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Time reversal of a high frequency signal based on time-varying guided wave system

Cheng-Guang Sun[a,b], Jia-Lin Li[a,c,*], Bing-Zhong Wang[a]

[a] School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu 610054, China
[b] Institute of Antenna and Microwave Techniques, Tianjin University of Technology and Education, Tianjin 300222, China
[c] Key Laboratory of Antenna and Microwave Technology, No. 14 Institute of Chinese Electronic Science and Technology Group, Nanjing 211113, China

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ABSTRACT

A full-electronic method to realize time reversal of electromagnetic (EM) signal by using analog signal processing (ASP) technique is reported in this paper. A time-varying guided wave system, based on a transmission line with periodically loaded microwave switches, is described and discussed theoretically, analytically and experimentally. Examinations on a prototype demonstrator show that an amplitude-modulated pulse signal can be time reversed effectively, where the pulse has a time duration of 7 ns and the amplitude-modulated carrier is 3.5 GHz.

1. Introduction

Time reversal of electromagnetic (EM) waves has been found many attractive applications in recent years [1–6]. The process of time reversal is shown in Fig. 1, where a signal generated by a target radiates through the surrounding medium, and is further received by the transducer elements denoted by small circles of the periphery in Fig. 1(a). As described in Fig. 1(b), the received signal is time-reversed and retransmitted by the transducer elements. Finally, the retransmitted signal could focus exactly on the target temporally and spatially [4,7]. Due to the temporal and spatial focusing characteristics, it shows some interesting and important applications in localization [8,9], detection [10], imaging [11] and wireless communications [1,2,12]. Further, for wireless sensor networks [13,14], the time reversal waves enable the sensor nodes to be wirelessly powered [15,16].

Time reversal mirror (TRM) is an essential device of a time reversal EM system. It functions to time reverse and retransmit the received signal. In general, the TRM should time reverse the EM signal dynamically, efficiently and accurately. To now, TRMs have been developed broadly by using digital signal processing (DSP) methods. But the DSP based methods are not suitable for high frequency EM signals due to the limited sampling rate of analog-to-digital and digital-to-analog convertors [17,18]. Analog signal processing (ASP) techniques, on the other hand, can be exploited to process arbitrary waveform signals. Some ASP based techniques to realize the time reversal have been reported [19–24]. At the low operation frequency, TRMs based on the surface acoustic wave technology cannot be applicable to the EM signals [19,20]. Optical solutions can perform time reverse a wideband microwave signal at the expense of high cost [21,22]. Based on microwave chirped delay lines, time reversal can be achieved by using dispersion compensation or temporal imaging techniques [23,24], where the performance needs to be further improved.

In this paper, a time reversal architecture is discussed based on a time-varying guided wave system. Such a system is further specified as time-varying transmission-line guided wave systems [25–27]. A prototype demonstrator is developed. Demonstration on an amplitude-modulated pulse signal with a carrier of 3.5 GHz and a pulse duration of 7 ns validates the analyses, theoretically and experimentally.

2. Operation principle

Fig. 2(a) shows the diagram of the studied system; it is composed of a microwave transmission line with periodically loaded microwave high-speed switches. Its equivalent circuit network can be formulated as illustrated in Fig. 2(b), where G_s and C_s represent the equivalent conductance and capacitance of a unit length of the transmission line, when the microwave switch is the on and off states, respectively. The equivalent inductance and capacitance per unit length of the transmission line are respectively L_0 and C_0 for a lossless case. Under the off state, G_s is disabled, thus we have

$$\partial V(z,t)/\partial z = -L_0 \partial I(z,t)/\partial t \quad (1)$$

$$\partial I(z,t)/\partial z = -(C_0 + C_s)\partial V(z,t)/\partial t \quad (2)$$

When the system is terminated by matched loads, the reflection wave will not exist within the system, thus (1) and (2) yield to

* Corresponding author at: School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu 610054, China.
E-mail address: jialinli@uestc.edu.cn (J.-L. Li).

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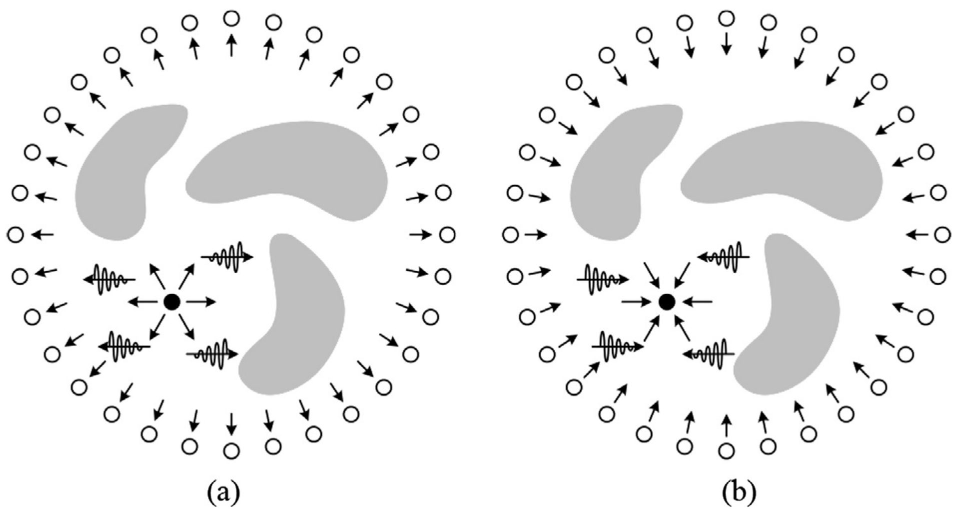

Fig. 1. The process of time reversal. (a) The signal generated by the target (denoted by the dot in the center) radiates through the surrounding medium, and is received by the transducer elements. (b) Transducer elements time-reverse the received signal and re-send it.

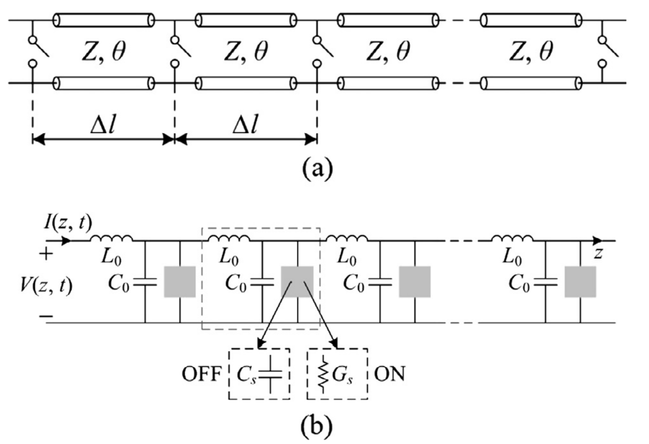

Fig. 2. Time-varying transmission-line system. (a) Schematic diagram. (b) Equivalent circuit network.

$$V(z,t) = U_i e^{j(\omega_i \cdot t - k_i \cdot z)} \tag{3}$$

$$I(z,t) = \sqrt{(C_0 + C_s)/L_0} \cdot U_i e^{j(\omega_i \cdot t - k_i \cdot z)} \tag{4}$$

where $\omega_i = k_i/\sqrt{L_0(C_0 + C_s)}$, k_i is the incident propagation constant, U_i is the incident voltage. On the other hand, when the switch is the on state, C_s malfunctions, leading to

$$\partial V(z,t)/\partial z = -L_0 \partial I(z,t)/\partial t \tag{5}$$

$$\partial I(z,t)/\partial z = -G_s V(z,t) - C_0 \partial V(z,t)/\partial t \tag{6}$$

We have

$$V(z,t) = U_r e^{-G_s/(2C_0)\cdot t} e^{j(-\omega_r \cdot t - k_r \cdot z)} + U_t e^{-G_s/(2C_0)\cdot t} e^{j(\omega_t \cdot t - k_t \cdot z)} \tag{7}$$

$$I(z,t) = [-\omega_r C_0/k_r - jG_s/(2k_r)] U_r e^{-G_s/(2C_0)\cdot t} e^{j(-\omega_r \cdot t - k_r \cdot z)} + [\omega_t C_0/k_t - jG_s/(2k_t)] U_t e^{-G_s/(2C_0)\cdot t} e^{j(\omega_t \cdot t - k_t \cdot z)} \tag{8}$$

where U_r is the reflection voltage, U_t is the transmission voltage, $\omega_r = \sqrt{k_r^2/(L_0C_0) - (G_s/2C_0)^2}$, $\omega_t = \sqrt{k_t^2/(L_0C_0) - (G_s/2C_0)^2}$, k_r and k_t are respectively the reflection and transmission propagation constants. Notice that k_r and k_t in this case should be $k_r = k_t = k$. As shown in (7) and (8), when the switches are turned from the off state to the on state, the incident wave is changed into two parts: the reflection wave and transmission wave. For a time-varying guided wave system, the propagation constant should be conserved [28], thus $k_i = k$. On the other hand, if $G_s = 2k\sqrt{(C_0C_s)/(L_0C_0 + L_0C_s)}$, the operation frequency meets $k/\sqrt{L_0(C_0 + C_s)} = \sqrt{k^2/(L_0C_0) - (G_s/2C_0)^2}$. Further, considering C_s and G_s of the practical switch, the following relation can maintain

$$\omega_i \approx \omega_r = \omega_t \tag{9}$$

Based on the above analysis, the characteristic impedance of the system can be suddenly changed between the off state and the on state within this guided wave system, thus characterizing the time varying. Further, the time-varying impedance enables time reversal of a high frequency signal to be real-time and dynamic, which can be validated from the reflection wave, described as the first part on the right of (7) and (8) compared with the incident wave. From (7)–(9), it is seen the time reversed signal maintains the same time scale, namely without stretching or compressing. Consequently, this reveals theoretically that the guided wave system can perform the time reversal of a high frequency signal.

3. Developing a time-varying guided wave system

As illustrated in Fig. 3, a guided wave system with a microstrip line periodically loaded microwave switches is further developed here. The switches are PIN diodes and can be on-and-off controlled by a sinusoidal signal. Under the off state, the system corresponds to a common transmission line with its characteristic impedance of Z_1, and the input signal can travel on it. When the diodes are switched to the on state, the characteristic impedance is changed from Z_1 to Z_2 drastically. Based on the above discussions, the reflection wave exists within the system and goes back to the left side. Further, the time reversed signal can be observed from the reflection wave. Assuming a weak dispersion system, both of the input and reflection waves can therefore travel on the line

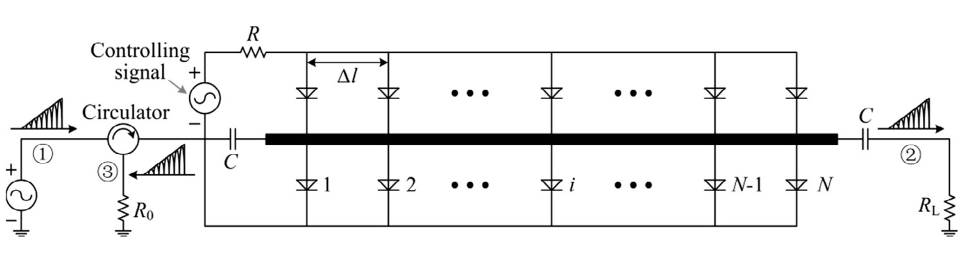

Fig. 3. Schematic diagram of the time-varying microstrip-line (guided wave) system, where port 1 is the input, port 2 is the transmission port, and port 3 is the output.