Reconstruction of Nonuniform Transmission Lines from Time-Domain Reflectometry

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***Abstract*— A novel technique is developed to reconstruct the physical structures of a nonuniform transmission line from its time-domain or frequency-domain reflection (scattering) coefficient. This technique takes the past history of reflection processes of nonuniform line into considerations, and its accuracy exceeds that of a conventional time-domain reflectometry (TDR) technique. Experimental results are presented to illustrate the validity of this reconstruction technique.**

I. Introduction

THE time-domain reflectometry (TDR) technique has been widely used to detect discontinuities of signal lines including both RF and optics transmission paths [1]–[4]. Not only does the TDR technique sense the discontinuities of transmission lines, it can also measure the "magnitude" of discontinuities. Perhaps the most versatile property of TDR is that it identifies the locations of discontinuities, which enables field engineers to fix broken cables or fiber wires promptly. The theory of TDR is simple; it is based on the fact that an incident step wave will experience reflection when it encounters a discontinuity, i.e., a reflected step wave will occur. By measuring the reflected step wave in time domain, we can calculate both the characteristic impedance variation and physical locations of discontinuities.

Most of the conventional TDR applications thus far have been limited to the detection of discrete discontinuities of transmission lines. For such a situation, each step change of the reflected wave is caused by a discrete isolated discontinuity. Because of the reasons mentioned previously, conventional TDR techniques fail when the transmission line consists of continuously varying or multiple/complex discontinuities. In other words, the conventional TDR neglects both transformer effect [5] and internal multiple reflection–transmission processes of nonuniform line. For a nonuniform line, the reflected wave at a certain time is due to the superposition of all multiple reflected signals that arrive at the input terminal at that instant time. If the reflected wave at certain time composes several signal components due to several individual discontinuities, the conventional TDR techniques will be unable to separate the reflected signal components caused by the corresponding discontinuities. To characterize the nonuniform line using TDR techniques, it is therefore necessary to study the internal multiple transmission–reflection processes of a signal line, wherein a nonuniform line is treated as a cascaded multiple-section transmission line.

Many authors [1]–[12] have contributed significantly to the study of wave interaction with transmission lines in both frequency and time domains. Most of the work thus far has focused mainly on the formulation and computation techniques of scattering waves on transmission lines. Only a few papers [8]–[10] were concerned with inverse scattering problems in which the structures of transmission lines are obtained from given scattering parameters. Burkhart and Wilcox [8] used a layer-peeling algorithm to generate transmission line profiles that produce arbitrary pulse shape. Hayden and Tripathi [10] employed time-domain measurements to investigate characteristics of multiple line interconnections. These were some of recent studies regarding the TDR applications.

To extend the applications of TDR techniques to the reconstruction of nonuniform transmission lines, we investigate the reflected wave caused by the impedance discontinuity of a nonuniform line. The reflected wave is divided into equal length multiple subintervals wherein the time duration of each subinterval defines the physical length of each subsection of nonuniform signal line. We find that the reflected wave at the input end of nonuniform line is due to the contributions of wavefront and nonwavefront signal components. By decomposing the reflected wave into wavefront and nonwavefront components, an algorithm is developed to convert the reflected wave into the characteristic impedance of nonuniform transmission line as a function of a space variable. Such a technique leads to the reconstruction of lossless nonuniform transmission lines when the reflected wave of a signal is specified in time domain. Several experiments are carried out to verify the theoretical results concerning the reconstruction of nonuniform transmission line from reflected wave in time domain. The results show that this new TDR technique produces better results than the conventional methods widely employed in the traditional TDR equipment.

II. Theory

We consider a reflected wave having an arbitrary waveshape. The reflected wave is due to an incident step wave upon a nonuniform transmission line. As shown in Fig. 1, the reflected wave $V_r(t)$ extends over an interval of time then it reaches a steady-state value as time t becomes large. Here, we assume that for $t \leq 0$ no incident wave exists, and the reflected wave is thus zero. The steady-state value of reflected wave is determined by the source and load terminations. When the terminated resistances on both sides of signal line are equal,

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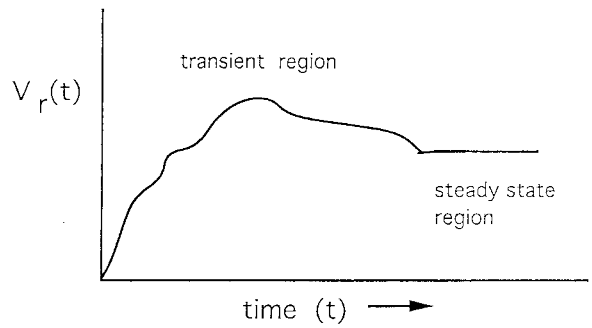


Fig. 1. A postulated reflected wave $V_r(t)$ due to an incident step wave upon a nonuniform line at the input end.

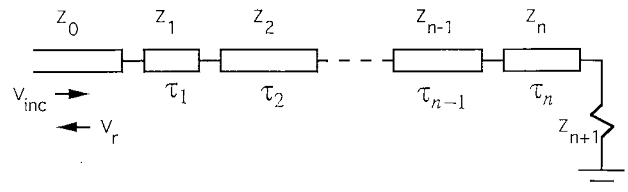


Fig. 2. The incident and reflected waves of a nonuniform line which is represented by a cascaded n-section uniform line.

the steady-state value of reflected wave is zero. For a signal line having continuous variation of characteristic impedance, the reflected wave appears to vary continuously. Of course, if the transmission line composes several sections of discrete signal lines, the reflected wave will be piecewisely continuous. However, each piecewise change in the reflected wave is not solely determined by a single discontinuity junction. Any change in the reflected wave could also be due to many of the impedance discontinuities, which cause the internal reflection-transmission signals to arrive at the input port at the same time. Once the reflected wave is obtained, we intend to find a way to reconstruct the transmission line from the waveshape of reflected wave. In other words, our goal is to obtain the characteristic impedance $Z(x)$ as a function of space once the step reflected wave is given. Here, we limit our attention to dispersionless lossless line, i.e., the transmission line consists of distributed elements only.

The time-domain reflected wave $V_r(t)$ on a nonuniform line is the result of a progressive process in which a reflected wave $V_r(t)$ is the summation of all signal components that suffer from internal multiple reflection–transmission processes and arrive at the input port at time t. In Fig. 2(a), we show an n-section transmission line wherein each section is characterized by the characteristic impedance Z_i $(i = 1, 2, \cdots, n)$ and the propagation delay τ_i. As n approaches infinity, the multiple section line can be used to represent a nonuniform signal line. For an incident step wave having the magnitude V_{inc}, the reflected wave $V_r(t)$ at the input port is [6]

$$
\begin{aligned}
V_r(t) = 2V_{\text{inc}} \Bigg[\Gamma_{0,1} u(t) + \sum_{m=1}^{n} \Gamma_{m,m+1} \\
\prod_{k=0}^{m-1} (T_{k,k+1} T_{k+1,k}) u\left(t - \sum_{k=1}^{m} 2\tau_k\right) \\
\cdot \left(1 + \sum_{i=0}^{m-1} \sum_{j=i+1}^{n} \Gamma_{i+1,i} \Gamma_{j,j+1} \prod_{l=i+1}^{j-1} (T_{k,k+1} T_{k+1,k}) \right. \\
\left. \cdot\, u\left(t - \sum_{k=1}^{m} 2\tau_k - \sum_{l=i+1}^{j} 2\tau_k\right) + \cdots\cdots \right) \Bigg]
\end{aligned} \tag{1a}
$$

where

$$\Gamma_{i,i+1} = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i} \tag{1b}$$

and

$$T_{i,i+1} = 1 + \Gamma_{i,i+1} \tag{1c}$$

and $u(t)$ is the unit step function, $\Gamma_{i,i+1}$ is the reflection coefficient for the signals reflected back into the ith sections at the $i, i+1$ interfaces, and $T_{i,i+1}$ is the transmission coefficient for the signals transmitted from the ith sections into the $i+1$th sections. The single summation term of the first line in (1) represents all the contributions from the single reflections at the discontinuities in the line. Note that every reflected signal suffers from an odd number of reflections at the discontinuities.

As is evident from (1), the conventional expressions of $V_r(t)$ yield little help for us to reconstruct the transmission line once the reflected wave is obtained. If a nonuniform line is treated as a cascaded n-section line, presumedly from (1) we may formulate n equations that relate the reflected wave at n distinct time points and the n characteristic impedances of signal line. The values of characteristic impedances can be obtained by solving these n equations.

A close examination on (1) reveals that the formation of reflected wave $V_r(t)$ is a result of progressive process. The value $V_r(t_s)$ at some specific instant t_s is due to the elements of transmission line that lie on the left side of the point $x = t_s v/2$, where v is the wave propagation velocity in the signal line. To construct a nonuniform line from the reflected wave $V_r(t)$, we divide the reflected wave into n equal-length subintervals, as shown in Fig. 3, where n is a large positive integer. We assume that the reflected wave begins with $t = 0$. Each subinterval expands over a time period of $\tau = t_o/n$, where t_o is the total time of interest. The portion where the reflected wave reaches the steady state contains only information on the terminations. Therefore, we focus on the portion of reflected wave that has transient ripple. As will be shown later, only the first certain portion of reflected wave is needed to completely reconstruct the transmission line. For $t = 0$ (as shown in Figs. 2 and 3) the characteristic impedance is related to the reflected wave $V_r(t)$ as

$$Z_1 = Z_0 \frac{-V_r(0) - 1}{V_r(0) - 1} \tag{2}$$

where Z_0 is the reference characteristic impedance on the left-hand side, Z_1 is the characteristic impedance extending over a physical length $\tau v/2$, and v is the signal propagation velocity. Note that the reflected wave is normalized with respect to the amplitude of incident wave. As we proceed to $t = \tau$, the characteristic impedance Z_2 is related to the reflected wave $V_r(\tau)$ as

$$Z_2 = Z_1 \frac{-V_{r2} - 1}{V_{r2} - 1} \tag{3}$$

where V_{r2} is

$$V_{r2} = \frac{V_r(\tau) - V_r(0)}{[4Z_0Z_1/(Z_0+Z_1)^2]}. \tag{4}$$

The characteristic impedance will again expand over a physical length $\tau v/2$. A close examination on the reflected wave $V_r(t)$ reveals that $V_r(t), t \leq t_o$, is due to the contribution of wavefront reflection as well as nonwavefront reflection, i.e.,

$$\begin{aligned} V_r(t) = & V_{\text{ref}}(\text{nonwavefront reflection}) \\ & + V_{\text{ref}}(\text{wavefront reflection}) \end{aligned} \tag{5}$$

where V_{ref} (wavefront/nonwavefront reflection) represents wavefront and nonwavefront signal components of reflected wave, respectively. The wavefront reflected wave is the wave component that passes through the discontinuity junctions and is reflected back to the input end by the last discontinuity junction of transmission line that the wavefront can reach. The nonwavefront reflected wave, on the other hand, experiences multiple reflection processes at discontinuity junctions other than the last junction of signal line. The reflected wave $V_r(t_l)$ occurring at $t = t_l$ is given by

$$\begin{aligned} V_r(t_l) = & V_{\text{ref}}(\text{nonwavefront reflection}) \\ & + \prod_{j=1}^{j=l-1} T_{j-1,j} \prod_{j=1}^{j=l-1} T_{j,j-1} \frac{Z_l - Z_{l-1}}{Z_l + Z_{l-1}} \end{aligned} \tag{6}$$

where $0 \leq l \leq n$. Because the reflected wave is normalized with respect to the amplitude of incident wave, no incident voltage appears in (6). The term V_{ref} (nonwavefront reflection) is a function of $Z_0, Z_1, \cdots, Z_{l-1}$ but not the the characteristic impedance variable Z_l, and its value can be obtained from (1). Rearranging the formulation in (6), we then get the characteristic impedance Z_l as follows:

$$Z_l = Z_{l-1} \frac{-V_{rl} - 1}{V_{rl} - 1} \tag{7}$$

where V_{rl} is

$$V_{rl} = \frac{V_r(t_l) - V_{\text{ref}}(\text{nonwavefront reflection}, t_l)}{\prod_{j=1}^{j=l-1} T_{j-1,j} \prod_{j=1}^{j=l-1} T_{j,j-1}}. \tag{8}$$

Equations (7) and (8) are the recursive formulations for the reconstruction process of nonuniform line. The new value Z_l is determined by the reflected wave $V_r(t_l)$ and preceding characteristic impedances $Z_0, Z_1, \cdots, Z_{l-1}$. The conventional TDR technique indicates that Z_l depends on the value of $V_r(t_l)$ only [1], [2] and is independent of any value of reflected wave for $t < t_l$. The novel technique described here reveals that the value of Z_l depends on the sequences and values of $V_r(t)$ for $t \leq t_l$. In other words, to obtain Z_l, we not only need to know the value of $V_r(t_l)$, but also we need to have the history of $V_r(t)$. A given value of $V_r(t_l)$ subject to different history of $V_r(t)$ $(t \leq t_l)$ will yield different value of Z_l $(t \leq t_l)$. It is pertinent to point out that the reconstruction process is valid for nonuniform lines providing that the step size τ is small enough to accurately represent the changes. Clearly, the piecewise constant approximation to the transmission line will fail over any section of the line that has a rapid change in impedance.

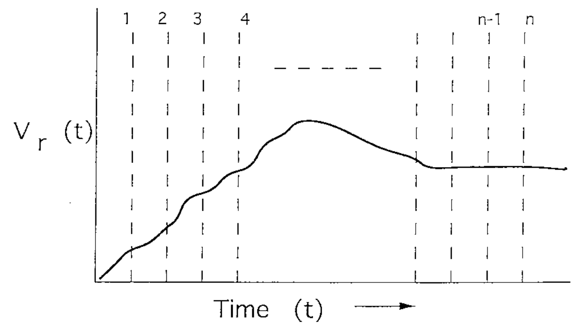


Fig. 3. A reflected wave is divided into n equal subintervals in time domain.

In general, the transient ripple of a nonuniform transmission line will last a rather long time, which could be much longer than the round trip time for the wave traveling back and forth the nonuniform section of signal line. This indicates that in the computation procedure, we may reach a converged load characteristic impedance at the load end well before the appearance of steady-state condition of the reflected wave. However, it is very difficult to determine the round-trip time of nonuniform line by merely observing the reflected wave $V_r(t)$. To assure the completeness of reconstruction of nonuniform lines, it is, therefore, a conservative choice that the time of interest extends from $t = 0$ to $t = t_o$, wherein the steady state is reached. If the round-trip transit time of nonuniform line is known, the reconstruction process only needs to consider a time equal to round-trip transit time from end to end of the unknown section. Another advantage of such a reconstruction process is that the portion following after the essential part of interest will not affect results of reconstruction.

III. Numerical Example

We present numerical as well as experimental results to illustrate the validity of the above reconstruction procedures for nonuniform transmission lines. The step response of the reflected wave of a nonuniform line is needed to complete the reconstruction process. However, it also may be obtained indirectly from the Fourier transformation of its corresponding frequency response of the signal line if sufficient bandwidth is included.

In Fig. 4, we show reflected waves of exponential lines terminated with matched loads at both ends of the signal lines when a unit step wave is incident upon the signal lines. The characteristic impedance of the signal line as a function of the space variable x is given by

$$Z(x) = Z_S \exp\left[\frac{\ln(Z_L/Z_S)}{l} x\right] \tag{9}$$

where l is the physical length and Z_S and Z_L are the characteristic impedances at the left (source) and right (load) sides of the exponential line, respectively. The step responses in Fig. 4 are obtained by taking direct integrations of their time-domain scattering parameters [7] for both $Z_L/Z_S = 9$ and $Z_L/Z_S = 4$, respectively. The horizontal scale is the time normalized to propagation delay across the line, i.e., $t = 1$ designates

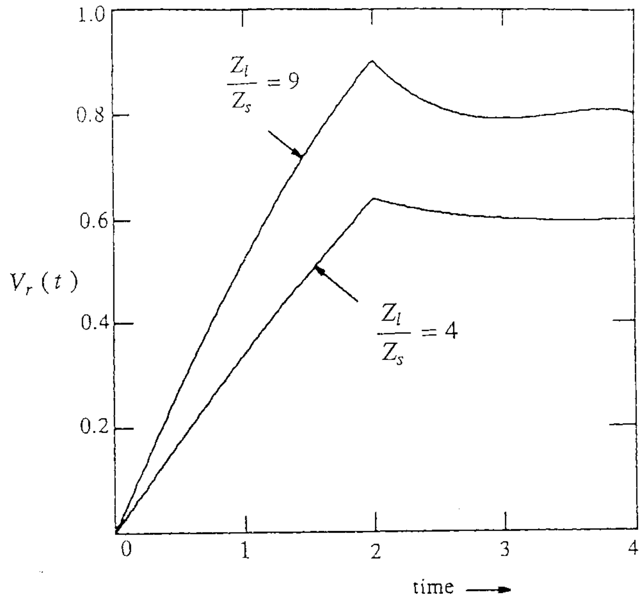


Fig. 4. The reflected waves $V_r(t)$ due to an incident step wave upon exponential signal lines from the source ends.

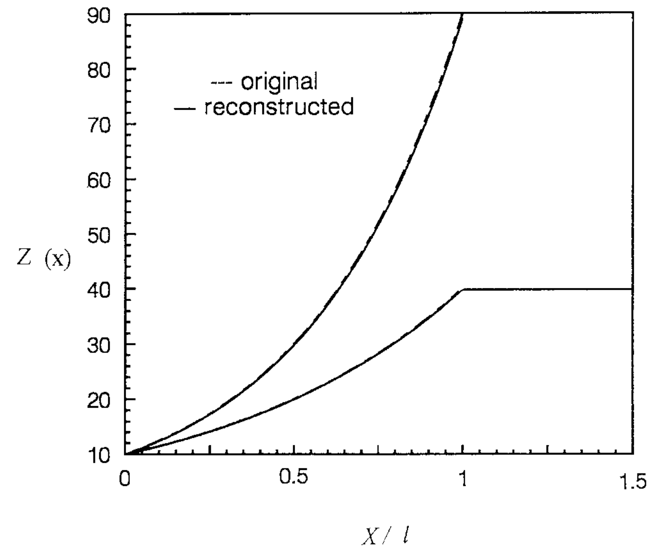
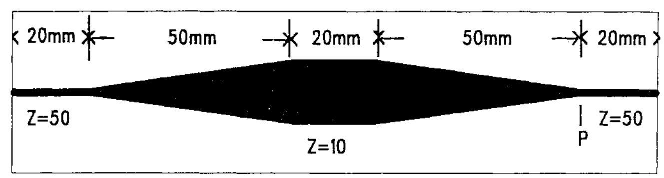
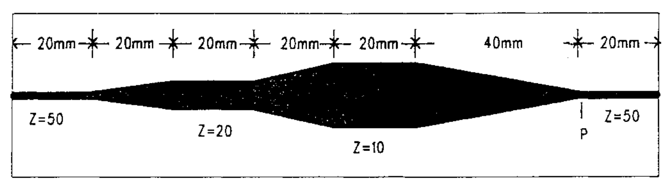


Fig. 5. The reconstructed and original exponential lines as a function of space variable x.



(a)



(b)

Fig. 6. The physical layouts of two nonuniform microstrip lines.

the time elapsed for signal traveling across the signal line. To reconstruct the signal line, we divide the reflected wave in Fig. 4 into 400 equal subintervals τ. Note that the wave has the same propagation velocity v in each portion of the exponential line [7]. The reconstructed signal line consists of cascaded multiple sections; each section has a characteristic impedance Z_i and a physical length of $v\tau/2$. Fig. 5 shows the variation of characteristic impedances of reconstructed signal lines as a function of x/l. We assume that Z_S is 10 Ω for both cases. To illustrate the accuracy of the reconstructed nonuniform lines, in Fig. 5 we show the dashed lines that represent the impedance of the exponential lines calculated by (9). Apparently, the characteristic impedance of the reconstructed nonuniform line reaches its steady-state value at $l/x = 1$, which corresponds to $t = 2$ in Fig. 4. This example reveals that the transition ripples for $t \geq 2$ in Fig. 4 are due to internal reflection–transmission processes of exponential lines, which are not caused by other reflection mechanism occurring at $x > l$. Since the line is terminated at both ends in a matched impedance, we should have realized that all time-domain activity after $t = 2$ must be due to multiple internal reflections even before the numerical simulation was run. However, our calculation results in Fig. 5 involve the time-domain response for $t \geq 2$ in Fig. 4.

IV. Experimental Results

Fig. 6 shows the layouts of two nonuniform microstrip lines. The variation of characteristic impedances as a function of space is also shown in the figure. Notice that the change from 50 to 10 Ω in Fig. 6(a) is set so that the width of signal line varies linearly. Therefore, the characteristic impedances of signal line may not vary linearly. A similar situation holds for the nonuniform line in Fig. 6(b). These two microstrip lines are built on Duroid substate having thickness 31 mils and relative dielectric constant 2.5. We use an HP8510C network analyzer to measure the reflection scattering parameters $S_{11}(f)$ of these two nonuniform microstrip lines with a frequency of 45 MHz–18.045 GHz. Complex reflection data are obtained at each 22.5-MHz interval. The reflection coefficient is set to zero at dc and $S_{11}(f)$ at 22.5 MHz is assumed to be the average value of reflection coefficients at dc and 45 MHz. These two data are added manually because of the limitation of operation frequency range of HP8510C network analyzer. Although HP8510C network analyzer provides some form of time-domain responses, the data is not useful for our method. These complex frequency-domain reflection coefficients are converted into time-domain parameters by taking an inverse Fourier transform via MATLAB software tool. It is pertinent to point out that to obtain real causal solution in time domain, it is necessary to get the complex conjugate of $S_{11}(f)$ first before performing inverse Fourier transformation. That is, the reflection coefficient [12] is cast in the form of

$$S_{11}^{*}(f) = S_{11}(-f). \quad (10)$$

To obtain the step response of nonuniform line from its frequency-domain coefficient, we employ the series form of inverse Fourier transform [13], which is as follows:

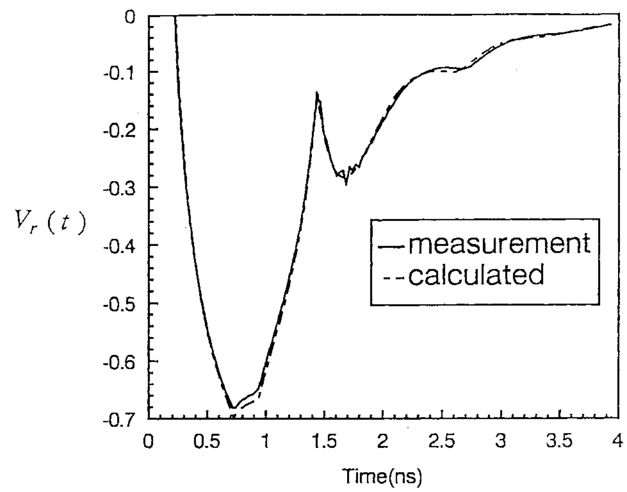
$$\left[\frac{1}{1-e^{-jk(2\pi/N)}}\right]a_k \xrightarrow{idft} \sum_{k=-\infty}^{n} V[k] \tag{11}$$

where $idft$ represents inverse discrete Fourier transform, $k, n = 0, 1, \cdots, N$, and N is the number of data involved in the computation, a_k is the frequency-domain reflection coefficient, and $\Sigma\ V[k]$ is the step response in time domain. Such an approach is employed due do the fact that using a step function is much more efficient from a computational standpoint than using the impulse function. The Fourier transform of the impulse is constant over all frequencies while the step function decreases as $1/f$ away from dc. This falloff helps the integral converge faster which is critical with band-limited data.

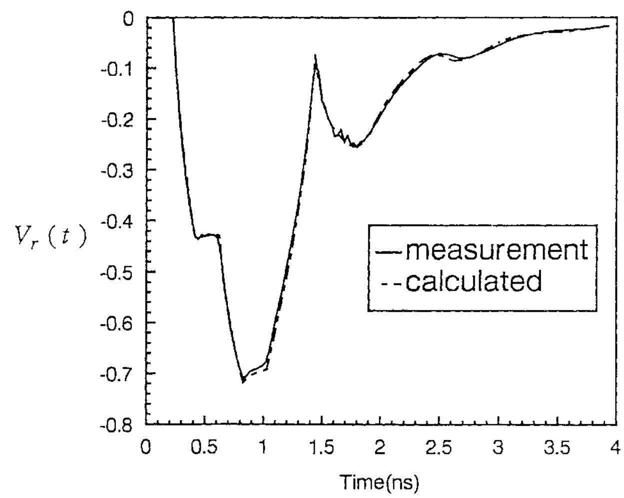
Fig. 7(a) and 7(b) are the reflected step responses $V_r(t)$ of nonuniform lines in Fig. 6(a) and (b), respectively, which are obtained by measuring scattering parameters $S_{11}(f)$ via network analyzer and taking the proper inverse Fourier transforms. When a step wave is incident upon these nonuniform lines due to the small value of characteristic impedance in the signal line, it produces negative reflected waves at the input ends of signal lines. As shown in Fig. 7, the reflected waves suffer several abrupt changes at the discontinuous junctions. Apparently, the reflected step waves last a rather long time before they reach steady-state value. The dashed lines in Fig. 7 show the reflected step waves of the nonuniform lines which are achieved by directly computing the reflected waves in time domain, as shown in (1). Since the width of nonuniform line is given (as shown in Fig. 6), the characteristic impedance Z_o and effective dielectric constant ε_e (or propagation delay) at every point on the nonuniform lines can be computed [11] from the following:

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{1}{(1 + 12d/W)^{1/2}} \tag{12a}$$

and (12b), shown at the bottom of the page, where ϵ_r is the relative dielectric constant of substrate, d is the thickness of substrate, and W is the width of signal line. Here, we assume that the structures are lossless and they are independent of signal frequencies. Clearly, the results obtained from experiments are in good agreement with those obtained by theoretical calculation. Such close agreement indicates that the $S_{11}(f)$ data obtained from HP8510C network analyzer are very accurate. In numerical calculation, we assume that the microstrip line structures considered here are lossless for the frequency range of interest. Fig. 8(a) and (b) shows the reconstructed characteristic impedances of nonuniform lines as a function of space variable x for the nonuniform lines in Fig. 6(a) and (b), respectively. Notice that two nonuniform



(a)



(b)

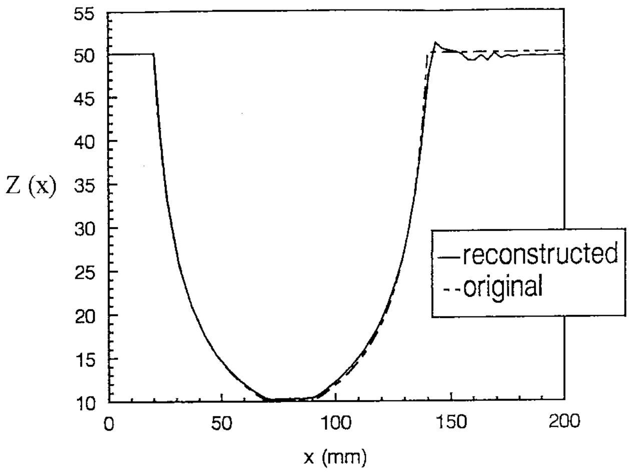
Fig. 7. The time-domain reflected waves of nonuniform lines in Fig. 6(a) and (b), respectively. The reflected waves are obtained from HP8510C network analyzer and inverse Fourier transform.

lines in Fig. 6(a) and (b) have the same physical length from the left end to the right end. We obtain the reconstructed characteristic impedances $Z(t)$ from $V_r(t)$ in Fig. 7 via (7), where t is the time. $Z(t)$ is then converted into $Z(x)$ by using the time-to-space translation:

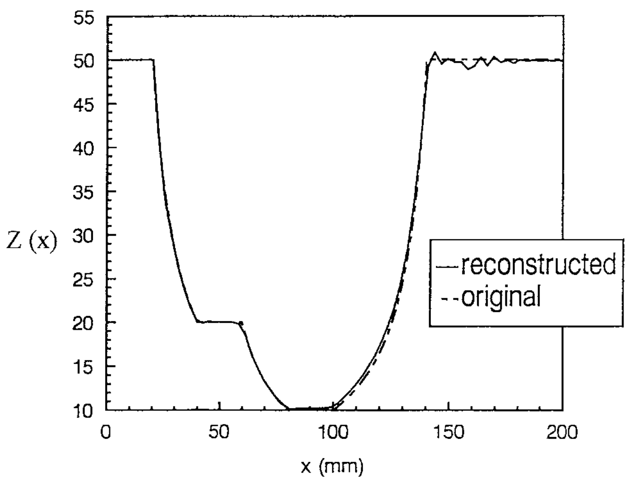
$$\Delta x = \frac{v\tau}{2} = \frac{c\tau}{2(\varepsilon_e)^{1/2}} \tag{13}$$

where Δx is the space subinterval, τ is the time subinterval, v is the signal propagation velocity, c is the speed of light in vacuum, and ε_e is the effective dielectric constant. As shown in (12), the effective dielectric constant ε_e can be obtained [11] if the characteristic impedance Z_o and relative

$$Z_o = \begin{cases} \dfrac{60}{(\varepsilon_e)^{1/2}} \ln\left(\dfrac{8d}{W} + \dfrac{W}{4d}\right) & \text{for } W/d \le 1 \\ \dfrac{120\pi}{(\varepsilon_e)^{1/2}[W/d + 1.393 + 0.667\ \ln(W/d + 1.444)]} & \text{for } W/d \ge 1 \end{cases} \tag{12b}$$

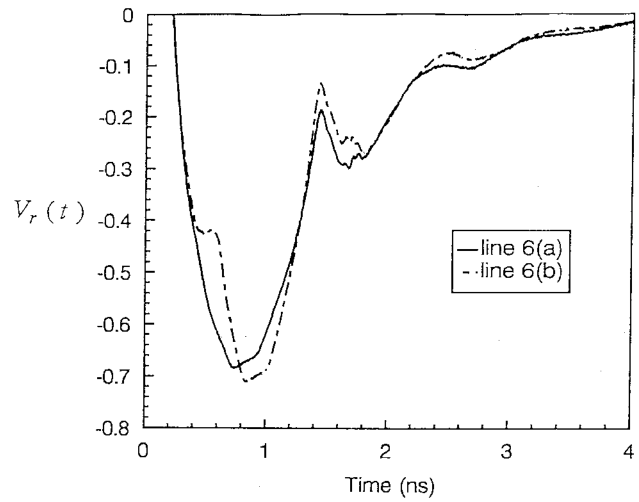


(a)

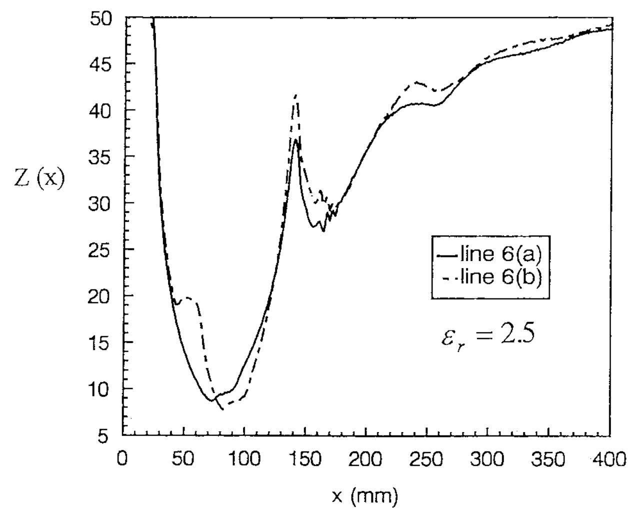


(b)

Fig. 8. The characteristic impedance distribution of original and reconstructed nonuniform lines for the configurations in Fig. 6(a) and (b), respectively.



(a)

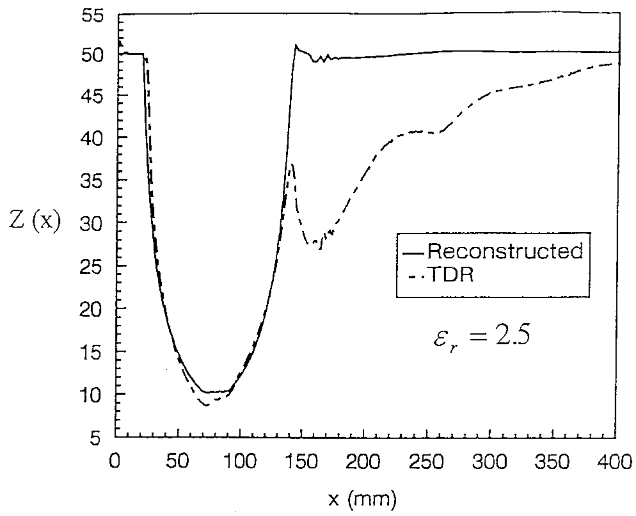


(b)

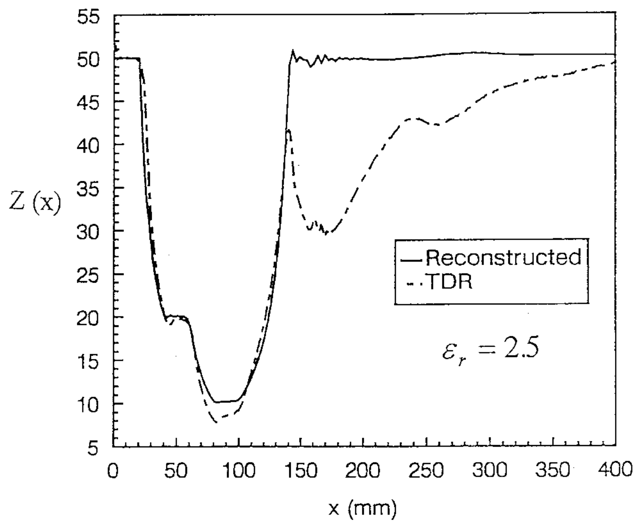
Fig. 9. HP54750A TDR measurement results of nonuniform lines in Fig. 6. (a) The reflected wave $V_r(t)$. (b) The characteristic impedance $Z(x)$.

dielectric constant ε_r are given. For convenience, we show the characteristic impedances computed from the physical layouts in Fig. 6, which are shown in dashed lines. The results reveal that the wavefront reaches point P in Fig. 6 and is reflected back to the input end at time $t = 1.42$ ns. The transient ripple occurring after $t = 1.42$ ns is due to internal reflection-transmission processes of nonuniform lines and is not caused by the reflection processes for the wavefront traveling beyond point P. The small transient ripple at time $t \approx 1.7$ ns is due to the mismatched effect of microstrip-to-coax connector on the right-hand side of nonuniform line, where the right-hand side connector is loaded with a 50-Ω termination. Note that this reconstruction method is based on the assumption that the nonuniform transmission lines are lossless and dispersionless. This method fails if losses and/or dispersion play a significant role.

To compare the results with those obtained from the conventional TDR measurements, in Fig. 9 we show the direct TDR measurement results of microstrip lines. Fig. 9(a) depicts the time-domain reflected wave $V_r(t)$ and Fig. 9(b) shows the measured characteristic impedance $Z(x)$. The experimental data are attained by employing HP54750A digital oscilloscope/TDR instrument. It is clear that the reflected waves $V_r(t)$ of TDR measurements are in good agreement with those obtained from network-analyzer/inverse Fourier-transform method. The HP54750A TDR measurements give us inaccurate characteristic impedances of the nonuniform microstrip lines in Fig. 6. Such a discrepancy is due to the fact that the conventional TDR method converts the reflected wave into the characteristic impedances by assuming that the the reflected wave $V_r(t)$ occurring at time t is caused only by the strike of step-incident wavefront at the discontinuity junction $x = vt/2$ with v being the propagation velocity of signal. The effect of such a faulty assumption on the measurement of characteristic impedance is twofold: it disregards the transformer effect of transmission line on the incident wavefront and it neglects the contribution of internal multiple reflection–transmission process to the reflected wave [5]. The former feature causes the inaccuracy in the magnitude of the characteristic impedance. The latter effect causes the "spreading" of nonuniform portion of the reconstructed



(a)



(b)

Fig. 10. The comparison between TDR results and the results in Fig. 8. (a) Signal line in Fig. 6(a). (b) Signal line in Fig. 6(b).

signal line in Fig. 9. In other words, the neglect of internal transmission–reflection phenomenon causes the deviation of characteristic impedance from 50 Ω for $t \geq 1.42$ ns in Fig. 9. For convenience, in Fig. 10 we show the comparison between the TDR measurement results and the results $Z(x)$ in Fig. 8.

V. Conclusion

We have developed a novel reconstruction technique for lossless nonuniform transmission lines. Such a reconstruction technique is superior to the conventional TDR method which is proven to be inaccurate when a transmission line consists of multiple discontinuities. This reconstruction technique is applicable to many other physical structures as long as those structures can be represented by equivalent transmission-line representations.

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