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A Method for Estimating Wideband Transients Using Transmission Loss of High Performance Semi-Rigid Coaxial Cable

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SUMMARY The very fast transients of micro-gap discharges driven by low voltage electrostatic discharging (ESDs) are investigated in the time domain. We previously developed a 12 GHz wideband measurement setup consisting of a distributed constant line system, however the observed transients due to micro-gap discharges had very fast rise times of 34 ps or less, which reached the limitation on our system. In this paper, we proposed a method for estimating wideband transients beyond the measurement limit by using the transmission loss of a high performance coaxial transmission line. The proposed method is validated by estimating an impulsive voltage waveform with rise/fall time of 16 ps from the waveform measured through a semi-rigid coaxial cable with a length of 10 m.

key words: *ESD, micro-gap discharge, fast transients, band-limiting, transmission line, estimation*

1. Introduction

Very fast transients of electromagnetic (EM) fields arise from micro-gap discharges due to electrostatic discharges (ESD) and electrical contacts. The transients due to such micro-gap discharge provide a very wide band (high frequency) EM noise source. Over the past few years a considerable number of studies have been made on EM noises of the ESD and contacts from the point of view of electromagnetic compatibility (EMC). The EM noise characteristics of micro-gap discharges are gradually becoming clearer [1]–[7]. However, there has been only a little amount of information about the voltage transients due to the start of the above-mentioned discharges of very wide band measurements in time domain [8]–[11]. Moreover, little is known about the voltage rising time in positive polarity and voltage falling time in negative polarity due to micro-gap discharges at voltages below 1500 V.

The main purpose of our study is to clarify the transients as EMI (electromagnetic interference) sources due to low voltage micro-gap discharges both in time domain and in frequency domain. As for the transients caused by micro-gap discharges, however, due to their rapidity, a wideband observation system is required. For this reason, we previously established a 12 GHz bandwidth measurement setup consisting of a distributed constant line system in order to observe the fast transients. Experimental results showed that the voltages and currents have very rapid rise/fall time of about 34 ps [12], [13], which already reach the limitation on our measurement system. This implies that real transients should be faster than 34 ps rise/fall time.

Then, we appreciate to the extent of rise and fall time at the transition duration due to discharges. In this paper, by using the transmission loss of a long high performance semi-rigid cable system, we propose a method for estimating the rise time of wideband transients over the 12 GHz bandwidth.

For the other estimation methods in the past studies, the input frequency characteristics of the vertical amplifier of an oscilloscope are being commonly used to obtain an input waveform from the measured waveform via a conventional de-convolution technique. However, it is difficult to conduct the de-convolution for a recent model of commercially available digital oscilloscopes because of the input characteristics having a sharp decline at frequencies over the measurement bandwidth [14]. The proposed method, on the other hand, enables one to estimate the fast transients beyond the measurement limit from the measured transients through a coaxial cable, whose insertion loss decays gently with frequency.

2. Method

Figure 1 shows a schematic diagram for estimating wideband transients by using the transmission loss of a coaxial cable with a characteristic impedance of $Z_o = 50\,\Omega$. Here, $v_i(t)$ is a waveform of real voltage transients due to micro-gap discharges, for example, which is assumed to be beyond our measurement limit. $S_{21}(j\omega)$ is the scattering transmission coefficient of a high performance cable in frequency domain, and $v(t)$ is the waveform of the cable output voltage, when $v_i(t)$ is traveling on the cable with the matched termination. Due to the transmission cable loss, the high frequency components of $v_i(t)$ should decay within our measurement limit so that the waveform of $v(t)$ be accurately measured with our measurement system. Base on this idea,

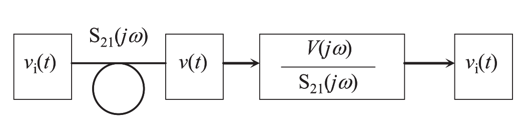

Fig. 1 Schematic diagram for estimating wideband transients by using the transmission loss of a coaxial cable.

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the real voltage transient $v_i(t)$ can be reconstructed from

$$v_i(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \frac{V(j\omega)}{S_{21}(j\omega)} \cdot e^{j\omega t} d\omega \tag{1}$$

where $V(j\omega)$ is the Fourier transform of $v(t)$.

3. Verification

Figure 2 shows the setup used to estimate voltage transients in order to validate the proposed method. The input voltage waveform $v_i(t)$ (original voltage waveform) was measured by above setup, and the output voltage waveform $v(t)$ (attenuated voltage waveform) measured by below setup. In lieu of the very fast voltage transients due to microgap discharges, we used a wideband step wave generator (PSPL4005, rise time: 5 ps) and an impulse forming network (PSPL5206, input: 5 ps step wave, output: 15 ps impulse wave) to produce a triangular voltage waveform with rise/fall time of 15 ps. Since the impulsive waveform of this kind is unlikely to be accurately measured with a commercially available real time digital oscilloscope at present, we used a sampling oscilloscope (Agilent: 86100B) with a 50-GHz sampling head (Agilent: 83484A) for measurement. A 50-Ω high performance semi-rigid cable (EZ141/M17) with a length of 10 m was used to connect through the 3.5 mm APC (compatible with SMA connector) between the pulse generator and the sampling oscilloscope.

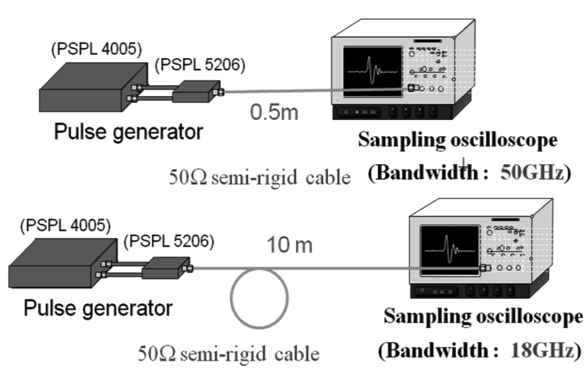

Fig. 2 Experimental system for verify the estimate method using 15 ps impulse waveform.

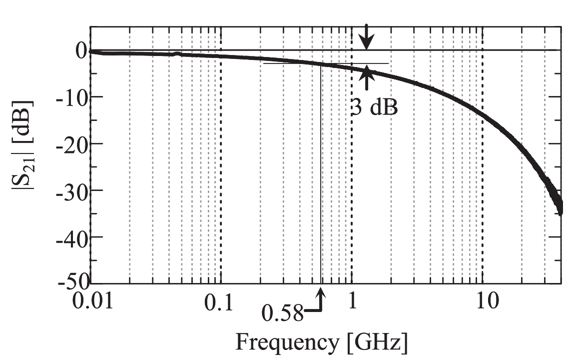

Fig. 3 Frequency characteristics of $|S_{21}|$ for 50-Ω semi-rigid coaxial cable with a length of 10 m.

Figure 3 shows the frequency characteristics of the absolute value of S_{21} $(j\omega)$ for a semi-rigid cable with a length of 10 m, which demonstrates that the cable has a cut-off frequency of 0.58 GHz and an insertion loss of about −33 dB at 40 GHz. Figures 4(a) and 4(b) show the frequency characteristics of the real part and imaginary part of S_{21} $(j\omega)$, respectively. Solid lines show the measured results, while thin lines represent the values calculated from

$$S_{21T}(j\omega) = |S_{21}(j\omega)| \cdot e^{-j\omega\tau} \tag{2}$$

where τ (= 47 ns) is the propagation time of the cable (propagation speed: 2.13×10^8 m/s). This equation was derived under the assumption that the cable has a linear phase constant. It is found that the calculated values approximately agree with the measured results.

Figures 5(a) and 5(b) show with solid lines the input voltage waveform $v_i(t)$ and output voltage waveform $v(t)$ of the coaxial cable, respectively, which were measured with the above-mentioned sampling oscilloscope. Due to the propagation time delay of the cable, the output voltage was observed in about 47 ns from the input voltage. The gray line in Fig. 5(a) represents the estimated voltage waveform from Eq. (1), which will be described later. It is found that the input voltage used has amplitude of 0.5 V and rise/fall time of about 15.9 ps, while the output voltage has amplitude of 0.11 V and rise time of about 22.6 ps, which should be due to the transmission loss of the cable. Cut-off frequencies of the input and output voltage waveforms can roughly be estimated as 16 GHz and 11 GHz, respectively, from the frequency spectrum of a triangular waveform with the same rise/fall time.

The FFT and IFFT processes were used for the actual

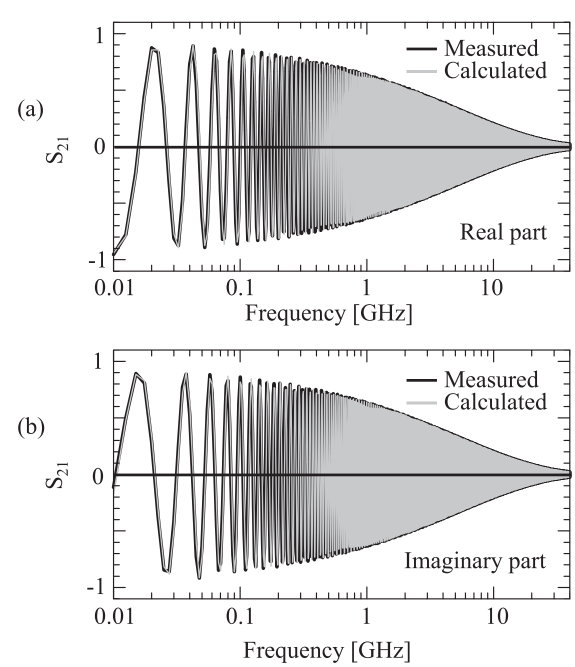

Fig. 4 Frequency characteristics of S_{21} for 50-Ω semi-rigid coaxial cable with a length of 10 m.

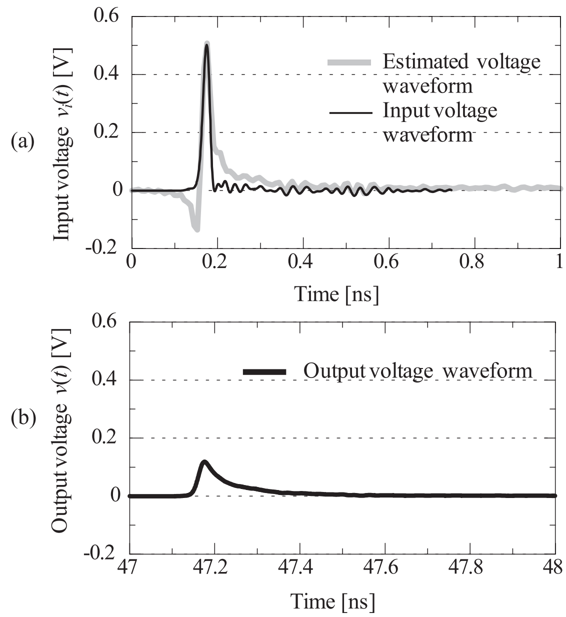

Fig. 5 (a) Input and estimated voltage waveform $v_i(t)$ and (b) output voltage waveform $v(t)$.

calculation. The measured output voltage waveform $v(t)$ has 32,768 points with about 0.741 ps per sample. The calculated frequency spectra $V(j\omega)$ has 16,384 frequency points with about 41 MHz bandwidth, besides, the frequency bandwidth divided to 1 MHz bandwidth using the spline interpolation. Also, frequency bandwidth of the scattering transmission coefficient $S_{21}(j\omega)$ was register to the calculated frequency spectra $V(j\omega)$ of 1 MHz bandwidth using the spline interpolation.

Using the frequency spectrum of the output voltage, we estimated the input voltage from Eqs. (1) and (2), which is shown with the gray line in Fig. 5. It was found that the estimated voltage has amplitude of 0.51 V and rise time of about 15 ps, which are almost the same as those of the input voltage and also that the waveform estimated approximately agree with the input voltage waveform, though there are some differences around the rising and falling parts, which may be due to the numerical errors of de-convolution computation.

4. Conclusion

We proposed a method of estimating the wideband transients due to micro-gap discharges by using the transmission loss of a high performance semi-rigid coaxial cable, and validated its effectiveness by estimating an impulsive voltage waveform with rise/fall time of 15 ps from the measured waveform through a semi-rigid coaxial cable with a length of 10 m. As a result, the estimated waveform agreed approximately with the input voltage one. Therefore, we could confirm that the proposed method enables to estimate the rise time of fast transients of about 15 ps. However, this method does not bring to the waveform estimation at this moment.

The future works are to improve the estimation accuracy of the proposed method, and also to estimate the very fast transients due to actual micro-gap discharges.

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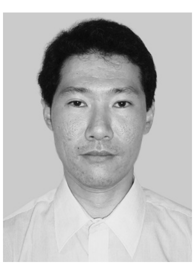

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