High Voltage Pulse Generator by connecting Normal Coaxial Cables in series and in parallel without using Blumlein method

Hitoshi Kijima, Koji Ochi
Polytechnic University
2-32-1 Ogawanshi Kodaira 187-0035 Tokyo
JAPAN
hkijima@uitec.ac.jp

Abstract: - In order to carry out the simulation of the 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 relay, and a terminator. 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 50 ohm 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 50 ohm, by connecting four coaxial cables in series and in parallel.

Key-Words: - **I**mpulse, Transmission Line Pulse, Noise immunity test, Coaxial cable, Blumlein method, Mercury relay,

1 Introduction

EMC technologies have been introduced in the articles [1]-[5]. A transient phenomenon is observed when the power line circuit is switched on or off. To simulate this phenomenon, we use a pulse generator having a coaxial cable.

Generally this method is called the **TLP** (**T**ransmission **L**ine **P**ulse) method. It consists of a high-voltage DC power supply, charge resistor, a coaxial cable, a coaxial relay, and a terminator.

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 50 ohm 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 4 kV. 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 (8 kV) of the switch relay of an impulse generator.

The Blumlein method was known to be able to generate the pulse of the same peak value as charge voltage [6]-[11]. 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. We have been developing a pulse generator with the same voltage as charge voltage while termination impedance was set at 50 ohm, by connecting four coaxial cables in series and in parallel [12],[13].

2 Principle and experimental results of the pulse generator using a coaxial cable

2.1 Principle of the pulse generator using a coaxial cable

Generally this method is called the **TLP** (**T**ransmission **L**ine **P**ulse) method, and as shown in Fig. 1. It consists of a high-voltage power supply E, charging resistor R_1, a coaxial cable CC, a switch relay S_1, and a terminating resistor R_2.

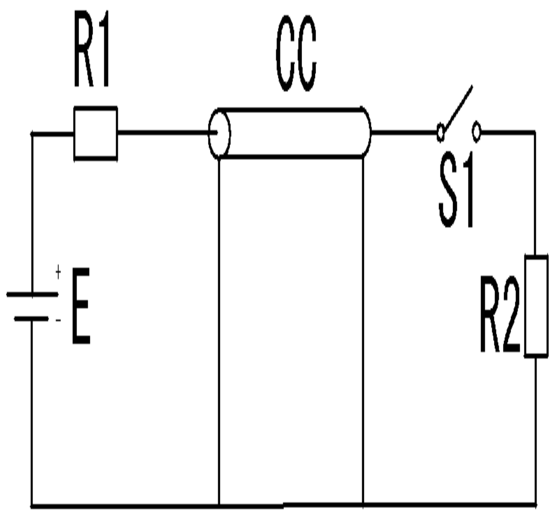
Pulse width is formed using the travelling wave reflection in a coaxial cable, and it becomes delay time twice the pulse width of the coaxial cable.

That is, since the coaxial cable with 50Ω characteristic impedance generally has the delay time is 5 ns per meter; the pulse width in the case of 1m length becomes 10 ns.

Moreover, pulse output voltage is decided by relation between the resistance value of a terminator (R_2), and the characteristic impedance Z_0 of a coaxial cable (50 Ω).

When the switch relay is open, electric energy is stored in a coaxial cable through charging resistor R_1 from a high-voltage power supply E.

If the point of switch relay closes, electric energy charged spreads to output coaxial cable CC in the both directions, and a high-voltage pulse will be outputted across the terminator 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 coaxial cable

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

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

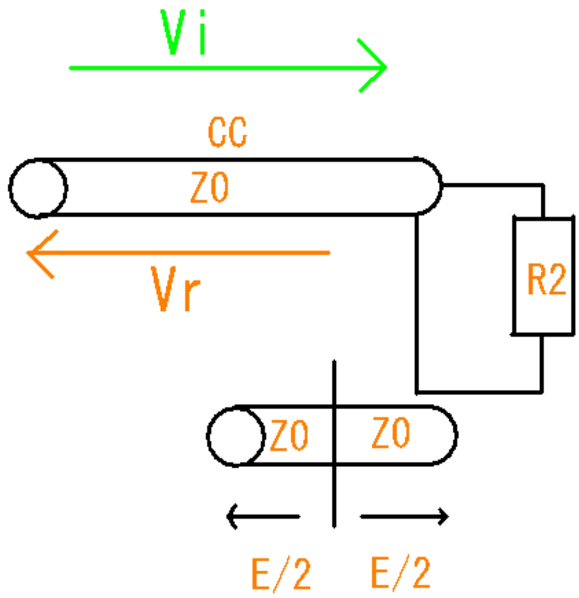
It means that only half voltage of charged voltage can be obtained.

On the other hand, in the case of that the charge voltage is E[V] and the termination of the terminator R_2 is carried out at infinit in Fig.1, the output voltage V_{out} across the terminator 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.



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

reflection Vr=0 ($Z_0 = R_2 = 50\,\Omega$)

Vr=Vi ($R_2 = \infty$)

Fig. 2 Travelling Wave Theory

In the case of charge voltage is E[V] and the termination of the terminator 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 terminator R_2 is carried out by high resistance value, the reflective voltage Vr will become Vr=Vi. Then it is set to V= Vi+Vr. It means that E [V] is outputted.

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

The simulation of the pulse generator output using a single coaxial cable was carried out as shown in

Fig.3. The charged voltage is 1 V. The characteristic impedance of the coaxtial cable is 50Ω. The delay time of the transmission line is 50 ns simulating coaxial cable having 10 m length.

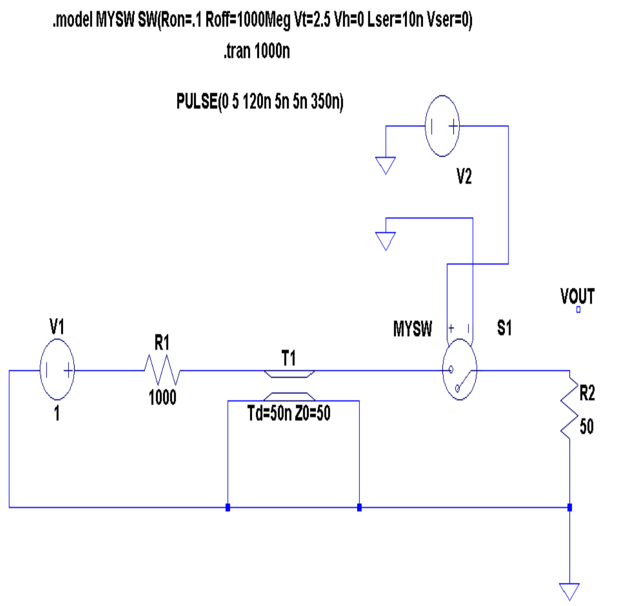
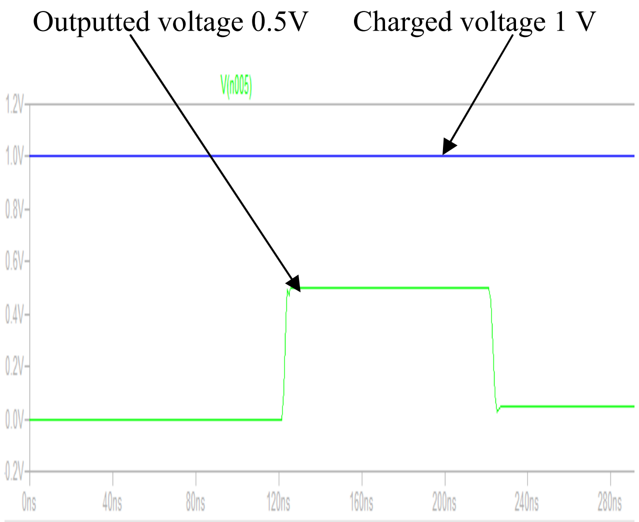


Fig.3 Spice simulation of the pulse generator using a single coaxial cable

The simulation result in the case of 50Ω termination is shown in Fig.4. The simulation result at the time of carrying out a termination at 50Ω is 0.5 V which is half value of charged voltage 1V. And the pulse width is 100 ns.



X：40 ns/div Y：0.2 V/div

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

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

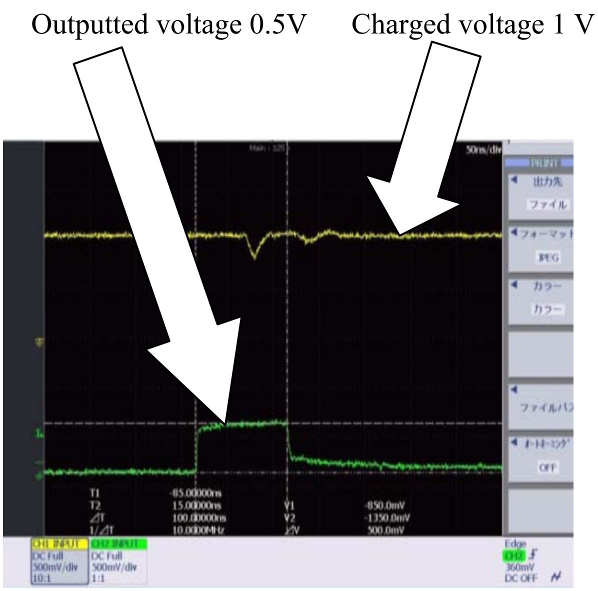
Fig.5 shows experimental equipment. The experimental equipment is consisting of a high-voltage power supply, charging resistor, a coaxial cable having 10 m length, a switch relay, and a terminating resistor. The characteristic impedance Z_0 of a coaxial cable (3D-2V) is 50 Ω. While the charge voltage is 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, waveforms in the case of 50 Ω are shown in Fig.6. The simulation result at the time of carrying out a termination at 50 Ω is 0.5V, and was in agreement with the actual measurement of 0.5V. And the pulse width is 100 ns. Moreover, other simulation results were in agreement with the actual measurements as listed in Table 1.

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

	Resistance (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

3 About the double voltage output method

3.1 Problem on double voltage output method

It is the feature that the target impulse generator can be generating the rectangular wave using a coaxial cable. And rise time can be around 1ns with high voltage such as 4 kV.

Since the output impedance of this pulse generator is 50Ω, when load impedance is 50Ω, it serves as "one half of output voltage" to the charge voltage of "1."

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

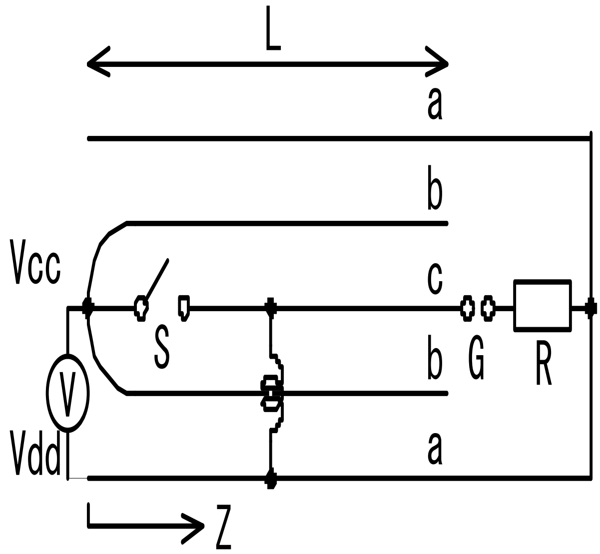
For this reason, we have been developing the generator under the following conditions. When a termination is carried out by the resistor of the same value as the characteristic impedance of a coaxial cable, the output pulse of the same voltage (twice over the past) as charge voltage should be outputted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

3.2 The outline of Blumlein method

The Blumlein method was known to be able to generate the pulse of the same peak value as charge voltage. 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.

Blumlein method uses double coaxial structure and generating a pulse between a central line and the outside conductor.

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



Z : Characteristic impedance of a coaxial cable

L : The length of a coaxial cable

(1)Blumlein method was known to be able to generate the same value of the charged voltage

(2)Coaxial cable having double structure is being used

(3)However this coaxial cable is not available on the market

Fig.7 Blumlein method

When the coaxial cable having double coaxial structure is considered, a central conductor is "c" of Fig.7, the following conductor is "b", and an outside 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). Therefore, since the both ends of gap "G" are the same voltage, they will be in an electric discharge state, and nothing occurs in terminator "R".

Since each conductor is separated by the inductance which is between "a" and "c" in a transient if switch "S" is set to ON, "c" turns into Vcc in an instant, and 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.

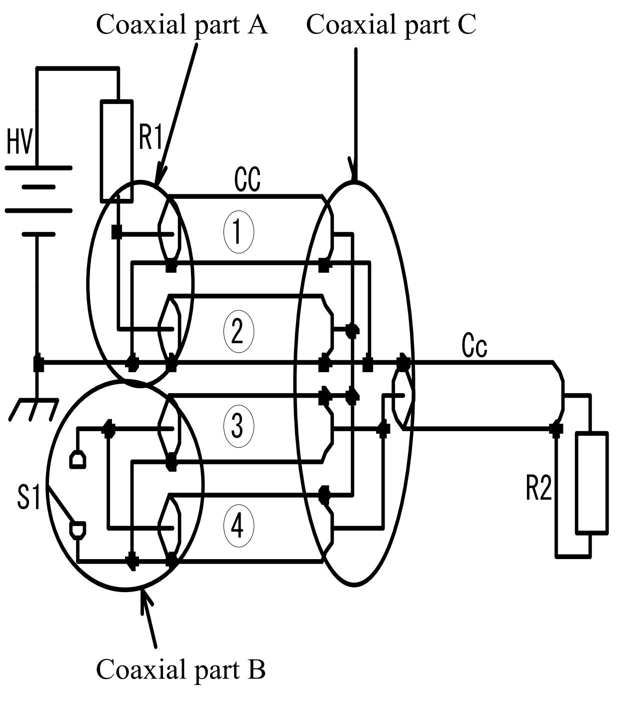
Since the potential of "b" is raised by "c" by Vcc, it becomes the voltage of 2×Vcc and pulse output voltage serves as the same Vcc as charge voltage.

3.3 How to realize the Blumlein method without using double coaxial structure

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

It is the method of preparing the four same coaxial cables. Coaxial cable ①,② are connected in parallel. And coaxial cable ③,④ are connected in parallel. Therefore the characteristic impedance of them become 25 Ω each.

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



R_1: Charging resistor R_2: Terminator
S_1: Switch relay
Coaxial-cable CC ①～④: The coaxial cable for pulse forming
Coaxial cable Cc : Coaxial cable for a pulse output

Fig.8 Composition of a generating parts

It consists of a high-voltage live part (coaxial parts A), coaxial cable CC for pulse width formation (four coaxial cables of the same length: (1)-(4), switch relay S_1 (coaxial parts B), a terminal area (coaxial parts C), and coaxial cable Cc for an output.

Coaxial cable ①,②and ③,④ become multiple connections.

Although the outer cover of ①and ② is GND, since the outer cover of ③ and ④ is not so, the isolation voltage between the outer covers of a coaxial cable is required more than 8 kV.

Moreover, since the outer cover of a relay switch requires the same high voltage as the outer cover of ③ and ④, high insulation withstanding voltage is needed also between the coils for a relay drive.

Since the round part within the limit was a part where characteristic impedance is mismatched easily and the result of these parts influenced pulse quality, it was small as much as possible and designed be easy to process it.

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.

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

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

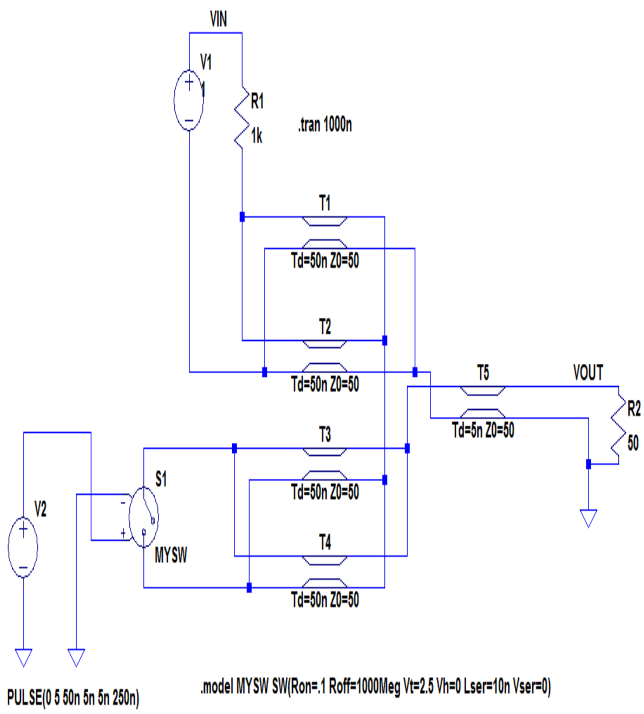
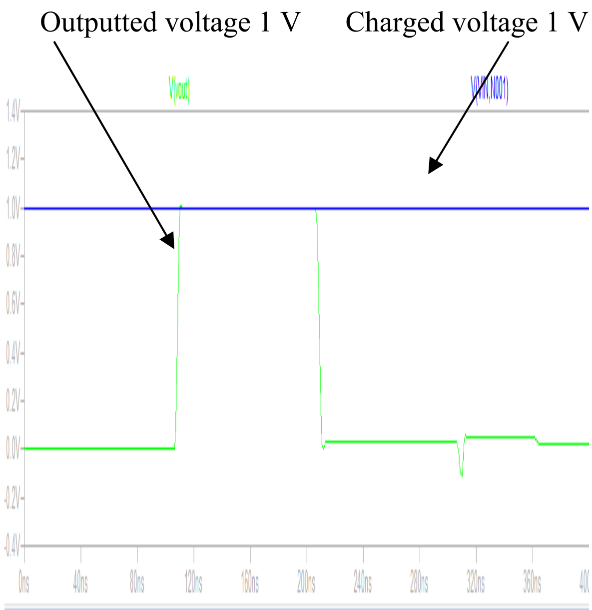


Fig.9 Spice simulation of the pulse generator using four coaxial cables

The charged voltage is 1 V. The characteristic impedance of each coaxtial cable is 50Ω. The delay time of the transmission line is 50 ns.

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 50 Ω is 1 V which is exactly the same value of charged voltage 1V. And the pulse width is 110 ns including the output coaxial cable length 1m.



X : 40 ns/div Y : 0.2 V/div

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

3.5 Specifications of pulse generator in the case of using four coaxial cables

We decided the specifications on output voltage and rise time as 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	Tip part ≦2 ns Whole ≦10 ns
Pulse width	50 ns～1 μs	100 ns
frequency	60 Hz	60 Hz

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

Next, although it is about the verification method, the measuring instrument which can perform measurement of the pulse of 8 kV in a broadband does not exist. It means that the withstanding voltage of a conventional measuring instrument is up to 4 kV. Therefore we decided to verify high-speed portions, such as rise time, on low voltage, and to verify a high-voltage part (for a rise time part to be affected since there are frequency restrictions) using a high-voltage probe.

4 Constructing techniques of coaxial parts

4.1 Coaxial part A

The photograph of the coaxial part A is shown in Fig. 11. It is the block which charges the coaxial cable for pulse forming from a high-voltage power supply. It wired taking isolation voltage into consideration. Since this part only reflects a standing wave, influence is not carried out so much to high frequency performance.

(a)Pulse forming part from a high-voltage power supply

(b)It wired taking isolation voltage into consideration

Fig.11 Appearance of the coaxial parts A

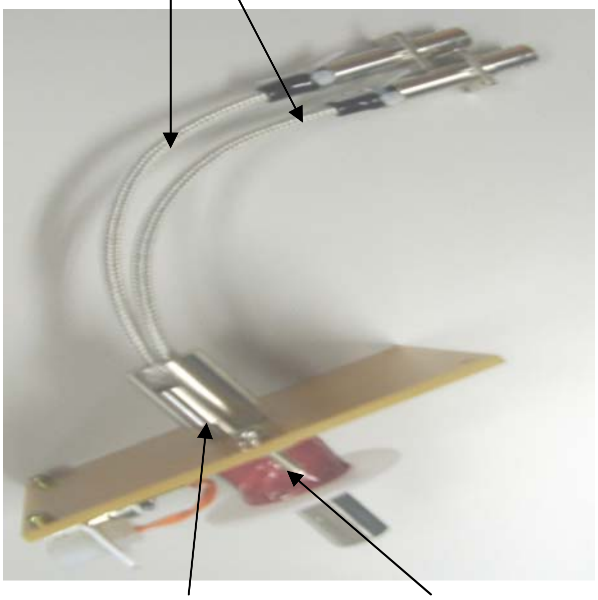
4.2 Coaxial part B

It was presupposed that the switch of a coaxial relay is considered as the mercury relay which uses a mercury switch in order to prevent a wave distortion and chattering. Multiple connection of the coaxial cable is carried out, it leads to one terminal of a mercury relay, and the other terminal of a mercury relay is the circuit block of connecting with the outer cover of a coaxial cable.

Moreover, since the high voltage (more than 8 kV) is generated between a core line and an outer cover, it is necessary to consider between a core line and outer covers as the design of high withstand voltage.

Moreover, since 8 kV turned on electricity to the outer cover of coaxial parts to GND, the isolation voltage more than 8 kV is needed to be secured also between the outer cover and the coil for a relay drive, and it was the most important element including construction and the processing method of structure.

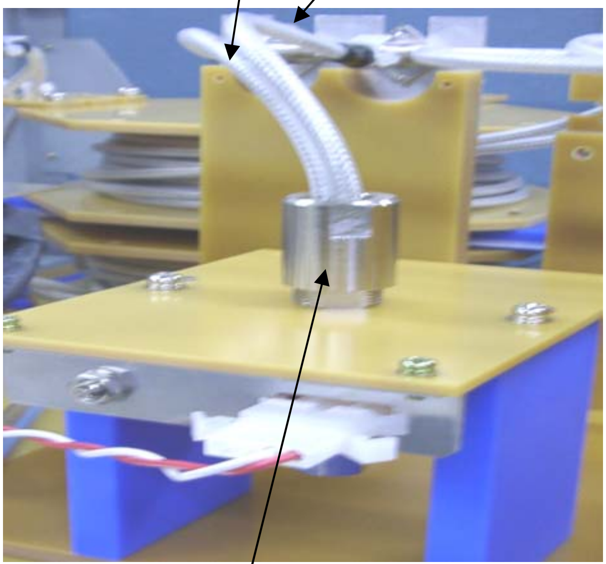
The state where attached the processing appearance of the mercury relay part is shown in Fig. 12, and the mercury relay unit was attached to apparatus is shown in Fig. 13.



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

Fig.12 Appearance of the coaxial parts B (Mercury relay part)

Although it was about the processing method, two coaxial cables were first connected to the mercury switch bottom. The core line of two coaxial cables was collectively connected to the mercury switch top terminal, and this processing put the insulated tube, and poured in silicon rubber (heat hardening type).



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

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

Furthermore, after carrying out air vacuum and carrying out heat hardening, it put into the case and the outer cover of the coaxial cable was processed.
In order to make it connect with a case, the mercury switch bottom rounded soft copper wire, made it the shape of a floor cushion, and was stuffed.

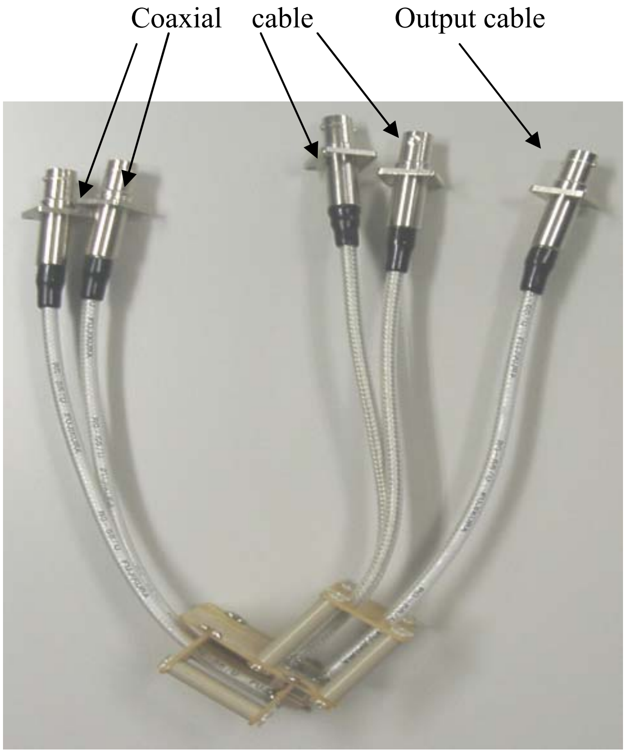
Moreover, the Mylar film was filled up around insulation between the mercury relay and the drive coil. The mercury relay of this state was attached to the insulated board, and was made into the mercury relay unit.

4.3 Coaxial part C

They are the parts which carry out multiple connection of every two coaxial cables, accumulate them (series connection), and are outputted as one coaxial cable. Each coaxial cable (①,② and ③,④) is charged at the maximum voltage of about 8 kV. In the case where the termination of the output end is carried out at 50 Ω as for coaxial cable Cc for an output, 8 kV pulse when an output end is open, pulse wave of double voltage 16 kV could be appeared. It was designed in consideration of this double voltage.

Fig.14 shows the photograph of a part which connected the coaxial cable, and Fig. 15 shows the photograph in the state where stored it in the bake board case. Since this part causes the mismatching of impedance, the dimension of this part should be small as possible.

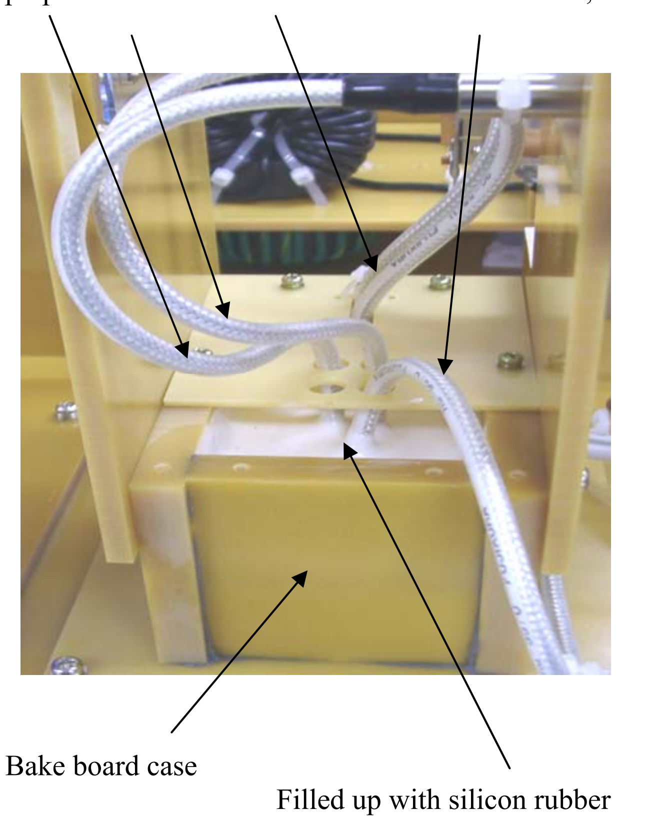
In Fig. 14, a lower printed circuit board part is a synthetic portion. The printed circuit board has been arranged perpendicular to the core line of the coaxial cable. In addition, since a coaxial cable was fixed and the printed circuit board was used further, it has two-step structure. Moreover, in order to raise withstanding voltage, the whole block was stored in the case and it was filled up with silicon rubber.



(a) As this part causes the mismatching of impedance, the dimension should be small as possible, (b) Multiple connections of every two coaxial cables, (c) outputted as one coaxial cable.

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

(a) The printed circuit board has been arranged perpendicular to the core line of the coaxial cable,



(b)The printed circuit board has been arranged perpendicular to the core line of the coaxial cable, (c) The whole block was stored in the case and it was filled up with silicon rubber

Fig.15 The inclusion state of the coaxial parts C

5 Evaluation results

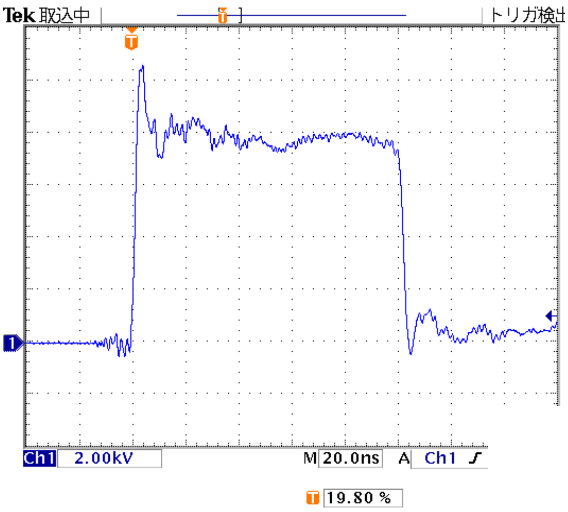
5.1 The example of 8 kV output wave observation in a high-voltage probe

The example of an output pulse shape is shown in Fig. 16.

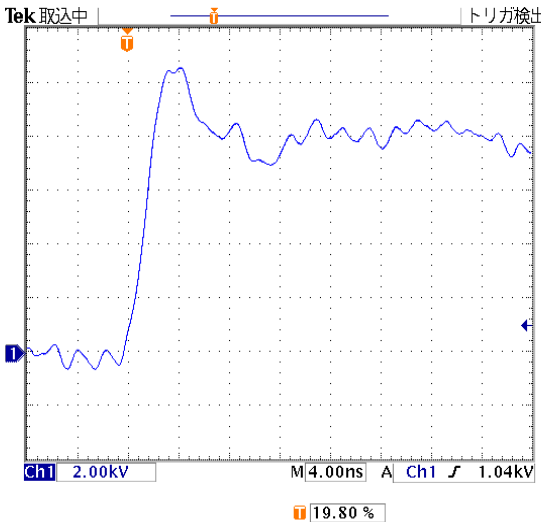
Since there was no 50 Ω-Attenuator which can be used for an 8kV pulse voltage wave, the termination was carried out by a 50 Ω resistor, and it observed with the high-voltage probe having not enough bandwidth (DC~50MHz).

It has been checked that pulse voltage was about 8kV. And the pulse width was 100 ns. In addition, since the rise time and a tip part were influenced by measuring equipment, the rise time was observed 4 ns.

The commercial coaxial cable was able to be used and the pulse of the same voltage as charge voltage was able to be made resulting from this evaluation test.



X：20 ns/div 4 ns/div Y：2k V/div



X：4 ns/div Y：2k V/div

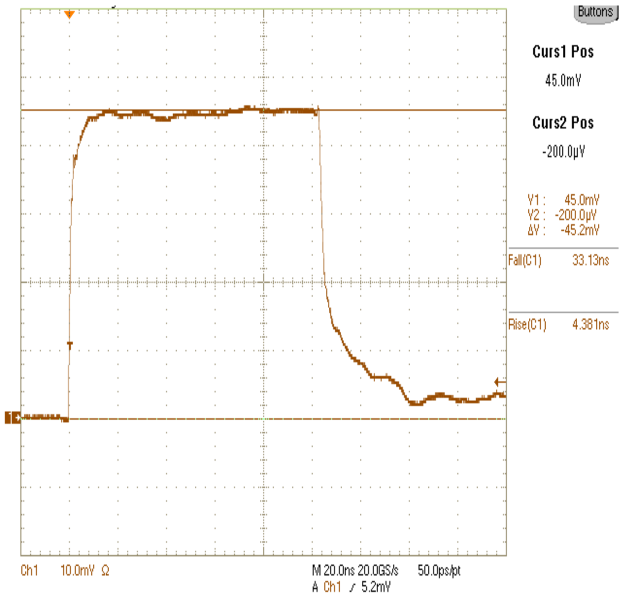
Oscilloscope：Tek TDS-3052
Probe ：Tek P-6015A
（bandwidth：DC～50 MHz）

Fig.16 The waveforms of 8kV output

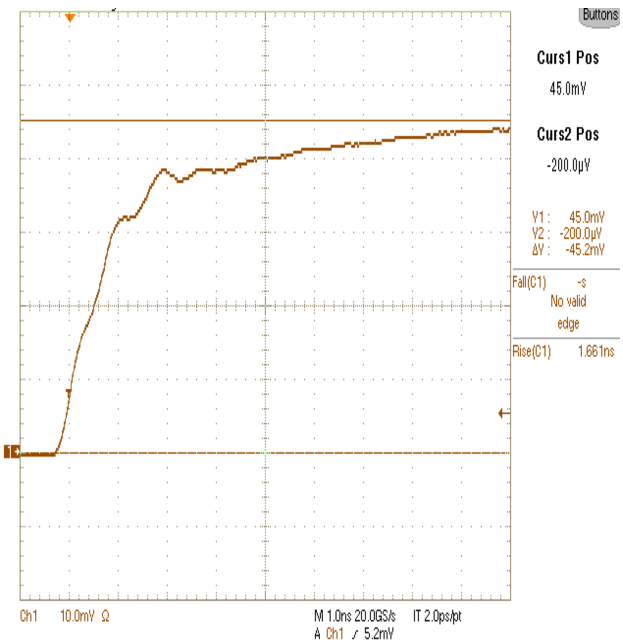
5.2 The example of observation using oscilloscope having frequency bandwidth of DC-4GHz

There is no high voltage probe having wide frequency band. Therefore the output voltage was made low such as 5 V. Then the rise time of the output pulse was observed with the oscilloscope having enough wideband（DC～4 GHz）as shown in Fig.17.

The rise time was 1.7 ns (designed value: 2 ns), and it checked fulfilling target specification.



X：20 ns/div Y：0.5 V/div



X：1 ns/div Y：0.5 V/div

Oscilloscope：Tek TDS-7404（DC～4 GHz）
Attenuator ：Tek 011-0059-03 Two pieces
（DC~2GHz、20 dB）
Charge voltage：About 5 V

Fig.17 The waveforms observed in a broadband domain

6 Conclusion

In order to carry out the simulation of the power supply noise etc., a pulse generator with fast rise time is needed. For this reason, the pulse generator using a coaxial cable is usually used. A pulse generator consists of a direct-current power supply, charge resistance, a coaxial cable, a coaxial relay, and a terminator.

However, although the same voltage as charge voltage was outputted when the termination of the impedance was carried out by high resistance at the load side of a pulse generator, when a termination was carried out by 50 ohms of characteristic impedance, there was a problem from which only the output of the half of charge voltage is obtained. For this reason, we decided to develop the pulse generator which can generate the same voltage as charge voltage without carrying out the termination of the load end by high resistance. As a result the pulse generator having output pulse voltage of 8kV which is two times higher value comprising with that of conventional one, and rise time of 1.7 ns has been developed while termination impedance was set at 50 ohm.

The following improvements are made further from now on.

(1) Improvement of a rise time

In the coaxial parts B and C, carrying out rise time fast further are possible by selecting the elements.

(2) Establishment of much better measurement

Broadband attenuator corresponding to the high voltage is required, and is supplying now.
Input/output impedance: 50 Ω
Dielectric strength: more than 8 kV
The amount of attenuation: 40 dB grade
Frequency bandwidth: DC - more than 500 MHz

(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 change four coaxial cables is under design.

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