Progress in sub-picosecond timing system development

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Abstract

We are reporting on research, development and indoor tests of the novel principle event timing system based on Surface Acoustic Wave (SAW) filter excitation as a time interpolator. Its operating principle is based on the fact that a transversal SAW filter excited by a short pulse can generate a finite signal with highly suppressed spectra outside a narrow frequency band. If the responses to two excitations are sampled at clock ticks, they can be precisely reconstructed from a finite number of samples and then compared so as to determine the time interval between the two excitations. We have designed and constructed a two-channel device which allows independent timing of two events. The device has been constructed using commercially available components, it is built in a standard 19'' rack of 2 unit height. The inputs are two NIM signals for epoch channels A and B and the 100MHz or 200MHz clock signal. The device is interfaced using USB type 1 interface to a host personal computer for data acquisition and processing. We have assessed the single-shot event time measurement precision of 0.9 ps r.m.s. per channel. The device exhibits extremely high timing linearity; the non-linearity is well below +/- 0.2 ps over an entire interpolator range. The temperature drift of the measured time interval is lower than 0.5 ps / K, the long term stability is typically better than +/- 0.03 ps per hour. These are to our knowledge the best values ever reported. These values were measured on the first prototype constructed without any additional temperature compensation or stabilization. The theoretical measurement dead time is 10 microseconds, the maximum continuous measurement rate is 300Hz. The limiting factor is the data transfer and computing power of the connected PC.

Introduction

The "time interval" (TI) or "time of arrival" (TOA) measurements are commonly used in a number of experimental techniques. We do report on construction of a time interval measurement device dedicated for application in extreme accuracy satellite laser ranging system. This application requires the picosecond timing resolution and precision as well as sub-picosecond timing device stability with respect to aging, temperature and other external influences [1].

All the high-resolution time interval meters are based on time interpolation. Traditional time interpolation methods can be found in comprehensive overviews [2], [3]. These methods usually utilize interval to voltage increment conversion, different variants of vernier principle or on pulse propagation through tapped delay lines. At the present time, the last of these methods is frequently used [3]-[5]. A novel time interval measurement method that makes use of a transversal SAW filter as a time interpolator has been introduced in [6]. The method is based on the fact that a transversal SAW filter excited by a short pulse can generate a finite signal with highly suppressed spectra outside a narrow frequency band. It results from the sampling theorem that if the responses to two excitations are sampled at clock ticks, they can be precisely reconstructed from a finite number of samples and then compared so as to determine the interval between the two excitations. An analysis of the deterministic

measurement error – nonlinearity - of this method has been given in [7]. It results from the analysis that the method excels in time interpolation efficiency since the time-interpolation error relative to clock period is very small. In other words, an accurate measurement can be achieved even with relatively low clock frequency. A detailed analysis of all random errors is the subject of the paper [8]. It implies from the analysis that even in a single-shot measurement all the random errors can be partially suppressed. It is possible thanks to averaging effect as the interpolation process is not based on the only one but many observations.

The ultimate goal of our project was the time interval measurement device providing the picosecond timing performance, simple and rugged design, low mass and low power and last but not least, not requiring any adjustment and recalibration in the field operation. According to the theoretical analysis as well as numerical simulations the SAW filter technique should provide all the performance required.

Measurement device

The interval measurement device has been designed in a two-channel configuration [9]. This enables to determine the TOAs of two independent pulses in a local time scale. The time interval between these two pulses may be computed as a difference of the two TOAs. This set up enables to measure both positive and negative time intervals without any dead time. The block scheme of one channel of the device is shown in Fig. 1.
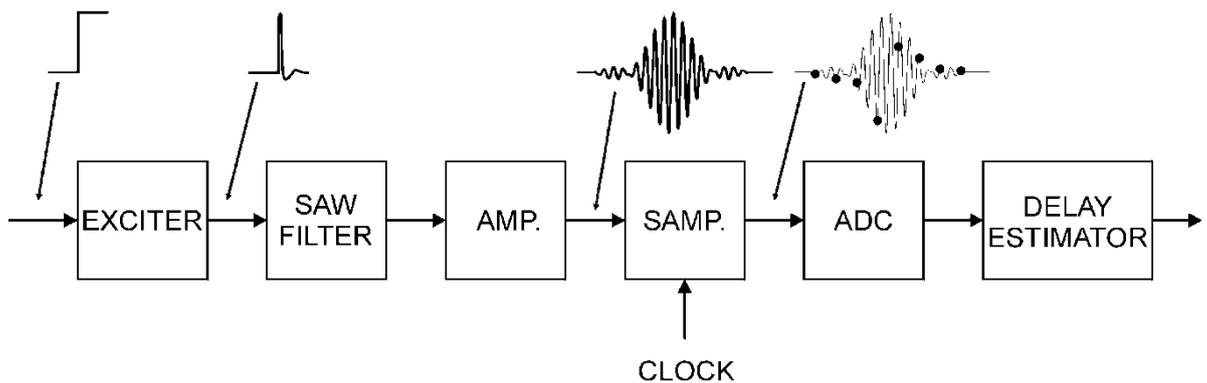
Figure 1. Architecture of the time interpolator based on SAW filter excitation

The external input pulses excite a transversal SAW band-pass filter whose output is sampled at clock ticks, see Fig. 2.
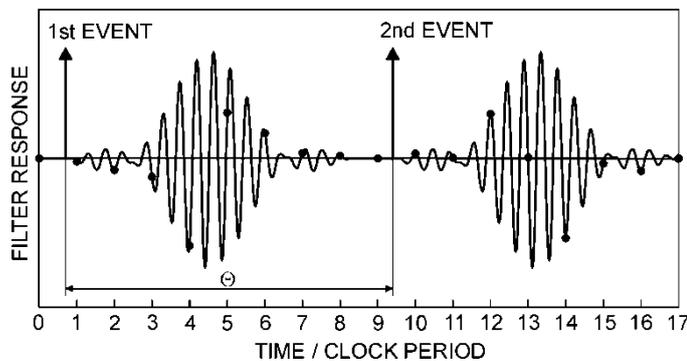
Figure 2. Sampled responses of the SAW transversal filter.

The samples are then converted by an analog to digital converter (ADC) and buffered. Once the external input pulse has been processed, the internally generated time mark is applied to the same circuit. This internal time mark is generated synchronously with the time base reference. After both responses have died out, they are reconstructed from the samples and then compared by means of cross correlation to estimate the time interval between the two events. All the processing steps can be integrated into a simple algorithm based on fast Fourier transformation (FFT). In Fig. 3 there is a photo of the prototype.
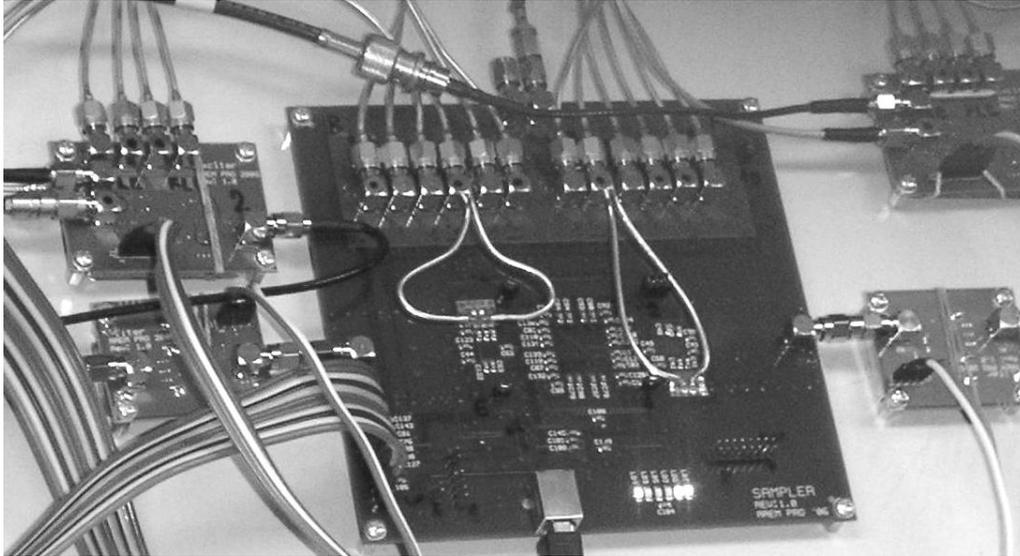
Figure 3. Photograph of the time interval measurement device prototype, the two timing channel version, the control, sampling, and communication module in a centre, the exciter modules in upper corners, the filter modules in lower corners.

The device consists of two exciter modules, two SAW filter modules and one control, sampling, and communication module, which is common for both channels. The device has been constructed strictly using commercially available components. The input and clock distribution circuits use the fast SiGe components to ensure low jitter and good delay stability. The other logical circuits use common CMOS components. Most of the device control, data collection, and communication functions are concentrated into a field programmable gate array (FPGA). The raw data from the device are collected via USB interface to a host computer where the TOAs and the length of time interval are computed. As the reference clock source we have used a frequency module built at the University of Applied Sciences, Deggendorf, Germany. This module provides 200 MHz LVECL clock signal with jitter below 1 ps rms. The filter response to the input time mark recorded by an oscilloscope is shown in the Fig. 4.

The upper trace shows the signal itself, the frequency spectrum of this pulse has been computed by the oscilloscope and plotted in a lower trace. The response is not longer than 500 ns and can be fully covered by 64 samples.
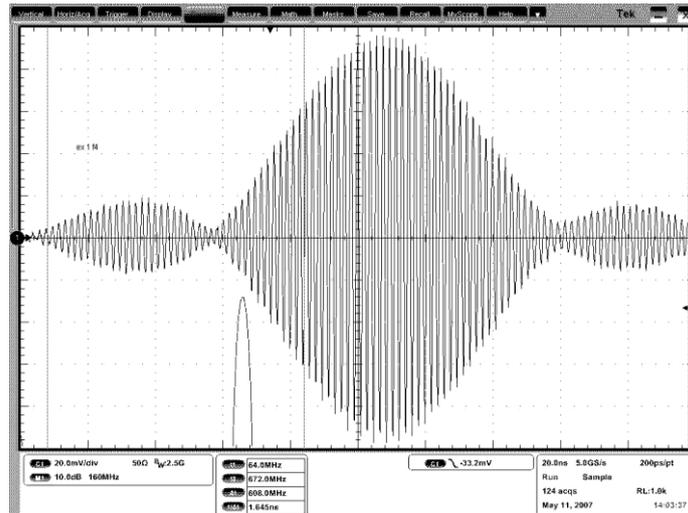
Figure 4. The shape of the output of the SAW filter (upper trace) and its frequency spectrum (lower trace), 2.5 GHz bandwidth oscilloscope, 10 ns/div, 156 MHz/div horizontal scale, 0.02 V/ div and 10 dB vertical scale.

Experimental results

The operational performance of the time interval measurements device has been proved by several tests. All the tests have been carried out in common laboratory environment. In the first test the both channels were triggered by the same time mark generated from an external fully asynchronous pulse generator. The repetition frequency of the time mark was set to ~10 Hz. The length of the trigger pulse active edge was to 100 ps. Due to different cable delays the channel B was triggered approximately 4.2 ns later than the channel A. We have taken sequence of 400 measurements. The measured TOAs and time intervals have been recorded and analysed. The resulting standard deviation of the time interval measurements is 1.3 ps. The histogram of the measured intervals is in Fig. 5. The error distribution is obviously close to normal.

The aim of the third test was verification of the long therm stability and the temperature dependence of the device. We have taken sequences of 400 measurements and evaluated the mean value from every sequence. We have completed series of measurements over the time interval of 4 hours after the device power on. Simultaneously we measured the temperature of the most critical component – the Exciter module. The results are plotted in Figure 6.

The device temperature raised for $+6^o$ Celsius within 30 minutes after power on and remained stable until the end of measurement. The drift of the mean value of the time interval is plotted as a function of time after power on. It can be noticed, that after the complete warm up, which takes several hours, the timing stability is excellent – the measured drift is better than +/- 0.03 picosecond / hour.
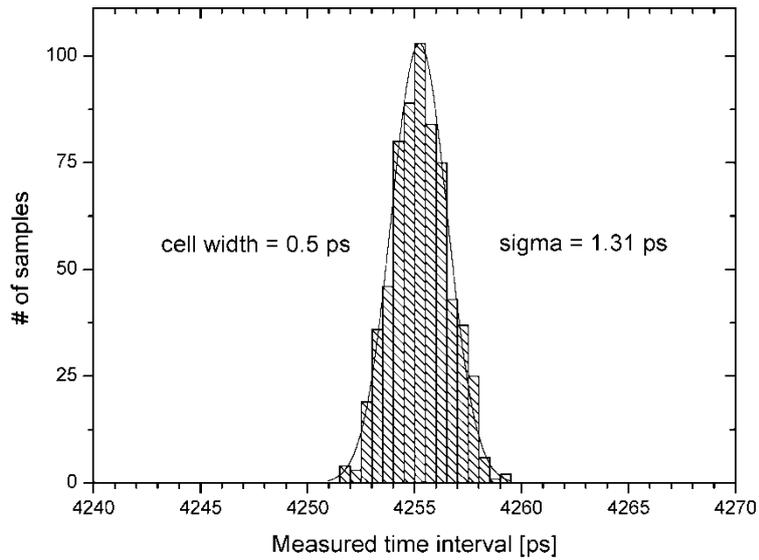
Figure 5. Histogram of time interval measurements. Times of arrival of pulses from the pulse generator have been measured on two channels. The time interval was evaluated as their difference. The generator output was passively divided into two equal pulses, these two pulses were fed to the channels A and B of the timing device using non-equally long cables. Horizontal scale is 0.5 ps per histogram cell, time units are picoseconds. The data distribution is very close to normal.
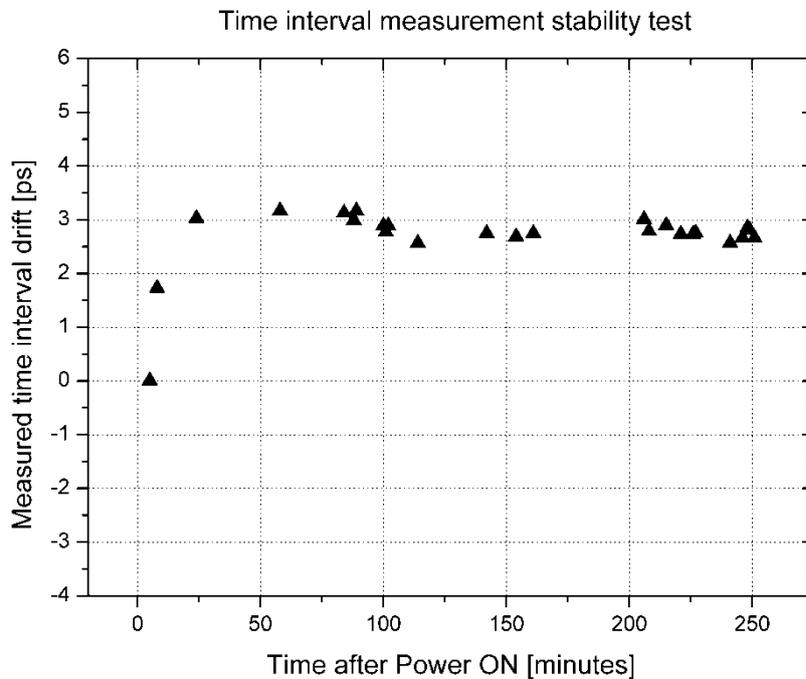
Figure 6. Temperature dependence and temporal stability of the time interval measurements. The device temperature raised for +6 K within 30 minutes after power on and remained stable until the end of measurement. The mean value of the series of 400 time interval measurements is plotted.

Summary and discussion

The goal of this work was to demonstrate the concept and capabilities of the new time interval measurement principle for picosecond precision timing. We have developed and constructed the time interval measurement device, which is based on a SAW filter as a time interpolator. The first results proved the concept. We have assessed the single-shot interval measurement precision of 1.3 ps rms which corresponds to the time of arrival precision of 0.9 ps rms in each channel. The error distribution is close to normal. The results are in good agreement with the error budget based on the theoretical analysis. We have identified the noise of the excitation as the source of the dominant contribution in the overall error budget. We suppose that after redesign of the excitation circuits the level of this noise can be reduced and the precision further improved. The temperature drift of the measured time interval on temperature is lower than 0.5 ps/K, the long term stability is better than +/- 0.03 ps per hour.

The entire device requires no calibration and parameter adjustment and hence it might be attractive also for applications, where long term stability, high reproducibility and low maintenance are obligatory. The time interval measurement system will be applied in the satellite laser ranging station with millimeter ranging precision.

Acknowledgements

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