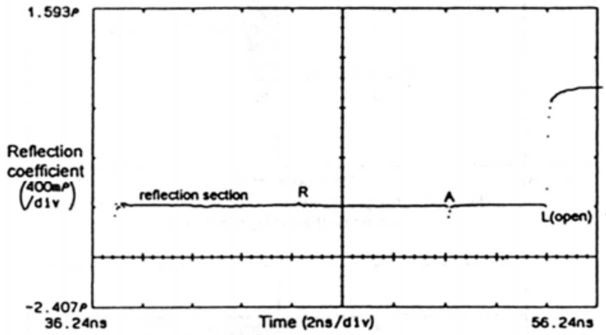



Fig.6(R). Waveform record with one crimp at point A, connected at R

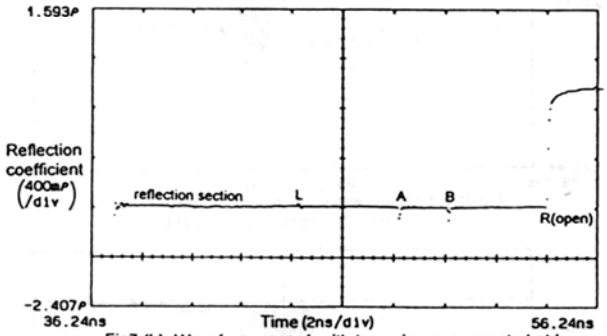



Fig7.(L). Waveform record with two crimps, connected at L

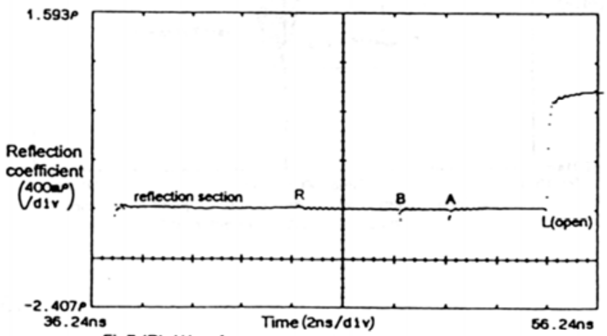



Fig7.(R). Waveform record with two crimps, connected at R

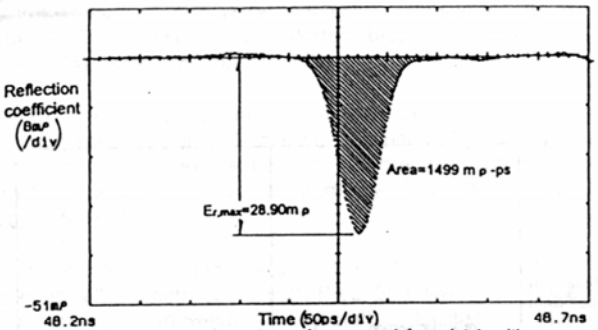


Fig.8(L). Enlarged waveform record for point A, with one crimp on the cable, conected at L

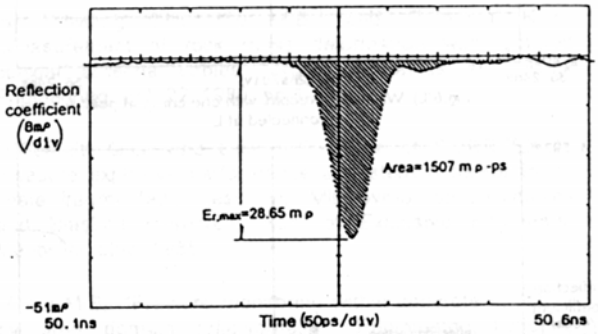


Fig.8(R). Enlarged waveform record for point A, with one crimp on the cable, conected at R

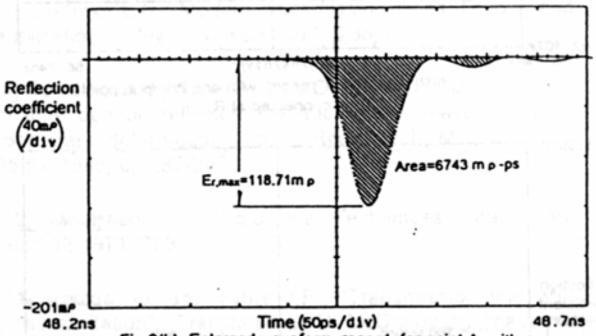


Fig.9(L). Enlarged waveform record for point A, with one crimp on the cable, conected at L

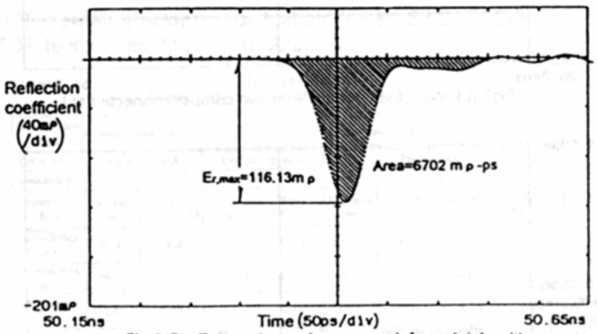


Fig.9(R). Enlarged waveform record for point A, with one crimp on the cable, conected at R

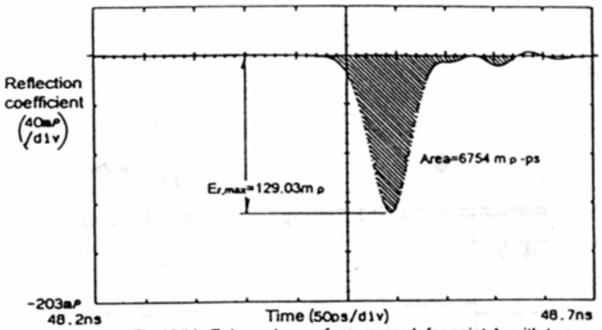


Fig.10(L). Enlarged waveform record for point A, with two crimps on the cable, conected at L

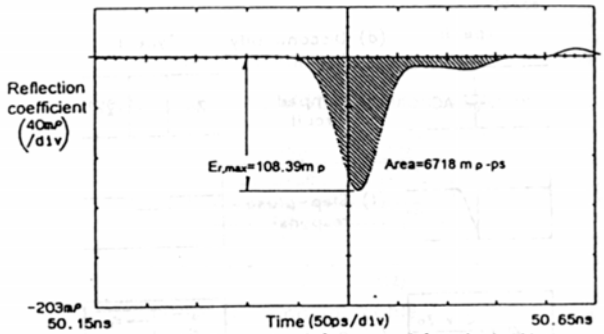


Fig10(R). Enlarged waveform record for point A, with two crimps on the cable, conected at R

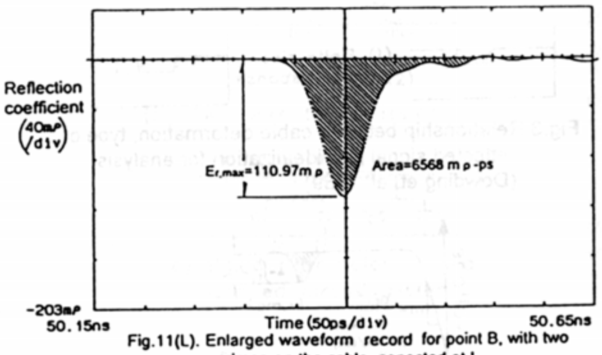


Fig.11(L). Enlarged waveform record for point B, with two crimps on the cable, conected at L

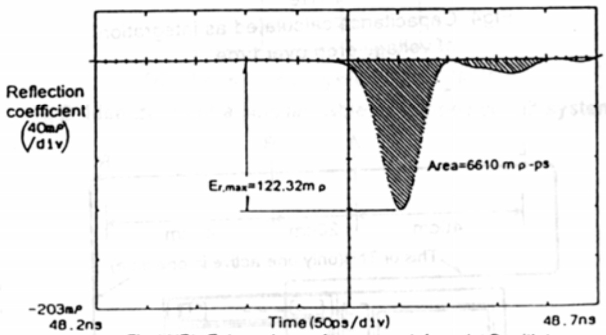


Fig.11(R). Enlarged waveform record for point B, with two crimps on the cable, conected at R