Solid-State Electronics 80 (2013) 105–109

Contents lists available at SciVerse ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

A solution to reducing insertion loss and achieving high sidelobe rejection for wavelet transform and reconstruction processor using SAW devices

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ARTICLE INFO

Article history:
Received 16 July 2012
Received in revised form 6 November 2012
Accepted 7 November 2012
Available online 23 December 2012

The review of this paper was arranged by Prof. E. Calleja

Keywords:
Surface acoustic wave (SAW) devices
Single-scale wavelet transform devices (SSWTDs)
Wavelet transform and reconstruction processor
Insertion loss
Sidelobe rejection

ABSTRACT

An arbitrary wavelet transform and reconstruction processor is composed of multiple single-scale wavelet transform devices (SSWTDs) with different scales. For improving the performance of the processor using surface acoustic wave (SAW) devices, this research investigates how to reduce the insertion loss (IL) and achieve a high sidelobe rejection. To reduce the triple transit echo (TTE) and to achieve a high signal–noise ratio (SNR), the structure of the SSWTD consists of two electrode-widths-controlled (EWC) single phase unidirectional transducers (SPUDTs). In the propagation process of the SAW, the unidirectional characteristic of the new structure reduces the bidirectional loss of the entire device. In addition, to enlarge the fractional bandwidth and the sidelobe rejection, the internal structure of the SSWTD uses an input apodized transducer according to the envelope of the Morlet wavelet function as well as an output withdrawal weighting transducer.

In this paper, we present a SSWTD for scale 2^{-2} as an example to illustrate the design method and experimental results. The new device is fabricated on 128° rotated YX-cut lithium niobate (Y128°X–$LiNbO_3$) with the electromechanical coupling coefficient $k^2 = 5.5\%$ and the SAW velocity 3992 m/s. We get the experimental frequency response with the center frequency 68.14 MHz, the minimum IL −9.96 dB, the fractional bandwidth 3.3%, the maximum passband ripples 0.4 dB and the sidelobe rejection greater than 40 dB. The proposed method and structure can be extended to an arbitrary SSWTD. The experimental results confirm that the performance of the wavelet transform and reconstruction processor can be improved by the proposed solution.

1. Introduction

Wavelet transform is an adaptive time–frequency analysis method which implements a multi-scale analysis according to the magnitude of frequencies [1,2]. Currently, a high-frequency singular signal generated in mechanical fault diagnosis, combustible gas detection and high-current measurement fields cannot be denoised with conventional filters. This is because the noise signal frequency is not within a single threshold. However, wavelet transform can achieve a multi-resolution analysis to the original input signal. The original signal can also be reconstructed by using the wavelet inverse transform after the signal denoising. Therefore, the wavelet transform and reconstruction technique demonstrates practical application values in the singular signal processing [3,4].

The study of implementing the wavelet transform and reconstruction processor with multiple single-scale wavelet transform devices (SSWTDs) using SAW devices is proposed in the literature [5]. The SAW devices have many advantages [6] (e.g., small size, high sensitivity, good reproducibility, high stability, no power consumption and compatibility with digital technologies). Based on the traditional structure using two bidirectional transducers (BDTs), the early SSWTD has the relatively large insertion loss (IL). Typically, the IL is more than 16 dB and the sidelobe rejection is no more than 30 dB. It cannot obtain a high signal–noise ratio (SNR) after the wavelet reconstruction processing [7]. In addition, we know that the mechanical SAW in interdigital transducers (IDTs) is produced by the inverse piezoelectric effect. However, the bulk acoustic wave (BAW) is also generated, affecting the performance of the device which produces some ripples and spurious components in the response curve. The literature [8,9] proposes another structure using the multistrip coupler (MSC) between the two BDTs to eliminate the BAW. This structure is sure to increase the substrate area and the technological difficulty of the manufacturing process. Furthermore, the literature [10] finds while using more electrode pairs makes the BAW weaker, this method still has the disadvantage of increasing the substrate area. Therefore, the early wavelet transform device cannot be used by

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http://dx.doi.org/10.1016/j.sse.2012.11.002

the instrumentation equipment requiring small size, high SNR, low loss and wide band in the detection field.

To solve the above problems, we proposes a new SSWTD which uses the structure with a combination of an apodization weighting EWC SPUDT and a withdrawal weighting EWC SPUDT. The new structure reduces the bidirectional loss of the early SSWTD and improves the sidelobe rejection. This article introduces the design method and measured experimental results of the new SSWTD. The proposed method and structure can be extended to an arbitrary SSWTD to obtain a high-performance wavelet transform and reconstruction processor which is used in the singular signal processing.

2. Fundamentals of reducing IL of wavelet transform device with EWC SPUDT

The structure with two EWC SPUDTs can achieve low IL and low TTE simultaneously. The key design goal of the EWC SPUDT is not to obtain the full single propagating acoustic wave. Rather, it is to obtain the zero reflection coefficient on the forward acoustic port under relatively good impedance matching conditions on the electrical port.

The EWC SPUDT can be treated as a three-port device with a forward acoustic port, a reverse acoustic port and an electrical port. The electroacoustic behaviour of the transducer can be expressed as a P-matrix shown in Fig. 1:

$$\begin{bmatrix} b_1 \\ b_2 \\ I \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ V \end{bmatrix}. \tag{1}$$

Among the nine terms of the P-matrix, only P_{11}, P_{13} and P_{33} are required for the design of the EWC SPUDT transducer. Under the condition that transducer electrodes are shorted-circuited, P_{11} is the reflection coefficient on the forward acoustic port. When the electrical port is driven by a voltage source with a constant amplitude at all frequencies, P_{13} is the generated acoustic wave amplitude function in the forward direction. P_{33} is the input admittance. The three coefficients are coupled and have to be computed by an iterative method in the design process [11,12].

The geometrical configuration of an EWC SPUDT cell is shown in Fig. 2 [11]. The transducer electrode width is $\lambda/8$ and the reflecting electrode width is $\lambda/4$, where λ is the acoustic wavelength. The distance between the reflection center and two adjacent transduction centers is $3\lambda/8$ and $5\lambda/8$ respectively.

The design of SPUDT includes not only the frequency response but also the reflected gate array. It is based on the following basic equation:

$$S_{11} = P_{11} + \frac{2P_{13}^2}{G_L + P_{33}}, \tag{2}$$

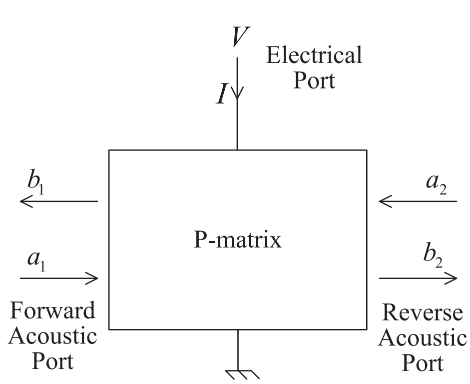

Fig. 1. P-matrix model.

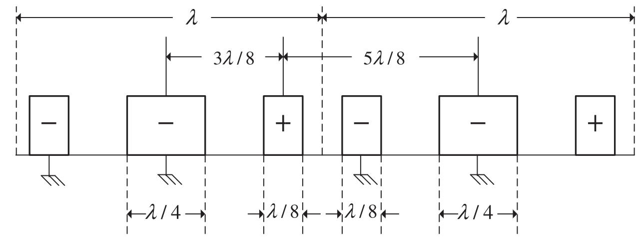

Fig. 2. Geometrical configuration of an EWC SPUDT cell.

$$S_{13} = \frac{2\sqrt{G_L}P_{13}}{G_L + P_{33}}. \tag{3}$$

As explained in [11], S_{11} in Eq. (2) is the reflected scattering parameter at the forward acoustic port. It is composed of a mechanical reflection term P_{11} and a regeneration reflection term $\frac{2P_{13}^2}{G_L+P_{33}}$. Under matched conditions, S_{13} in Eq. (3) is the scattering parameters from the electrical port to the forward acoustic port, which is related to the desired frequency response of the EWC SPUDT. G_L is the effective load conductance. Under the expected IL and frequency response, the key to implement the wavelet transform device with the EWC SPUDT is the design of a reflective gate array weighting function P_{11}. This effectively offsets the reflection of the acoustoelectric regeneration to achieve zero reflection with $S_{11} = 0$ at the forward acoustic port.

3. Implementation of wavelet transform and reconstruction processor

3.1. Implementation of an arbitrary SSWTD

In practical engineering applications, we can define the form of a wavelet function as

$$\psi_{2^k,\tau}(t) = 2^{-\frac{k}{2}}\psi\left(\frac{t-\tau}{2^k}\right). \tag{4}$$

In Eq. (4), 2^k denotes the discrete scale of a band in the frequency domain and τ is the continuous-time variable [13].

If $f(t)$ is the input signal with the noise, the output signal after the wavelet transform processing is given by

$$WT_{2^k}(\tau) = f(t) * \psi_{2^k,\tau} = 2^{-k/2}\int_R f(t)\psi\left(\frac{\tau-t}{2^k}\right)dt. \tag{5}$$

The input signal $f(t)$ convolving with the wavelet function $\psi_{2^k,\tau}(t)$ is shown in Eq. (5). The symbol $*$ is the convolution symbol.

In engineering practice, we select the Morlet wavelet as the wavelet function expressed by

$$\psi_{2^k,\tau}(t) = 2^{-\frac{k}{2}}\psi\left(\frac{t-\tau}{2^k}\right) = 2^{-\frac{k}{2}}e^{-\frac{1}{2}\left(\frac{t-\tau}{2^k}\right)^2}e^{j2\pi f_0\left(\frac{t-\tau}{2^k}\right)}. \tag{6}$$

By substituting Eq. (6) into Eq. (5), we get the following equation:

$$\begin{aligned} WT_{2^k}(\tau) &= \int_R f(t)2^{-\frac{k}{2}}\psi\left(\frac{\tau-t}{2^k}\right)dt \\ &= \int_R f(t)2^{-\frac{k}{2}}e^{-\frac{1}{2}\left(\frac{\tau-t}{2^k}\right)^2}e^{j2\pi f_0\left(\frac{\tau-t}{2^k}\right)}dt. \end{aligned} \tag{7}$$

Eq. (7) shows that the dyadic wavelet transform is achieved when k is an integer. In fact, for a specific scale, the total ideal frequency response of the SSWTD is the Fourier transform of the Morlet wavelet function $\psi_{2^k,\tau}(t) = 2^{-\frac{k}{2}}e^{-\frac{1}{2}\left(\frac{t-\tau}{2^k}\right)^2}e^{j2\pi f_0\left(\frac{t-\tau}{2^k}\right)}$.