

Article

A Novel Single-Channel Arrangement in Chirp Transform Spectrometer for High-Resolution Spectrum Detection

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Abstract: Chirp transform spectrometer (CTS) has become a powerful tool widely used in spectral analysis nowadays. In this paper, a novel single-channel structure of Chirp transform spectrometer for high-resolution spectrum detection is developed. By adding an additional signal source, a mixer, a power divider, and a combiner, one channel of the classical CTS is replaced and the matching problem between the two channels is avoided. The circuit principle and characteristics of the novel single-channel structure are presented. Two simulation models with ideal devices and nonideal devices for the classical two-channel CTS structure and the improved single-channel structure are built to verify the effectiveness of the novel structure. Simulation results show that the time distributions of the obtained compression pulses resulting from the improved structure are the same as that from the classical two-channel CTS. The obtained amplitudes and spectral resolution are almost the same in both structures with ideal devices. The introduced nonideal devices mainly influence the amplitudes of the output pulses. In addition, an experiment with hardware implementation is verified on real chains. The influence of nonideal devices is measured and analyzed. Compared to the classical two-channel structure of CTS, the modified one-channel arrangement avoids the matching problem between different channels and saves devices.

Keywords: spectrum measurement; pulse compression; chirp transform spectrometer; surface acoustic wave filters

1. Introduction

In active radar system, the target identification ability is closely associated with average transmission power. Limited by the finite peak power, the promotion of target identification ability usually depends on the increase of transmission pulses' bandwidth. However, the increase of transmission pulses' bandwidth will degrade the range resolution. To resolve the contradictions between the identification ability and the range resolution, a process of broadening the pulses' bandwidth in transmitter and compressing them in receiver is utilized. This technique is called pulse compression [1] and its schematic diagram is shown in Figure 1. The input measured signal is mixed with the chirp modulation signal to expand its bandwidth, then the modulated signal is compressed into pulses by a digital pulse compression method or an analog dispersive device. An analog dispersive device of surface acoustic wave (SAW) filter was previously used for pulse compression; nowadays, methods of digital pulse compression are frequently utilized for signal expansion and pulse compression instead of SAW filters [2,3].

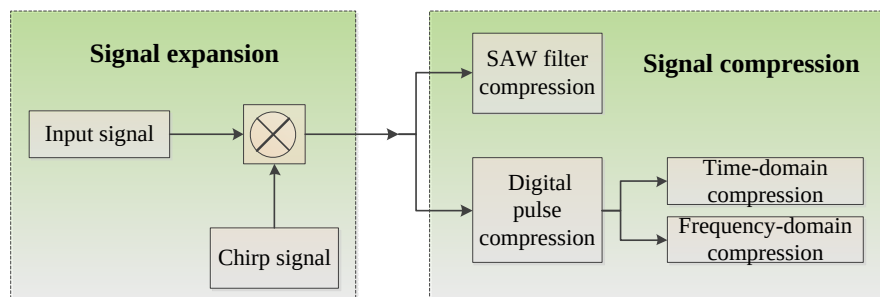


Figure 1. Schematic diagram of pulse compression procedure in radar system. SAW—surface acoustic wave.

As early as in 1960s, the technology of radar pulse compression was firstly utilized to represent Fourier transform by Klauder [4]. Afterwards, a much more detailed discussion of spectral analysis utilizing the radar pulse compression was described by Darlington [5]. Nowadays, the Darlington' system is known as the chirp transform spectrometer (CTS). In a CTS system, the pulse compression is usually realized by using the SAW filters and this makes it possible to apply to real-time spectrum measurement. The CTS system was later spread to the field of atmospheric radiation measurement by Hartogh and Hartmann [6], Hartogh and Lis et al. [7–9], and Hartogh and Osterscheck [10]. An improved CTS system with a novel digital dispersive matching network instead of the SAW devices for signal expansion helped to improve the accuracy of the measured spectrum and the system's linear response, which greatly improved the system's performance [11]. As a new passive detection method, the CTS back-end was developed into a mature tool widely used in weather and astronomical observation. Early in the 1990s, CTS back-end had been applied for ground-based submillimeter observation of planets [12] and comets [13]. Subsequently, CTS was used for atmosphere components investigation of Comet Chyruymov Gerasimenko in Rosetta Orbiter, which was launched in 2004 for deep-space detection [14]. With the advantage of high spectral resolution and high stability, the CTS back-end was mounted on the high-resolution spectrometer of the German Receiver for Astronomy at Terahertz Frequencies (GREAT) on board the Stratospheric Observatory for Infrared Astronomy (SOFIA) for planetary and cometary research in recent years [15–19].

Compared to fast Fourier transform (FFT) algorithm, the CTS has relatively low weight and power consumption, high spectral resolution and extremely high stability, which makes it quite suitable for space/airborne applications to make a study of comets, planetary atmospheres, interstellar medium, and even early universe. In the classical CTS system, a push–pull arrangement with two uniform channels are adopted to make up the bandwidth mismatch between the expander and compressor. This two-channel arrangement helps to guarantee the maximum sensitivity that can be obtained for the instrument. However, the frequency accuracy and amplitude consistence are directly affected by the match between the two channels. This matching problem, especially the match between different SAW filters, may increase the difficulty of hardware implementation. Meanwhile, the doubled devices also increase the mass and power consumption of the CTS system.

In this paper, a new conception of single-channel CTS system with less components was developed. One channel was replaced by only adding a source, a mixer, a splitter, and a combiner in the novel structure, which helps to avoid the matching problem between the two channels in the classical structure with acceptable system performance. In addition, in the novel structure, the sequential control of the output pulses is simplified for the later digital sampling and storage. The structure and detailed principle of the classical CTS is described in section two. The description and principle of the novel single-channel CTS system is shown in section three. The simulation verification with ideal and nonideal devices and the experiment analysis of the obtained results are presented in section four and five, respectively. Finally, a brief conclusion is drawn in the last section.

2. Chirp Transform Spectrometer

2.1. Principle of the CTS System

Based on the radar pulse compression technology and the special device of SAW filter with dispersion characteristics, the classical CTS can realize spectrum measurement by physical transform. The measured signal $f(t)$ is firstly mixed with a chirp modulation signal to expand its frequency bandwidth. The chirp modulation signal is a linear frequency modulated signal having a certain dispersion constant (μ_e) and time-bandwidth product ($T_e B_e$), where B_e represents the bandwidth of the chirp signal. This chirp signal can be expressed as a quadratic phase modulated signal:

$$f_{chirp}(t) = e^{-j\pi\mu_e t^2/T_e} \quad 0 < t < T_e. \quad (1)$$

The modulated signal with expanded bandwidth resulting from the mixer can be expressed as

$$f_{mix}(t) = f(t) \cdot f_{chirp}(t) = f(t) \cdot e^{-j\pi\mu_e t^2/T_e}. \quad (2)$$

This process is known as the signal expansion, which substantially expands the bandwidth of the measured signals. Subsequently, the expanded modulated signal carrying the information of the measured signal will be amplified, filtered, and compressed into pulses by a SAW filter, which is called the compressor. Considering a perfect match between the expander and compressor, the SAW filter has a certain dispersion constant (μ_c), which is a complex conjugate with that of the chirp signal ($\mu_c = -\mu_e$) and time-bandwidth product ($T_c B_c$), where T_c and B_c represent the time duration and working bandwidth of the compressor, respectively. The output signal from the compressor is the convolution of the system impulse response $h(t)$ and the modulated signal $f_{mix}(t)$:

$$f_{compress}(\tau) = \int_{-\infty}^{+\infty} f_{mix} \cdot h(\tau - t) dt. \quad (3)$$

Considering ($\mu_c = -\mu_e$) and ignoring the time length of the expander and compressor:

$$\begin{aligned} f_{compress}(\tau) &= \int_{-\infty}^{+\infty} f(t) \cdot e^{-j\pi\mu_e t^2} \cdot e^{j\pi\mu_e(\tau-t)^2} dt \\ &= e^{j\pi\mu_e \tau^2} \int_{-\infty}^{+\infty} f(t) \cdot e^{-j2\pi\mu_e \tau t} dt \\ &= e^{j\pi\mu_e \tau^2} \int_{-\infty}^{+\infty} f(t) \cdot e^{-j2\pi f t} dt. \end{aligned} \quad (4)$$

Considering a phase factor $e^{-j\pi\mu_e \tau^2}$ added to (4), the compressed signal is just the Fourier transform of the input measured signal. This procedure is called pulse compression of the modulated signal. The spectral information can therefore be found by detecting the time distribution and amplitude envelope of the output pulses in the time domain [15].

2.2. Classical Two-Channel Structure of CTS

Generally, there are two similar structures that can be applied to the CTS system. One is the $M(s) - C(l)$ arrangement, in which the time period of the modulation chirp signal is shorter than that of the SAW matching filter. Another is the $M(l) - C(s)$ arrangement, in which time duration of the modulation chirp signal is long [12,13,20]. The utilized symbol M represents signal multiplication for bandwidth expansion; C denotes signal convolution for matched filtering; and (l) and (s) mean long and short duration time, respectively. In this paper, we present the classical $M(l) - C(s)$ arrangement shown in Figure 2.

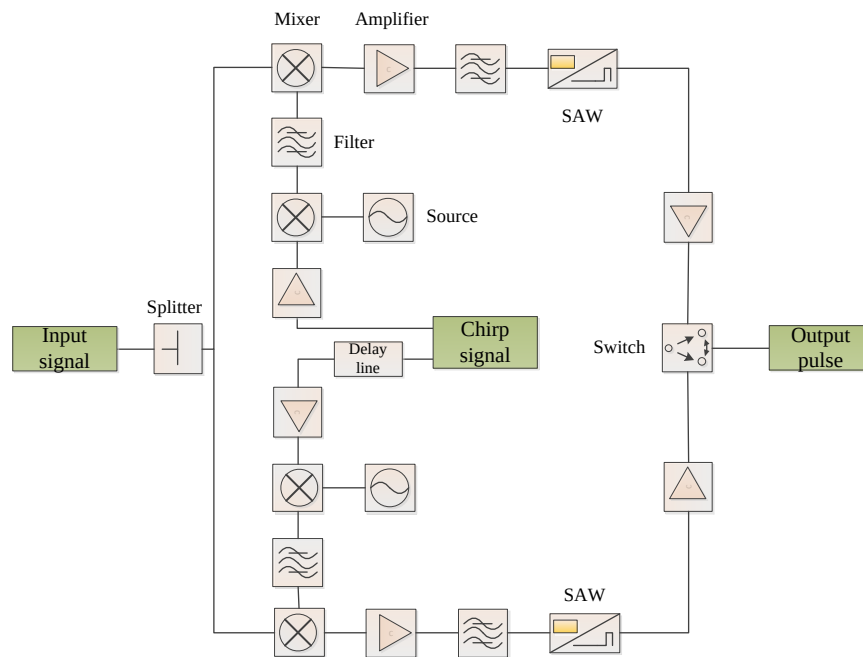


Figure 2. Classical $M(I) - C(s)$ arrangement of the chirp transform spectrometer.

Figure 3 is the schematic diagram of signal expansion and compression procedure in the CTS. The time duration between the maximum point and first zero-crossing point of amplitude envelope of the output pulses is approximately equal to $1/B_c$, and hence, the frequency resolution is $\Delta f = |\mu|/B_c = 1/T_c$, where B_c is the operation bandwidth of the SAW filter and T_c is the time length of the SAW filter's impulse response. When T_c is greater than 10 μs , the frequency resolution Δf is less than 100 KHz. This means that the character of the high-frequency-resolution in CTS depends on the property of large time-bandwidth product ($T_c B_c$) of the compressor. For processing technology reasons, it is usually advisable to utilize the minimum possible value of the expander time-bandwidth product ($T_c B_c$) [12,21]. This results that the expander bandwidth is twice the bandwidth of the compressor.

As the bandwidth is different between the expander and the compressor, it is appropriate to adopt a push-pull arrangement with two uniform channels to make up the bandwidth mismatch between the expander and compressor, which can ultimately improve the system's sensitivity. Meanwhile, the push-pull structure can avoid spectrum leakage when dealing with nonstationary signals. Figure 4 shows the time-frequency schematic diagram of the classical two-channel structure. All the working parameters are the same as that in [22]. The frequency of the input signal ranges from 1.9 GHz to 2.3 GHz and the frequency of the LO input chirp signal ranges from 2.7 GHz to 3.5 GHz. The time period of the chirp signal is 20 μs , the time duration of the impulse response of the SAW filter is 10 μs , and its working bandwidth is 0.8–1.2 GHz. Here, we take three input signals with fixed frequencies (e.g., 1.9 GHz, 2.1 GHz, and 2.3 GHz) as an example to clarify the working principle of the classical two-channel structure of CTS. The three input signals will first be transformed to three chirp signals with 20- μs time duration and 800-MHz bandwidth. Then, a common part with 400 MHz bandwidth (0.8–1.2 GHz) is filtered out from the three chirp signals as the input of the SAW filter for pulse compression. As the input times of the three chirp signals are different, the time of the output pulses will be different, which indicates the different frequencies of the input signals. The two-channel structure helps to make up the mismatch of time period between the expander and the SAW compressor. Obviously, the push-pull two-channel structure can avoid spectrum leakage and make sure that the output pulses can be obtained over the entire measured time.

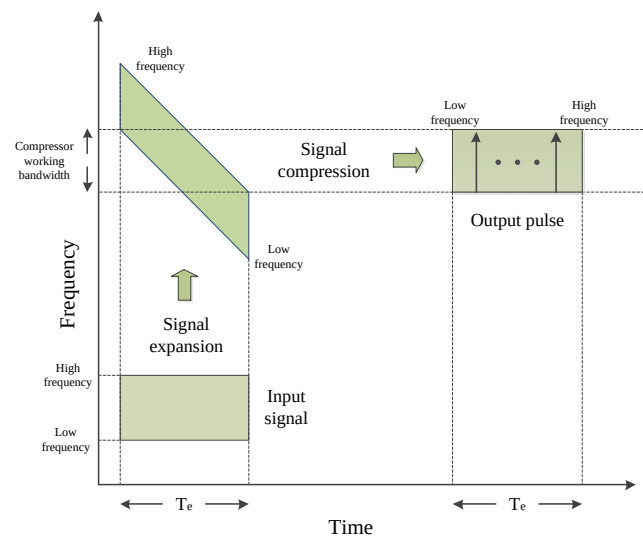


Figure 3. Schematic diagram describing the principle of the chirp transform spectrometer (CTS). The input signal shown in the left side is expanded to wide-band chirp signal by mixing it with the input chirp signal. Subsequently, the modulated chirp signal is compressed to a pulse through the SAW filter, which distributes on the time-domain shown on the right side.

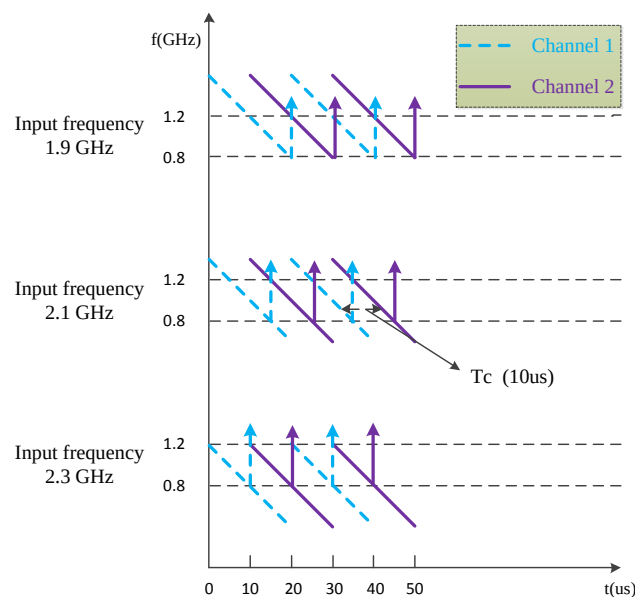


Figure 4. Time–frequency relation schematic diagram of the input frequencies and output pulses of the two-channel structure.

For the classical push–pull arrangement of the CTS system, the two channels are separated; thus, there is little interference between the two channels. Reasonable structure design of the classical CTS can obtain very high frequency resolution and has real-time processing capability and very high stability. These high system performances require a perfect match between the two channels. Usually, some cost and challenges need to be considered when implementing the classical CTS shown as follows. The device numbers (such as filters, amplifiers, mixers, and the SAW filters) are doubled in the classical CTS system. The power consumption and mass of the system also increases accordingly, thus increasing the cost of the system. The matching between the two channels need to be precise to

ensure the right temporal relations between the obtained pulses. This indicates that the same devices in the system need to have the same characteristics and the time-delay characteristics of the two channels also need to match well. The spectral accuracy will be influenced by the time-delay match between the two channels, and the amplitude consistency of the spectrum will be influenced by the insertion loss of the mixers. High-resolution spectrum detection of the measured signals demands an accurate match of chirp rate between signal expansion and compression. The match between the two SAW filters for pulse compression is also significant. Generally, it is very difficult to get two of the same SAW filters having the same chirp rate over the entire bandwidth. There is a switch before the digital sampling and storage procedure to combine the signals resulting from the two channels. So, an accurate time sequence control system is needed to manage the temporal relations of output pulses between the two channels.

3. Design of Novel Single-Channel Structure for CTS

To deal with the matching problem and simplify the structure, a single-channel arrangement is developed. The circuit frame diagram of the developed novel single-channel arrangement is demonstrated in Figure 5. In the new structure, one channel is replaced by only adding a small number of devices. The front part used for signal expansion is the same as the classical CTS structure, and the extension signal is then divided into two parts by the power divider. One is used for signal mixing, and the outputs have both the up-and-down conversion signals. This part is then combined with another part to obtain a complete signal distribution over the entire measuring time. At last, the complete modulated chirp signals resulting from the combiner are delivered to the SAW device for pulse compression. The signal send to the LO port of the mixer is a sine signal with a fixed frequency that is equal to the compression bandwidth. A matching network is added to adjust the little difference of the line delay and eliminate the influence of the added mixer. Usually, in real hardware implementation, the dispersion of mixer, power splitter, and combiner is very small and the introduced mismatch can be ignored.

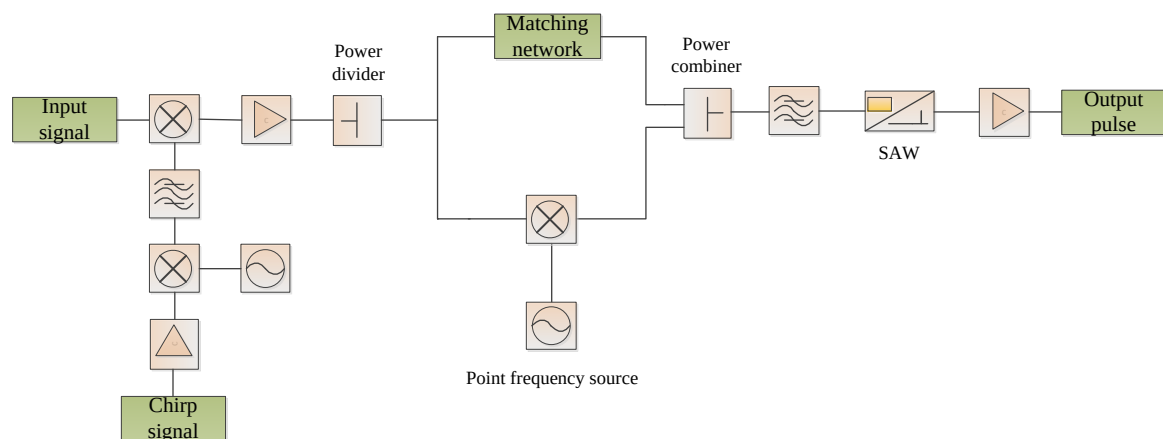


Figure 5. Frame diagram of the novel single-channel arrangement.

In the $M(l) - C(s)$ arrangement, the real input signal is firstly premultiplied by the chirp signal $C_1(t)$ for signal expansion, then passed through the SAW filter $H_0(t)$. The output of the filter is given by a convolution integral

$$S(t) = \int_{-\infty}^{+\infty} f(\tau) C_1(\tau) H_0(t - \tau) d\tau. \quad (5)$$

Considering that the impulse response of the premultiplying chirp $C_1(t)$ and the SAW filter $H_0(t)$ are both of the form

$$C_1(t) = \Pi\left(\frac{t-T_1}{T_1}\right) W_1(t) \cdot \cos\left(\omega_1 t - \pi\mu t^2 + \phi_1\right), \quad (6)$$

where $\Pi\left(\frac{t-T_1}{T_1}\right)$ is a rectangular gating function with duration T_1 centered on time T_1 . $W_1(t)$ is an arbitrary weighting function and here it is set to be unity. Notation μ is the chirp rate of the chirp signal and ϕ_1 is a phase term. Thus, Equation (5) can be rewritten as

$$S(t) = \Pi\left(\frac{t-t'}{T''}\right) \int_{-\infty}^{+\infty} \hat{f}(\tau) \cdot \cos\left(\omega_1 \tau - \pi\mu \tau^2 + \phi_1\right) \cdot \cos\left(\omega_0(t-\tau) + \pi\mu(t-\tau^2) + \phi_0\right) d\tau, \quad (7)$$

where

$$\hat{f}(\tau) = f(\tau) \Pi\left(\frac{t-\tau-\frac{1}{2}T_0}{T_0}\right), \quad (8)$$

$$t' = \frac{1}{2}(T_0 + T_1) \quad T'' = T_1 - T_0 \quad (T_1 > T_0). \quad (9)$$

Multiplication of the cosine terms produces integrals that involve terms in $(\omega_1 + \omega_0)$ and $(\omega_1 - \omega_0)$. Ignoring those terms depends on $(\omega_1 + \omega_0)$; Equation (7) can be expanded in the form

$$S(t) = \Pi\left(\frac{t-t'}{T''}\right) \left[\int_{-\infty}^{+\infty} x(\tau) \cdot \exp(-j\Omega\tau) d\tau + \int_{-\infty}^{+\infty} x^*(\tau) \cdot \exp(j\Omega\tau) d\tau \right], \quad (10)$$

where $\Omega = \omega_0 - \omega_1 + 2\pi\mu t$ and

$$x(\tau) = \hat{f}(\tau) \cdot \exp\left[j\left(\omega_0 t + \pi\mu t^2 + \phi_0 + \phi_1\right)\right]. \quad (11)$$

The notation $*$ means complex conjugation. Since $f(t)$ is real, Equation (10) can be written as [20]

$$S(t) = \Pi\left(\frac{t-t'}{T''}\right) (X(\Omega) + X^*(\Omega)), \quad (12)$$

where $X(\Omega)$ is the Fourier transform of $x(t)$; and Equation (12) can be further written as

$$S(t) = \Pi\left(\frac{t-t'}{T''}\right) \text{Re}\left\{\hat{F}(\Omega) \cdot \exp\left[j\left(\omega_0 t + \pi\mu t^2 + \phi_0 + \phi_1\right)\right]\right\}, \quad (13)$$

where Re means the real part and $\hat{F}(\Omega) = \hat{F}(\omega_0 - \omega_1 + 2\pi\mu t)$ is the Fourier transform of $\hat{F}(t)$. Considering $\hat{F}(\Omega)$ in form of the magnitude and phase angle

$$\hat{F}(\Omega) = |\hat{F}(\Omega)| \angle \Phi(\Omega), \quad (14)$$

Equation (13) becomes

$$S(t) = \Pi\left(\frac{t-t'}{T''}\right) |\hat{F}(\Omega)| \cdot \cos\left[\omega_0 t + \pi\mu t^2 + \phi_0 + \phi_1 + \Phi(\Omega)\right]. \quad (15)$$

Equation (15) indicates that the envelope of the signal $s(t)$ resulting from the SAW filter is the amplitude spectrum of the (truncated) real input signal $f(t)$. It is important to stress that the gating function shown in Equation (15) is sliding across $f(t)$, only embracing different parts of $f(t)$ while at the same time performing Fourier transformation in a time-ordered manner [20]. For the classical CTS structure described in [22], the time duration of the premultiplying chirp signals (20 us) is twice that of the SAW filters (10 us), thus, only half of the input signal is measured according to Equation (15) for

one $M(l) - C(s)$ arrangement. So, the push–pull two-channel structure is adopted to obtain the full duty cycle of the expander–compressor arrangement.

In the single-channel structure, an additional up-and-down conversion mixing process is adopted. So, the output of the SAW filter for the additional up-and-down conversion signals can be written as

$$S_1(t) = \int_{-\infty}^{+\infty} f(\tau) \cdot \cos(2\pi\mu T_0\tau) \cdot C_1(\tau) \cdot H_0(t - \tau) d\tau, \quad (16)$$

where $\cos(2\pi\mu T_0\tau)$ means the added mixer with a fixed LO input frequency of μT_0 . Equation (16) can be further written as

$$S_1(t) = \prod\left(\frac{t - t'}{T''}\right) \int_{-\infty}^{+\infty} \hat{f}_1(\tau) \cdot \cos(\omega_1\tau - \pi\mu\tau^2 + \phi_1) \cdot \cos\{\omega_0(t - \tau) + \pi\mu(t - \tau)^2 + \phi_0\} d\tau, \quad (17)$$

where

$$\hat{f}_1(\tau) = f(\tau) \prod\left(\frac{t - \tau - \frac{1}{2}T_0}{T_0}\right) \cos(2\pi\mu T_0\tau) \quad (18)$$

Let $\Omega_1 = \omega_0 - \omega_1 + 2\pi\mu(t \pm T_0)$ and $x_1(\tau) = \hat{f}(\tau \pm T_0) \cdot \exp[j(\omega_0 t + \pi\mu t^2 + \phi_0 + \phi_1)]$; Equation (17) can be written as

$$S_1(t) = \prod\left(\frac{t - t'}{T''}\right) (X_1(\Omega) + X_1^*(\Omega)), \quad (19)$$

where $X_1(\Omega)$ is the Fourier transform of $x_1(t)$. This indicates that $M(l) - C(s)$ arrangement with the additional up-and-down conversion mixing process essentially represents the Fourier transform of $\hat{f}(\tau \pm T_0)$ —meaning the previous and later parts of $f(t)$ with time interval of T_0 . This actually has the same effect with the push–pull two-channel structure of obtaining the full duty cycle of the expander–compressor arrangement.

Here, we assume that the working parameters are the same as that in [22]. The schematic diagram with corresponding temporal relations of the novel structure is shown in Figure 6.

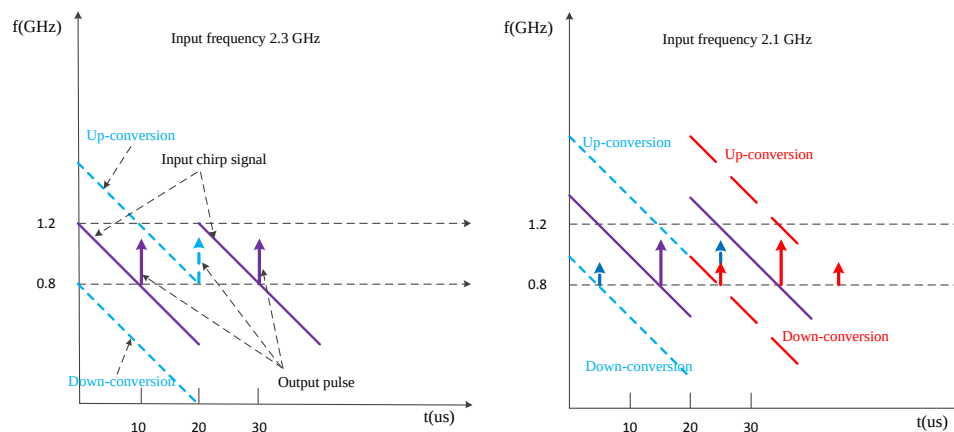


Figure 6. The time–frequency relation between output pulses and input signals. The input signals are firstly modulated by a chirp signal, then multiplied by a mixer to get another two chirp signals. Combination of the three chirp signals will get complete output pulses distribution at each period.

In Figure 6, two input signals with frequencies of 2.3 GHz and 2.1 GHz are modulated by a chirp signal firstly and then are up-and-down converted. The obtained up-and-down conversion modulated chirp signals will be compressed into output pulses through the SAW filter. These output pulses are just identical to that resulting from one channel of the classical CTS system. For the measured signals,

if the frequencies are equal to the boundary of the measured bandwidth (i.e., 1.9 GHz and 2.3 GHz), the output pulses from the novel single-channel structure will be completely the same as that from the classical two-channel structure, as shown in the left part of Figure 6. In general, there would be some little differences between the output pulses at the first and last time period of the compression procedure (see the right part in Figure 6). However, these little differences become insignificant in consideration of the digital process of data accumulation for noise elimination in practical application.

For the introduced power combiner, some possible interferences of the three modulated chirp signals may exist at the output of the power combiner. A possible solution is to put two bandpass filters in front of the power combiner and remove the bandpass filter just before the SAW filter. Even though the three modulated chirp signals coexist in the proposed single-channel structure, after passing through the bandpass filter, the time arriving at the power combiner would be different for the three modulated chirp signals. This can minimize the possible interferences of the three signals.

4. Simulation and Analysis

4.1. Simulation Models with Ideal and Nonideal Devices

To verify the novel single-channel CTS structure, two simulation models with two sets of parameters are built in Advanced Design System (ADS). One of the parameters is based on ideal devices and another is based on nonideal devices. Two models built for the classical two-channel CTS system and the novel one-channel system are based on the schematics shown in Figures 2 and 5 individually. The matching network in the novel one-channel system is ignored as the dispersion characteristics of the introduced mixer is quite small compared to the pulse width in time domain. The measured signals are set to be some discrete sinusoidal signals with identical power so as to verify the spectrum accuracy and amplitude consistency. The modulation chirp signal is generated by the voltage source of ADS. An S2P file with fixed bandwidth, time duration, and chirp rate is created to represent the SAW filter for final pulse compression. The total simulation time is set to be five times of the compression period, and the max time step is smaller than the time width of output pulses.

In the model with ideal devices, the frequencies of the input measured signals are 1.9 GHz, 1.95 GHz, 2.05 GHz, and 2.2 GHz, in which the frequency interval increases linearly. Compared to the classical two-channel CTS system, the novel single-channel system only adds a source, a mixer, a splitter, and a combiner. So, we set another parameter with conversion loss for the nonideal mixer and download S3P files for the splitter and combiner. The frequencies of the input measured signal are 1.8 GHz, 1.9 GHz, 2.0 GHz, and 2.1 GHz, with identical frequency interval in the model with nonideal devices.

4.2. Comparison and Analysis of Simulation Results

In the model with ideal devices, the measured discrete sinusoidal signals with linearly increased frequency interval are ultimately compressed into four pulses, as shown in the left side of Figure 7. The repetition period of the obtained pulses is 10 μ s. It can be seen that the time spans of the four compressed pulses are 1.25 μ s, 2.5 μ s, and 3.75 μ s, which correspond to the frequency spans of 50 MHz, 100 MHz, and 150 MHz of the four input measured signals. The output compressed pulses of the novel single-channel system are shown in the right part of Figure 7. The additional introduced devices play a moving role, which actually move the modulated chirp signals to the nearby period for pulse compression. This essentially replaces one channel of the classical CTS system. In Figure 7, the temporal relations and magnitudes of the final compressed pulses are almost the same both in the classical CTS model and the novel CTS model. It can be seen that there are three pulses that exist at the beginning period with smaller amplitudes in the left part, they are not noise or clutter. This little difference is caused by the frequency conversion of the modulated chirp signals carrying the information of the input frequencies and it substantially reflects the pulses periodically moving function of the added mixer. In general, these little differences become insignificant in consideration of

the digital process of data accumulation for noise elimination in practical application. Figure 8 is an enlarged comparison version of one single pulse at 31.26 us from the two CTS models. The measured maximum value of the single pulse is 0.998 V and 1.076 V for the classical CTS and the single-channel structure, individually. The little difference in the amplitudes is mainly caused by the added mixer and the signal splicing of the up-conversion and down-conversion of the modulated chirp signal. It is obvious that the envelope of the pulse has the shape of a sinc function, and the measured 3dB pulse widths of 1.667 ns corresponding to the spectral resolution of 100 kHz are the same. The match of the temporal relations, pulses' amplitudes, and spectral resolution between the two CTS models verifies that the novel single-channel structure has the same performance as the classical CTS system.

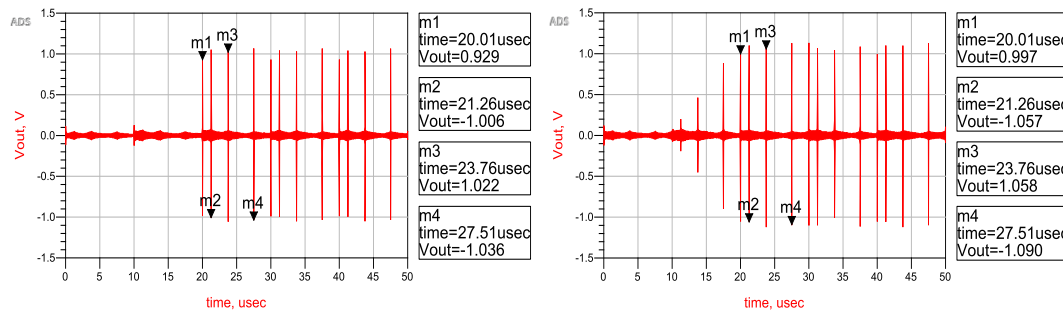


Figure 7. Compressed pulses resulting from the classical CTS system (left) and the single-channel system (right) with four measured signals. The devices used in both models are ideal.

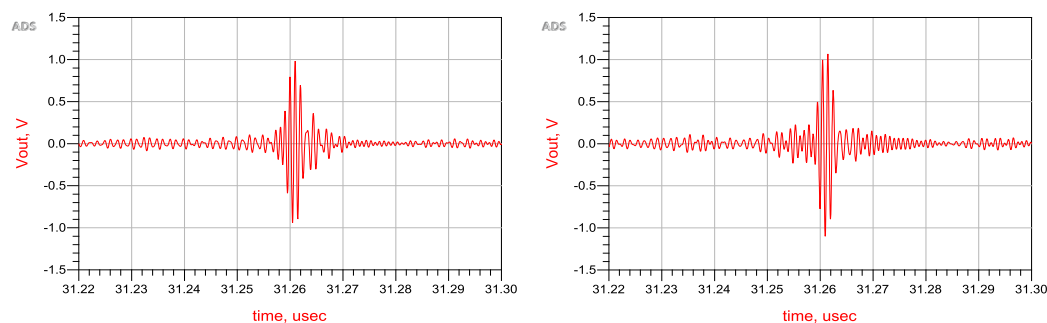


Figure 8. An enlarged comparison version of one single pulse at 31.26 us from the classical CTS system (left) and the single-channel system (right).

In the model with nonideal devices of the novel structure, the four measured signals with identical frequency span (100 MHz) are also compressed into four pulses. Accordingly, the output pulses have identical time intervals (1.667 us), as shown in Figure 9. The added nonideal power splitter and combiner in the novel structure introduce the amplitude unbalance that can be seen at points of m1, m2, m3, and m4. The overall amplitudes of m5, m6, m7, and m8 are smaller than that of m1, m2, m3, and m4. This is mainly caused by the added nonideal mixer. As the dispersion of real mixer is usually less than 1 nanosecond, which is much smaller than the time resolution of output pulses, its influence on signal resolution can be ignored.

There are some differences of pulse amplitudes in the simulation results with ideal elements (Figure 8) and with nonideal devices (Figure 9). For the simulation with ideal elements, the ideal concept mainly means the ideal mixer without insertion loss. However, the frequency response of the bandpass filter is nonideal, that is, there is transitional band in the simulation model of the bandpass filter, which may cause the amplitudes inconsistency of the output pulses. For the big amplitudes differences in the simulation with nonideal devices, the main reason is the insertion loss of the nonideal mixer and the difference insertion loss for the up-conversion and down-conversion. The downloaded S2P files of the power splitter and combiner from the website of Mini-Circuit have nonideal frequency

response, which may also have a slight influence on the amplitudes. These differences introduced by the nonideal devices with insertion loss can be calibrated in the subsequent signal processing.

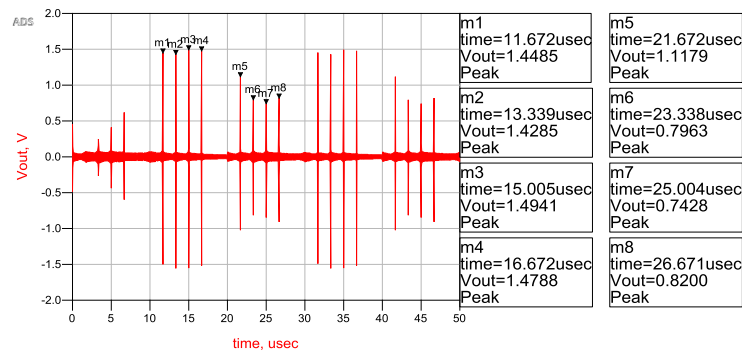


Figure 9. Output pulses of the single-channel system with four input frequencies of the model with nonideal devices.

5. Experiment and Analysis

To test the applicability and performance of the novel structure, we build an experiment with hardware implementation on real chains shown in Figure 10. Limited by the processing difficulty and high-cost manufacturing of the SAW filter, an S2P file is instead used to produce the SAW filter. As shown in Figure 10, an arbitrary waveform generator (AWG7082C) is used for the generation of the chirp signal $f_{chirp}(t)$ and the input measured signal $f(t)$. Frequency of the chirp signal starts from 2.5 GHz to 3.7 GHz, the time duration is 20 us, and the chirp rate is 60 MHz/us. The measured signal with four frequencies of 1.8 GHz, 1.9 GHz, 2.0 GHz, and 2.1 GHz is generated by the AWG. The measured signal is first mixed with the chirp signal through the mixer 1 to get the modulated signal $f_{mix}(t)$. The modulated signal is then divided into two channels shown in Figure 10. Signals of channel 2 are mixed with a fixed frequency signal (600 MHz) generated by an analog signal generator and then combine with channel 1. Signals from the combiner are then filtered by the bandpass filter with band-pass width ranging from 700 MHz to 1.3 GHz. Then, a digital phosphor oscilloscope (DPO) with 2-GHz bandwidth is used to sample and store the output signals for the final pulse compression. At last, the sampled signals from DPO are sent to the ADS for pulse compression.

Figure 11 shows the final compression results. The pulses appearing at m1, m2, m3, and m4 result from the pulse compression of channel 1. It can be seen that there are some differences in the amplitudes of these pulses. This is mainly caused by two aspects. One is the different convention loss for different input RF signals of mixer 1. Another is that the insertion loss of the power splitter and combiner changes slightly over the input frequency range. The pulses appearing at m5, m6, m7, and m8 result from the pulse compression of channel 2. The amplitudes of these pulses are much lower than that of pulses resulting from channel 1, and the difference ranges from roughly 10 dB to 12 dB. Not only are they influenced by mixer 1, power splitter, and combiner, but the amplitude differences between these pulses are also affected by the difference convention loss for different input RF signals as well as the difference convention loss between up-conversion and down-conversion of mixer 2. The up-conversion loss and down-conversion loss are shown in Figures 12 and 13, respectively. The horizontal axes of Figures 12 and 13 show the sweep range of RF input signal when the LO input signal is fixed to 600 MHz. It can be seen that the conversion loss of mixer 2 is approximately equal to the amplitude differences between pulses at m1, m2, m3, m4, and pulses at m5, m6, m7, and m8. The influence on amplitudes due to the mixers, power splitter, and combiner can be compensated in the later digital signal processing.

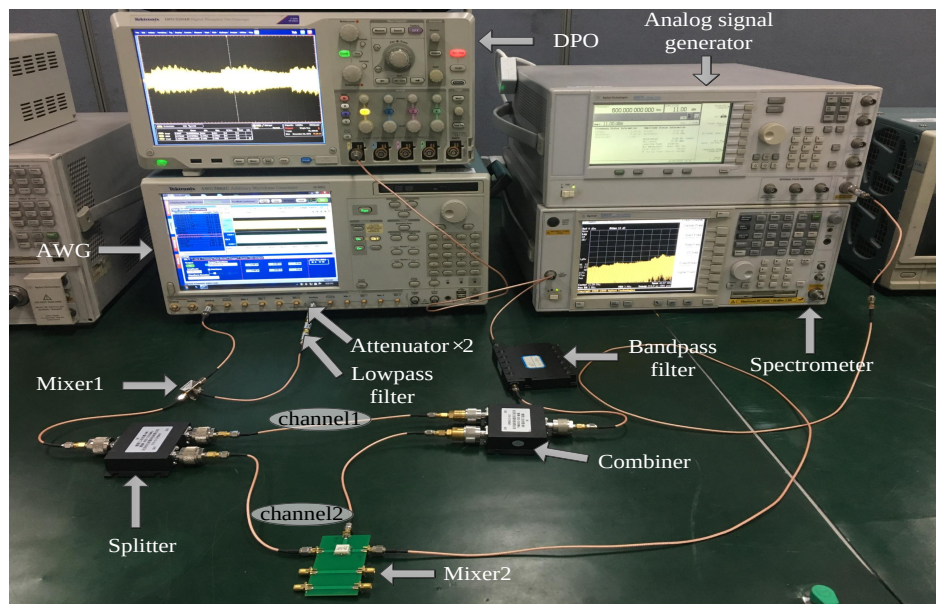


Figure 10. Hardware testing for the novel single-channel CTS structure.

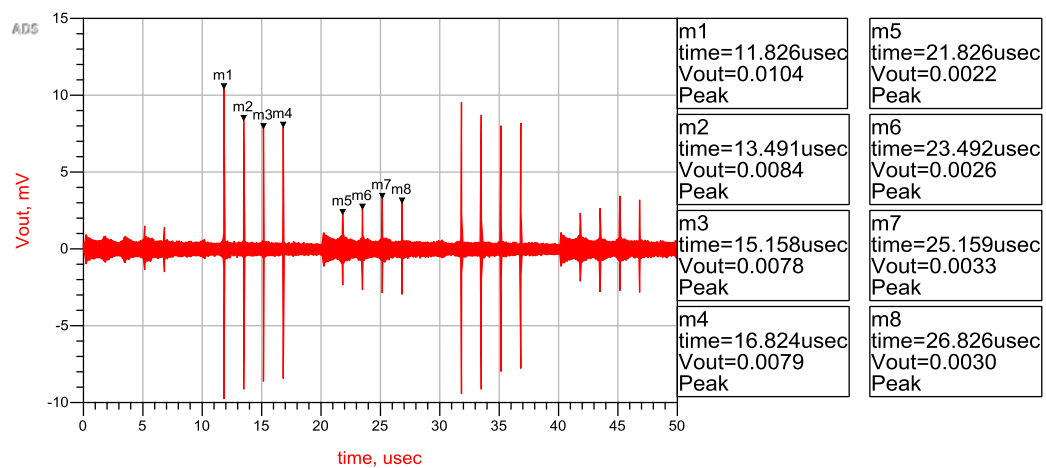


Figure 11. Output pulses from experiment results of the novel single-channel CTS structure.

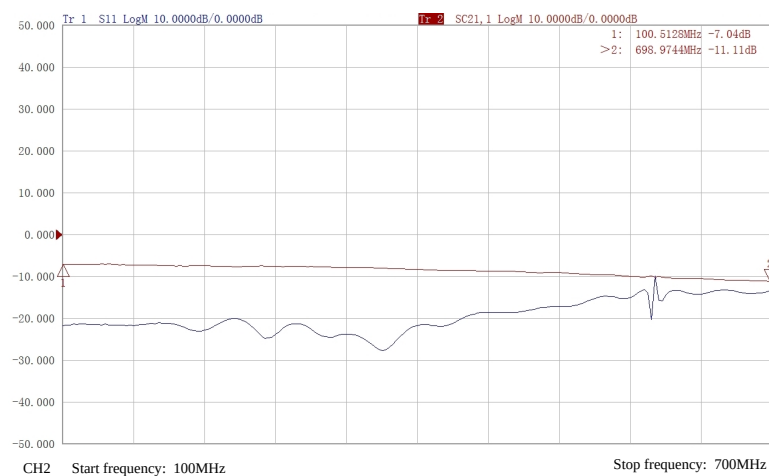


Figure 12. Up-conversion loss of mixer 2.

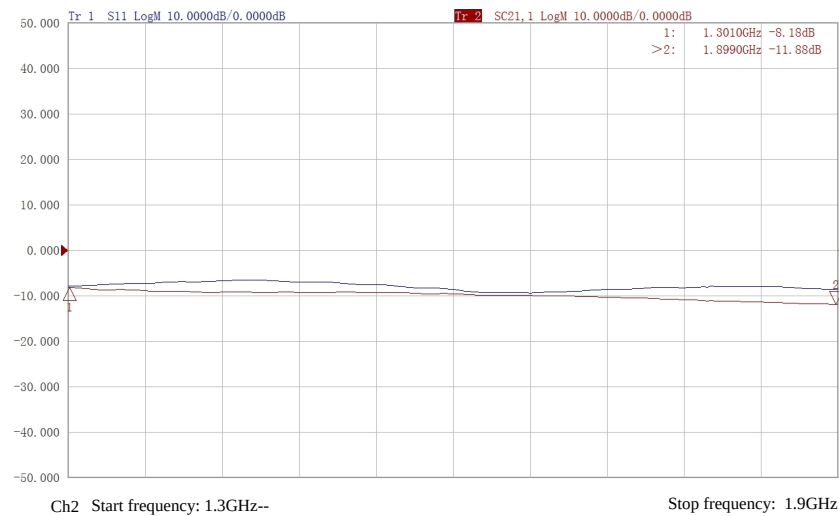


Figure 13. Down-conversion loss of mixer 2.

Usually, there are two ways to retrieve the instrument's spectral resolution. One is to obtain the time difference between the maximum value and the first zero-crossing point from the amplitude envelope of the output pulses, and the spectral resolution is approximately equal to the product of the time difference and the chirp rate. Another is to derive the full-width half-maximum (FWHM) to obtain the average FWHM [15]. Here, we use the FWHM method to retrieve the spectral resolution. Firstly, the response of the novel single-channel CTS system to a sinusoidal input is measured at different input frequencies. Then, the relative half-width half-maximum (HWHM) to the right and left could be obtained from the measurements and thus, the full-width half-maximum (FWHM) is derived. Figure 14 shows the measured average FWHM to be 90.503 kHz. This value is particularly close to the maximum achievable spectral resolution ($\frac{0.88}{T_C} = 88$ kHz) of the expander–compressor arrangement, which is determined by the compressor's working bandwidth.

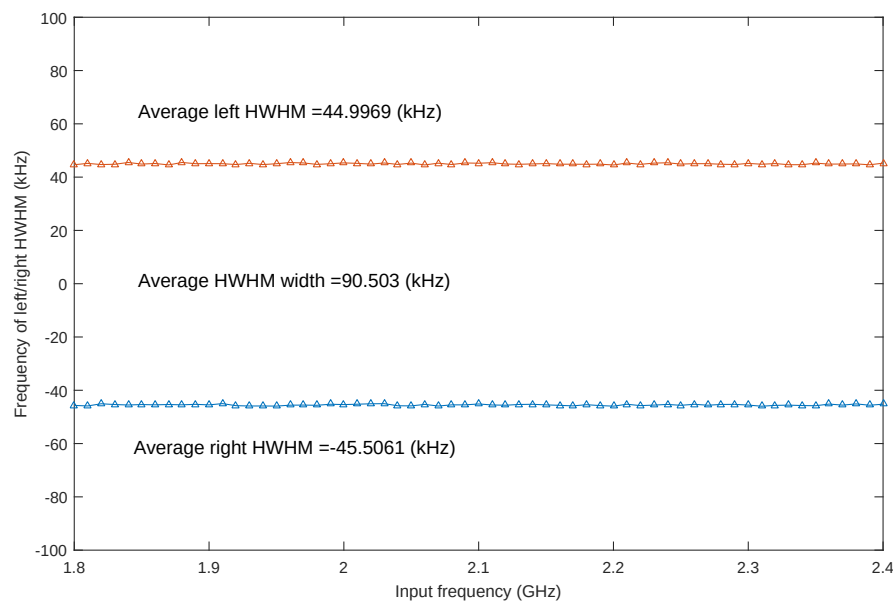


Figure 14. The novel single-channel CTS system's spectral resolution derived from the left and right half-width half-maximum (HWHM). The location of the maximum and the neighbor half-maximum points are retrieved from the high-resolution sampling data of 5 kHz.

6. Conclusions

A novel design of a single-channel arrangement for the CTS system is introduced in this paper. By adding an additional source, a mixer, and a splitter\combiner, one channel of the classical CTS system is replaced. The output pulses from the two simulation models with ideal devices match well. Considering the introduced nonideal devices of the mixer and power splitter\combiner, the main influence is that differences exist between the amplitudes of the output pulses, which have been observed both in results of the simulation model with nonideal devices and in the real hardware circuit experiment. Generally, the amplitude differences of output pulses can be compensated in the later digital signal processing. The dispersion of the introduced mixer, power splitter, and combiner is usually very small, and its influence on signal resolution can be ignored. In addition, the experimental results indicate that the retrieved instrument's spectral resolution is particularly close to the maximum achievable spectral resolution of the expander–compressor arrangement.

Compared to the classical two-channel arrangement CTS structure, the novel single-channel structure can save three amplifiers, two filters, a SAW filter, and a switch. The structure of the CTS system is simplified due to the saved active devices. The matching problem between the two channels is ignored and the sequential control system can be simplified. This indicates that the novel single-channel CTS system may have the potential feasibility for practical application. However, as the simulation and experiment only focus on the signal detection and fundamental spectral analysis without real SAW filter and the subsequent signal processing, there still exists some main characteristics (such as the system linearity and power spectral density accuracy) of the CTS system needing further investigation. Even though the single-channel structure is simple, the introduced mixer and power splitter\combiner may cause uncertain signal interference influencing the system performance, which would not occur in the classical two-channel structure. An additional data compensation procedure is also needed in the subsequent signal processing which will increase additional power consumption. Further research will be focused on compensating actual measured data in the later digital signal processing; investigating the implementation of the novel signal-channel CTS system with real SAW filter and subsequent signal processing; and evaluating system performance with other main characteristics of power spectral density accuracy, linearity, and sensitivity, along with the front-end antenna system and the retrieval algorithm.

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