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PHENOMENA OF PAIRED ECHOES AND TRANSMISSION CHARACTERISTICS OF THE PULSE SIGNAL IN DISPERSIVE TRANSMISSION LINES WITH DISCONTINUITIES

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Abstract—The performance of wideband radar system may be degraded by signal distortion occurring in anyplace of the transmission channel of the system. If the amplitude response is not flat or the signal delay is not constant in the transmission of the wideband signal, then signal distortion will occur, which can reduce the SNR and resolution. The available theory indicates that a small sinusoidal ripple variation in either amplitude-frequency or phase-frequency response of a linear system will cause signal distortion and the phenomena of paired echoes in the output signals of the time domain. In this paper, whether a dispersive transmission line with discontinuities will lead to the phenomena of paired echoes is discussed by means of finite difference time domain (FDTD) method and theoretical analysis. The results show that the technique of paired echoes is unsuited to analyze the influence of dispersive transmission line with discontinuities on time domain pulse signal. The method of Taylor series expansion shall be chosen as a more appropriate method. Meanwhile, simulations also show that a pulse signal transmitting in dispersive transmission lines with discontinuities including passive components such as filters and directional couplers will not lead to the phenomena of paired echoes.

1. INTRODUCTION

Owing to the existence of dispersive characteristics and discontinuities in microwave and millimeter-wave transmission line systems, the time domain pulse signal will become distortional during propagation. The signal distortion will make the extraction of the signal's characteristic parameters more difficult. Through simulation analysis

for propagation of time domain pulse signal, the influence due to dispersion and discontinuities of transmission line is investigated in this paper. Moreover, whether dispersion and discontinuities of transmission system will lead to the phenomena of paired echoes are also discussed. The effect of the amplitude and phase of signal deviating from the ideal is often studied by using the technique of paired echoes (not to be confused with target echoes). The technique was proposed by MacColl in 1931 [1] and developed further by Wheeler in 1939 [2]. It states that a small sinusoidal variation of either phase or amplitude with frequency in a linear system will produce a pair of echoes in waveform of the output signal, one lagging and the other leading the major response to the input signal.

Any actual system will produce some distortion. Signal distortion of radar is produced by amplitude and phase ripple associated with the radar's transfer function. The total transfer function is the product of individual transfer functions of components in the signal transmission path, including transmitter, transmission line, antenna, propagation media, receiver components and signal procession. According to this technique, for a nonideal but linear system where the time domain pulse signal is inputted, if the amplitude and phase of the transfer function of the system can be described as a Fourier series expansion on the frequency band of interest and not all first order items of expression are zero, then the system will produce the phenomena of paired echoes. This phenomena were also analyzed in band-pass systems [3, 4]. The technique of paired echoes has been successfully applied to the error analysis of amplitude and phase fluctuations of transfer function and extended to analysis of other nonideal models, in which the nonideal characteristics can be represented by convenient series of ideal model over the parameter range of interest [5]. When the input signal is linear FM signal, the distortion of characteristics in frequency domain or waveform in the time-domain in launching system will result in the phenomenon of paired echoes of impulse response [6, 7].

The transmission characteristics and scattering characteristics of electromagnetic waves in dispersive media, discontinuous structure have been extensively researched [17–22]. This paper mainly discusses the topic that whether dispersion and discontinuities of microwave and millimeter-wave transmission line system will lead to the phenomena of paired echoes of time domain pulse signal. The contents consist of two parts. The first part discusses whether dispersion of transmission system will induce the phenomena of paired echoes. Firstly, the technique of paired echoes is analyzed briefly. Then the FDTD method, which is one of full-wave analysis methods, is applied to simulate the dispersive transmission system in order to determine whether the

phenomena of paired echoes exist when the time domain pulse signal is transmitted. Finally, we prove that the technique of paired echoes is unsuitable to analyze this system. The method of Taylor expansion should be chosen.

The second part discusses whether the discontinuities of transmission system will induce the phenomena of paired echoes. As we know, a single mismatch in source port or load port of a dispersive transmission line system will not introduce non-linear insertion phase shift. However, if two or more mismatches occur anywhere along the transmission line, a nonlinear phase variation with frequency will appear [8]. The variation of phase can be represented as a kind of ripple form. Whether the ripple form of the phase will produce the phenomena of paired echoes is the focus of our attention. In this paper, we explore the influence of discontinuities by simulating typical components such as filters, directional couplers.

2. THE TECHNIQUE OF PAIRED ECHOES AND ITS PARAMETERS ANALYSIS

A linear system can be described by its transfer function $H(\omega)$ or impulse response $h(t)$ as follows [9]:

$$s_o(t) = h(t) * s_i(t) \tag{1}$$

$$S_o(\omega) = H(\omega) \cdot S_i(\omega) \tag{2}$$

where $s_i(t)$ is the input signal of the system, $s_o(t)$ is the output signal, $S_i(\omega)$ represents the spectrum of the input signal, $S_o(\omega)$ represents the spectrum of the output signal, the asterisk "$*$" denotes convolution, ω is angular frequency, that is,

$$S_i(\omega) = \int_{-\infty}^{+\infty} s_i(t)e^{-j\omega t}dt, \quad S_o(\omega) = \int_{-\infty}^{+\infty} s_o(t)e^{-j\omega t}dt \text{ and } \omega = 2\pi f.$$

The steady-state transfer function of a linear network is expressed in complex form as

$$H(\omega) = A(\omega)e^{j\phi(\omega)} \tag{3}$$

where$A(\omega)$, $\phi(\omega)$denote the amplitude and phase response of system respectively.

For a non-distortion linear system, the transfer function must satisfy

$$A(\omega) = a_0 \tag{4a}$$

$$\phi(\omega) = b_0\omega \tag{4b}$$

where the Eq. (4a) denotes that the amplitude-frequency response $A(\omega)$ is a constant independent of frequency; the Eq. (4b) denotes that the phase-frequency response $\phi(\omega)$ increases linearly with frequency and produces the constant delay of output signal in time domain. It is well-known that a pulse signal is undistorted when it transmits through an ideal linear system, and only produces a time delay. However, in any actual linear system signal distortion including amplitude distortion and phase distortion is inevitable because there are always the fluctuations of the phase and amplitude.

MacColl had depicted a nonideal but linear system by perturbing the amplitude-frequency and phase-frequency of an ideal linear system and put forward the famous technique of paired echoes. The specific contents are described as follows.

Assume that transfer function of a system is

$$A(\omega) = a_0 + \sum_{i=1}^{\infty} a_i \cos(ic\omega) \tag{5a}$$

$$\phi(\omega) = b_0\omega + \sum_{i=1}^{\infty} b_i \sin(ic\omega) \tag{5b}$$

where (5a) represents the cosine error modulation of amplitude response, (5b) represents the sinusoidal error modulation of phase response, a_i and b_i are constants, c is common modulation parameter of the two kinds of error modulations.

If only one term of the Fourier series (5a) and (5b) is considered, the model (5) is simplified to

$$A(\omega) = a_0 + a_1 \cos(c\omega) \tag{6a}$$

$$\phi(\omega) = b_0\omega + b_1 \sin(c\omega) \tag{6b}$$

To obtain $s_o(t)$ from $s_i(t)$, we can get $S_o(\omega)$ by (2), then obtain $s_o(t)$ by Fourier inverse transform with $S_o(\omega)$, that is,

$$\begin{aligned} S_o(\omega) &= H(\omega) \cdot S_i(\omega) = (a_0 + a_1 \cos c\omega) e^{j(b_0\omega + b_1 \sin c\omega)} S_i(\omega) \\ &= \left(a_0 + a_1 \frac{e^{jc\omega} + e^{-jc\omega}}{2} \right) e^{jb_0\omega} S_i(\omega) e^{jb_1 \sin c\omega} \end{aligned}$$

The last factor of above expression can be simplified by means of Jacobian equation. Jacobian equation is essentially the expansion of

Bessel generating functions, that is,

$$\cos[\beta \sin \omega_m t] = J_0(\beta) + 2\sum_{n=1}^{\infty} J_{2n}(\beta) \cos[2n\omega_m t] \tag{7a}$$

$$\sin[\beta \sin \omega_m t] = 2\sum_{n=1}^{\infty} J_{2n-1}(\beta) \sin[(2n-1)\omega_m t] \tag{7b}$$

After expanding $S_o(\omega)$ by (7), by Fourier inverse transform we can obtain

$$\begin{aligned} s_o(t) = {} & a_0 J_0(b_1) s_i(t+b_0) \\ & + J_1(b_1)\left[\left(a_0+\frac{a_1}{b_1}\right)s_i\,(t+b_0+c) - \left(a_0-\frac{a_1}{b_1}\right)s_i(t+b_0-c)\right] \\ & + J_2(b_1)\left[\left(a_0+\frac{2a_1}{b_1}\right)s_i\,(t+b_0+2c) + \left(a_0-\frac{2a_1}{b_1}\right)s_i(t+b_0-2c)\right] \\ & + J_3(b_1)\left[\left(a_0+\frac{3a_1}{b_1}\right)s_i\,(t+b_0+3c) - \left(a_0-\frac{3a_1}{b_1}\right)s_i(t+b_0-3c)\right] \\ & + \cdots\cdots \end{aligned} \tag{8}$$

As the amplitude of error modulations, a_1 and b_1 are small. When $b_1 \ll 1$, by means of a small argument approximation of Bessel function:

$$\lim_{x\to 0} J_0(x) = 1 - \left(\frac{x}{2}\right)^2; \quad \lim_{\substack{x\to 0 \\ n\neq 0}} J_n(x) = \frac{(x/2)^2}{n!} \tag{9}$$

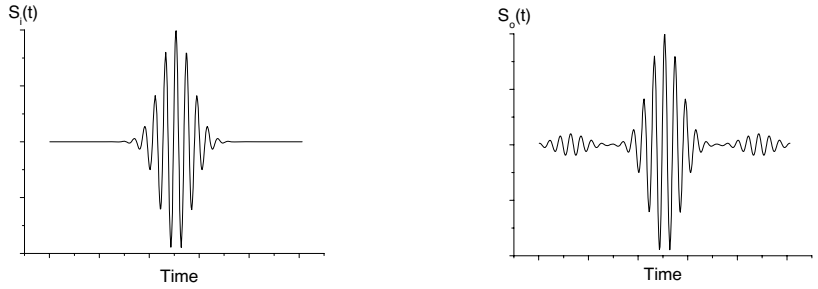
and we have

$$J_0(b_1) \approx 1, \quad J_1(b_1) \approx \frac{b_1}{2}, \quad J_n(b_1) \approx 0 \quad (n \geq 2) \tag{10}$$

Substituting (10) into (8), (8) becomes

$$\begin{aligned} s_o(t) = {} & a_0 J_0(b_1) s_i(t+b_0) \\ & + J_1(b_1)\left[\left(a_0+\frac{a_1}{b_1}\right)s_i(t+b_0+c) - \left(a_0-\frac{a_1}{b_1}\right)s_i(t+b_0-c)\right] \\ = {} & a_0\left[s_i(t+b_0) + \frac{1}{2}\left(b_1+\frac{a_1}{a_0}\right)s_i(t+b_0+c)\right. \\ & \left. + \frac{1}{2}\left(\frac{a_1}{a_0}-b_1\right)s_i(t+b_0-c)\right] \end{aligned} \tag{11}$$

When $c > 0$ in (11), $s_i(t + b_0)$ is the "mainlobe" of the output waveform, $s_i(t + b_0 + c)$ is the "sidelobe" which leads the "mainlobe" and $s_i(t + b_0 - c)$ is the "sidelobe" which lags the "mainlobe". Fig. 1 is the schematic diagram of the phenomena of paired echoes.



(a) The waveform of input signal (b) The waveform of output signal

Figure 1. The schematic diagram of the phenomena of paired echoes.

From (8) and (11), we know that

(1) when b_1 is much less than 1, it is completely reasonable to consider the first pair of sidelobe because the values of high-order Bessel function of b_1 are very small;

(2) when $a_1 = 0$ or $b_1 = 0$, the phenomenon of paired echoes still exist;

(3) when $a_1 = 0$ and $b_1 = 0$, there are only the main response and not the phenomenon of paired echoes, which corresponds to the case of the ideal linear system.

3. THE DISCUSSION WHETHER DISPERSIVE TRANSMISSION LINE WILL LEAD TO THE PHENOMENA OF PAIRED ECHOES

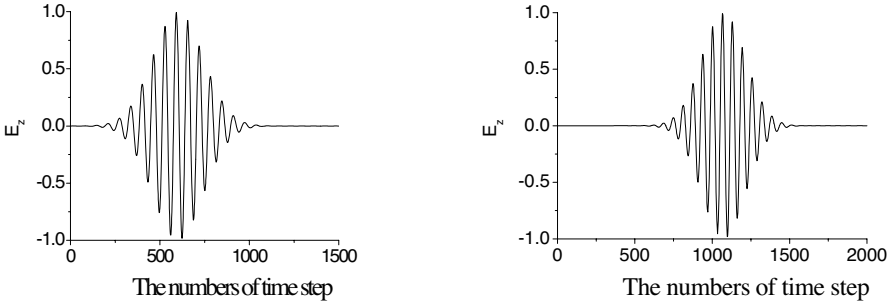
3.1. FDTD Simulation of the Pulse Signal Transmitting in Dispersive Transmission Line

The FDTD method can give the evolution process of electromagnetic fields conveniently, and furthermore, display the physical processes clearly [10–12, 23]. Therefore, the FDTD method is adopted to discuss whether dispersive transmission line will lead to the phenomena of paired echoes. The standard rectangular waveguide of W-band is taken as example.

The parameters of simulation model are set as follows: broadside a and narrow side b of the rectangular waveguide are 2.54 mm and

1.27 mm respectively; the input signal is Gaussian pulse with the center frequency of 94 GHz; only the dominant mode H_{10} is transmitted and x axis is the transmission direction; the step length of mesh $\Delta s = a/20$; the time step $\Delta t = \Delta s/2c$. These settings are enough to ensure the stability of numerical calculation. The two ports of the waveguide are truncated by the PML absorbing boundary.

Simulating results is indicated in Fig. 2. Although the output waveform has changes in magnitude and phase shift compared with the input waveform, there is no the so-called phenomenon of paired echoes in hollow waveguide whose transmission length of is 16.5 mm. The electromagnetic wave is transmitted without reflection. The transmission coefficient S_{21} of the network is nearly equal to 1 and the reflection coefficient S_{11} closes to zero.



(a) The time domain waveform of input signal

(b) The time domain waveform of output signal

Figure 2. The waveform of input signal and output signal under dominant mode.

In order to enhance the dispersion of transmission line, we increase the length of the waveguide to 25.4 mm and adopt same excitation source as shown in Fig. 2(a); there is still no phenomenon of paired echoes on the output signal which is shown in Fig. 3. Furthermore, a waveguide filled with E-plane dielectric slab ($\varepsilon_r = 6$, $\tan\delta = 1 \times 10^{-3}$) as shown in Fig. 4 is also simulated when both material dispersion and mode dispersion are embodied, where $a = 2.54$ mm, $b = 1.27$ mm, $a_1 = 0.8$ mm and the waveguide length $l = 20$ mm. The simulation results as shown in Fig. 5 indicate that there is no phenomenon of paired echoes on the output signal although the dispersive characteristics brings the distortion of pulse signal, for example, a decrease of amplitude and the trailing phenomenon in the output waveform.

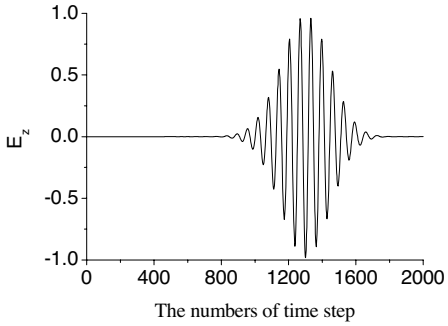


Figure 3. The output waveform of waveguide with increased length.

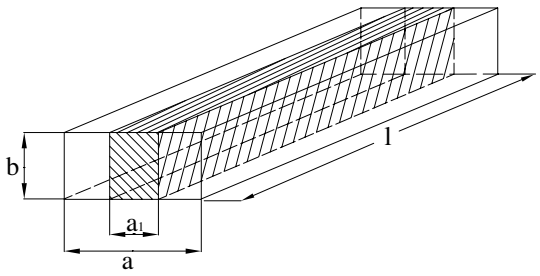
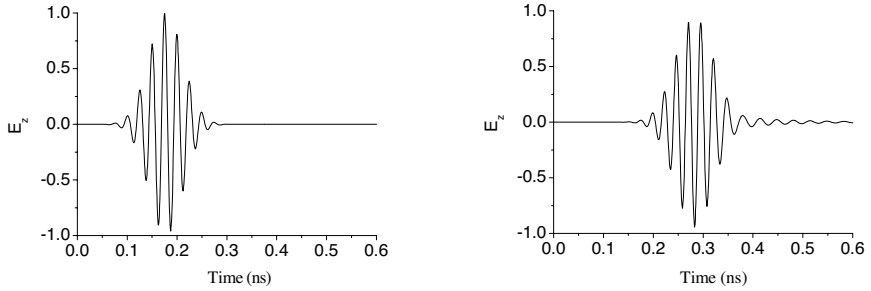


Figure 4. The structure of waveguide filled with E-plane dielectric slab.



(a) The waveform of input signal (b) The waveform of output signal

Figure 5. The waveform of two ports of waveguide filled with E-plane dielectric slab.

3.2. Theoretical Explanation on the Dispersive Transmission Lines Do Not Lead to the Phenomenon of Paired Echoes

The above simulation results do not show the existence of the phenomenon of paired echoes. From the view of the model of transfer

function, a theoretical analysis and interpretation are to be done as follows.

3.2.1.

Firstly, the technique of paired echoes can be extended to the following propositions:

Proposition A. If the transfer function satisfies the model (5), then as long as both a_i and $b_i (i \neq 0)$ are not zeroes simultaneously there must be the phenomenon of paired echoes in output signal.

Proposition B. If the amplitude-frequency and phase-frequency of the transfer function satisfy the following model

$$A(\omega) = a_0 + \sum_{i=0}^{n} \left[a'_i \cos(ic\omega) + a''_i \sin(ic\omega) \right] \tag{12a}$$

$$\phi(\omega) = b_0\omega + \sum_{i=0}^{n} \left[b'_i \sin(ic\omega) + b''_i \cos(ic\omega) \right] \tag{12b}$$

then as long as a'_i, b'_i, a''_i and b''_i are not all zero there must be the phenomenon of paired echoes in output signal.

3.2.2.

From the view of the propagation factor of guided wave, the transfer function of the lossless rectangular waveguide is

$$H(\omega) = e^{-jk_z z} \tag{13}$$

where z is the displacement along the propagation direction, k_z is the propagation constant;

$$k_z = \sqrt{k^2 - k_c^2} = \sqrt{\frac{\omega^2 \varepsilon_r}{c^2} - k_c^2} \tag{14}$$

k is the wave number in the media ε_r, k_c is the intrinsic constant or cut-off wave number.

To conveniently compare model (12) and model (13), the two models are rewritten as follows:

$$H'(\omega) = \left\{ a_0 + \sum_{i=0}^{n} \left[a'_i \cos(ic\omega) + a''_i \sin(ic\omega) \right] \right\} e^{j\left\{ b_0\omega + \sum_{i=0}^{n} \left[b'_i \sin(ic\omega) + b''_i \cos(ic\omega) \right] \right\}} \tag{12c}$$

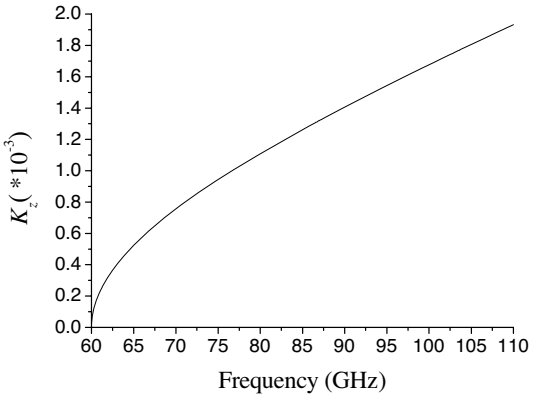


Figure 6. Propagation constant curve of waveguide.

$$H(\omega) = e^{-j\phi_1(\omega)} \tag{15a}$$

where

$$\phi_1(\omega) = k_z z = \left(\sqrt{\frac{\omega^2 \varepsilon_r}{c^2} - k_c^2}\right) z \tag{15b}$$

What we concern is whether $H(\omega)$ of (15a) can be written into the form of $H'(\omega)$ of (12c), that is, whether $\phi_1(\omega)$ can be expanded into the Fourier series form as (12b). In fact, in the actual treatment $\phi_1(\omega)$ can not be expanded into the form of (12b). The reasons are stated as follows:

A. Since $\phi_1(\omega)$ as shown in Fig. 6 is not the periodic function of ω, the traditional Fourier series expansion can not be obtained.

B. If a section of the definition of $\phi_1(\omega)$ is intercepted and extended periodically, then the resulted function can be expanded into the form of Fourier series. Although the series is convergent in terms of Dirichlet-Jordan test [14], but in reality there exist the following two problems: Firstly, the interception of the limited terms, which can approximate to the infinite terms of the series, will brings truncation error; secondly, because of the existence of discontinuous points due to the extension of the function, there must exist Gibbs phenomenon on convergence of the Fourier series [15], that is, as shown in Fig. 7 the amplitude of the neighborhood domain of discontinuous points have a greater oscillation when the superposition terms number of the series are different. Therefore, If $\phi_1(\omega)$ is expanded by the above approach, then the main response of the output signal can be approximated fully, but the approaching form of ripple oscillation will have brought

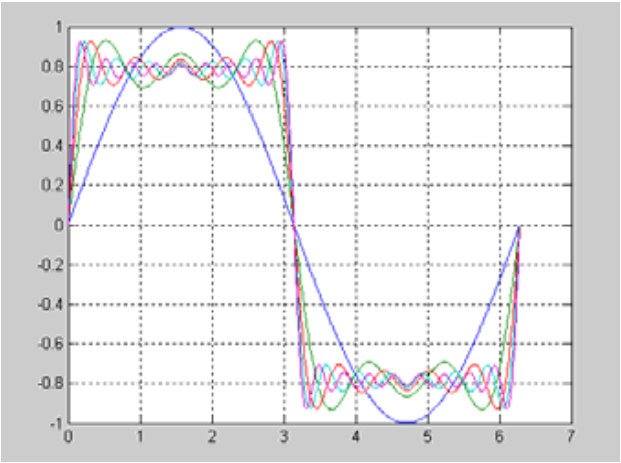


Figure 7. The schematic diagram of the square wave approached by Fourier series.

error (including truncation error) unavoidably. The effect of paired echoes obtained by Proposition B is due to the approaching method of ripple oscillation essentially, rather than the real physical effects of $\phi_1(\omega)$. Theoretically, the more the terms number of the limited terms intercepts, the weaker the effect of paired echoes resulting from the above treatment method is. However, no matter how small truncation error is, this expansion will always bring the effect of paired echoes, which the system itself does not lead to.

Therefore, model (13) can not be written into the form of model (12), that is, two models can not be uniformed. The transfer function of waveguide can not be analyzed by the generalized technique of paired echoes.

3.2.3.

In the common expansion method, Taylor series expansion is a different method from the approached method of ripple oscillation of Fourier series. So we attempt to expand $\phi_1(\omega)$ by means of Taylor series and (13) is equivalent to the following expression.

$$H(\omega) = A(\omega)e^{j\phi(\omega)} \tag{16a}$$

$$A(\omega) = 1 \tag{16b}$$

$$\phi(\omega) = -\left[\phi_1(\omega_0)z + \phi_1'(\omega_0)z(\omega-\omega_0) + \frac{\phi_1''(\omega_0)}{2!}z(\omega-\omega_0)^2 + \cdots + \frac{\phi_1^{(n)}(\omega_0)}{n!}z(\omega-\omega_0)^2 + \cdots\right] \quad (16c)$$

We can easily know that as long as the appropriate expansion point ω_0 is chosen, the series (16c) of $\phi(\omega)$ must be convergent [12].

As for the transfer function model expanded by Taylor series, the following conclusion is correct.

Proposition C. If the amplitude-frequency and phase-frequency of the transfer function satisfy the following model

$$A(\omega) = a_0 \quad (17a)$$

$$\phi(\omega) = b_0 + b_1\omega + b_2\omega^2 + \cdots + b_n\omega^n + \cdots \quad (17b)$$

then there is no phenomenon of paired echoes in the output signal $s_o(t)$.

Therefore, when the model (16) is used to analyze the lossless rectangular waveguide, we can know there is no phenomenon of paired echoes in the output signal by using Proposition C. For other dispersive transmission lines, the same conclusion can be obtained because their transfer function models are similar to the case of rectangular waveguide.

4. THE INFLUENCE OF THE DISCONTINUITIES OF TRANSMISSION LINE ON TIME DOMAIN PULSE SIGNAL

In wideband radar system, the multiple reflections along the transmission lines, which can be caused by the inhomogeneity or discontinuity of transmission system, will produce the distortion of signals. Although the power of transmitted signal may be reduced by a single mismatch, wideband signals are not be distorted. However, when two or more mismatches or discontinuities occur anywhere along transmission line, the inter-reflection and superposition of the signal among discontinuities will produce a nonlinear phase variation with frequency. The nonlinear phase variation will lead to the distortion of signals, which is called the "long-line effect" of broadband systems in [8].

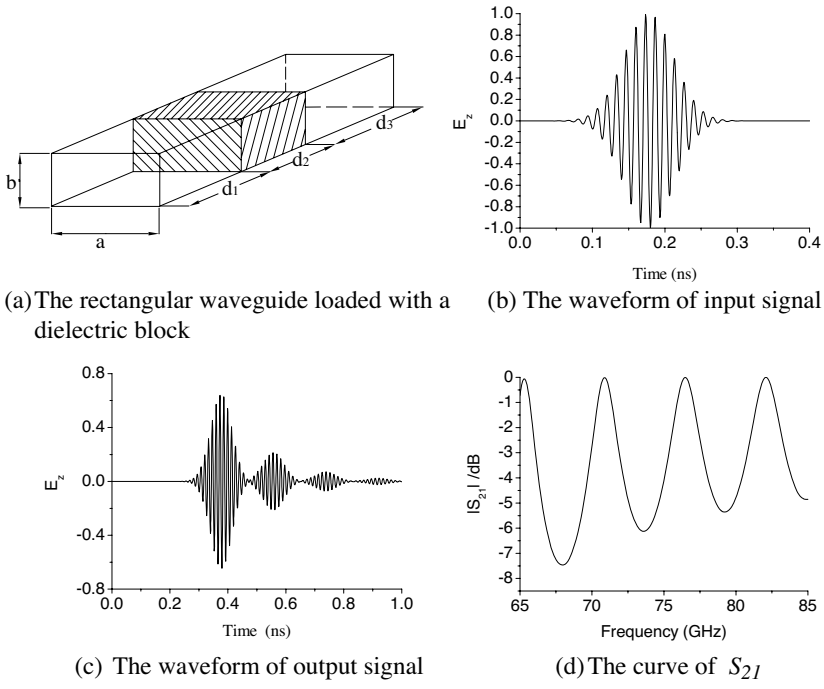
In the following cases, we will discuss whether the discontinuities will lead to the phenomenon of paired echoes by simulation and theoretical analysis. Furthermore, the influence of passive microwave

components with discontinuities on the time domain pulse signal is obtained.

Take waveguide as an example, several typical discontinuous structures are simulated.

4.1. Waveguide Loaded with Dielectric Block

As shown in Fig. 8(a) a rectangular hollow waveguide ($a = 2.54\,\text{mm}$, $b = 1.27\,\text{mm}$) is loaded with a dielectric ($\varepsilon_r = 6$) block, where $d_1 = d_2 = d_3 = 10\,\text{mm}$. The front surface and back surface of the dielectric block constitute two discontinuity surfaces. The simulation results are shown in Figs. 8(b) and (c).



(a) The rectangular waveguide loaded with a dielectric block

(b) The waveform of input signal

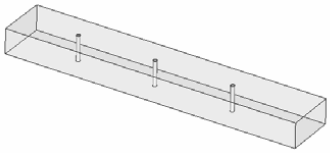
(c) The waveform of output signal

(d) The curve of S_{21}

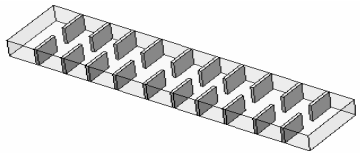
Figure 8. The input waveform, output waveform and S parameter of a waveguide loaded with dielectric block.

When dielectric properties of loaded materials are changed into lossless medium ($\varepsilon_r = 2$) or loss medium ($\varepsilon_r = 11.9$ and $\tan\delta = 4 \times 10^{-3}$) respectively, the figure of the output waveform and Sparameter curves are similar to Figs. 8(c) and (d).

From Fig. 8, we know that there are several smaller transmission



(a) The waveguide loaded with full height dielectric cylinders



(b) The waveguide loaded with multiple isotropic dielectric slabs

Figure 9. The schematic diagrams of some discontinuous structures.

peaks behind the main transmission peaks and no phenomenon of paired echoes. The same results can be obtained for the case of waveguide structure loaded with multiple dielectric blocks.

4.2. The Simulation of Other Discontinuous Structures

By the simulation of the waveguide loaded with multiple dielectric cylinders and metal cylinders (see Fig. 9(a)), we know that there are several smaller transmission peaks behind the main transmission peaks and serious distortion of the main transmission peaks but no phenomenon of paired echoes.

By the simulation of the waveguide loaded with multiple isotropic dielectric slabs (see Fig. 9(b)), we know that this structure has certain filter characteristics. Compared with the input waveform, the output waveform has a very obvious multiple reflections, a serious distortion of the main transmission peaks, but no phenomenon of paired echoes.

The conclusion in the case of filter structure which is consisted by microstrip line is similar, that is, the output waveform has obvious tailing phenomenon similar to Fig. 5(b), but no phenomenon of paired echoes. The results of simulation are not given here for saving space.

From the above simulation results, we can know that the discontinuities of transmission line (for example the waveguide and microstrip) do not produce the phenomenon of paired echoes when the time domain pulse signal is transmitting through them.

5. CONCLUSION

In summary, the model (5) used by technique of paired echoes and model (12) only describe the system within the framework of the minimum perturbation of non-distortion linear system. They are not suitable to analyze the transfer function of linear and dispersive transmission lines. Taylor series expansion method

is appropriate to analyze it. The existence of dispersion and discontinuity in transmission system will lead to the distortion of time domain pulse signals, rather than the phenomenon of paired echoes. Meanwhile, microwave and millimeter-wave dispersion transmission line, transmission line including discontinuity and passive components such as filters, directional couplers will also not lead to the phenomenon of paired echoes.

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