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# High-voltage isolation transformer for sub-nanosecond rise time pulses constructed with annular parallel-strip transmission lines

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A novel annular parallel-strip transmission line was devised to construct high-voltage high-speed pulse isolation transformers. The transmission lines can easily realize stable high-voltage operation and good impedance matching between primary and secondary circuits. The time constant for the step response of the transformer was calculated by introducing a simple low-frequency equivalent circuit model. Results show that the relation between the time constant and low-cut-off frequency of the transformer conforms to the theory of the general first-order linear time-invariant system. Results also show that the test transformer composed of the new transmission lines can transmit about 600 ps rise time pulses across the dc potential difference of more than 150 kV with insertion loss of −2.5 dB. The measured effective time constant of 12 ns agreed exactly with the theoretically predicted value. For practical applications involving the delivery of synchronized trigger signals to a dc high-voltage electron gun station, the transformer described in this paper exhibited advantages over methods using fiber optic cables for the signal transfer system. This transformer has no jitter or breakdown problems that invariably occur in active circuit components. © *2011 American Institute of Physics*. [doi:10.1063/1.3606448]

## I. INTRODUCTION

The use of transmission lines to construct transformers for fast-rise time pulses is a well-established method. The signals can propagate in the transformer with the transverse electromagnetic mode, thereby producing good response characteristics. Such transformers have been called transmission line transformers (TTLs). Many reports of TTLs have described inversion, isolation, and other applications.[1–3] Generally in high-power or high-voltage applications, TTLs have been constructed from coaxial cables with or without high-permeability magnetic materials.[4,5] Another type of transmission line for such applications is an ordinary parallel-strip transmission line.[6] A TLT constructed using such a transmission line can realize dc isolation and design for good impedance matching. However, some difficulties arise in the design and construction of the TLTs for high-voltage applications because ordinary parallel-strip transmission lines have a somewhat complicated structure for construction of TLTs.

In this study, a parallel-strip transmission line with new topology, an *annular parallel-strip transmission line*, was devised and used instead of the ordinary parallel-strip transmission line to construct the TLTs easily.[6] A remarkable characteristic of this topology is the capability of separating spaces perfectly using a dielectric material plate between the primary and secondary of the transformer. That separation can produce a simple structure for the design and construction of high-isolation voltage TLTs while maintaining good impedance matching.

Instead of the transmission line approach, the step response was calculated using simple ordinary frequency domain analysis, assuming that the transformer obeys the theory of the general first-order linear time-invariant (LTI) systems because the reflection diagram method described in a previous report[6] was difficult for designers who are typically interested in the practical applications of TLTs.

## II. BASIC OPERATION OF THE TRANSFORMER

A schematic diagram of the transformer is presented in Fig. 1. Two annular conductors with identical geometry form annular parallel-strip transmission lines 1 and 2, each with identical characteristic impedance. The conductor of the input side is called the primary conductor. That of the output side is called the secondary conductor. The spacing between the two conductors was maintained with a slab of dielectric material, which dominantly determines the withstanding voltage of the transformer. Arrows in the figure indicate the direction of the electric lines of force. The input signal, traveling on the coaxial line with impedance of Z ( = 50 Ω), is divided into two signals on parallel-strip transmission lines 1 and 2, each with impedance of Z/2 at the input junction. Then signals travel toward the output junction, where they join again as the output signal and travel down the coaxial line with impedance of Z. To conclude this operation successfully, the relative angle between the input and output junctions must be held to 180°, or two parallel-strip transmission lines 1 and 2 must maintain the same physical line lengths. Consequently, the dc isolation and inversion of the input signals can be made. Considering the two conductors as primary and secondary windings, the transformer can be regarded as an ordinary 1:1 air core transformer. Details of the structure and dimensions will be described in Sec. III of this report.

### A. Time constant for the unit step response

The annular conductors themselves can be regarded as a one-turn loop connecting the input or output of the

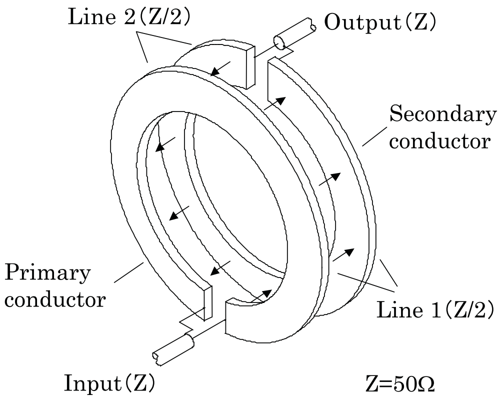

FIG. 1. Schematic diagram of the transformer. The two annular conductors constitute parallel-strip transmission lines 1 and 2. Arrows indicate the electric lines of force.

transformer separately if the wavelength λ of the input signals is larger than the dimension between the input and output of the transformer $\ell$, i.e., $\ell \ll \lambda$ is sufficiently satisfied. This approximation yields a simple low-frequency equivalent circuit model of the transformer, as presented in Fig. 2, where $L_t$is the loop self-inductance. The fundamental idea and procedure leading to this equivalent circuit have been described in detail in previous articles.[6–8] From this circuit, the frequency response function of the transformer $A(\omega) = V_o(\omega)/V_i(\omega)$ can be written as

$$A(\omega) = \frac{i\omega L_t}{Z + i\omega L_t} \qquad \frac{\ell}{\lambda} \ll 1. \tag{1}$$

The step response function of the transformer is obtainable using the Laplace transform equation of this circuit. The output of this Laplace circuit $\tilde{e}(s)$ for the step input $2u(t)$ is written as

$$\tilde{e}(s) = \frac{1}{(Z/L_t + s)}. \tag{2}$$

Then the step response of the transformer $e(t)$ is obtained using the inverse Laplace transform of Eq. (2), as shown below,

$$e(t) = e^{-(1/\tau)t}, \quad \tau = \frac{L_t}{Z}. \tag{3}$$

In those equations, $\tau$ represents a time constant for the unit step response of the transformer. The low cut-off frequency $\omega_{Low-3\,\mathrm{dB}}$, where the gain $|A(\omega)|$ falls $1/\sqrt{2}$in Eq. (2), provides a simple relation,

$$\omega_{Low-3\,\mathrm{dB}} = \frac{1}{\tau}. \tag{4}$$

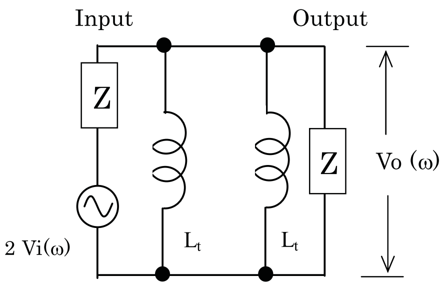

FIG. 2. Low-frequency equivalent circuit model of the transformer. $L_t$ is the self-inductance of the primary and secondary annular conductors.

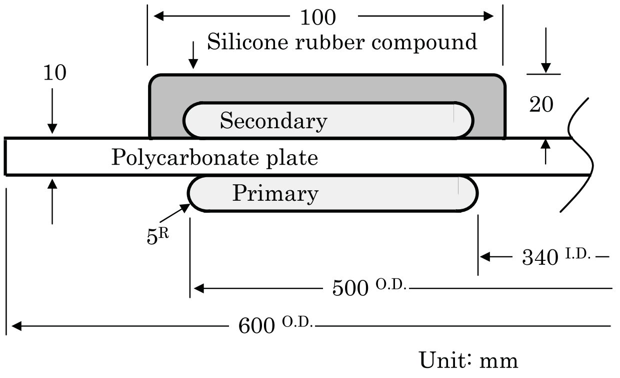

FIG. 3. Cross-sectional view of the parallel-strip annular transmission line. The secondary conductor (high-voltage side) is sealed with electrical insulating material to prevent corona discharge into the air.

This well-known relation is also apparent in the theory of general LTI systems. The low cut-off frequency $\omega_{Low-3\,\mathrm{dB}}$ of the transformer can be determined from Eq. (4) exactly if we estimate the value of inductance$L_t$ by measuring it or calculating it. Increase of the self-inductances of the annular conductors is necessary if an application demands a large time constant or lower cut-off frequency.

## III. CONSTRUCTION AND TEST

The transformer presented in Fig. 1 was designed, constructed, and tested. The transmission lines and coaxial lines were mutually connected directly at the input and output junctions, as presented in Fig. 1: the electromagnetic mode conversion from coaxial line to the parallel-strip transmission lines at the junctions has been neglected. Because of the transit time, signals passing through the junctions are shorter than the rise time of the sub-nanosecond pulses to be transmitted.

### A. Detailed structure of the transformer

A cross-sectional view of the annular parallel-strip transmission line is depicted in Fig. 3. The inner and outer diameters of the conductors are, respectively, 340 mm and 500 mm. The conductor width is 80 mm. Spacing between the primary and secondary conductors of the transformer is kept at 10 mm with the polycarbonate plate. A typical value of the dielectric strength of polycarbonate plate adopted here was 33 kV/mm. Therefore, withstanding voltage of more than 300 kV can be expected. To prevent a corona discharge in the air, the corner edges of the conductors were rounded with a 5 mm radius. Furthermore, the secondary conductor was covered with a silicone rubber compound with dielectric strength of 20 kV/mm.

It is difficult to determine the exact impedance of parallel-strip transmission line because signals will not be traveling exactly on the lines with transverse electromagnetic modes. Furthermore, the dielectric constant of the polycarbonate in the high-frequency region is not well known.

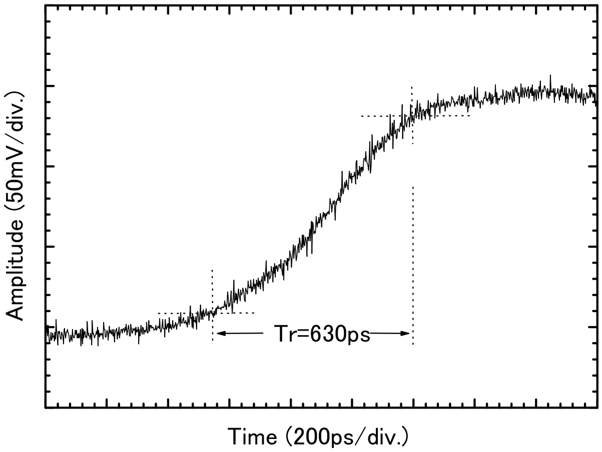

FIG. 4. Rise time response of the test transformer. The input signals, respectively, have 25 ps 10%–90% rise time, and 200 mV pulse height.

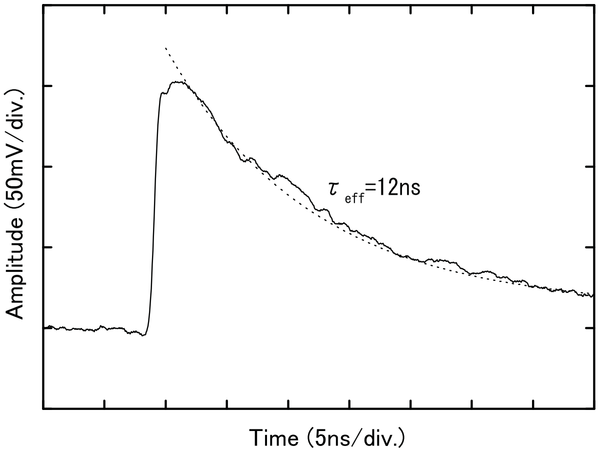

FIG. 5. Output waveform for a much longer time scale than that portrayed in Fig. 4. The superimposed exponential fitted curve shows the effective time constant of the test transformer.

Therefore, the line was approximated as straight, and the dielectric constant of the polycarbonate plate for all frequencies was inferred to be constant with a typical value of $\varepsilon_r = 3$. For these conditions, the line impedance is estimated as about 26 Ω using the following formula for characteristic impedance of parallel-strip transmission line, as $Z = (120\pi/\sqrt{\varepsilon_r})(d/w)$, where parameters $d$ and $w$, respectively, signify the line spacing and width.[9]

The self-inductance$L_t$ of the annular conductors was measured using a grid dip meter (Mita Musen Kenkyusho Ltd.). With this measured value $L_t$ of 0.6 $\mu$H and the input and output impedances of 50 Ω, the time constant of the transformer $\tau$ was estimated from Eq. (2) as 12.0 ns.

### B. Test performance of the transformer

The rise time response of the transformer for a step pulse input is presented in Fig. 4. The input signals have 200 mV amplitude and 10%–90% rise time of 25 ps, respectively, as measured using an oscilloscope with 12.4 GHz bandwidth. The output signal amplitude was measured as about 150 mV. Then the insertion loss of this transformer was estimated as about −2.5 dB with the input–output ratio. As described in a previous paper, a small part of the signal being transmitted with the transformer also escapes into the space inside of the annular transmission line.[6,7] Then those escaped signals invariably appear in the transformer, leading to attenuation of the output signals.

The rise time $T_r$ of the output waveform was estimated as about 630 ps. The leading cause of this degradation for the rise time response can be regarded as leakage of the electromagnetic wave radiated from both sides of the conductors of the annular parallel-strip transmission lines.

The output waveform for a much longer time scale than that in Fig. 4 is presented in Fig. 5, where the exponential function is also superimposed. With this fitting, the effective time constant $\tau_{\mathrm{eff}}$ was evaluated as 12 ns, which agreed exactly with the theoretical value obtained from Eq. (2). The low cut-off frequency of the transformer $\omega_{Low-3\,\mathrm{dB}}$ was also estimated from Eq. (4) as 80 MHz.

Because of limits of the test equipment and the experimental environment, the transformer was not capable of testing the withstanding voltage of 300 kV that was expected with the dielectric strength of the polycarbonate plate. However, the withstanding voltage of 150 kV necessary for this study was tested. Stable operation was also confirmed. The transformer has been used to deliver sub-nanosecond trigger pulses across a high dc potential stage higher than 100 kV, exhibiting good stability and durability.

Transformers incorporating the transmission line topology proposed in this paper are expected to be useful for other applications in fields such as a transient electronics. Good low-frequency characteristics and a large time constant are readily obtainable by increasing the self-inductance of the annular conductors using high-permeability magnetic materials if high voltage operation is not demanded for applications. In addition, a smaller design of the transformer with or without magnetic materials will be improved for higher frequency responses because the electromagnetic waves leaked from the transmission lines and mode conversion of the signals at the input and output junctions will be decreased.

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