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Design and Fabrication of Reflective Array Type Wideband SAW Dispersive Delay Line

Jun-Ho Choi · Jong-Won Yang · Sun-Phil Nah · Won Jang

Abstract

A reflective array type surface acoustic wave(SAW) dispersive delay line(DDL) with high time-bandwidth at the V/UHF-band is designed and fabricated for compressive receiver applications. This type of the SAW DDL has the properties of the relative bandwidth of 20 %, the time delay of 49.89 usec, the insertion loss of 38.5 dB and the side lobe rejection of 39 dB. In comparison with a commercial SAW DDL, the insertion loss, amplitude ripple and side lobe rejection are improved by 1.5 dB, ±0.6 dB and 4 dB respectively. Using the fabricated SAW DDL, the prototype of the compressive receiver is developed. It is composed of RF converter, fast tunable LO, chirp LO, A/D converter, signal processing unit and control unit. This prototype system shows a fine frequency resolution of below 30 kHz with high scan rate.

Key words : Surface Acoustic Wave(SAW), Dispersive Delay Line(DDL), Electronic Warfare(EW), Multiply-Convolve-Multiply(M-C-M), Compressive Receiver.

Ⅰ. Introduction

A modern electronic warfare(EW) receiver requires the abilities of wideband frequency coverage and multiple simultaneous signal detection for high probability of intercept operation, high sensitivity and wide dynamic range for detecting all types of the weak signals, fine frequency resolution, and real-time signal operation in a high dense EW signal environments[1]. To achieve these requirements, the several types of the receivers are developed such as superheterodyne, channelized, digital and compressive receiver. Generally, the superheterodyne receiver has high sensitivity while it has low probability of detecting unanticipated signals. The channelized and digital receiver provide the best performances for EW receiver applications. However, they require large size, much weight and power, and high cost. The different type of the receiver using DDL, the compressive receiver has the properties of fine frequency resolution, wide bandwidth, high scan rate and capability to process multiple simultaneous signals. As the SAW techniques and the high speed logic circuits are advanced, the compressive receiver is currently receiving considerable attention in the design of real-time signal detection system for monitoring the frequency hopping spread spectrum system with high hopping rates because of high potential performances[2],[3].

One of the main technologies of the compressive receiver is the development of the DDL because the performances such as frequency resolution and scan rate depend on the time-bandwidth of the DDL. The design approaches of the DDL are the magnetostatic wave type, the crimped coaxial type, the electromagnetic type and the SAW type[4]. The former, two types are not easy to design to meet the desired frequency range, dispersive time, and frequency versus time slope. The latter two types are commonly used. Especially, The SAW type is useful for the DDL because of compact size, wide bandwidth and the low cost of reproducing a given design.

In this paper, the reflective array type SAW DDL with wide bandwidth and large time delay is designed and fabricated on the Y-Z cut of $LiNbO_3$ substrate material for compressive receiver applications. This SAW DDL provides good performances compared with the commercial SAW DDL. Using the fabricated SAW DDL, we developed the prototype of the wideband compressive receiver at V/UHF-band for real-time signal detection. It provides the properties of high scan rate, fine frequency resolution and small volume, and is useful for monitoring frequency hopping spread spectrum signals.

Ⅱ. SAW Chirp Transform Operation

As shown in Fig. 1, one of the arrangements to perform SAW chirp Fourier transformation is the multiply-convolve-multiply(M-C-M). This operation is derived

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from the Fourier transform $F(\omega)$ of the input signal $f(t)$[5]:

$$F(w) = \int_{-\infty}^{\infty} f(\tau) e^{-jw\tau} d\tau \tag{1}$$

where $\omega = 2\pi\mu t$ is angular frequency, and μ is chirp slope(rate of linear frequency change with time). Using the identity $2\tau t = \tau^2 + t^2 - (\tau - t)^2$, the equation (1) is converted as:

$$F(2\pi\mu t) = e^{-j\pi\mu t^2} \cdot \int_{-\infty}^{\infty} [f(t) e^{-j\pi\mu\tau^2}] \cdot e^{j\pi\mu(\tau - t)^2} d\tau \tag{2}$$

This formula can be represented as the multiplication and convolution of the input signal with chirp signal:

$$F(2\pi\mu t) = h_2(t)[f(t) h_1(t) * h_c(t)] \tag{3}$$

where $h_1(t)$ is the first multiplying chirp signal, $h_2(t)$ is the second multiplying chirp signal, and $h_c(t)$ is the impulse response of the SAW chirp filter. In the signal spectrum measurement, the second chirp signal which compensates the phase distortion caused by the first chirp signal can be removed because the desired information is the envelope of the Fourier transform. The practical implementation of chirp algorithm is multiply-convolve(M-C) (see Fig. 1).

III. Configuration of the SAW DDL

The SAW DDL is composed of the input interdigital transducer(IDT) and the output IDT printed on the surface of the piezoelectric crystal, the phase correction pattern which compensates the phase and amplitude errors, and the etched grooves as the reflective elements in the propagation path as shown in Fig. 2. The IDT is used to convert an electric signal into a surface acoustic wave and vice versa. The surface wave is reflected by symmetrically placed frequency sensitive grating etched on the crystal surface. These are the frequency dependent elements so the grooves preferentially reflect the different frequencies to the output IDT. By placing these elements at the different distances periodically, the reflected frequencies depend on the distance from the IDT.

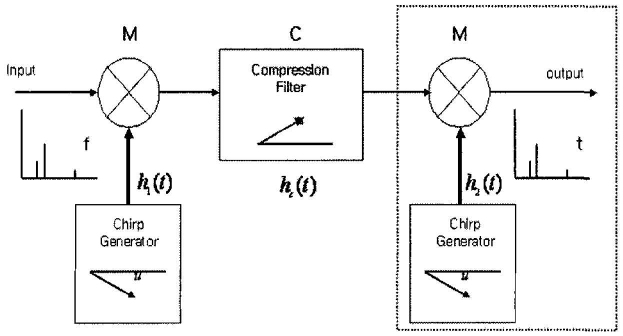


Fig. 1. SAW chirp Fourier transform of M-C-M.

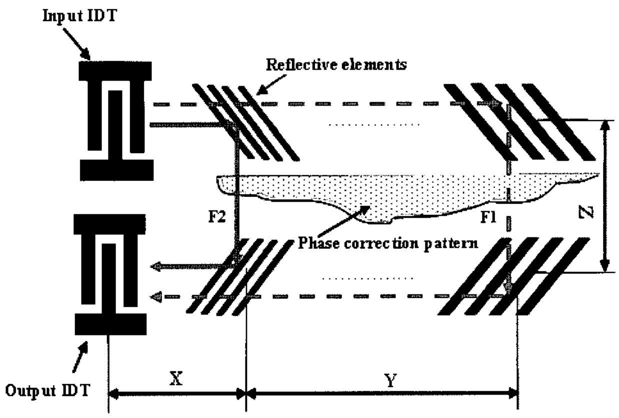


Fig. 2. SAW DDL with reflective elements.

The characteristics of the SAW DDL are determined by two frequencies, F_1 and F_2, and delay time T. If $F_1 > F_2$, the correspondent DDL is down-chirp, other wise it is called up-chirp. The delay time as the maximum propagation time from the input IDT to the output IDT is determined by:

$$T = 2(X + Y + Z) / V_{SAW} \tag{4}$$

where V_{SAW} is SAW velocity. The reflection angle of the grating grooves is not equal to 45 degrees. It is slightly adjusted by considering the SAW velocity of the material. The reflection coefficient is controlled by varying the groove depth. The phase correction pattern is written by using the laser trimming technique to compensate phase and amplitude errors between the symmetrically reflective elements because the quadratic phase errors resulted from the grating perturbation, crystal mis-orientation, material variation and temperature change cause the broadening pulse width and limit time spurious dynamic range[6]. These structures are implemented on th Y-Z cut of $LiNbO_3$ substrate material which provides high coupling efficiency, low acoustic loss and low diffraction loss[7].

3-1 Design of the Inter Digital Transducer

The frequency response of the IDT is the superposition of all the waves contributed by the individual sources. When the voltage is applied toward the i-th finger, the transfer function of IDT can be expressed as follows[8]:

$$H(f) = \sum_{i=1}^{N} A_i \exp(j2\pi f t_i) \tag{5}$$

where A_i is amplitude of the waves which is proportional to applied voltage, t_i is the position of the finger with index "i" which expresses time scale, and N is the number of fingers. Time scale and distance are connected through the SAW velocity:

$$x_i = V_{SAW} \times t_i \tag{6}$$

where x_i is the position of the i-th finger. If one knows the positions x_i for all fingers, it is possible to restore geometry of the IDT. After applying the formula of the sum of terms, the equation (5) is presented as Sinc function:

$$H(f) \approx N\left|\frac{\sin(N\theta/2)}{N\theta/2}\right| \tag{7}$$

where θ is $\pi(\omega-\omega_c)/\omega_c$ and ω_c is $2\pi f_c$. It is possible to conclude 4 dB bandwidth of the IDT. $\Delta\omega$ is given by:

$$\Delta\omega = \frac{2\omega_c}{N} \tag{8}$$

If one knows the required bandwidth, the number of the fingers is determined by equation (8). The electrical performances of the IDT can be evaluated from analyzing the its admittance because the IDT is presented as the capacitance. Thus the input admittance Y_{11} for the IDT is given by[9]:

$$Y_{11}(f) = G_a(\omega_c)\left|\frac{\sin(N\theta/2)}{N\theta/2}\right|^2 + j\omega N C_p \tag{9}$$

$$G_a(\omega_c) = N^2\omega_c(\varepsilon_0+\varepsilon_p^T)Wk^2 g \tag{10}$$

$$C_p = W(\varepsilon_0+\varepsilon_p^T) \tag{11}$$

Note that from equation (9) to equation (11), the constants depend on the type of crystal and geometry. In case of normally Y-Z cut of LiNbO$_3$, the constants are $k^2=0.048$, $g=2.871$, $\varepsilon_p^T=50.2\times\varepsilon_0$, and W=IDT aperture respectively.

3-2 Design of the Reflective Array Elements

The reflective elements are placed in different positions to guarantee correct time delay for given frequency of the SAW DDL. The main formula for determining positions of the reflective elements is given by:

$$\phi(t_n) = 2\pi\left(f_s t_n + \frac{B}{2T}t_n^2\right), \ (n=0,1,\cdots M) \tag{12}$$

where f_s is starting frequency, B is bandwidth of the DDL, T is total delay time of the DDL, and t is processing time. In case of down-chirp DDL, the starting frequency is the maximum frequency of the effective bandwidth and the sign of B is changed minus and vice versa. Because of the maximum processing time, $t_M = T$, the total number of the reflective elements is determined by:

$$M = Tf_c \tag{13}$$

This formula is used to estimate the degree of distortions caused by the second order effects because they are proportional to M. If the reflective elements are sequentially placed in accordance with equation (12), the total response of the reflective elements can be calculated by:

$$M(f) = \sum_{i=1}^{M} r_i \exp(j2\pi f t_i) \tag{14}$$

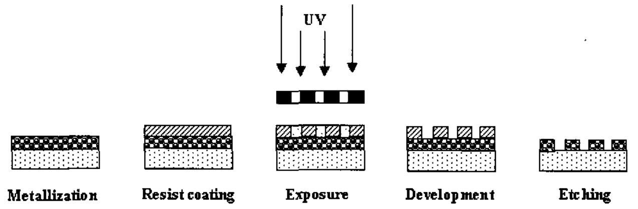
where t_i is processing time and r_i is the reflection coefficient of the individual reflective elements. The amplitude of r_i is proportional to the groove depth and surface wave frequency. It is given by[7]:

$$r_i = j\alpha\frac{h}{\lambda_{SAW}} \tag{15}$$

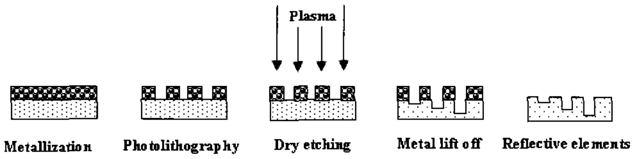
where α is the coefficient of reflectivity, h is groove depth, and λ_{SAW} is the wavelength of the SAW. For Y-Z cut LiNbO$_3$, α is around 0.3. Once the positions of the reflective elements and the structure of the IDT fingers are determined, the total frequency response of SAW DDL can be evaluated. Generally, SAW DDL has quite high insertion loss, which means that we can neglect triple transient echo and all types of multiple reflections. In this case, the transfer function of the DDL is the multiplication of transfer functions of the IDT and the reflective elements. If the bandwidth of the IDT is much wider than that of the reflective elements, the influence of the IDT is only insertion loss. The insertion loss of the IDT in the Y-Z cut of LiNbO$_3$ is around 15 dB. The transfer function of the reflective elements placed by equation (12) gives normally flat amplitude response with linear phase. Unfortunately, because of second order effects such as bulk wave generation, the passband response can be disturbed. To compensate this distortion, it is necessary to modify r_i. The modification of r_i is done by changing groove depth or appropriate displacement of the reflective elements.

Ⅳ. Fabrication and Measurement of the SAW DDL

The SAW DDL is manufactured by using the photolithography process and the plasma dry etching process on Y-Z cut of LiNbO$_3$. The former process is used to print IDT pattern and the latter process is used to implement reflective elements. The quality of plasma dry etching process should be kept constant to guarantee the value of reflective coefficient in the etched grooves. In all cases, the distortion of phase and amplitude caused by manufacturing process should keep as small as possible. To achieve reasonable low distortion, it is often necessary to put additional laser trimmed bar to compensate phase and amplitude errors as shown in Fig. 2. The fabrication process for the DDL is presented in Fig. 3. The performances of SAW DDL strongly depend on the quality of the ground and feed-through cancellation. To reduce the RF electromagnetic feed-through, SAW DDL chip is mounted on the metal package as shown in Fig. 4.



(a) Photolithography process for the IDT



(b) Dry plasma etching process for the reflective elements

Fig. 3. Fabrication process of the SAW DDL.

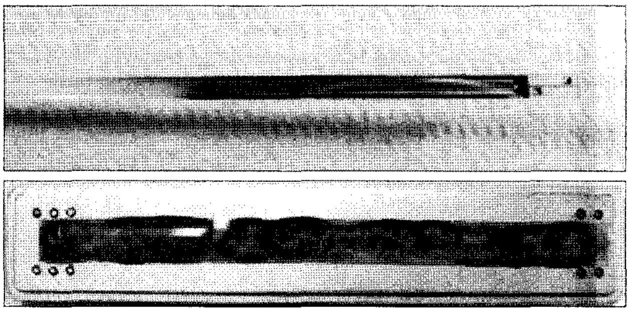


Fig. 4. Fabricated SAW DDL chip.

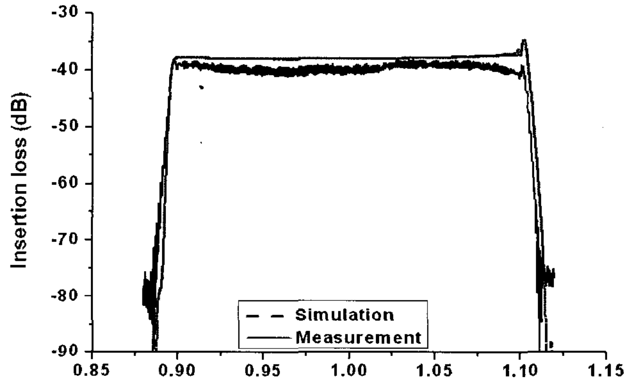


Fig. 5. Insertion loss of the SAW DDL.

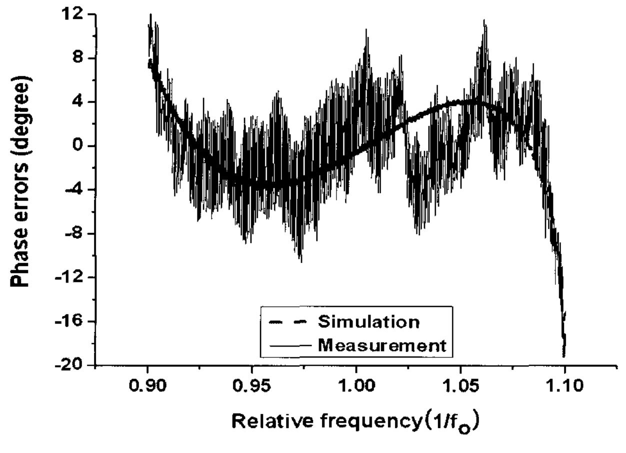


Fig. 6. Phase errors of the SAW DDL.

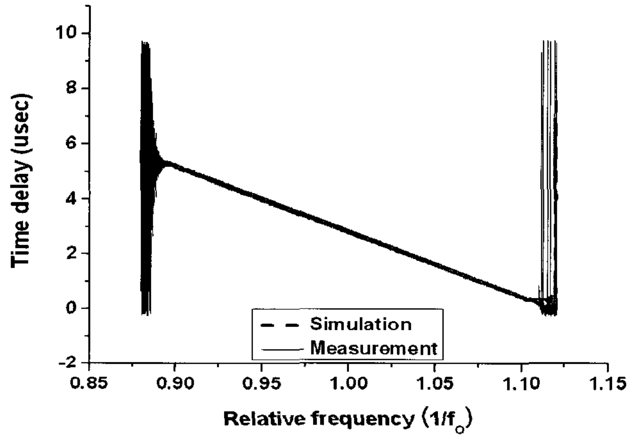


Fig. 7. Time delay of the SAW DDL.

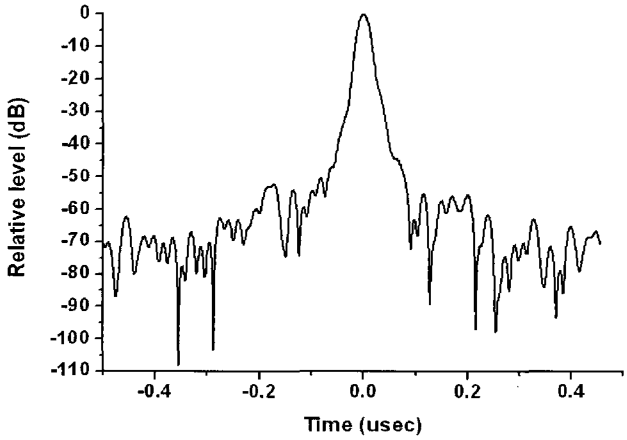


Fig. 8. Compressed pulse of the SAW DDL.

The performances of the SAW DDL are measured by the computerized 8510C network analyzer. As shown in Fig. 5, the insertion loss is around 38.5 dB and the amplitude errors are within ±1.6 dB. The rms value of the phase errors is 4.4 degrees and the time delay is 49.89 usec in the desired frequency ranges. These per-

Table 1. Performances of the SAW DDL[10].

Parameter	Measured results	RDT 005E (TEMEX)
Relative bandwidth	20 %	20 %
Time delay	49.89 usec	50 usec
Amplitude ripple	±1.6 dB	±2.2 dB
Insertion loss	38.5 dB	40 dB
Phase error	4.4 degree (rms)	4 degree (rms)
Side lobe rejection	39 dB	35 dB

formances are presented in the Fig. 6 and Fig. 7 respectively. Fig. 8 shows the compressed pulse when the hamming weighting is applied to the SAW DDL. The side lobe rejection is obtained by 39 dB. These results show reasonable agreement compared with the simulated results. The differences of the insertion loss and phase errors may be caused by manufacturing process. The fabricated SAW DDL presents good performances more than commercial SAW DDL developed by the TEMEX company in insertion loss, side lobe rejection and amplitude ripple error[10]. The performances are summarized by Table 1.

V. Application for Compressive Receiver

Using the fabricated SAW DDL, the prototype of the compressive receiver is designed as the multiply-convolve structure for unknown frequency measurement as shown in Fig. 9. It is composed of RF converter, fast tunable LO, chirp LO, A/D converter, signal processing unit and control unit. A set of sweep chirp multiplying signals is generated by impulse excitation of two SAW DDLs. Although this impulse based technique has the disadvantage of the limited multiple signal dynamic range due to inherent S/N loss of the SAW DDL, it yields excellent chirp linearity and slope matching to the weighted SAW DDL of the RF converter[11]. The structure of the chirp LO is presented in Fig. 10. The input signal is firstly up-converted by high speed tunable local oscillator with fast lock time of 50 usec to cover the wide frequency range. This signal is multiplied by sweep chirp signals with down-slope generated by the chirp LO and then applied to the hamming weighted SAW DDL with up-slope. The compressed output signal is narrow pulse with a pulse width of K/B_c and amplitude of $(T/B_c)^2$, where B_c is the bandwidth of the SAW DDL, and K is a constant near unity determined by the hamming weighting function. The envelope of the compressed output signal is translated to the video signal by the logarithmic amplifier with fast rising and recovery time of 2 nsec and 18 nsec respectively. This compressed pulse appears at point of time determined by input frequency. Thus, the signal spectrum can be measured by counting the time intervals between the output compressed pulse and the triggering pulse of the reference signal. In our system, the video signal is sampled by 200 MHz A/D converter and then counted by an interval of 5 nsec at the settling time of the tunable local oscillator. Hence, the frequency of the unknown input signal is calculated by the counted

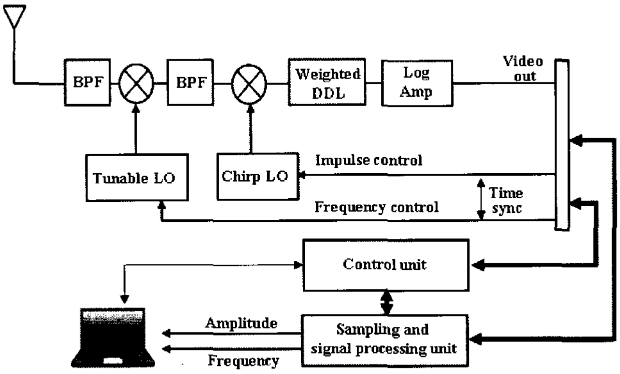


Fig. 9. Configuration of the compressive receiver.

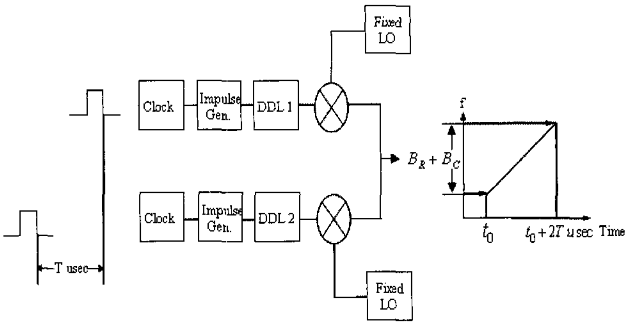


Fig. 10. Block diagram of the chirp LO.

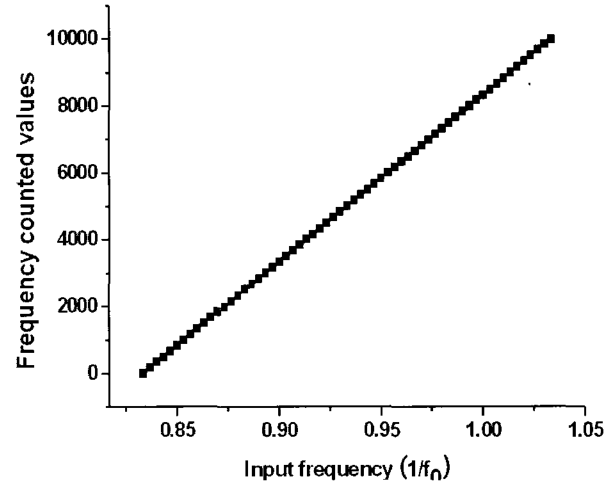


Fig. 11. Counted values versus input frequency.

values as shown in Fig. 11. The implemented prototype of the compressive receiver is presented in Fig. 12.

This prototype system offers the time-bandwidth of 3000 and analysis time of 100 usec. The analysis time is limited by the speed with which the chirp LO board can generate two times larger than instantaneous bandwidth and time delay of the weighted SAW DDL in the RF converter. Although we can count frequency bin number by interval 5 nsec, because the frequency resolution is limited by the width of the compressed pulse and the time delay of chirp filter, this prototype system cannot be achieved by the frequency resolution of 6 kHz. The time delay of 50 usec provides the frequency resolution of 20 kHz theoretically. The sensitivity of the compressive receiver can be calculated by using the receiving bandwidth B_R, video bandwidth B_V and signal processing gain TB_c. The sensitivity is achieved by −95 dBm as shown in Fig. 13. To confirm chirp Fourier operation, the compressive receiver is tested by using the digital oscilloscope. Fig. 14 shows the ability to analyze multiple input simultaneous signals when two CW signals are applied to the compressive receiver. The input signals are presented by video pulse position relatively to pulse triggering of the reference signal. This system provides excellent performances such as fine frequency resolution and high scan rate in the wide frequency range.

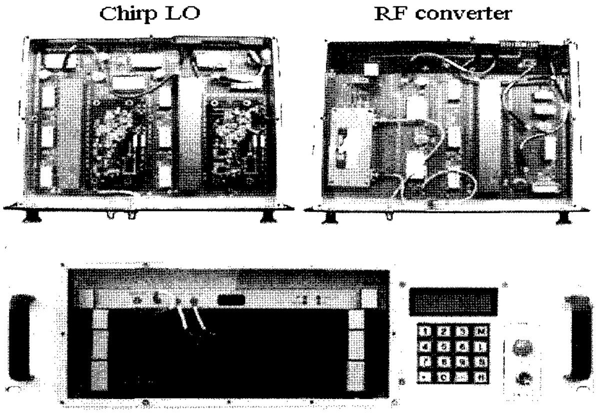


Fig. 12. Photograph of the compressive receiver.

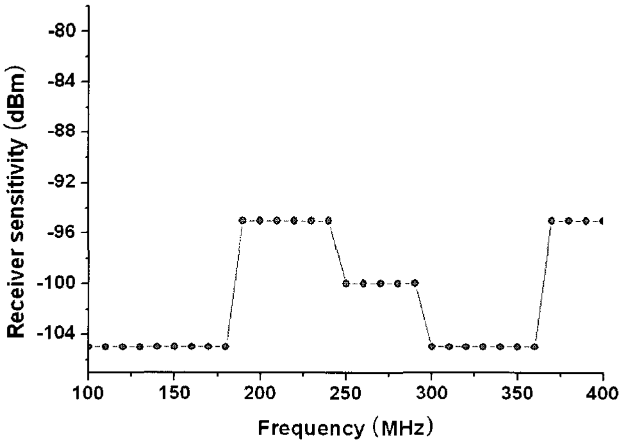


Fig. 13. Sensitivity of the compressive receiver.

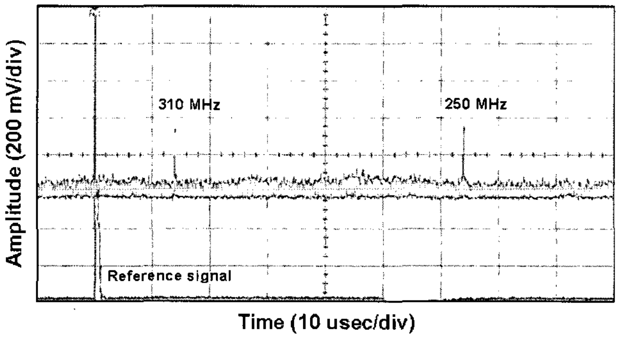


Fig. 14. Spectrum of two CW signals.

Ⅵ. Conclusion

The reflective array type wideband SAW DDL is designed on the Y-Z cut of $LiNbO_3$ substrate material for compressive receiver applications. The relative bandwidth of 20 %, the insertion loss of 38.5 dB and the time delay of 49.89 usec are achieved. When the hamming weighting is applied to the SAW DDL, the side lobe rejection is obtained by 39 dB. This SAW DDL shows the good performances compared with the commercial SAW DDL. Using the fabricated SAW DDL, we have developed the prototype of the SAW-based compressive receiver. It has many special features such as high sensitivity, fine frequency resolution, wide instantaneous bandwidth, high scan rate and small volume. The high scan rate makes it useful for spectrum monitoring of frequency hopped spread spectrum signals.

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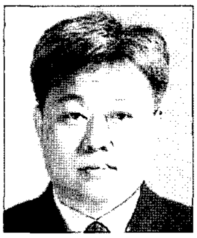

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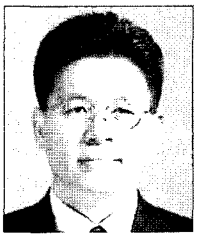

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