TDR ANALYSIS OF RADIATION IMPEDANCE FOR A MONOPOLE ANTENNA

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Abstract: Paying attention to the availability of time domain reflectometry (TDR) in extracting partially the reflected voltage waveforms at remarkable portions of a transmission line in time domain, we showed a method for the frequency characteristic analysis at a discontinuous point of a transmission line from TDR measurement. We applied this method to the derivation of the radiation impedance of a monopole antenna with respect to various reflection times, and confirmed its validity via comparing the results in the steady state with that measured with a network analyzer.

Key words: TDR, time domain measurement, monopole antenna, radiation impedance.

1. Introduction

In electronic and information systems, electromagnetic (EM) radiation noises are increasing due to the high-speed operations and high-density assembles of digital circuits. These EM noises may be generated from the mismatched terminations, discontinuities of signal traces on printed circuit boards, and circuit elements themselves [1][2]. The radiations range in a broadband of frequencies up to several GHz. In many cases, it is reasonable to assume the radiation source as a composition of many short dipoles or monopole elements [3], and therefore understanding the basic characteristics of a dipole and monopole in a broadband of frequencies is essential for EMI (Electromagnetic Interference) control.

On the other hand, it is known that TDR is a useful means in pinpointing the mismatching, discontinuities and radiation positions on transmission lines or signal traces on printed circuit boards [4]-[7]. In the TDR method a steep step is used as the incident voltage so that broadband frequency characteristics are analyzable. The time-domain reflection voltage obtained by TDR can be extracted at various discontinuity points according to their propagation time, and consequently the reflection characteristics corresponding to the discontinuity points can be obtained. Such an analysis is helpful to a deeper understanding of the radiation mechanism.

In this paper, we show a TDR method for analyzing the radiation impedance of a monopole antenna, which can be treated as a transmission line with a discontinuity at the connection to a monopole element on a metal ground plane. The validity of the analysis is confirmed in comparison with the results obtained via a network analyzer.

2. Experiment and Analysis

Figure 1 shows the experimental configuration of a monopole antenna and TDR measuring instrument. The monopole antenna with a length of 10 cm was set at the center of an aluminum plate with dimensions of 20 cm × 10 cm, and was soldered directly to the center conductor of an SMA connector. The TDR was connected to the monopole antenna through the SMA connector via a coaxial cable with a characteristic impedance of $Z_0 = 50\ \Omega$. Denote by $v_i(t)$ the incident step voltage. Then the measured voltage waveform $v(t)$ can be considered as the superposition of the input step voltage $v_i(t)$ and the

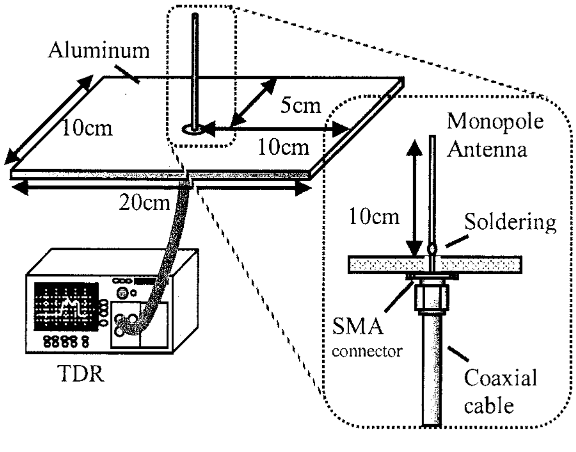


Fig. 1 Experimental configuration.

reflected voltage $v_r(t)$, which is given simply by

$$v(t) = v_i(t) + v_r(t). \tag{1}$$

The shorter rise time of the incident voltage, the wider bandwidth and finer geometric resolution the TDR has. In this study, the incident voltage had a step of 0.2 V and a rise time of about 40 ps, as shown in Fig. 2. The waveform A in Fig. 2 is the incident voltage generated by the TDR itself, while the waveforms B and C are the voltage waveforms at the end of the coaxial cable (or input to the monopole antenna via the SMA connector) with an opened and shorted terminals, respectively, which are not identical to the waveform A due to the cable loss. Since the input to the opened terminals is applied to the monopole antenna, we used the waveform B as the incident voltage $v_i(t)$.

Denoting by $Z(j\omega)$ the radiation impedance of the monopole antenna, we have the following relationship between the incident voltage and reflection voltage in the Laplace domain:

$$V_r(s) = \frac{Z(s) - Z_0}{Z(s) + Z_0} \times V_i(s) \tag{2}$$

where s is the Laplace variable.
From Eq. (2), it follows that

$$\begin{aligned} Z(s) &= \frac{V_i(s) + V_r(s)}{V_i(s) - V_r(s)} \times Z_0 \\ &= \frac{sV_i(s) + sV_r(s)}{sV_i(s) - sV_r(s)} \times Z_0 . \end{aligned} \tag{3}$$

Since the reflected voltage waveform is measured with the TDR in the time domain, it is possible to extract a partial waveform during an arbitrary time-period. Denoting by $v_r^{(n-1)}(t)$ the reflected voltage at the n-th time-period (n=1,2,3,...), we can express it as

$$\begin{aligned} v_r^{(n-1)}(t) &= v_r(t) \ \{u(t) - u(t - 2l_a n / c_p)\} \\ &= v_r(t) \ \{u(t) - u(t - n\tau)\} \end{aligned} \tag{4}$$

where τ ($=2l_a/c_p$) is the time until the reflection reaches the observation point, l_a is the length of the monopole and c_p is the velocity of light. Using the reflected voltage $v_r^{(n-1)}(t)$ at the n-th time-period, we can derive the radiation impedance $Z^{(n-1)}(j\omega)$ as a function of frequencies from Eq. (3) via the following equation:

$$Z^{(n-1)}(j\omega) = \frac{\displaystyle\int_{-\infty}^{+\infty} \left\{ \frac{d}{dt} v_i(t) + \frac{d}{dt} v_r^{(n-1)}(t) \right\} \cdot \exp(-j\omega t)\, dt}{\displaystyle\int_{-\infty}^{+\infty} \left\{ \frac{d}{dt} v_i(t) - \frac{d}{dt} v_r^{(n-1)}(t) \right\} \cdot \exp(-j\omega t)\, dt} \times Z_0 . \tag{5}$$

The integration in the above equation can easily be performed using the Fast Fourier Transformation (FFT). It should be noted that $Z^{(n-1)}(j\omega)$ derived in such a way corresponds to the radiation impedance including only the characteristics of the monopole before the n-th time reflection occurs.

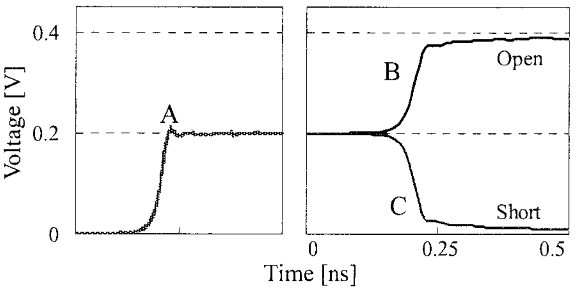


Fig. 2 Incident voltage and reflected voltages with opened or shorted terminals.

3. Experimental Results and Discussion

Figure 3 shows the TDR measured voltage waveforms for the monopole antenna. The waveform just before the incident voltage reached the monopole was shown. The first reflection from the monopole tip occurred at the timing of the end of the shaded region where the incident wave just reached the monopole tip, and then the reflection repeated. The total voltage waveform approached to 0.4 V that was twice of the incident step voltage, after a time-period of about 10τ or 12rd-time reflection, which means the steady state.

Figure 4(a) shows the incident voltage waveform $v_i(t)$ and reflected voltage waveform $v_r^{(0)}(t)$ of the net part before the reflection from the monopole tip occurred. Similarly, it is also available to extract other reflected voltage waveforms with respect to different reflection times. The small swells in the reflected voltage waveform before the timing of zero were due to the SMA connector. Fig. 4(b) shows the differential waveforms of the incident voltage and reflected voltage. Substituting them into Eq. (5) yielded the radiation impedance $Z^{(0)}(j\omega)$, which is shown in Fig. 5. It is interesting to note that this radiation impedance should be the one of a monopole antenna with an infinite length because the extracted reflected voltage waveform was within the time-period before the wave reached the monopole tip. As can be seen in Fig. 5, the resistive component of the radiation impedance decreases with frequencies from about 350 Ω at 300 MHz, and the reactive component has capacitive characteristics between 300 MHz and 3 GHz.

In the same way, it is straightforward to derive $Z^{(n-1)}(j\omega)$ which includes the characteristics before the n-th reflection occurs. Due to the space limitation, only $Z^{(1)}(j\omega)$ and $Z^{(12)}(j\omega)$ are shown in Fig. 5. Also shown in this figure with thick lines is the input impedance $Z_{NTW}(j\omega)$ of the monopole antenna measured by using a network analyzer. Since the TDR-derived radiation impedance did not include the effect of the SMA connector, we derived it by shifting the phase via assuming the SMA connector as a transmission line with its characteristic impedance of 50Ω. That is to say, denoting by $Z_{NTWC}(j\omega)$ the measured input impedance at the calibration plane of the network analyzer, we have

$$Z_{NTW}(j\omega) = \frac{Z_{NTWC} - jZ_0 \tan\beta l}{Z_0 - jZ_{NTWC} \tan\beta l} \times Z_0 \quad (6)$$

where β is the phase constant, and l is the length of the SMA connector. In comparison with $Z_{NTW}(j\omega)$ in Fig. 5, the TDR-derived $Z^{(12)}(j\omega)$, which is nearly in the steady state, is in good agreement. This assured the validity of the TDR analysis shown here for the radiation impedance of monopole antennas.

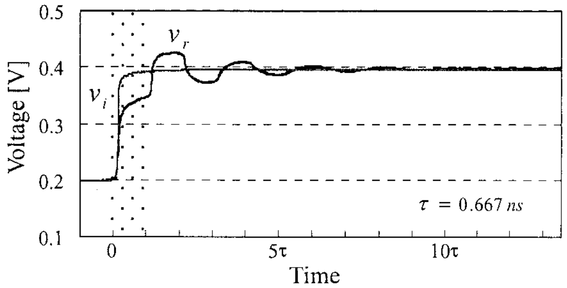
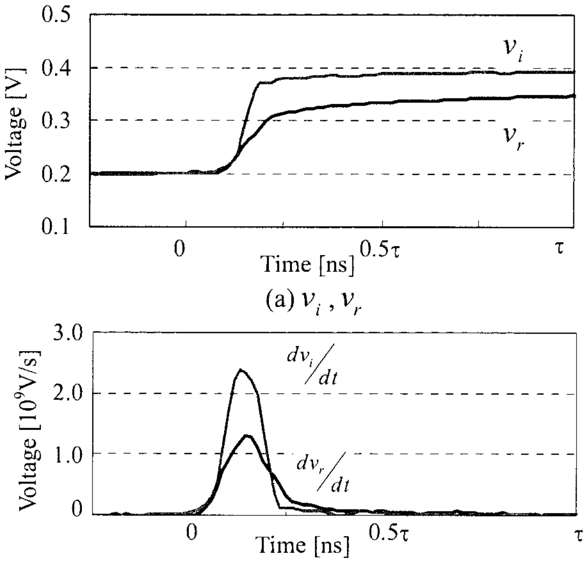


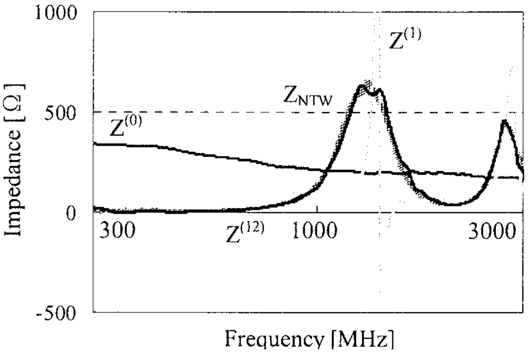
Fig. 3 TDR-measured reflected voltage waveform for a monopole antenna.



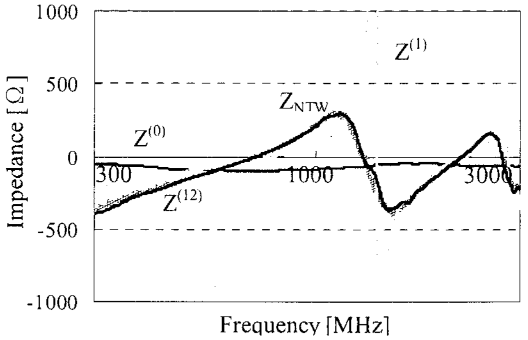
(a) v_i, v_r

(b) dv_i/dt, dv_r/dt

Fig. 4 (a) Incident voltage and extracted reflected voltages before the wave reaches the monopole tip, and (b) their differential waveforms.



(a) Resistive component



(b) Reactive component

Fig. 5 Frequency characteristics of radiation impedance of the monopole antenna with different reflection times.

4. Conclusion

TDR measurement is a powerful means to gain a deeper understanding for the radiation mechanism of a discontinuity in a transmission line, because it is available to extract partially the reflected voltage waveforms at the remarkable portions of the transmission line in the time domain. In this paper, we have demonstrated a TDR analysis method for the derivation of the radiation impedance of a monopole antenna with respect to various reflection times, including for a monopole antenna with an infinite length by extracting the reflected voltage waveform in the time domain before the wave reaches the monopole tip. The validity of the TDR-derived radiation impedance has been confirmed in comparison with that measured by using a network analyzer in the steady state.

The future subject is to clarify the physical meaning of the results obtained for the radiation impedance of monopole antennas.

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