Hindawi
International Journal of Antennas and Propagation
Volume 2023, Article ID 9971860, 8 pages
https://doi.org/10.1155/2023/9971860

Research Article

A Compact High-Gain, High-Power, Ultrashort Pulse Signal Acquisition Device

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Received 20 December 2022; Revised 9 February 2023; Accepted 22 February 2023; Published 1 March 2023

Academic Editor: Atsushi Mase

Ultrashort pulse (USP) signal with high peak power is also called ultrawideband signal, which has a broad application prospect in radar detection and electronic countermeasures and other fields. In this paper, an acquisition device is proposed to obtain the USP signal with ultrahigh compression efficiency (CE) and ultrahigh power compression gain (PCG). The long input pulse with a time length of μs level can be compressed to a narrow pulse with a pulse width of 450 ps level (2.6–3.9 GHz) by using the proposed USP acquisition device. Under the condition without loss, the CE of the USP acquisition device can reach up to 98% according to the simulated results. In the simulation, if the material of the acquisition device is set to copper material, then the CE has some reduction due to conductor loss. In order to demonstrate the effectiveness of the proposed USP acquisition device, a USP acquisition device is established and measured. According to the measurement results, a measured PCG of 27 dB is achieved and the pulse width is approximately 460 ps. The peak power of the output USP signal reaches to 100 kW under the condition of input pulse with a power of 200 W.

1. Introduction

The ultrawideband pulse signal with a high peak power has a broad application prospect in communication, radar detection, and electronic countermeasures. Therefore, the ultrawideband pulse signals have been widely studied. The USP signal usually refers to the signal with a pulse width of 100 ps level or less. In this paper, the USP signal represents the pulse signal with sub-ns pulse width, and this is consistent with the description in reference [1].

There are many generation methods to obtain the high-power USP signal with a pulse width of dozens of ps or sub-ns levels. But these methods have their own different limitations. A typical method is to adopt the pulse transformer with a gas switch or light conduction switch to generate a USP signal. At present, the pulse voltage of the generated USP signal can reach up to the MV level by using a microwave switch. However, the pulse width of the obtained USP signal is difficult to reach the level below ns and the repetition frequency is difficult to reach the level above kHz. Another USP signal-generated method is adopting the solid state devices, such as avalanche diode or avalanche triode. The pulse width of the obtained USP signal generated by using a solid state device can reach to 100 ps level. The repetition frequency of several hundreds of kHz can also be achieved. But the output voltage is usually in the order of several hundreds of kV. When converted into the power (50 ohm load), the output power is generally in the tens of the kW level. The total energy utilization efficiency is also not very high.

The pulse compression method is an effective way to obtain a narrow pulse signal. A long pulse with the length of μs level can be compressed to a short pulse with the length of the nanosecond level through the pulse compression method [2]. The time-reversal technology is an effective way to obtain the input long pulse used for pulse compression. The input long pulse is realized by measuring the pulse response signal of a reverberation chamber and then reversing it in the time domain. With the in-depth study of time-reversal technology, the concept of electromagnetic kurtosis is introduced in reference [3]. Electromagnetic kurtosis is an index parameter describing the peak characteristics of the narrow pulse signal, which can effectively reflect the magnitude of electromagnetic wave intensity of narrow pulse signals.

On the basis of a previous study, the reversal technology was studied in detail at the Naval Research Laboratory. And an ultrawideband microwave pulse compressor is presented to generate the microwave narrow pulse signal with sub-ns pulse width [4]. This device has the characteristic of ultrawideband. A rectangular waveguide is adopted as the feeding port to realize the input and output of the high-power microwave. Initially, the compression gain of the narrow pulse generated by using this device is only more than tens of times [5]. Through further research on time-reverse technology, the compression gain has been improved in reference [6]. A maximum compression gain of 24 dB and an energy utilization efficiency of 22% are achieved. The instantaneous peak power reaches to the level of 39.2 kW.

In reference [2], the path encoding pulse compression is proposed to obtain the high-power microwave pulse signal with ultrahigh repetition frequency. The path encoding pulse compression method is to change the group speed and path of a wide pulse by encoding the frequency, phase, and amplitude of the electromagnetic wave corresponding to different times. The encoded pulse is input into the energy storage device, and then the energy is quickly extracted from the energy storage device to realize pulse synchronization at the time of reaching the output port, which makes the pulse width narrow and obtains a higher power compression gain. In this paper, based on the concept of path encoding pulse compression, an ultrahigh efficiency signal acquisition device is proposed for obtaining the USP signal, compared with the traditional high-power microwave generation systems such as the high-power klystron, traveling-wave tube, or other high-power microwave devices, which are often more than ten cubic meters in size and tons in weight. The acquisition device is only a few cubic meters and hundreds of kilograms in the case of generating the same output power. According to the measurement results, the input long pulse with 7 μs time length can be effectively compressed to a USP signal with a pulse width of 450 ps by using the proposed signal acquisition device. A measured PCG of 27 dB is achieved. And the peak power of the obtained USP signal reaches to 100 kW under the condition of input long pulse with a power of 200 W. The measured energy utilization efficiency can be reached up to 40%. Compared with the results in reference [6], the output power, compression gain, and energy utilization efficiency have reached a new high level.

2. Technique Mechanism and Numerical Simulation

The method used in this paper to obtain a USP signal is basically consistent with the method described in reference [1], which can also be called the time-reversal compression method. However, the essence of the method used in this paper is to take the advantage of the multipath scattering effect of a rectangular reverberation chamber. For any dispersive system, the input long pulse can be divided into N segments with frequency and phase encoding. A narrow pulse with a pulse width of $1/N$ can be obtained at the output of the dispersive system after each subpulse satisfies certain conditions [2]. Then, the peak power of the output pulse is improved.

A rectangular waveguide has been taken as an example to illustrate the abovementioned principle in reference [2]. In that case, a BJ-32 rectangular waveguide with a length of $L = 20$ m was adopted. The input long pulse with a time length of 25 ns is divided into 5 part subpulses, and the carrier frequencies of the five subpulses were set to 2.8 GHz, 2.9325 GHz, 3.1146 GHz, 3.3812 GHz, and 3.8119 GHz, respectively. Then, an input encoding long pulse signal is obtained. When the obtained encoding long pulse is fed into the rectangular waveguide, a narrow pulse with a pulse width of 5 ns is obtained at the output of the rectangular waveguide. The peak power is improved by 9 times compared with the input pulse signal. The abovementioned results show that a narrower pulse signal can be generated by using the pulse compression characteristic of a dispersion system.

Although taking a rectangular waveguide for obtaining a narrow pulse signal is feasible in theory, it has no practical value in the factual application. The fundamental reason is that the dispersion paths provided by the rectangular waveguide are single and limited [2], so a very long length is required. In this paper, a rectangular reverberation chamber is adopted for providing abundant scattering paths. As shown in Figure 1, if the cross-section of a rectangular reverberation chamber is larger than that of the BJ-32 rectangular waveguide, then more dispersion paths can be used to realize pulse compression, and a USP signal with a shorter pulse width can be obtained. This is called the path encoding pulse compression method.

In this paper, the rectangular reverberation chamber is adapted to generate the USP signal with a pulse width of 450 ps, which is based on the path encoding pulse compression method. Of course, the time-reversal pulse compression method is just one way to achieve pulse encoding. Theoretically, there are some other methods to achieve path encoding for realizing pulse compression.

In order to verify the effectiveness of rectangular reverberation chamber multipath scattering for USP generation, a simulation model is first established and shown in Figure 2. The material of the rectangular reverberation chamber is set to a perfect electric conductor (PEC). In the design of a rectangular reverberation chamber, two basic principles are followed. The first one is that the pulse scattering paths can be separated enough. The second one is that the losses of the scattering paths are as small as possible.

Thus, the metal cavity is designed as a cuboid shape. Two BJ-32 waveguides, which are set at the two opposite square faces of the rectangular reverberation chamber, are used as the input and output for transmitting and receiving the microwave signals. The shape of the reverberation chamber has a variety of structures. At present, the rectangular reverberation chamber used in this paper is only for the

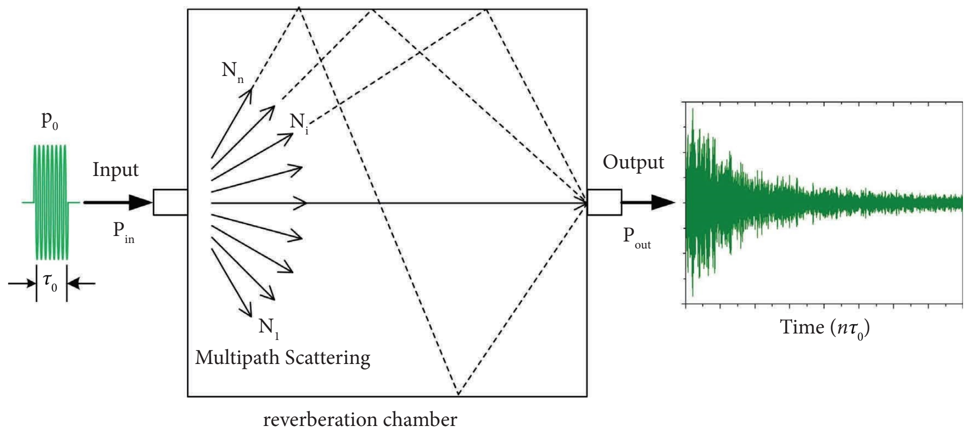


Figure 1: The multipath scattering principle of a rectangular reverberation chamber (the rectangular reverberation chamber has a larger cross-section compared with the wavelength of the operating wavelength frequency).

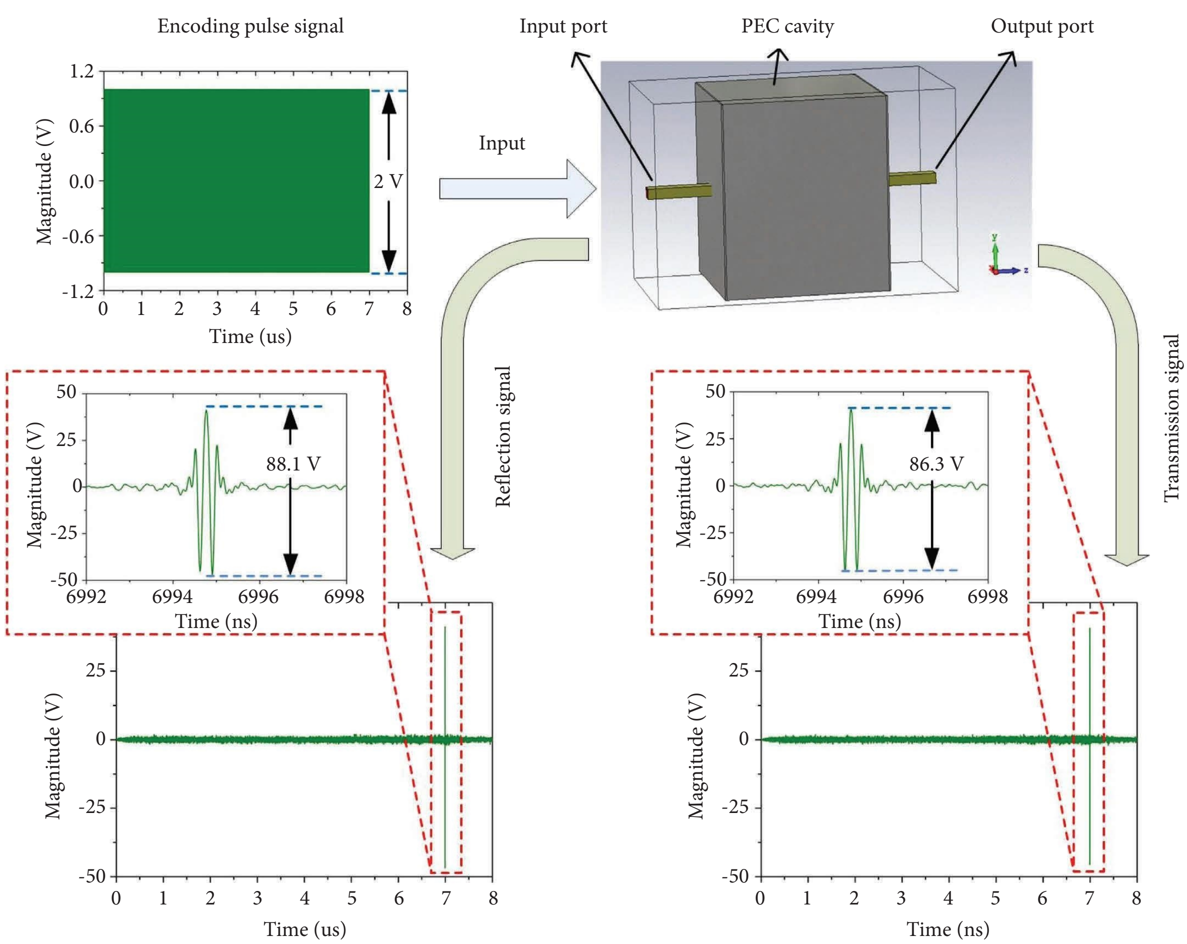


Figure 2: The established simulation model with two BJ-32 ports for obtaining the USP signal by using the multipath scattering effect of a rectangular reverberation chamber (the size of the chamber is 1 m × 1 m × 1 m).

purpose to show the feasibility and effectiveness of the proposed method.

In the simulation, the sizes of the rectangular reverberation chamber model are selected as 1 m × 1 m × 1m for the convenience of subsequent manufacture. The simulated USP signals obtained from the input and output ports are also shown in Figure 2. The time length of the input pulse is selected as 7 μs. As shown in Figure 2, it is observed that the compressed USP signals can be obtained from both the input and output ports. It means that the input long pulse can be effectively compressed to a narrow pulse by using a rectangular reverberation chamber for obtaining a USP

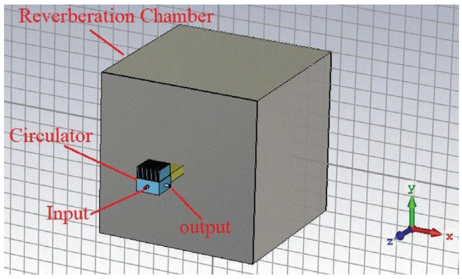


Figure 3: The established improved simulation model with combined input and output, and the output USP signal is extracted through a high-power circulator.

signal. The USP signals obtained from the input port and output port have approximately equal magnitudes. By combining the input and output ports, a USP signal with higher power can be obtained and the energy utilization efficiency can be further improved.

In reference [1], many methods are used to improve the energy utilization efficiency for obtaining a higher PCG. However, the maximum PCG is only 24 dB, and the energy utilization efficiency is not too high. The main reason for this result is that the physical nature of the pulse path encoding is not considered. Based on the understanding of pulse path encoding, the pulse compression technology is reformed from three aspects in this paper. The first one is to increase the volume of the rectangular reverberation chamber, especially the cross-section of the chamber. Then, the more abundant electromagnetic wave scattering paths can be obtained for pulse compression. The second one is that a high-power circulator is adopted to realize the sharing of input and output ports, which is similar to the method given in reference [6]. The third one is to reduce the prepulse output by improving the encoding mode.

The established simulation model with a high-power circulator is shown in Figure 3. A BJ-32 waveguide is used to connect the circulator and rectangular reverberation chamber. For the rectangular reverberation chamber, the input and output signals share one channel. The output USP signal is extracted from the shared channel by using the high-power circulator. The simulated USP signal is shown in Figure 4. It is observed that the amplitude of the obtained USP signal is higher than that of the two-port simulation model shown in Figure 2. The energy utilization efficiency has been greatly improved. Due to the magnitude of the input long pulse signal being 1, the PCG can be reached to 40 dB when the 7 μs input long pulse was selected. The pulse width of the obtained USP signal is about 450 ps according to the simulated result shown in Figure 4.

In reference [1], the cavity efficiency is defined as in [4] as the ratio of the total energy of the output signal (compression USP signal) to the total energy of the input signal (encoding signal).

$$\eta_{\mathrm{cav}} = \frac{\int_{t=0}^{T} y(t)^2 \mathrm{d}t}{\int_{t=0}^{t=T} f(t)^2 \mathrm{d}t}, \tag{1}$$

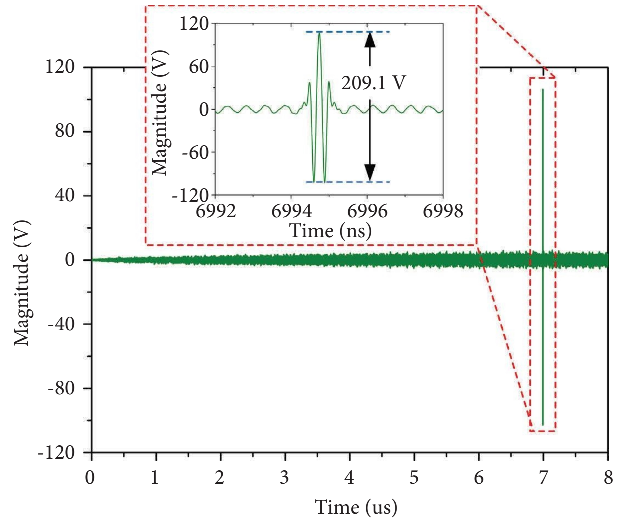


Figure 4: The obtained simulated USP signal by using the improved simulation model shown in Figure 3 with PEC material.

where $y(t)$ is the output compression USP signal of the cavity and $f(t)$ is the input encoding signal.

This cavity efficiency contains the influence of clutter signal except the main pulse peak signal. Here, we are interested in the power compression gain. The cavity efficiency defined in formula (1) cannot effectively reflect the pulse compression performance. Thus, we first define the PCG as follows:

$$\mathrm{PCG} = \frac{|y(t)|_{\max}}{|f(t)|_{\max}}, \tag{2}$$

where $y(t)$ is still the output compression USP signal of the cavity, $f(t)$ is the input encoding signal, $y(t)_{\max}$ is the maximum value of $y(t)$, and $f(t)_{\max}$ is the maximum value of $f(t)$.

Then, the CE is defined as the ratio of the PCG to the time compression gain (TCG). The TCG is defined as follows:

$$\mathrm{TCG} = \frac{T_{\mathrm{tl}}}{t_{\mathrm{pw}}}, \tag{3}$$

where T_{tl} is the time length of the input encoding long pulse signal, t_{pw} is the pulse width of the excited narrow pulse, and TCG represents the ideal maximum pulse compression gain.

Then, the CE is expressed as follows:

$$\eta_{CE} = \frac{\mathrm{PCG}}{\mathrm{TCG}} = \frac{|y(t)|_{\max}/|f(t)|_{\max}}{T_{\mathrm{tl}}/t_{\mathrm{pw}}}. \tag{4}$$

For the rectangular reverberation chamber with PEC material, the compressed result of the input pulse with different time lengths is shown in Figure 5.

According to the simulated results shown in Figure 5, the PCG of a rectangular reverberation chamber with the PEC material is very close to the TCG. It means that the rectangular reverberation chamber with the PEC material has a very high CE. Under the condition of input pulse with

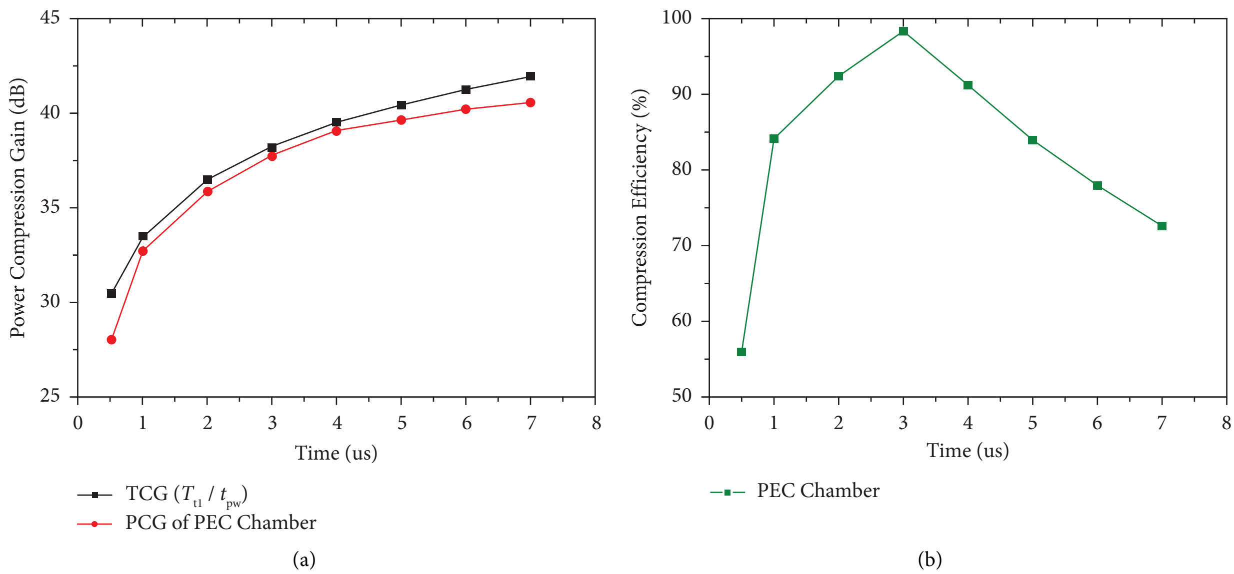


Figure 5: The simulated pulse compression performance along with the time length of the input pulse for the rectangular reverberation chamber with PEC material. (a) Comparison of the TCG and PCG along with the time length of the input pulse. (b) The simulated variation of the CE along with the time length of the input pulse.

a time length of 2 μs, a PCG of 36 dB can be achieved. The simulated CE is higher than 92%. If the time length of the input pulse continues to increase, then the simulated PCG increases relatively slowly. The simulated CE is gradually decreased when the time length of the input pulse is greater than 3 μs. This is mainly caused by the reduction of encoding efficiency. When the time length of the input pulse is selected as 7 μs, then the simulated PCG can reach up to 39 dB, and the CE will still be higher than 70%.

In fact, the electrical conductivity of the reverberation chamber material will affect the PCG. When the material of the reverberation chamber is set to copper ($\delta = 5.7 \times 10^7$), then the compressed result of the input pulse with different time lengths is shown in Figure 6. According to the simulated results, the PCG of 36 dB can be still obtained under the condition of an input pulse with the time length of 2 μs. The simulated CE can reach up to 89%. If the time length of the input pulse is increased, the simulated CE gradually decreases. This is mainly caused by the loss of the reverberation chamber material. When the time length of the input pulse is also selected as 7 μs, then the simulated PCG of the reverberation chamber with copper material can also reach up to 37 dB. Also, the simulated CE will still be greater than 58%. This phenomenon means that the reduction of reverberation chamber loss is beneficial to increase the peak power of the compressed pulse. The simulated USP signal is shown in Figure 7. As shown in Figure 7, the pulse width of the USP signal for the rectangular reverberation chamber with copper material is also about 450 ps.

3. Experiment Research

In this section, the USP acquisition device is established and shown in Figure 8 for measurement. This USP acquisition device consists of an arbitrary waveform generator (AWG) with a sampling rate of 50 GS/s, a power amplifier (PA) with 200 W output power, a rectangular reverberation chamber with the sizes of 1 m × 1 m × 1 m, a high-power circulator, and a high-speed sampling oscilloscope (the sampling rate is also set to 50 GS/s).

As shown in Figure 8, one BJ-32 waveguide is set at one face of the rectangular reverberation chamber for transmitting and receiving the microwave signals. The high-power circulator is used to extract the compressed USP signal from the rectangular reverberation chamber. In order to avoid instrument damage, an appropriate high-power attenuator is added to the output of the circulator as the output pulse peak power is kept in the safe receiving range of the oscilloscope.

Figure 9 gives the measured pulse compression performance of the rectangular reverberation chamber with copper material. According to the measured results shown in Figure 10, the PCG of 22.5 dB is obtained under the condition of the input pulse with a time length of 1 μs. The measured CE can reach up to 69%. As the time length of the input pulse increases, the measured PCG also slowly increases. When the time length of the input pulse is selected as 7 μs, then the measured PCG can reach up to 27 dB, and the measured CE is greater than 40%. The difference between measurement and simulation is mainly caused by the thermal noise which is introduced by the actual system. The encoding efficiency is reduced when the noise is introduced. Thus, how to reduce the noise effect of the actual system is the key content of future works.

Figure 10 gives the measurement results of the output USP signal waveforms for the input pulse with different time lengths. As shown in Figure 10(a), for the input pulse with 2 μs time length, the pulse width of the obtained USP signal is about 450 ps level according to the simulated result. The measured PCG can reach up to 22.5 dB and the peak power

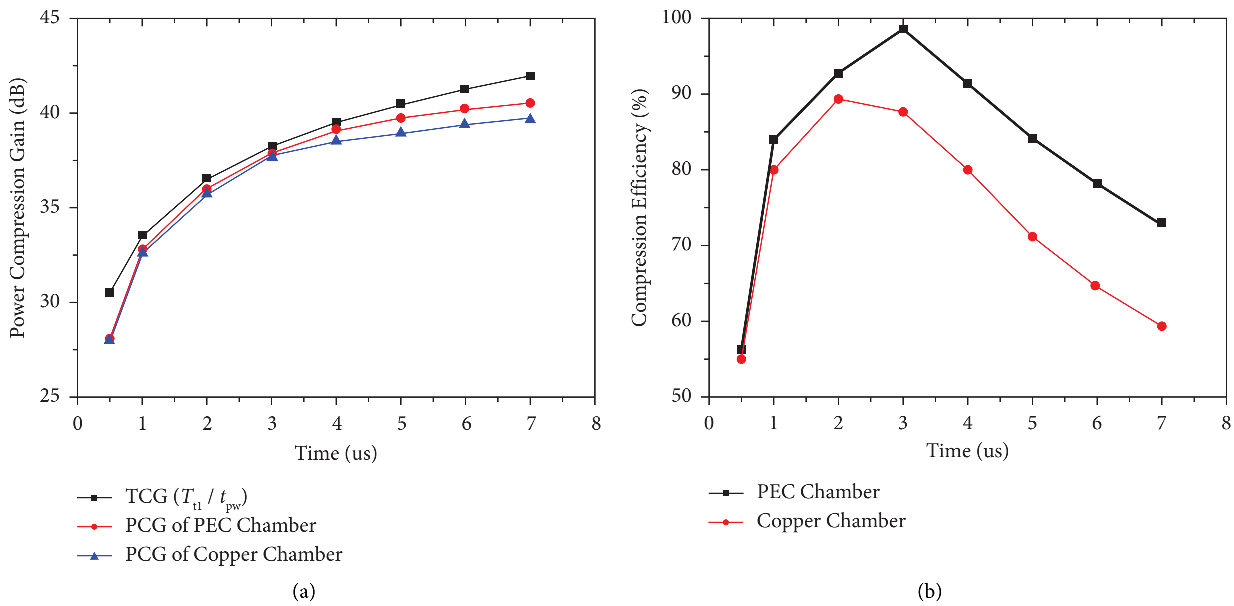


FIGURE 6: The simulated pulse compression performance along with the time length of input pulse for the rectangular reverberation chamber with different materials. (a) Comparison of the simulated PCG along with the time length of input pulse for the rectangular reverberation chamber with PEC and copper materials. (b) Comparison of the simulated CE along with the time length of input pulse for the rectangular reverberation chamber with PEC and copper materials.

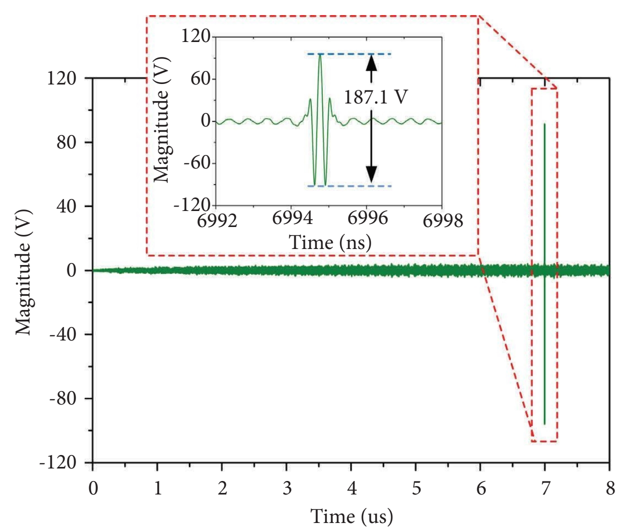


FIGURE 7: The obtained simulated USP signal by using the improved simulation model is shown in Figure 3 with the copper material.

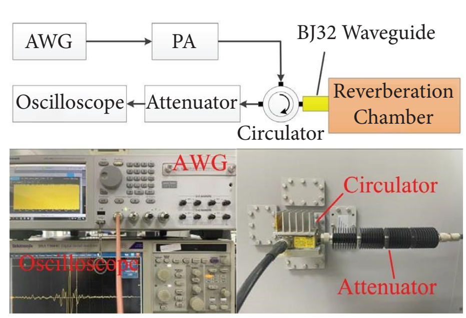
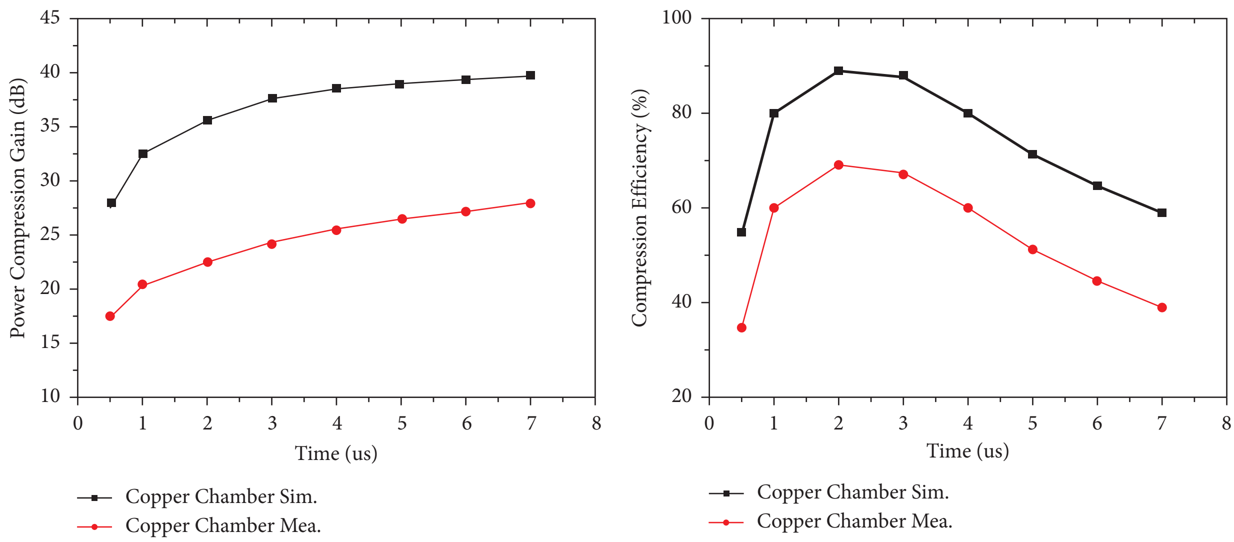
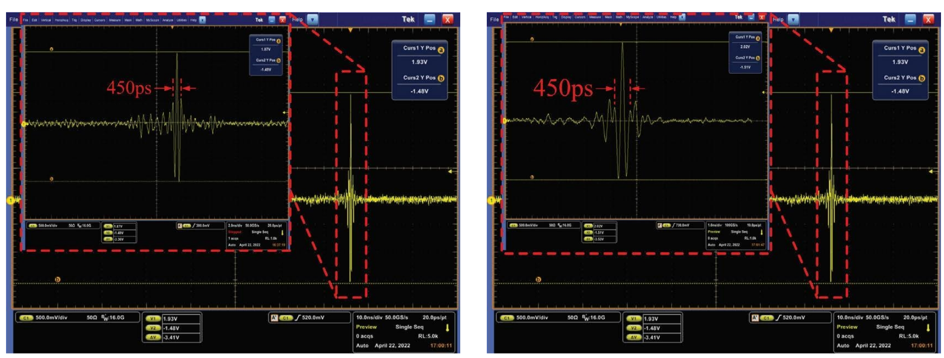


FIGURE 8: Photographs of the established USP acquisition device.



(a) (b)

Figure 9: Comparison of measured and simulated pulse compression performance along with the time length of input pulse for the rectangular reverberation chamber with copper material. (a) Comparison of the measured and simulated PCG along with the time length of input pulse for rectangular reverberation chamber with copper material. (b) Comparison of the measured and simulated CE along with the time length of input pulse for rectangular reverberation chamber with copper material.



(a) (b)

Figure 10: The measured compressed USP signal waveforms of the input pulse with different time lengths. (a) The measured compressed USP signal waveform of the input pulse with 2 μs time length. (b) The measured compressed USP signal waveform of the input pulse with 7 μs time length.

Table 1: The comparison of parameters between this device and other devices.

Name	Our device	Reference [2] device	Reference [6] device	Reference [4] device	Reference [5] device
Size	1 m × 1 m × 1m	1 m × 1m × 2 m	0.65 m × 0.45 m × 0.04 m	0.58 m × 0.32 m × 0.04 m	25.4 cm × 12.7 cm × 2.54 mm
CE	58%	17.1%	24.8%	<10%	<10%

of the output USP signal can reach up to 35 kW level. When the time length of the input pulse is increased, the peak power will also be increased. As shown in Figure 10(b), the measured PCG is 27 dB for the input pulse with 7 μs time length. The peak power of the output USP signal is greater than the 100 kW level. The pulse width of the measured USP signal for the input pulse with 7 μs time lengths is also approximately 450 ps level. The measured CE is greater than 58% according to the measured results, and the comparison of the parameters between this device and other devices is shown in Table 1.

Compared with the results in reference [1], the obtained measured results by using the proposed USP acquisition device is better, and a higher CE is achieved and this is verified by the measured results. Furthermore, the bandwidth of this acquisition device is also less than that of reference [1]. It means that the proposed USP acquisition device can use a less bandwidth to generate the USP signal with high peak power. If the noise effect of the actual system is reduced, the peak power of the output USP signal can be further improved.

4. Conclusions

In this paper, a USP acquisition device is proposed to obtain the narrow pulse signal with ultrahigh CE and ultrahigh PCG. The potential and limitations of this device are mainly determined by the front excitation source and the size and material of the cavity. On one hand, the working frequency band and the working bandwidth of the device are determined by the preexcitation source, which can improve its output power based on the performance of the preexcitation source. On the other hand, the size and material of the cavity will affect the loss and path of the microwave in the cavity, thus affecting the pulse compression gain. The power compression gain of the device can be changed by the length of the encoded signal and the bandwidth of the encoded signal. Generally, the longer the encoded signal is, the greater the compression gain is. The maximum peak output power of this device is determined by the input power and the bandwidth of its preexcitation source. Based on the understanding of the pulse path encoding method, the USP acquisition device has been reformed from three aspects. The first one is to increase the volume of the rectangular reverberation chamber for obtaining abundant electromagnetic wave scattering paths. The second one is that a high-power circulator is adopted to achieve the sharing of the input and output ports. The third one is to reduce the prepulse output by improving the encoding mode. Then, a USP acquisition device is established. The measured results verified the effectiveness of the proposed USP acquisition device. The measured PCG can reach up to 27 dB and the peak power of the output USP signal is greater than the 100 kW level. Moreover, the pulse widths of the measured USP signals for the input pulse with different time lengths are both approximately 450 ps according to the measured results. The total CE is more than 58% according to the measured results. Compared with the previous results, the measured and simulated results obtained in this paper have a qualitative improvement.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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