Proposal of double voltage transmission line pulse generator using four coaxial cables

Hitoshi Kijima, Koji Ochi

***Abstract*—** In order to carry out the simulation of an electrical noise, a pulse generator with fast rise time is needed. For this reason, the pulse generator using a coaxial cable is usually used. The pulse generator consists of a DC power supply, a charging resistor, a coaxial cable, a switch relay, and a terminating resistor. Even the same voltage as charge voltage was outputted when the termination of the impedance was high, only the output of the half of charge voltage is obtained when the termination impedance was set at 50Ω which is the characteristic impedance of the coaxial cable. For this reason, we have been developing a pulse generator with the same voltage as charge voltage while termination impedance was set at 50Ω, by connecting four coaxial cables in parallel and in series.

***Keywords*—** Pulse generator, Transmission Line Pulse, EMC technologies, Coaxial cable, Blumlein method, Characteristic impedance, Mercury switch relay

I. Introduction

EMC technologies have been introduced in the articles [1]-[11]. A transient phenomenon is observed when a power circuit is switched on or off. To simulate this phenomenon, we use a pulse generator having a coaxial cable. Generally this method is called **TLP** (**T**ransmission **L**ine **P**ulse) method. It consists of a high-voltage DC power supply, a charging resistor, a coaxial cable, a switch relay, and a terminating resistor. Even the same voltage as charge voltage was outputted when the termination of the impedance was high, only the output of the half of charge voltage is obtained when the termination impedance was set at 50Ω which is the characteristic impedance of the coaxial cable. The rise time of waveform generated by this generator is very fast such as 1 n sec, and the maximum peak voltage is 4kV. Considering the noise immunity type test, the further high voltage such as 8kV is required. However the maximum output voltage is restricted by the limit of the electric strength of the switch relay of the pulse generator.

Blumlein method was known to be able to generate the pulse of the same peak value as charge voltage [12]-[16]. The coaxial cable having double coaxial structure is being used for this method. However this coaxial cable is not available on the market. Therefore we have been developing a pulse generator with the same voltage as charge voltage without using double coaxial structure while termination impedance was set at 50Ω, by connecting four coaxial cables in parallel and in series.

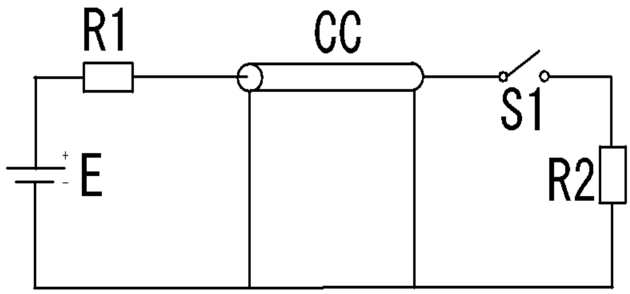
H. Kijima works for Polytechnic University of Japan. He is now with the Electrical Department, Tokyo, Japan, *(e-mail: hkijima@uitec.ac.jp)*

K. Ochi works for Polytechnic University of Japan. He is now with the Electrical Department, Tokyo, Japan, *(e-mail:K.oti@nifty.com)*

II. Principle and Experimental Results of the Pulse Generator Using a Coaxial Cable

A. Principle of the pulse generator using a coaxial cable

Generally this method is called **TLP** (**T**ransmission **L**ine **P**ulse) method, and as shown in Fig. 1. It consists of a high-voltage power supply E, a charging resistor R_1, a coaxial cable CC, a switch relay S_1, and a terminating resistor R_2. The pulse width is formed by the travelling wave reflection in the coaxial cable CC, and it becomes delay time twice the pulse width of the coaxial cable CC. That is, since the coaxial cable with 50Ω characteristic impedance generally has the delay time of 5 ns per meter; the pulse width in the case of 1m length becomes 10 ns. Moreover, the pulse output voltage is determined by relation between the resistance value of the terminating resistor R_2 and the characteristic impedance Z_0 of the coaxial cable. When the switch relay S_1 is open, the electric energy is stored in the coaxial cable CC through the charging resistor R_1 from the high-voltage power supply E. If the point of the switch relay S_1 closes, the electric energy charged spreads to the output coaxial cable CC in the both directions, and a high-voltage pulse will be outputted across the terminating resistor R_2.



E : High-voltage power supply
R_1 : Charging resistor
CC : Coaxial cable
S_1 : Switch relay
R_2 : Terminating resistor

Fig.1 Pulse generator using a TLP method

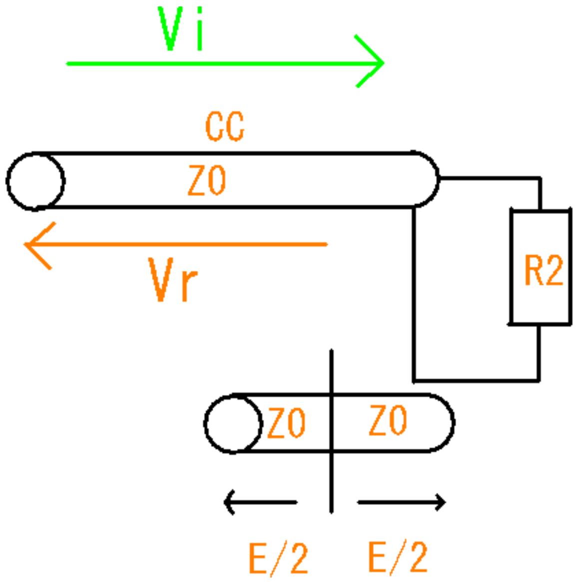
In the case of charge voltage is E[V] and the termination of the terminating resistor R_2 is carried out at 50Ω in Fig. 1, the output voltage V_{out} across the terminating resistor R_2 becomes

$$V_{out} = E/2.$$

It means that only half voltage of charged voltage can be obtained. On the other hand, in the case of that the charge voltage is E[V] and the termination of the terminating resitor R_2 is carried out at infinit in Fig.1, the output voltage V_{out} across the terminating resistor R_2 becomes

$$V_{out} = E$$

It means that the same voltage of charged voltage can be outputted. This phenomenon can be explained using following travelling wave theory.



$Vr = Vi \times (R_2 - Z_0) / (R_2 + Z_0)$

Reflective voltage $Vr = 0$ ($Z_0 = R_2 = 50\Omega$)

$Vr = Vi$ ($R_2 = \infty$)

Fig.2 Travelling Wave

In the case of charge voltage is E[V] and the termination of the terminating resitor R_2 is carried out at 50Ω in Fig. 2, the incoming voltage V_i becomes E/2. This is because a travelling wave spreads every E/2 in the direction of rightside and leftside. On the other hand, if impedance differs from Z_0 and R_2, the reflective voltage Vr will arise. If the termination of the terminating resistor R_2 is carried out by high resistance value, the reflective voltage Vr will become

$$Vr = Vi$$

Then it is set to $V_{total} = Vi + Vr$. It means that E [V] is outputted.

B. Spice simulation of the pulse generator in the case of using a single coaxial cable

Spice simulation of the pulse generator output in the case of using a single coaxial cable was carried out as shown in Fig.3. The charged voltage is 1V. The characteristic impedance of the coaxtial cable is 50Ω. The delay time of the transmission line is 50ns simulating coaxial cable having 10m length.

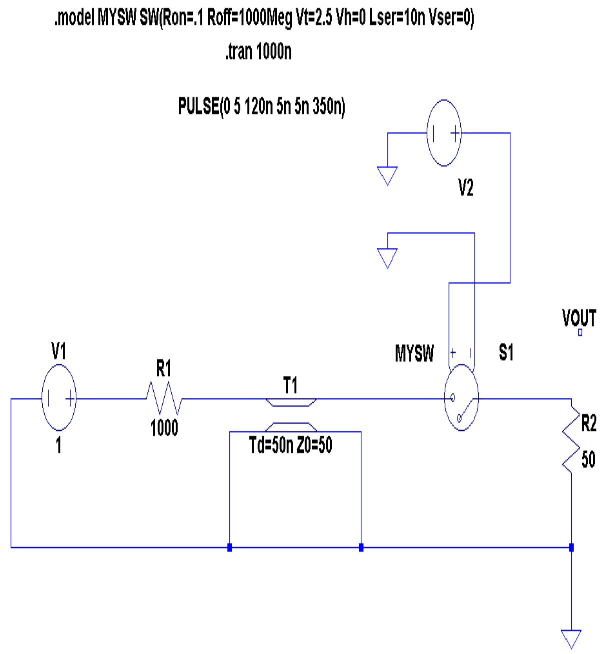


Fig.3 Spice simulation of the pulse generator using a single coaxial cable

The Spice simulation result in the case of 50Ω termination is shown in Fig.4. The simulation result under the condition of 50Ω termination is 0.5V which is half value of charged voltage of 1V. And the pulse width is 100ns.

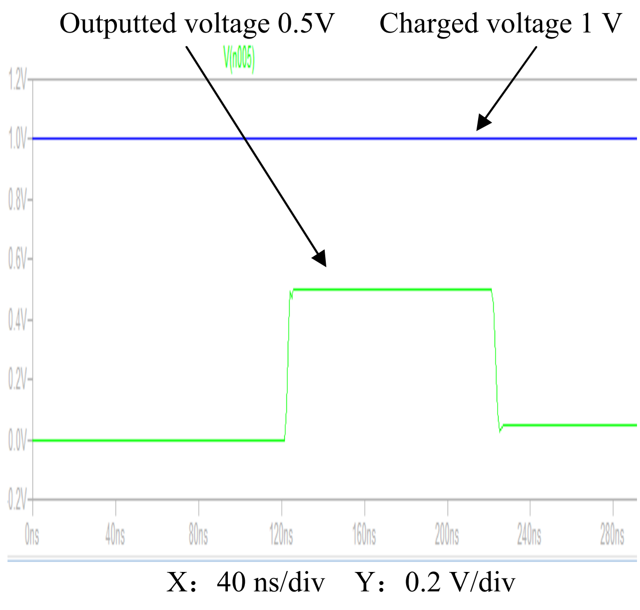


Fig.4 Spice simulation result in the case of 50Ω termination

C. Experimental results of the pulse generator in the case of using a single coaxial cable

Fig.5 shows experimental test equipment. The experimental test equipment is consisting of a high-voltage power supply, a charging resistor, a coaxial cable having 10m length, a switch relay, and a terminating resistor. The characteristic impedance Z_0 of a coaxial cable (3D-2V) is 50Ω. While the charge voltage was fixed 1 V, resistance value of terminating resistor R_2 were changed as follows.

(1) $Z_0 > R_2$（R_2=25Ω）
(2) $Z_0 = R_2$（R_2=50Ω）
(3) $Z_0 < R_2$ (R_2=100,1000Ω)

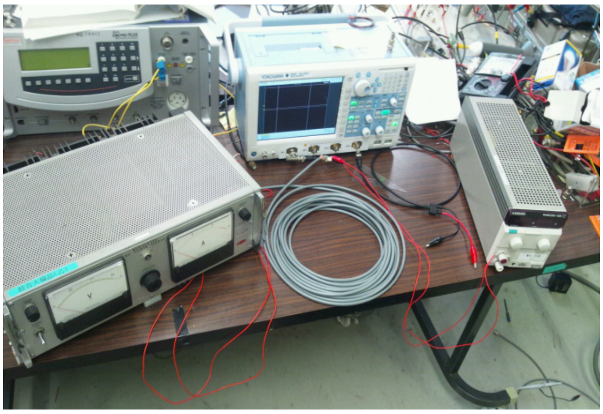
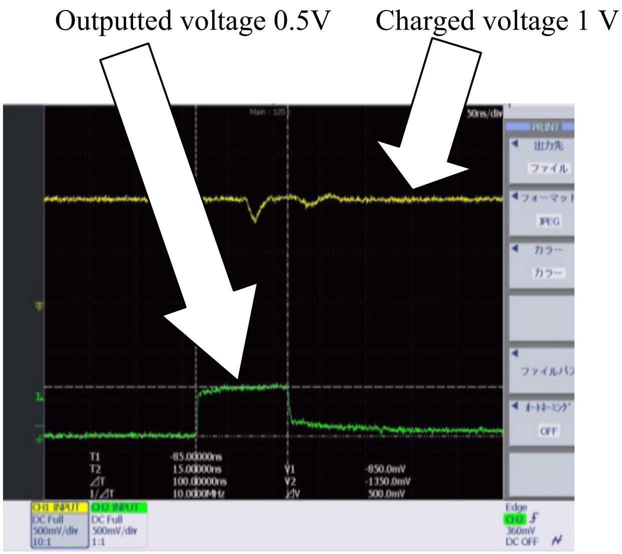


Fig.5 Pulse generator using a single coaxial cable



X: 100 ns/div Y: 0.5 V/div

Fig.6 The measurement result in the case of $Z_0 = R_2$（R_2=50Ω）

As an example of a measurement result, the waveform in the case of 50Ω termination is shown in Fig.6. The simulation result at the time of carrying out a termination at 50Ω is 0.5V, and was in agreement with the actual measurement result of 0.5V. And the pulse width is 100 ns. Moreover, other simulation results were in agreement with the actual measurement results as listed in Table 1.

Table 1 The comparison of measurement results and Spice simulation results on outputted voltage

	Resistance Value (Ω)	Voltage (V)	
		Simulation	Experiment
Single Coaxial Cable	25	0.33	0.33
	50	0.5	0.5
	100	0.6	0.6
	1000	0.95	0.95

III. ABOUT THE DOUBLE VOLTAGE OUTPUT METHOD

A. Problem on double voltage output method

It is the feature that the target impulse generator can generate the rectangular wave using a coaxial cable. And the rise time can be around 1ns with high voltage such as 4kV. Since the output impedance of this pulse generator is 50Ω, when terminating resistance value is 50Ω, only the output of the half of charge voltage is obtained.

In the noise immunity type test for power installations, the further high voltage such as 8kV is needed. However the maximum output voltage is restricted by the limit of the electric strength of the switch relay of the pulse generator.

For this reason, we have been developing the pulse generator under the following conditions. When a termination is carried out by the resistor of the same value as the characteristic impedance of a coaxial cable, the output pulse of the same voltage as charge voltage (two times high voltage value comparison with that of conventional pulse generator) should be outputted without increasing the electric strength of the switch relay.

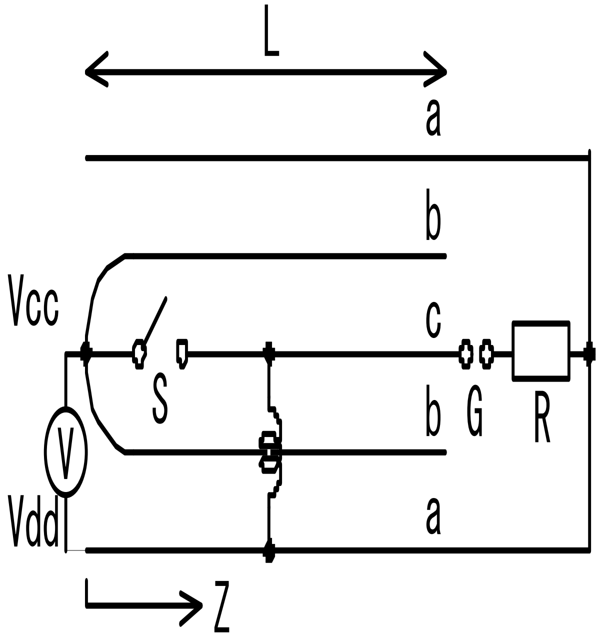
B. The outline of Blumlein method

Blumlein method was known to be able to generate the pulse of the same peak value as charge voltage [12]-[16]. The coaxial cable having double coaxial structure is being used for this method. However this coaxial cable is not available on the market. Therefore we have been investigating to obtain the output pulse voltage of the same voltage as charge voltage without using double coaxial structure.

An outline of Blumlein method is shown in Fig. 7.

When the coaxial cable having double coaxial structure is considered, a core conductor is "c" of Fig.7, the following conductor is "b", and an outer conductor is "a".

It is assumed that the upper part of DC power supply "V" in Fig.7 is "+", and lower part of DC power supply "V" in Fig. 7 is "-". At switch "S" is OFF state, "a" and "c" becomes -(Vdd), and "b" is charged as + (Vcc). Since the both ends of gap "G" are the same voltage, nothing occurs in terminating resistor "R".



Z：Characteristic impedance of a coaxial cable
L：The length of a coaxial cable

Fig.7 Blumlein method

Since each conductor is separated by the coil installed between "a" and "c", if switch "S" is set to ON, "c" turns into Vcc in an instant. Then the voltage of Vcc is generated across the both ends of gap "G", it will be in an electric discharge state, and the output of a pulse will be started.

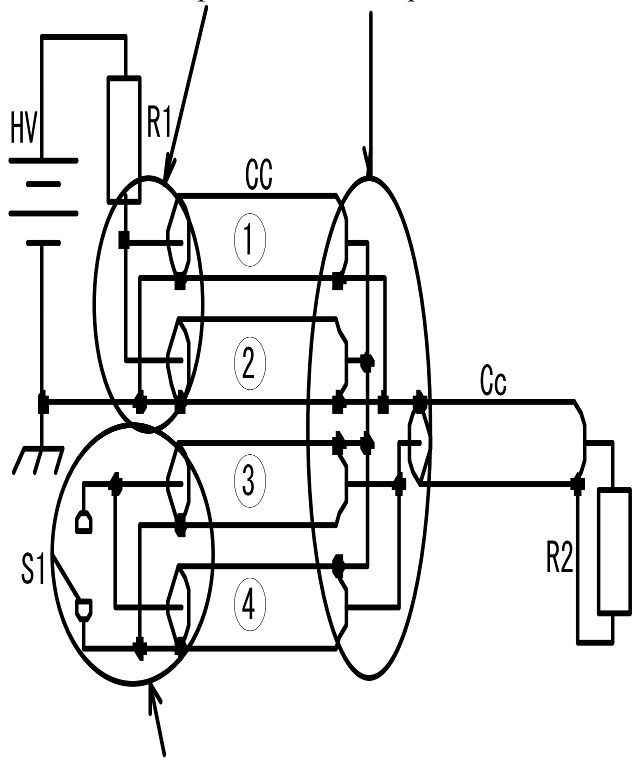
Since the potential of "b" is raised by "c" by Vcc, it becomes the voltage of 2×Vcc and pulse output voltage serves as the same Vcc as charge voltage.

C. Proposal how to realize the Blumlein method without using double coaxial structure

The method using normal coaxial cables instead of using double coaxial structure was examined. The composition of the proposed method is shown in Fig. 8.

It is the method of using the same four coaxial cables without using double coaxial structure. Coaxial cables ① and ② are connected in parallel. And coaxial cables ③ and ④ are connected in parallel. Therefore the characteristic impedance of them become 25 Ω each.

Then the connected coaxial cables ① and ②, and the other connected coaxial cables ③ and ④ are bonded in series. Therefore the characteristic impedance of it becomes 50Ω which is the characteristic impedance of normal coaxial cable. Where Cc is an output coaxial cable.



HV: High-voltage power supply
R_1: Charging resistor
R_2: Terminating resistor
S_1: Mercury switch relay
Coaxial-cable CC ①～④: Coaxial cables for pulse forming
Coaxial cable Cc : Coaxial cable for a pulse output

Fig.8 Composition of the pulse generating parts

It consists of part A which the coaxial cables ① and ② are connected in parallel and charged by a high-voltage power supply (HV), part B which two coaxial cables ③ and ④ are collectively connected to the mercury switch relay S_1, and part C which four coaxial cables ①~④ are accumulated as one coaxial cable Cc.

Although the outer conductor of ① and ② is GND, the outer conductor of ③ and ④ is not so, the isolation voltage between the outer conductors of coaxial cables ①,② and the outer conductors of coaxial cables ③,④ are required more than the charged voltage.

Moreover, both the mercury switch relay and the coil for the switch relay drive require the same high voltage.

Since pulse width is determined by the length of a coaxial cable, the connection with each block used the connector so that change of pulse width might also be possible.

D. Spice simulation of the pulse generator in the case of using four coaxial cables

The simulation of the pulse generator output in the case of using four coaxial cables was carried out as shown in Fig. 9.

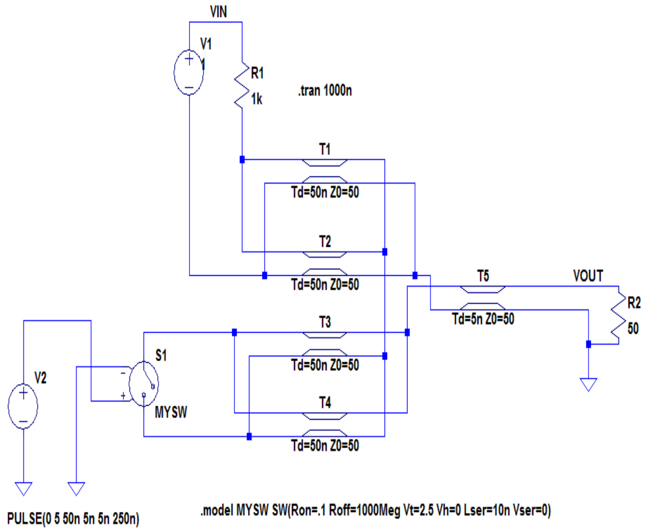
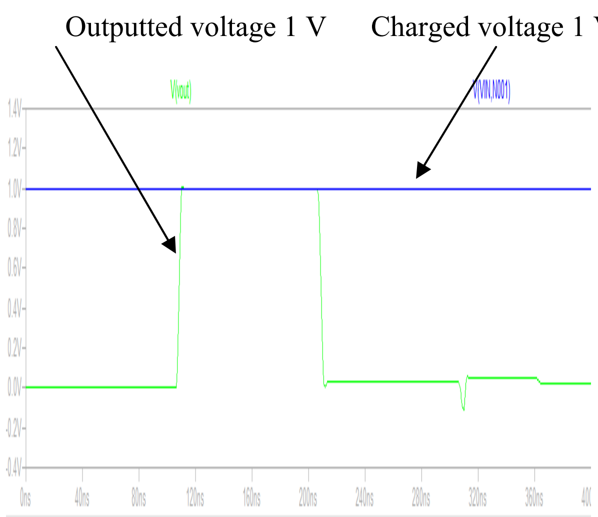


Fig.9 Spice simulation of the pulse generator using four coaxial cables

The charged voltage is 1V. The characteristic impedance of each coaxtial cable is 50Ω. The delay time of the four coaxial cables is 50ns each simulating 10m long cables, and the delay time of the output coaxial cable is 5ns simulating 1m long cable.

The simulation result in the case of 50Ω termination is shown in Fig.10. The simulation result at the time of carrying out a termination at 50Ω is 1V which is exactly the same value of charged voltage 1V. And the pulse width is 110ns including the output coaxial cable length of 1m.



X：40 ns/div Y：0.2 V/div

Fig.10 Spice simulation result in the case of 50Ω termination

E. Specifications of the pulse generator in the case of using four coaxial cables

The specifications of the pulse generator in the case of using four coaxial cables are listed in Table 2.

TABLE 2 COMPARISON OF SPECIFICATIONS

	Conventional specification	Target specification
Charge voltage	8 kV	8 kV
Output voltage	4 kV	8 kV
Rise time	≦1 ns	≦2 ns
Pulse width	50 ns～1 μs	100 ns
frequency	60 Hz	60 Hz

The key technology for increasing output voltage is a mercury switch relay. Furthermore, since the mercury switch relay with high electric strength did not exist, it is a trial in which target specification could be achieved using the mercury switch relay having the conventionally same electric strength.

IV. CONSTRUCTING TECHNIQUES OF COAXIAL PARTS

A. Constructing techniques on coaxial part A

The photograph of the coaxial part A is shown in Fig. 11. It is the block which two coaxial cables are connected in parallel and charged by a high-voltage power supply. It was wired taking isolation voltage into consideration. Since this part A only reflects a standing wave, the influence is not so much for high frequency performance.

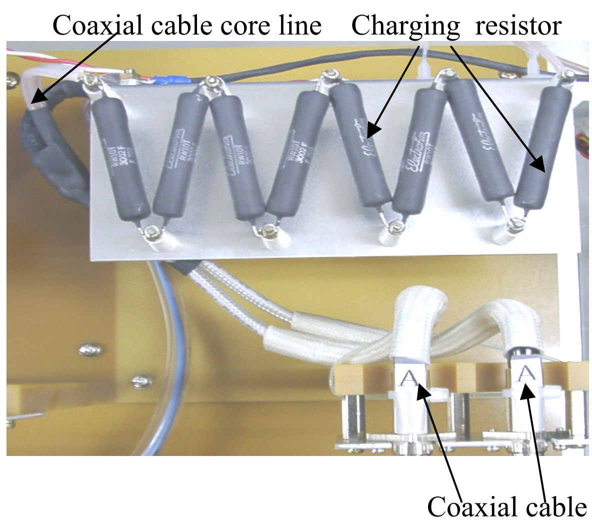


Fig.11 Appearance of the coaxial part A

B. Constructing techniques on coaxial part B

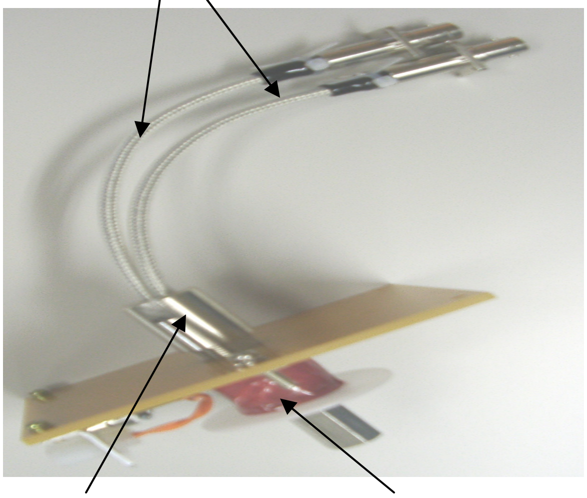
It is the block which two coaxial cables were collectively connected to the mercury switch relay. We used a mercury switch relay in order to prevent a waveform distortion and a chattering noise.

First of all two coaxial cables were connected in parallel. Then the core conductors of them were connected to one end of the mercury switch relay, and the outer conductors of them were connected to the other end of the mercury switch relay.

Since more than 8kV is generated across the core conductor and the outer conductor, it is necessary to consider this high withstand voltage. Moreover, the isolation voltage more than 8 kV is needed to be secured between the outer conductor and the coil for a switch relay drive.

In order to increase the withstanding voltage, the insulating tube was put and the heat hardening type silicon rubber was poured in.

The appearance of the mercury switch relay part is shown in Fig. 12.

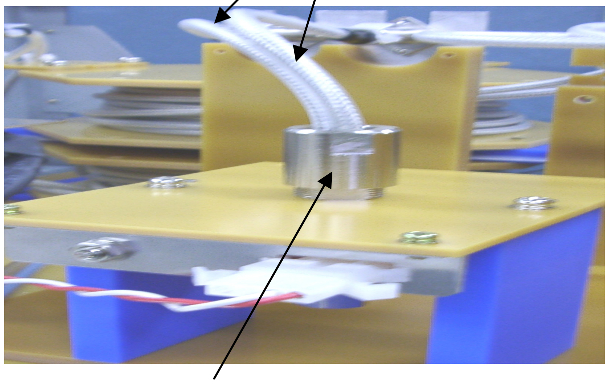


(a) Mercury switch relay was used as a switch to prevent a waveform distortion and a chattering noise, (b) The core conductor of two coaxial cables were collectively connected to the mercury switch relay, (c) To put the insulated tube and silicon rubber

Fig.12 Appearance of the coaxial part B (Two coaxial cables are connected in parallel)

Furthermore, after carrying out air vacuum and carrying out heat hardening, it was put into the case and the insulating cover of the coaxial cable was processed as shown in Fig. 13.

Moreover, the Mylar film was filled up around insulation between the mercury switch relay and the drive coil. The mercury switch relay of this state was attached to the insulated board.



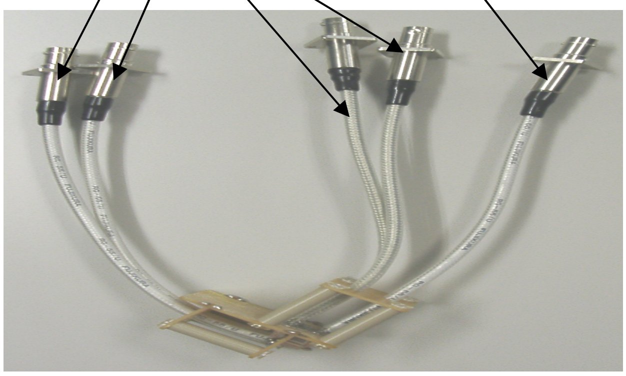
(a)Air vacuum was carried out, (b) The Mylar film was filled up around insulation between the mercury switch relay and the drive coil, (c) The mercury switch relay was attached to the insulated board

Fig.13 Appearance of the coaxial part B (Mercury switch relay attachment state)

C. Constructing techniques on coaxial part C

It is the block which four coaxial cables are accumulated as one coaxial cable. Each coaxial cable (①,② and ③,④) is charged at the maximum voltage of 8kV. In the case where the termination of the terminating resistor is carried out at 50 Ω as for coaxial cable Cc, the output voltage can be 8kV. However when the terminating resistance value is high, 16kV could be appeared. It should be designed taking into consideration of this much higher voltage.

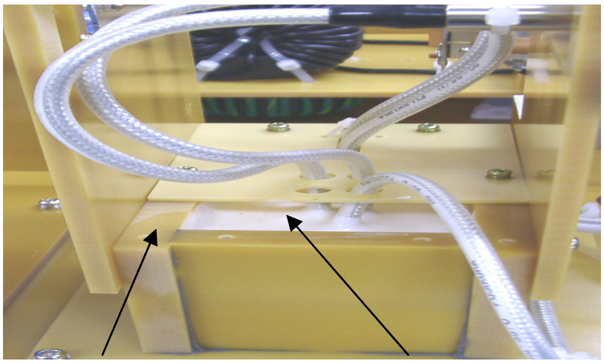
Fig.14 shows the photograph of part C which the four coaxial cables were accumulated. Since this part causes the mismatching of impedance, the dimension of this part should be small as possible.



(a) Series connection of every two coaxial cables,
(b) Outputted as one coaxial cable.

Fig.14 Appearance of the coaxial part C (Accumulation part of four coaxial cables)

Fig. 15 shows the photograph of part C. In order to raise withstanding voltage, the whole block was stored in the bake board case and it was filled up with silicon rubber.



Bake board case Silicon rubber

Fig.15 The inclusion state of the coaxial part C

V. Evaluation Results

A. Evaluation method

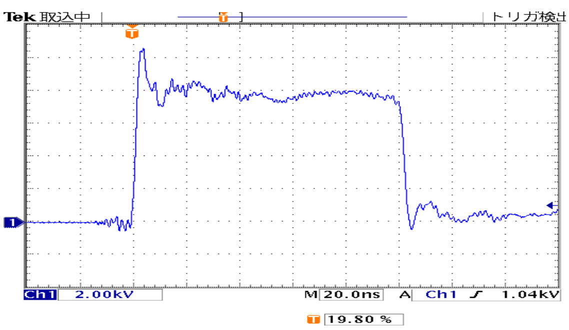
The measuring equipment which can perform measurement of the pulse of 8kV having broadband frequency does not exist. It means that the withstanding voltage of conventional measuring equipment is up to 4kV. Therefore the evaluations of the specifications are divided into the following two steps.

One is to verify the 8kV peak value of the pulse to apply high voltage such as 8kV using a high-voltage probe having narrow frequency range. The other is to verify the rise time to apply low voltage such as 5V using coaxial attenuator having broad frequency range.

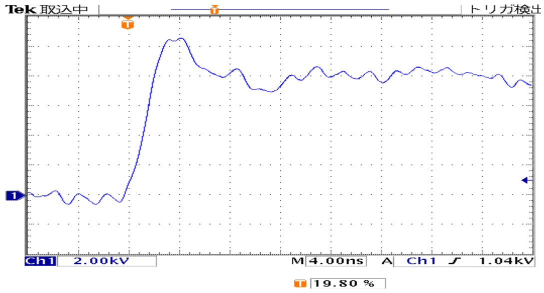
B. The example of the peak value observations using measuring equipment having frequency range of DC-50MHz

The example of an output pulse waveform is shown in Fig. 16. Since there was no 50Ω-Attenuator which can be used for an 8kV pulse voltage wave, the termination was carried out by a 50Ω resistor, and it observed with the high-voltage probe having narrowband frequency range (DC~50MHz).

It has been checked that pulse voltage was about 8kV. And the pulse width was 100ns. Since the rise time was influenced by the narrowband frequency range of the measuring equipment, the rise time was observed as 4ns.



(a) X：20 ns/div 4 ns/div Y：2k V/div



(b) X：4 ns/div Y：2k V/div

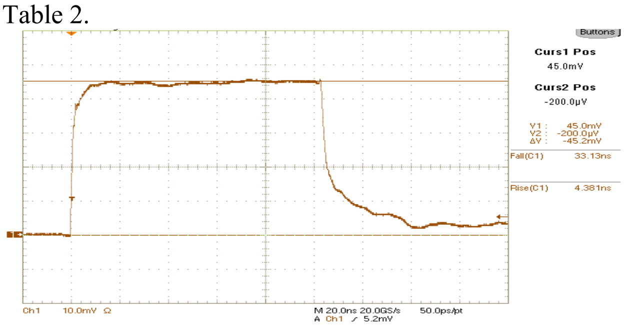
Oscilloscope：Tek TDS-3052

Probe：Tek P-6015A (DC～50 MHz）

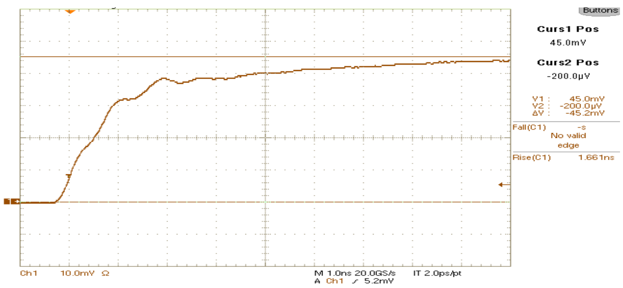
Fig.16 The measured waveforms of 8kV peak value using the experimental equipment having narrowband frequency range

C. The example of the rise time observations using measuring equipment having frequency range of DC-2GHz

There is no high voltage probe having wideband frequency range. Therefore the applied voltage was made low such as 5V. Then the rise time of the output pulse was observed with both the oscilloscope having broadband frequency range (DC～4GH）and the attenuator having broadband frequency range (DC～2GH）as shown in Fig.17. The rise time was observed as 1.7 ns (designed value: 2 ns), and it checked fulfilling the target specification as listed in Table 2.



(a) X：20 ns/div Y：0.5 V/div



(b)X：1 ns/div Y：0.5 V/div

Oscilloscope：Tek TDS-7404（DC～4 GHz）

Attenuator：Tek011-0059-03（DC~2GHz、20 dB）

Applied voltage： 5 V

Fig.17 The measured waveforms of 1.7ns rise time using the experimental equipment having broadband frequency range

VI. CONCLUTIONS

In order to carry out the simulation of an electrical noise, a pulse generator with fast rise time is needed. For this reason, the pulse generator using a coaxial cable is usually used. The pulse generator consists of a DC power supply, a charging resistor, a coaxial cable, a switch relay, and a terminating resistor.

Even the same voltage as charge voltage was outputted when the termination of the impedance was high, only the output of the half of charge voltage is obtained when the termination impedance was set at 50Ω which is the characteristic impedance of the coaxial cable. For this reason, we have been developing a pulse generator with the same voltage as charge voltage while termination impedance was set at 50Ω, by connecting four coaxial cables in parallel and in series.

As a result, the pulse generator having output pulse voltage of 8kV which is two times higher value comparison with that of conventional one has been developed while termination impedance was set at 50Ω.

The following improvements are made further from now on.

（1） Improvement of the rise time
It is possible to make the rise time faster by selecting the components installed in the coaxial parts B and C.

（2）Establishment of much better measurement
Broadband attenuator having much higher withstanding voltage is supplying now.

（3）To make pulse width variable
In order to change pulse width, it is necessary to exchange four coaxial cables of the same length simultaneously. The connector to be able to easily change four coaxial cables is under design.

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Hitoshi Kijima

He received his BS and MS in Electrical engineering from Yamanashi University and his Ph.D. from Tokyo University. He works for Polytechnic University of Japan. He obtained the best paper award for the 9th WSEAS Conference EHAC '10, Cambridge University, UK, 2010

Koji Ochi

He received his BS in Electrical engineering from Tokyo Denki University. He had been working for Iwatsu Electric Co., Ltd, Noise Laboratory Co., Ltd. He works for both Cosmic Medical Engineering Co., Ltd and Polytechnic University of Japan.