Design and fabrication of low loss and high suppression monolithic inverse wavelet transform processor

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Abstract: This paper presents a low loss and high suppression monolithic inverse wavelet transform processor (MIWTP) using surface acoustic wave (SAW) devices. New functions for achieving the MIWTP have been derived. Its structure combines a withdrawal weighted single phase unidirectional transducer (SPUDT) with an apodized SPUDT. The experimental device is achieved with the aluminum electrode and the 128 degree rotated Y-cut lithium niobate (LiNbO\textsubscript{3}) substrate. Measured results demonstrate the center frequency 68.1 MHz, the minimum insertion loss (IL) 5.4 dB, the 3-dB fractional bandwidth 1.3\% and the sidelobe suppression over 40 dB.

Keywords: inverse wavelet transform, surface acoustic wave devices, single phase unidirectional transducer, lithium niobate, insertion loss

Classification: Ultrasonic electronics

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1 Introduction

Wavelet reconstruction is based on the thought of multi-scale analysis. The size of the time-frequency window adapts to signal frequency variations. Generally, signal processing systems require the inverse wavelet transform processor (IWTP) has small size, low loss, high suppression and low cost in flaw detection, image processing, wireless communication and other fields. Many methods, such as analog circuits, digital circuits and surface acoustic wave (SAW) devices, have been proposed to implement the inverse wavelet transform (IWT) in hardware [1, 2, 3, 4, 5, 6].

To realize the complex wavelet reconstruction algorithm with SAW devices, the literature [4] presents the cascade-connected scheme with two-stage wavelet transform processors. However, this scheme produces the second loss during the signal processing. It also causes the large size and the high cost. In addition, the literature [5] proposes another scheme which implements the monolithic inverse wavelet transform processor (MIWTP) using the structure with two bidirectional transducers (BDTs). This structure combines an input apodized interdigital transducer (IDT) with an output apodized IDT. However, this early MIWTP has the relatively large size and the high insertion loss. Typically, the minimum insertion loss is in the region of 11–16 dB and the 3-dB fractional bandwidth reaches 1.1%. For these reasons, the low signal-to-noise ratio (SNR) affects the efficiency and accuracy of signal processing. Furthermore, using the multistrip coupler (MSC) structure can implement the IWT, but the drawback is the substrate size will be increased [6].

In this work, we describe a new MIWTP using the structure with two electrode widths controlled single phase unidirectional transducers (EWC SPUDTs). This structure combines an input withdrawal weighted SPUDT with an output apodized SPUDT. This new scheme reduces the total loss and the size. It improves the suppression and the SNR during the signal processing. Therefore, this new MIWTP is suitable for achieving the high-performance wavelet reconstruction signal processing.

2 Principle of monolithic inverse wavelet transform processor

We select a Morlet wavelet as the wavelet function by [4, 5]

$$\psi_{2^k}^{\tau}(t) = 2^{-k/2} \psi \left( \frac{t - \tau}{2^k} \right) = 2^{-k/2} e^{-\frac{1}{2} \left( \frac{\omega}{\omega_0} \right)^2} e^{\frac{j 2 \pi f_0}{\omega_0} \frac{\omega}{\omega_0}}. \quad (1)$$

Here $k$ is an integer, $2^k$ is the discrete scale, $t$ is the continuous-time variable, $\tau$ is the displacement factor, and $f_0$ is the frequency value. The dyadic wavelet transform of the input signal $f(t)$ is

$$WT_{2^k}(\tau) = f(t) * \psi_{2^k}^{\tau}(t) = \int_{-\infty}^{\infty} f(t) 2^{-k/2} e^{-\frac{1}{2} \left( \frac{\omega}{\omega_0} \right)^2} e^{\frac{j 2 \pi f_0}{\omega_0} \frac{\omega}{\omega_0}} dt. \quad (2)$$
where * is the convolution symbol. The dyadic IWT formula is described by

\[ y(t) = \sum_{k \in \mathbb{Z}} \int_{\mathbb{R}} W T_{2^k}(\tau) \psi_{2^k, r}(t) d\tau, \]  

(3)

where \( y(t) \) is the output signal and \( \psi_{2^k, r}(t) \) is the dual frame of \( \psi_{2^k, r}(t) \). The first order approximation of \( \psi_{2^k, r}(t) \) is described by [4, 5]

\[ \psi_{2^k, r}(t) = \frac{2}{A + B} \psi_{2^k, r}(t). \]  

(4)

By substituting Eq. (2) and Eq. (4) into Eq. (3), the following IWT equation is obtained through formula deviations as follows:

\[ y(t) = \frac{2}{A + B} \sum_{k \in \mathbb{Z}} f(t) * [\psi_{2^k, r}(t) * \psi_{2^k, r}(t)]. \]  

(5)

When \( A \) is close to \( B \), Eq. (5) reconstructs the original input signal \( f(t) \) more accurately. From Eq. (5), we get the new function for achieving the IWT as follows:

\[ h_{2^k}(t) = \psi_{2^k, r}(t) * \psi_{2^k, r}(t) = \sqrt{\pi} e^{-\frac{t^2}{2}} e^{i 2\pi f_0 t}. \]  

(6)

The Fourier transform of the function \( h_{2^k}(t) \) is

\[ H_k(w) = 2^{k+1} \pi \times e^{-2\pi i (w - 2^{-k} w_0)^2}. \]  

(7)

Here the relationships \( w = 2\pi f \) and \( w_0 = 2\pi f_0 \) are used in deriving Eq. (7). Thus, the total frequency response of the MIWTP can be designed according to the frequency response of the convolution of two identical wavelet functions.

Fig. 1. Diagram of the multi-scale MIWTP for three different scales.

Based on the above new formulas, the new structure of an arbitrary single-scale MIWTP is achieved by using an input withdrawal weighted SPUDT and an output apodized weighted SPUDT. Furthermore, the multi-scale MIWTP can be implemented with multiple single-scale MIWTPs for different scales. Fig. 1 shows the diagram of the multi-scale MIWTP for three different scales. To simplify the description of the principle, we only draw three different scales for \( 2^{k-1}, 2^k, \) and \( 2^{k+1} \) in Fig. 1.
3 Design of the monolithic inverse wavelet transform processor

The implementation of a high performance single-scale MIWTP is the key to realize the complex wavelet reconstruction algorithm. We take the scale $2^{-2}$ as an example to illustrate the study of the MIWTP. We get $h_{2^{-2}}(t) = \sqrt{2}e^{-\frac{4\pi^2}{5}t^2}e^{j2\pi f_0 t}$ in this case. The design of a SPUDT is based on the couple-of-modes (COM) analysis which utilizes multiple internal reflections within the transducer to achieve the unidirectional behavior. The design schematic diagram is shown in Fig. 2. Each EWC SPUDT cell includes three electrodes. Two of them are the transducer electrode and the other is the reflective grating electrode [7, 8, 9]. The transducer electrode width is $\lambda/8$ and the reflective grating electrode width is $\lambda/4$, where $\lambda$ is the acoustic wavelength. The distance between the reflection center and two adjacent transduction centers is $3\lambda/8$ and $5\lambda/8$ respectively. In addition, transducer electrodes of the output SPUDT are designed in accordance with the function $g_{2^{-2}}(t) = 2e^{-\frac{8\pi^2}{5}t^2}$. Also, dummy electrodes help to eliminate the wavefront distortion produced by apodized electrodes. Consequently, this structure reduces the end and diffraction effect. The design gets a low loss and large sidelobe suppression performance.

![Design schematic diagram for scale $2^{-2}$ with an input withdrawal weighted SPUDT and an output apodized SPUDT.](image)

4 Experimental results

Using aluminum electrodes, the experimental MIWTP for scale $2^{-2}$ has been fabricated on the 128 degree rotated Y-cut lithium niobate (LiNbO$_3$) with an electromechanical coupling coefficient $K^2 = 5.5\%$ and a SAW velocity of 3890 m/s. Section photographs of the input withdrawal weighted SPUDT and the output apodized SPUDT are presented using a scanning electron microscopy Zeiss Supra 55 in Fig. 3. The length of a cell which equals to the acoustic length is 57.2 µm. Due to the experiment process control error and the measurement error, the transducer electrode width is 7.2 µm and the reflective grating electrode width is 14.4 µm. The number of transducer electrode pairs in the input and output transducer is 64 and 65, respectively. The substrate size of experimental MIWTP is smaller than that of the early MIWTP which has approximately the uniform electrode width of 12 µm and the total number of electrode pairs of 200 [5].
The Agilent network analyzer E5071C is used for measurement. Fig. 4(a) demonstrates the observed amplitude response of the experimental MIWTP for scale $2^{-2}$. The measured values show the center frequency 68.1 MHz, the 3-dB fractional bandwidth 1.3%, the minimum insertion loss 5.4 dB, better than 40 dB sidelobe suppression in a 50-ohm system. Fig. 4(b) shows ripples in the passband do not exceed 2.2 dB in the 3-dB bandwidth. Also, it can be seen from Fig. 4(c) that group delay ripples are almost less than 200 ns over the entire 3-dB bandwidth.

Fig. 3. Section photographs of (a) the input withdrawal weighted SPUDT and (b) the output apodized SPUDT.
5 Conclusion

By using the structure with dual-weighted EWC SPUDTs, we have achieved the new MIWTP. We get the center frequency 68.1 MHz, the minimum insertion loss 5.4 dB, the 3-dB fractional bandwidth 1.3% and the sidelobe suppression greater than 40 dB. Thus, the new MIWTP promotes the hardware implementation of the high-performance wavelet reconstruction signal processing which has broad application prospects in flaw detection, image processing, wireless communication and other fields.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 61274078), Innovation Project of Shanghai Municipal Education Commission (No. 13ZZ049), Doctoral Scientific Fund Project of Ministry of Education of China (No. 20120075110006) and Applied Research Projects of Science and Technology Bureau of Nantong (No. BK2013047).

Fig. 4. Measured curves. (a) Amplitude response. (b) Top of the amplitude response. (c) Group delay response.