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A novel power-combination method using a time-reversal pulse-compression technique

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The electromagnetic time-reversal (TR) technique has the characteristics of spatiotemporal focusing in a time-reversal cavity (TRC), which can be used for pulse compression, thus forming an electromagnetic pulse with high peak power. A time-reversed pulse-compression method in a single channel has high pulse compression gain. However, single channel pulse compression can only generate limited gain. This paper proposes a novel TR power-combination method in a multi-channel TRC to obtain higher peak power based on TR pulse-compression theory. First, the TR power-combination model is given, and the crosstalk properties of the associated channel and the influence of the reversal performance are studied. Then, the power-combination performances for the TR pulse compression, such as combined signal to noise ratio (SNR) and combined compression gain, are analyzed by numerical simulation and experimental methods. The results show that the proposed method has obvious advantages over pulse-compression methods using a single channel cavity, and is more convenient for power combination.

Keywords: time reversal, time-reversal cavity, power combination, pulse compression

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1. Introduction

The time-reversal (TR) method refers to when the response signal of a system is turned into a reversal signal and then input into the system, and the original waveform is reconstructed at the initial position.[1,2] TR has the characteristics of spatiotemporal focusing, which can be used in various fields such as pulse compression,[3–5] secret communication,[6,7] reversal imaging,[8,9] beam forming,[10–13] positioning,[14,15] perturbation detection,[16,17] etc. The first electromagnetic reversal system consisted of a single transmitting and receiving antenna and a reverberation chamber with a high Q value.[1] The reverberation chamber used in the system has closure features, also known as a time-reversal cavity (TRC). It not only has strong electromagnetic scattering characteristics, but also can overcome the temporal and spatial coverage limitations of the transmitting and receiving antenna, which enables the system to have good TR performance. The spatiotemporal focusing characteristics of the TRC can be proved by diffraction theory and Green's function.[18,19] Specific to the TR characteristics of the TRC, a multipath channel mode with attenuation and crosstalk has been established, and the side lobe time shift and spatial focusing characteristics have been studied.[2] To expand the applications of TRCs, the influence of parameters such as TRC loss and shape structure upon the reversal performance have also been studied.[20,21] The influence of the original signal upon the reversal performance has been studied by both theoretical and experimental methods.[22] All these research results lay a foundation for the application of TR technology.

Pulse compression is the compression of a wide pulse into a narrow pulse, which is mainly used to improve peak power, and can produce high power and narrow pulse signals. For example, using the frequency domain dispersion characteristics of a slow wave structure, a signal with a certain bandwidth can be compressed to generate high-power microwaves (HPMs).[23] The SLAC energy doubler (SLED) method using resonant cavity energy storage technology can also be used for pulse compression for particle accelerators and HPM generation, and a compression gain of about 4.7 has been obtained.[24] The TR method is a passive pulse-compression technology, which is not only applicable to narrowband and broadband signals, but also can generate high pulse repetition rate (PRF) HPM pulses.[5]

In TR pulse compression, a one-bit TR (OBTR) and path-compensation method (PCM) have been proposed.[3] Based on the OBTR method, a HPM pulse with a repetition frequency of 250 kHz and a peak power of more than 100 kW (with a maximum gain of 23 dB) was experimentally obtained.[5] In addition, for a UWB (5–18 GHz) pulse, a compression gain of 21.2 dB was obtained in a two-dimensional cavity.[25] Unlike the HPM-generation techniques using vacuum electronic devices with relativistic cathodes,[26,27] TR pulse compression has the characteristics of being simple, compact, and lightweight, and has a high repetition rate.

However, only a single channel of the TRC was used in

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the above research. In a single channel mode, the compression gain of the TRC system is limited. Consequently, in order to increase the output power further, this paper proposes a power-combination method by multichannel pulse compression based on TR theory. This can generate higher compression gain.

A power-combination method for TR pulse compression is studied in this paper. First, a multichannel power-combination model is proposed based on TR multipath channel theory, and the channel crosstalk and combined signals are studied. Then, according to the definition of combined signal-to-noise ratio (SNR) and combined gain, the combination performance is studied and verified by numerical simulation and experimental results.

2. Basic theory

2.1. TR theory

When the conductivity and permeability tensors of a medium are both real symmetric matrices, the system has electromagnetic TR symmetry, also known as electromagnetic TR invariance. The TR process can be expressed as a convolution and deconvolution process of the system, as shown in Fig. 1; that is,

$$s_{\mathrm{rec}}(t) = s_{\mathrm{ini}}(t) \cdot h(t) \cdot h(-t), \tag{1}$$

where $s_{\mathrm{rec}}(t)$ is the TR reconstructed signal, $s_{\mathrm{ini}}(t)$ is the initial signal, and $h(t)$ is the impulse response function. This shows that the reversal performance of the system is closely related to the autocorrelation function $\kappa(t) = h(t) \cdot h(-t)$ of the impulse response function. Ideally, if the autocorrelation function (ACF) is $\kappa(t) = \delta(t)$, the initial signal can be completely reconstructed by the time reversion. However, in an actual situation, crosstalk will occur in the system due to scattering, diffusion, attenuation, and other factors, namely, the ACF is $\kappa(t) \neq \delta(t)$. Based on the convolution theorem, the reconstructed signal can be divided into main lobe and side lobe noise. The main lobe waveform is basically consistent with the initial signal.[2]

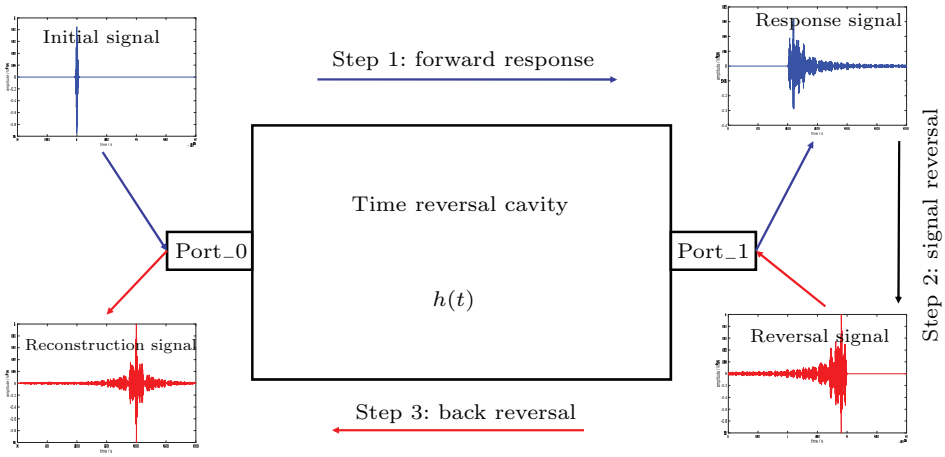


Fig. 1. Typical time-reversal process.

During the TR process, generally the reversal signal $s_{\mathrm{rev}}(t)$ is the inversion of the response signal $s_{\mathrm{res}}(t) = s_{\mathrm{ini}}(t) \cdot h(t)$, i.e., $s_{\mathrm{rev}}(t) = s_{\mathrm{res}}(-t)$. For the electrically large TRC, when the pulse width of the initial signal is narrow, its response signal will have obvious oscillation and attenuation; that is, the pulse width of the response signal is much greater than that of the initial signal. In this case, TR has an obvious pulse-compression effect.

2.2. Power-combination model

In a single channel mode, pulse compression can occur in the TRC system. For a multichannel TRC, TR pulse compression results in different channels being used for power combination. A typical multichannel (multi-port) TRC system is shown in Fig. 2. If Port_0 is the input port for the initial signal (and also the output port for the reconstructed signal), and Port_1, ..., Port_n are the input ports for the reversal signal, then n reversal channels can be formed for power combination. Among these, Port_0–TRC–Port_1, ..., Port_0–TRC–Port_n channels used for TR are defined as the reversal channels. Other channels not used for reversal combination, such as Port_ 1–TRC–Port_1 and Port_1–TRC–Port_2, can be defined as non-reversal channels. Based on TR theory, these non-reversal channels are irrelevant to the reconstruction of the initial signal.

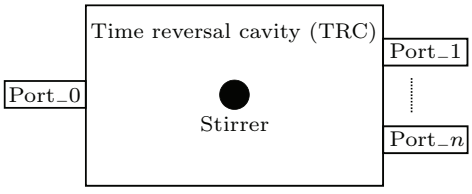


Fig. 2. A multi-port TRC model.

For multichannel TR, the response of each channel can be expressed as $h_i(t)$. Under linear superposition conditions, the

reconstructed combined signal $s_{\rm com}(t)$ at the initial port is

$$s_{\rm com}(t)=\sum_{i=1}^{n}s_{{\rm rec},i}(t)=\sum_{i=1}^{n}s_{\rm ini}(t)\cdot h_i(t)\cdot h_i(-t), \tag{2}$$

where $s_{{\rm rec},i}(t)$ is the reconstructed signal of the i reversal channel.

For the electrically large TRC with a high Q value, the time interval between two adjacent paths is much less than the attenuation time constant of the cavity. As a result, the attenuation coefficient and correlation index of the path can be considered as a constant. Based on the multichannel model,[2] the autocorrelation function and the reversal reconstructed signal can be expressed as

$$\begin{cases}\kappa_i(t)=\sum\limits_{i',j'}^{m}k_{i,i'}k_{i,j'}a_{i'j'}a_{j'i'}\delta\left(t-\tau_{i'}+\tau_{j'}\right),\\ s_{{\rm rec},i}(t)=\sum\limits_{i',j'}^{m}k_{i,i'}k_{i,j'}a_{i'j'}a_{j'i'}s_{\rm ini}\left(t-\tau_{i'}+\tau_{j'}\right),\end{cases} \tag{3}$$

where $k_{i,i'}$ is the attenuation coefficient on the i' path of the i path, $a_{i'j'}$ is the correlation between the i' path and the j' path, δ is the singular function, and $\tau_{i'}$ and $\tau_{j'}$ are the response delay times (i.e., path flight time) on the i' path and j' path.

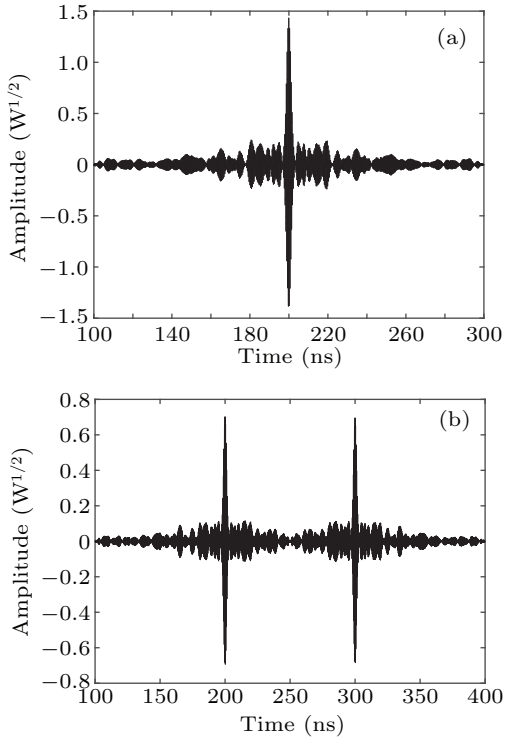


Fig. 3. TR pulse-combination analysis. (a) Main lobe power combination; (b) combined pulse burst.

By properly adjusting the input delay time of each reversal signal, the main lobe of the reconstructed signal can generate a synchronous superposition at the initial position, thus forming the power combination of the main lobe, as shown in Fig. 3(a). Consequently, such technology is also known as TR pulse-compression power-combination technology. If the input among each reversal signal has a certain delay, it may generate a group of pulse strings, as shown in Fig. 3(b). The calculation model used for these calculation results is shown in Fig. 2, in which the dimensions of the TRC are 900 mm×700 mm×43.18 mm, and the port is a BJ26 waveguide port. We choose $n=2$, and the input ports of the two reversal signals at the right-hand side are symmetrically distributed. To improve the scattering and chaos of the TRC, the radius of the cylinder at the center of the cavity is 40 mm. In addition, the initial signal is the Gaussian modulating pulse with a carrier frequency of 2.4 GHz and a pulse width of 3 ns, and the input maximum amplitude of the two reversal signals is 1. The simulating calculation result also verifies that the combined main lobe field intensity satisfies a linear superposition.

2.3. Channel crosstalk

According to the path crosstalk,[2] the crosstalk among the channels mainly occurs in the channels with the same input port, such as between Port_1–TRC–Port_0 and Port_1–TRC–Port_2. For two channels with the same input port, the cross-correlation function $\kappa_{i,j}$, which describes the channel crosstalk properties, can be expressed as

$$\kappa_{i,j}=h_i(t)\cdot h_j(-t),\quad i\neq j. \tag{4}$$

Based on the multichannel theory, the channel crosstalk is essentially path crosstalk. The cross-correlation function of the above definition is $\kappa_{i,j}\neq 0$, and its crosstalk response signal $s_{{\rm cro},ij}(t)$ can be expressed as

$$\begin{cases}\kappa_{ij}(t)=\sum\limits_{i',j',l'}^{m}k_{i,i'}k_{j,l'}a_{i,i'j'}a_{j,l'i'}\delta(t-\tau_{i'}+\tau_{l'}),\\ s_{{\rm cro},ij}(t)=\sum\limits_{i',j',l'}^{m}k_{i,i'}k_{j,l'}a_{i,i'j'}a_{j,l'i'}s_{\rm ini}(t-\tau_{i'}+\tau_{l'}),\end{cases}\quad i\neq j, \tag{5}$$

where $a_{i,i'j'}$ is the correlation between the i' path and the j' path in the i channel, and $a_{j,l'i'}$ is the cross-correlation between the l' path in the j channel and the i' path in the i channel.

The two different channels of the TRC have different paths. As a result, the attenuation coefficient $k_{i,i'}$ and $k_{j,l'}$ of the corresponding path are different, and the correlation coefficient $a_{i,i'j'}$ and the cross-correlation coefficient $a_{j,l'i'}$ are also different. In this case, the side lobe noise generated by the reversal channel is also different from the response generated by the crosstalk in the non-reversal channel. This is related to the crosstalk ability among the channels, and can be expressed by the 'isolation' of the channels. According to the channel response of the TRC, different channels have different transfer functions or filtering characteristics. Therefore, the isolation can be expressed by the reciprocal of the 'similarity' of the two channel-transfer functions. Thus, in this paper, the isolation $\beta_{i,j}$between two channels can be defined as

$$\beta_{i,j}=20\log\left(\frac{\sqrt{\sum\limits_{\omega}|H_1(\omega)|^2\sum\limits_{\omega}|H_2(\omega)|^2}}{\sum\limits_{\omega}|H_1(\omega)H_2(\omega)|}\right), \tag{6}$$

where $H_1(\omega)$ and $H_2(\omega)$ are the transfer functions of two channels, respectively. When the isolation is 0, the transfer functions of the two channels are completely the same. When the isolation is infinite, the transfer function is completely different, which can be considered as completely isolated. When the isolation between the associated channels is greater, the channel crosstalk during TR is smaller, which is more favorable to TR.

According to the filtering characteristics of the cavity, different frequencies of different channels can be realized by fine-tuning the cavity structure. Therefore, in the frequency range of interest, such a method can increase the isolation degree between channels. In this way, the reversal signal energy can propagate mainly through the reversal channels, so as to improve the reversal performance of the system, as shown in Fig. 4. The model in this example is the same as above, and the radius of the used cylinder is $R = 40$ mm and $R = 50$ mm, respectively. The reversal performance of the system with a radius of 50 mm is better than that of the system with a radius of 40 mm. The isolation of the reversal channel Ch01 (Port_0–TRC–Port_1) and non-reversal channel Ch21 (Port_2–TRC–Port_1) of the two systems is 1.4 and 1.5, respectively.

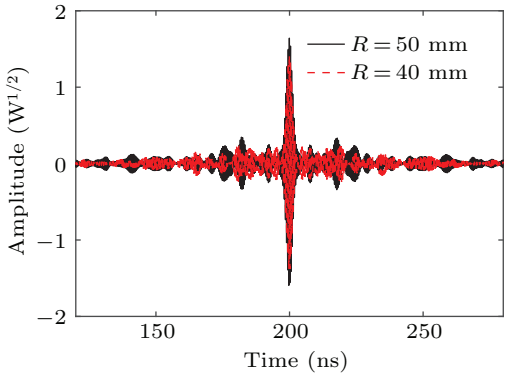


Fig. 4. Comparison of combined signals with different cylinder radii.

On the whole, the channel crosstalk can be considered as the port loss of the TRC. Therefore, reversal performance can be directly analyzed by cavity (channel) loss characteristics.

3. Combination analysis

In the study of power-combination performance for pulse compression, this paper mainly discusses two parameters: combined SNR and combined gain.

3.1. Combined SNR

In a TR pulse-compression power combination, the combined SNR is defined as the ratio of the main lobe of the combined signal to the maximum side lobe, which is expressed as

$$\mathrm{SNR_c} = 20\log\left(\frac{\|s_{\mathrm{com}}(t), t \in T_0\|_\infty}{\|s_{\mathrm{com}}(t), t \notin T_0\|_\infty}\right), \tag{7}$$

where T_0 is the pulse width of the initial signal, namely, the main lobe time, and $\|\cdot\|_\infty$ is the infinite norm. Based on the linear superposition principle, the combined SNR can be further expressed as

$$\mathrm{SNR_c} = 20\log\left(\frac{\sum_i^n \|s_{\mathrm{rec},i}(t), t \in T_0\|_\infty}{\sum_i^n \|s_{\mathrm{rec},i}(t), t \notin T_0\|_\infty}\right). \tag{8}$$

In the TR power combination, although the same TRC is used, the combined reversal channel is different. Therefore, the side lobe time shift may also be different for each reversal channel. In this case, the main lobe of the reconstructed signal can generate a coherent superposition, but the side lobe will not generate a completely coherent superposition. When the response of the reversal channel is exactly the same, the side lobe may generate a completely coherent superposition. As a result, the combined SNR satisfies

$$\mathrm{SNR_c} \geq \max\left\{20\log\left(\frac{\|s_{\mathrm{rec},i}(t), t \in T_0\|_\infty}{\|s_{\mathrm{rec},i}(t), t \notin T_0\|_\infty}\right)\right\}. \tag{9}$$

That is, the combined SNR is superior to the reversal SNR of the single channel, as shown in Table 1. To make a difference in the response functions of the two reversal channels in the above example, the cylinder in the TRC center is horizontally moved in Table 1.

Table 1. Comparison of SNR.

No.	Decentralization (mm)	Ch01 (dB)	Ch02 (dB)	Combination (dB)
1	0	13.5	13.5	13.5
2	5	13.0	10.6	16.7
3	100	16.1	13.3	21.2

3.2. Combined gain

The purpose of the pulse compression power combination is mainly to improve the peak output power of the system. If the maximum amplitude of the input reversal signal in each reversal channel is the same and expressed as $s_{\mathrm{rev},i}(t)$, then the pulse compression combined gain G_{com} can be expressed as

$$G_{\mathrm{com}} = 20\log\left(\frac{\|s_{\mathrm{syn}}(t), t \in T_0\|_\infty}{\|s_{\mathrm{rev},i}(t)\|_\infty}\right). \tag{10}$$

Similarly, under linear superposition conditions, the combined gain can be further expressed as

$$G_{\mathrm{com}} = 20\log\left(\frac{\sum_{i=1}^n \|s_{\mathrm{rec},i}(t), t \in T_0\|_\infty}{\|s_{\mathrm{rev},i}(t)\|_\infty}\right). \tag{11}$$

In addition, supposing the reversal performance of each reversal channel is the same, then the compression gain of each channel is also the same. In this case, the combined gain can be expressed as

$$G_{\mathrm{com}} = 20\log(n) + 20\log\left(\frac{\|s_{\mathrm{rec},i}(t), t \in T_0\|_\infty}{\|s_{\mathrm{rev}}(t)\|_\infty}\right). \tag{12}$$

Table 2. Comparison of combined gain.

No.	Decentralization (mm)	Three-port TRC (dB)			Two-port TRC (dB)
		Ch01	Ch02	Combination	
1	0	−1.8	−1.8	4.3	1.6
2	5	−1.3	1.0	6.1	2.5
3	100	0.6	−1.0	5.9	2.5

Note: the second reversal port closure in the three-port TRC constitutes the two-port TRC in this example.

It follows that the combined gain and channel number are logarithmically increased when the single channel gain is the same. However, when the reversal channel is increased, the TRC reversal input ports will also be increased, which leads to an increase in the loss of attenuation of the reversal channel. In this case, the compression gain of the single channel will be decreased; that is, the second term on the right-hand side of Eq. (12) will be smaller. In general, especially for the cavity with a high Q value, the combined gain of the multichannel is superior to the compression gain of the single channel, as shown in Table 2.

3.3. Experiment results

According to the above results, a TRC experimental system with three ports and two reversal channels has been built in this paper, as shown in Fig. 5. The material of the TRC is aluminum and the dimensions are 900 mm×700 mm×43.18 mm. The initial signal is a Gaussian modulated pulse with a carrier frequency of 2.4 GHz and a pulse width of 3 ns. The arbitrary waveform generator is an 8190A and the oscilloscope is a DSOV134A. Besides, each of the three waveguide output ports of the TRC has a 3 dB attenuator.

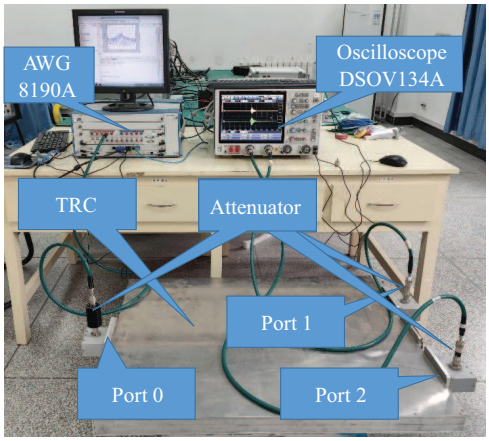


Fig. 5. Experimental system layout.

When the maximum amplitude of the input reversal signal is 700 mV, the TR combined waveform of two channels and the reversal reconstructed waveform of a single channel are obtained, as shown in Fig. 6. In addition, the corresponding TR SNR and compression gain are shown in Table 3. It follows that the experimental results are consistent with those in the theoretical study.

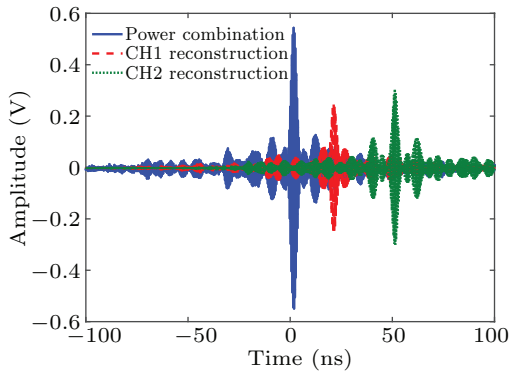


Fig. 6. Comparison of two-channel combined waveform and single-channel reversal reconstructed waveform.

Table 3. Comparison of experimental SNR and gain.

	Ch01	Ch02	Combination
SNR (dB)	15.7	14.2	19.5
Gain (dB)	−3.1	−1.4	3.8

4. Conclusion

Based on TR pulse-compression theory, a multichannel TR power-combination model is established, and the channel crosstalk and combination performance are further studied in this paper. Compared to single-channel reversal pulse compression, the multichannel power-combination method can not only increase the reversal SNR, but also increase the compression gain. Consequently, the TR power-combination method is an effective way to increase the peak output power, which can be used to generate microwave pulses with high peak values. In addition to peak power combination, multichannel TR can also be used to generate pulse strings with high repetition frequency. Furthermore, a quasi-two-dimensional cavity with an electrical size of about 7.2 and a limited Q value is used in the TRC example in this paper, resulting in a TR combined gain of about 3.8 dB. To further improve the combined gain, a three-dimensional electrically large cavity with a higher Q value could be applied. For example, the single channel reversal pulse compression gain with a 3D electrically large cavity is about 23 dB in Ref. [5].

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