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Estimating the Precision of a Leading-Edge Discriminator with Amplitude Correction

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Abstract—The formation of time stamps that are independent of the sensor output pulse amplitude in the domain of event timing is well-known problem. It is shown that the time-stamp accuracy (time walk) can be estimated using high-speed arbitrary-signal generators and general-purpose time meters with an uncertainty of the estimate of no worse than 0.2 ps. The efficiency of the technique is demonstrated for a leading-edge discriminator (LED). The proposed LED version combined with an amplitude meter and amplitude correction has a 17-ps time walk.

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INTRODUCTION

In a physical experiment, measurements that are related to recording the moments that events occur are widespread. Events are recorded by sensors whose pulsed output signal usually has a large spread of amplitudes. This is typical, e.g., for sensors such as high-speed photomultipliers (PMT). Therefore, when carrying out time measurements, there is a problem of timing, i.e., obtaining time stamps that are independent of the pulse amplitudes.

This problem is solved by time stamp shapers (TSSs), for which analog constant-fraction discriminators (CFDs) are typically used [1]. The time walk for different variants of such circuits lies in the range of 25–50 ps [2–4]. Leading-edge discriminators (LEDs) can serve as an alternative of CFDs [5, 6]. The main advantage of such discriminators is the ease of implementation, while their main drawback is the low accuracy due to a pronounced correlation between the delay of the discriminator output signal and the pulse amplitude at its input (the walk effect).

This disadvantage can be eliminated if this correlation is determined and the amplitude of the input pulses is measured. On this basis, the amplitude correction of the measurement results is realized in the online [7] or offline [8] modes, which allows one to provide a picosecond time walk. However, methods for assessing such an accuracy have almost not been developed, especially when the issue is that of using measuring equipment with a wide application.

The task of this work was to develop such a technique and demonstrate its capabilities using the example of assessing the accuracy of a time-stamp shaper based on a LED with amplitude correction.

THE FORMER OF TIME STAMPS BASED ON A LEADING-EDGE DISCRIMINATOR

In many experiments it is necessary to register only signals that fall within a specified time window to increase the signal/noise ratio; therefore, the first element of the time-stamp shaper (TSS) is the time selector (*Sel*) (Fig. 1).

When a PMT pulse passes through the selector it is important to preserve the steepness of its leading edge, thus ensuring a minimum of the LED delay jitter. In the proposed TSS, the time selection is performed by a high-speed AMP LMH6703 operational amplifier (OA), which has a special function of switching the output off (Fig. 2). The selection is performed when a *Window* signal, which has passed through a comparator *Cm*, arrives at the control input of the amplifier output (pin 8 of the OA).

The amplifier has a wide amplification band for both small (1.8 GHz) and large (1.2 GHz) signals and allows transmission of the pulse front with a duration of 0.5 ns and more at a voltage difference of 2 V. The delay of the switching the output on/off (≤10 ns) and the range of the amplifier output amplitudes (up to ±3 V) are sufficient for the time selection. The fundamental disadvantage of analog-signal selectors is the presence of glitches, that is, parasitic signals at the selector output at the instants of time that the time-window fronts occur. The certificate value of the glitch

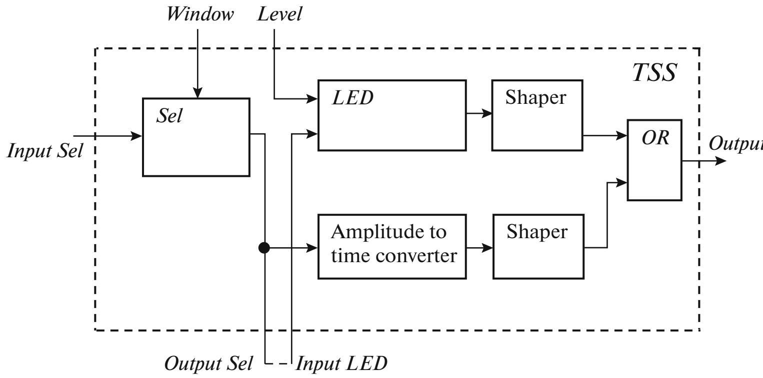

Fig. 1. A block diagram of the TSS.

of the LMH6703B OA is 50 mV; however, in the proposed circuit, due to an additional negative current in the feedback circuit (through the R_6 resistor from the negative voltage source), it was possible to completely eliminate negative-polarity glitches.

The pulses that pass the time selection (see Fig. 1) arrive at both the leading-edge discriminator LED and the amplitude-to-time converter (ATC). A high-speed comparator (ADCMP561), which responds to pulses with durations longer than 0.7 ns, is used as the LED. The discrimination level is usually set as close as possible to zero but above the noise level. The converter of the amplitude of short pulses into a time interval of the ATC is based on the principle of a peak detector with time stretching and was described in detail in [9]. Pulses from the LED and ATC that were duration-normalized using shapers come through an OR circuit to the TSS output.

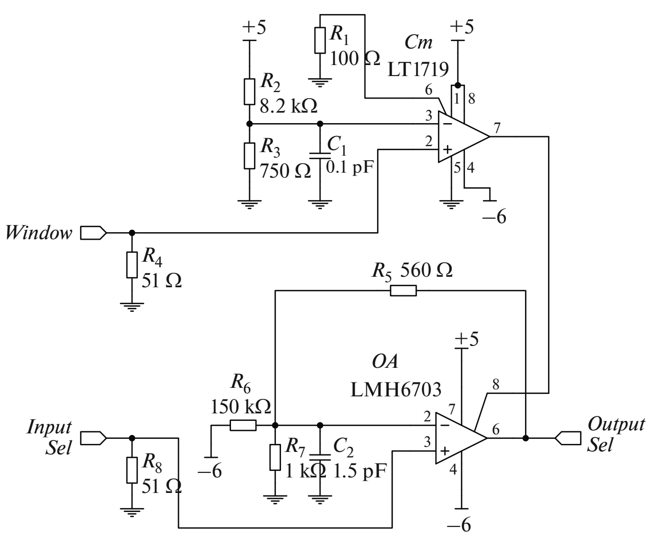

Fig. 2. The circuit diagram of the *Sel* unit.

From the principle of operation of the LED with a constant threshold, it follows that the delay of the moment of its operation significantly depends on the input-signal amplitude. This effect can be corrected if the pulse amplitude is known and the correlation between the amplitude and the delay of the discriminator is established [7, 8]. Preliminary calibration is required to identify this correlation. It is most correct to do this in a real experiment using a specific sensor. In particular, this is possible in experiments related to the measurement of time intervals between the initializing and secondary light pulses (for example, in pulsed laser location systems, calibration can be carried out at the location of a stationary target and variations of the reflected-signal intensity in a wide range). In this case, the advantage occurs that it is possible to correct not only LED delays, but also the influence of other, different in nature, correlations between the signal amplitude and delays of the measuring path. These data serve as the basis for determining the correction function, using which the measurement results are subsequently corrected in the offline mode. In [10], the aspects of constructing the correction function taking the errors of measurements of both time intervals and pulse amplitudes into account were considered in detail.

THE TECHNIQUE FOR ESTIMATING THE ACCURACY OF THE TIME STAMP SHAPER

It is impossible to estimate the accuracy of the TSS in a real experiment because of the high noise level of the entire measuring path. Therefore, the emphasis in this paper is on assessing the accuracy of the simulation of real sensor signals with low-noise equipment. This method is based on measurements of a fixed time interval that is specified by *Start* and *Stop* pulses (Fig. 3) provided that the amplitude of *Stop* signals in the operating range changes. The accuracy of the time reference (the time walk) is estimated as the maximum

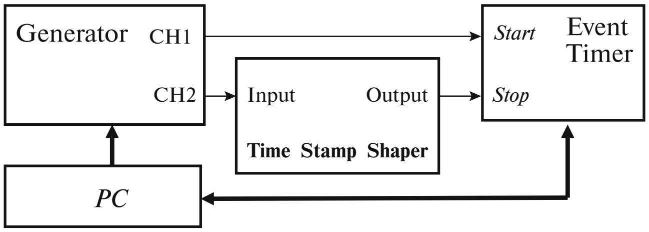

Fig. 3. The arrangement of measurement for estimating the accuracy of the TSS.

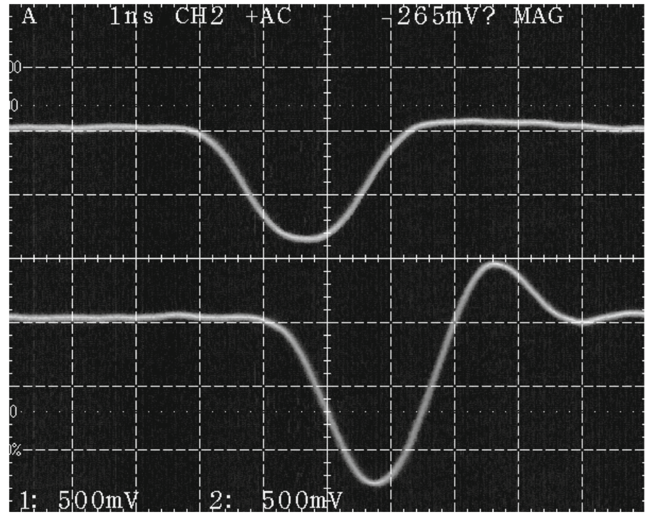

Fig. 4. An output pulse of the WS8352 generator in the "fast" mode before (upper waveform) and after the passage through the *Sel* unit (lower waveform). The vertical and horizontal scales are 500 mV/division and 1 ns/division, respectively.

spread of the results of measurements of time intervals under changes in the amplitude of stop signals.

This measurement scheme is known from [11]; however, it involves the use of unique highly specialized equipment. In this paper, we propose the use of modern equipment with wide application. The generation of *Start* and *Stop* pulses is performed with a two-channel generator for which the amplitudes of output pulses can be varied in a wide range, while the time intervals are measured with a precision event timer, which is able to provide continuous recording of a large number of time intervals.

This technique implies storing an array of n results from measuring the time intervals P_{ij} for a specified amplitude value A_j of a stop pulse. The amplitudes A_{ij} of stop pulses are simultaneously measured and the results of measuring P_{ij} are corrected; as a result, an array P_{cij} of corrected measurement results is formed. Each ith measurement results in the array contains both a random noise component (which is determined by the jitter of the generated time interval, the error of the time-interval meter, and the intrinsic noise of the TSS) and the component that depends on the amplitude A_j.

To reduce the influence of noise, estimates of the average values over the $M[P_j]$ and $M[P_{cj}]$ arrays are calculated. After such measurements for all values of A_j from the operating range of amplitudes, it is possible to determine the difference between the maximum and minimum average values, $\max M[P_c] - \min M[P_c]$, which actually gives the value of the time walk. Ideally, the value of $M[P_{cj}]$ must not depend on the signal amplitude A_j; however, some residual dependence practically takes place and characterizes the accuracy of the TSS operation. Accordingly, the range of variation of the $M[P_j]$ values gives the value of the time walk of the LED without using the amplitude correction. Due to the presence of noise, the average values $M[P_j]$ and $M[P_{cj}]$ are determined with a certain error, whose generally accepted estimate depends on the variance of the measurement results $D[P]$ and decreases with increasing the number of tests n:

$$\pm 3\sqrt{D[P]}/\sqrt{n}. \qquad (1)$$

Based on the precision of the equipment and the acceptable number of tests this ratio allows determination of the error of the proposed method.

The technique and equipment are applicable to estimating the accuracy of not only an LED with amplitude correction (this is the most difficult option), but also any time-stamp shaper, where the accuracy is determined by the difference $\max M[P] - \min M[P]$.

REQUIREMENTS FOR THE MEASURING EQUIPMENT

The first requirement for the measuring equipment is that the stop signals in their parameters should be similar to pulses from the output of the high-speed PMT. Numerous publications have shown that the shape of amplified PMT pulses is characterized by a leading edge of 1–2 ns, a duration of 2–4 ns, and an amplitude range from tens of millivolts to 1.5–2 V [12]. Modern high-speed arbitrary-waveform generators based on direct digital synthesis (DDS) make it possible to generate pulses with such parameters. In particular, these are AFG3252 two-channel generators (and their faster AFG31252 version) by Tektronix, as well as a WS8352 generator by Tabor Electronics Ltd. Figure 4 shows a waveform of an output pulse from the WS8352 generator in the fast mode (the pulse amplitude is 850 mV, the rise time is 1 ns, and the width is 3 ns).

The second requirement is low generator noise and a small meter error. The applicability of the above DDS-based generators is limited by the fact that the short-term instability (it is now customary to use the term jitter) of the generated time interval (interchannel

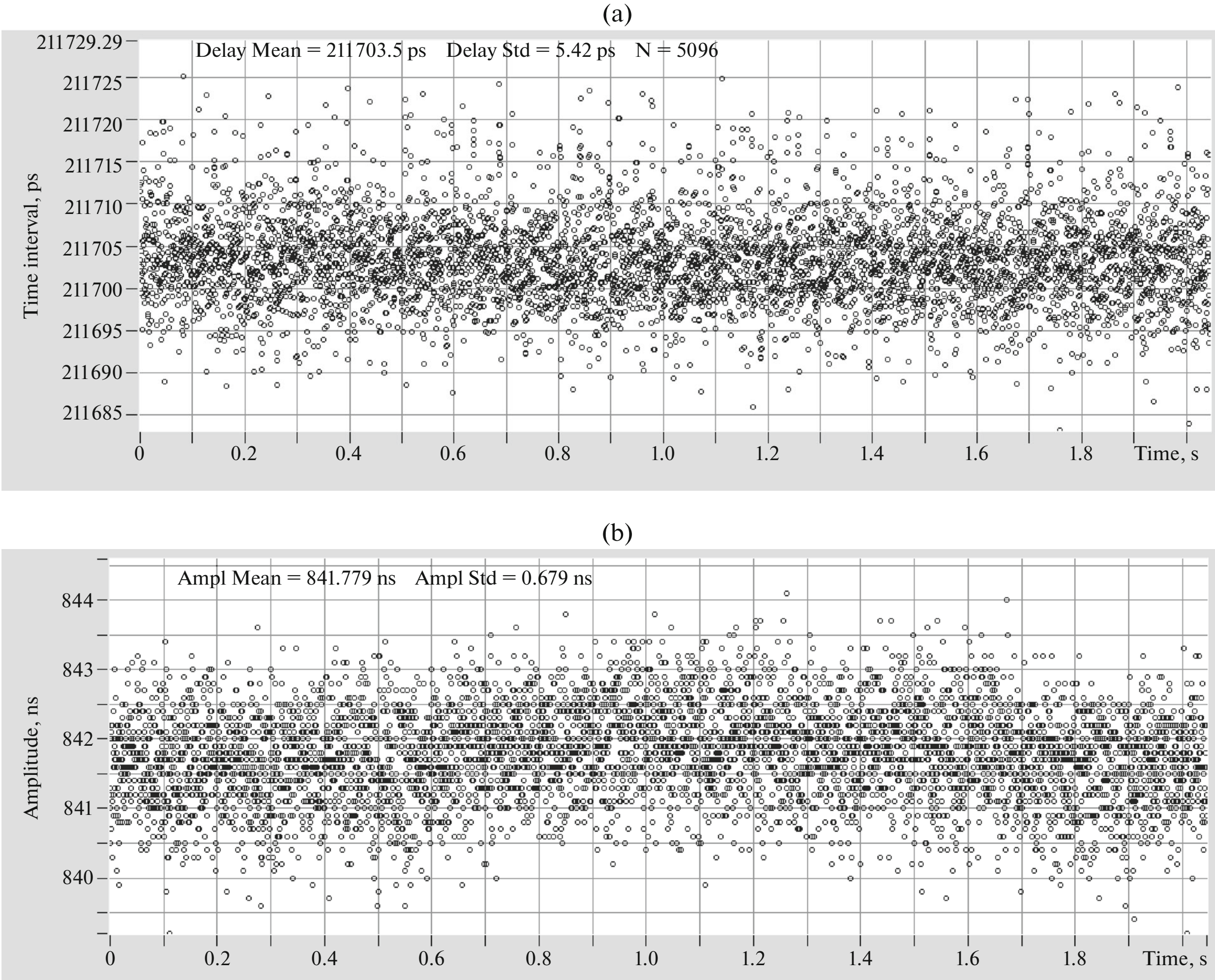

Fig. 5. The results of measuring (a) a fixed time interval at a fixed *Stop* signal amplitude and (b) the amplitude of this signal.

delay) is unspecified, has a rather complex dependence on both the value of the time interval and their repetition rate, and reaches a minimum at a multiplicity of the time interval to the generator clock period. Therefore, time intervals of 200 ns with a repetition rate of 2.5 kHz were measured in tests. The generated *Start* and *Stop* pulses were 3 ns wide and their amplitude could be set in the range from several millivolts to 2 V. An A033 precision event timer (Eventech) [13] with a time-interval measurement error of 2.5 ps was used as the meter.

Figure 5a shows the results of measuring time intervals according to the scheme presented in Fig. 3 for the case of a fixed *Stop* pulse amplitude of -1.0 V. The results show that the variance of the measurement results when using this equipment is $D[P] = 5.42^2 = 30$ ps^2, which for a number of tests $n = 5096$, specifies the error of the technique, according to (1), at a level of 0.2 ps.

The results of measuring the amplitude of stop pulses that are presented in Fig. 5b show that a pulse amplitude of -1.0 V is converted into a time interval of ~840 ns, whose measurement accuracy is 0.7 ns (rms deviation).

The event timer is functionally a precision recorder of the times of input events and allows continuous measurements of time intervals; therefore, the graphs in Fig. 5 are scans of the results of measuring time intervals in time (there is a certain analogy with a digital oscilloscope, only time intervals act here as signals). These are much more informative measurements (which allow one, for example, to investigate the introduced or parasitic modulation of time intervals in comparison with conventional equipment such as multi-channel time-interval meters, where the measurement results are presented in the form of histograms of distributions).

The third requirement: to perform calibration with simulation signals, a programmable coordinated interaction of the generator that simulates PMT signals and the precision of time-interval meter is required. This equipment allows organization of such an interaction, as it operates under a software control

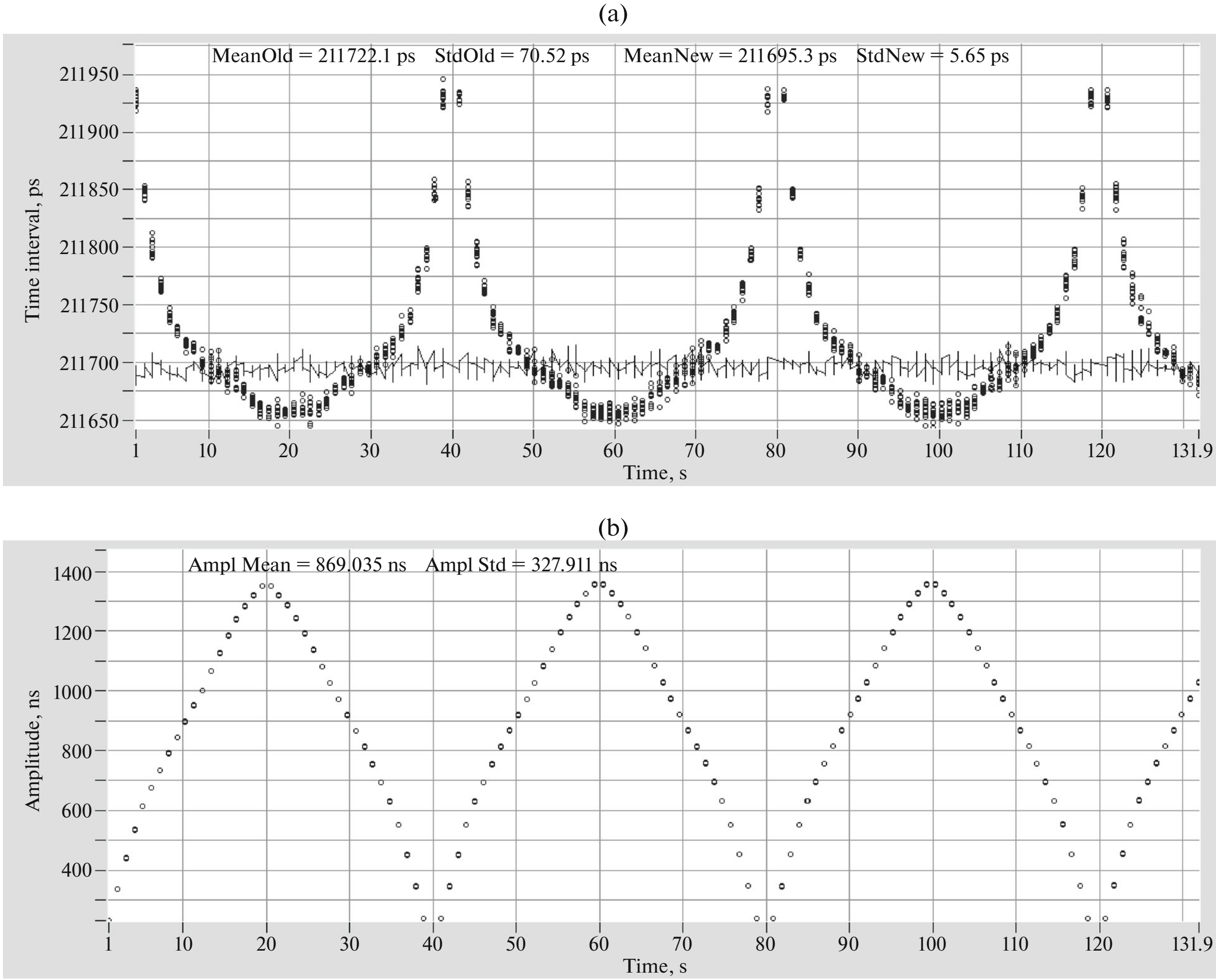

Fig. 6. The results of calibration tests: (a) the results of measuring time intervals before (bold lines) and after (thin lines) the correction; (b) the results of measuring the *Stop* pulse amplitude. The pulse amplitudes were set in the range from –0.1 to –2 V with a step of 0.1 V. The duration of time intervals is 200 ns, the repetition rate is 2.5 kHz.

from a PC. During calibration, the signal amplitude A_j at the input of the TSS varies linearly over a wide range (from $A_{min} = -0.1$ V to $A_{max} = -2$ V with a step of 0.1 V) directly in the process of storing the measurement data array according to the scheme in Fig. 3. The measurement and generator-control processes are synchronized by a computer program: after every 20 measurements of time intervals the measurement process was stopped, a new value of the pulse amplitude A_j was set, a delay interval for transients in the generator was held, and the measurements were resumed. The graphs of such calibration tests are shown in Fig. 6. They indicate the presence of a nonlinear dependence of the LED delay on the pulse amplitude at its input (a characteristic feature is that the delay for pulses with small amplitudes is sharply increased). These data serve as the basis for determining the correction function, which is further used to correct the results of measurements of time intervals.

Figure 6a also shows (thin lines) the result of the correction as applied to the calibration data. At the same time, the rms deviation of the time-interval measurement results decreases from 70 (StdOld) to 5.6 ps (Std New), which demonstrates the efficiency of the amplitude correction.

ESTIMATION OF THE TSS ACCURACY

The accuracy of the TSS was evaluated using the above-described method according to the diagram in Fig. 3; the range of amplitude changes was the same as in the calibration (from –0.1 to –2.0 V with a step of 0.1 V). For each amplitude value, $n = 5000$ results of measurements were stored and estimates of the average values of $M[P_j]$ and $M[P_{cj}]$ were calculated. The dependences of $M[P]$ and $M[P_c]$ on the signal amplitude A are shown in Fig. 7. It follows from the graph of $M[P_c]$ that the time walk of $\max M[P_c] - \min M[P_c]$ for

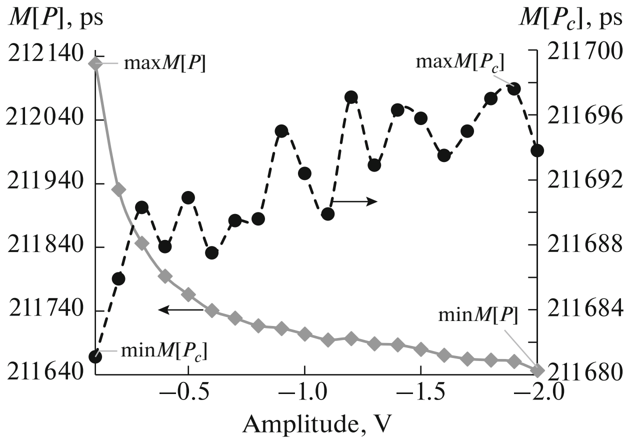

Fig. 7. The dependences of the average value of the time intervals $M[P]$ (bold line) and the average value of the corrected time intervals $M[P_c]$ (dashed line) on the signal amplitude A.

the investigated shaper is 17 ps when using the amplitude correction. The range of variation of the $M[P]$ value is ~500 ps, which corresponds to the LED time walk without using the amplitude correction. As already mentioned, the error of these estimates is 0.2 ps.

Among other TSS parameters, the delay and introduced jitter are of interest. These parameters can be determined by comparing the measurement results obtained at a fixed stop-signal amplitude (Fig. 5) and the measurement results according to the diagram in Fig. 3, but with the exception of the TSS unit. The delay of the TSS was 5.5 ns and its jitter was 1.15 ps.

CONCLUSIONS

The capabilities of modern widely applied generators and time meters are such that they allow simulation of signals of high-speed sensors and investigation of the time walk at a level of several picoseconds.

The proposed technique is applicable to estimation of the accuracy of any TSS type and provides an error of 0.2 ps or less.

The LED shaper of time stamps, which is combined with an amplitude meter and amplitude correction, can provide a time walk in the picosecond range.

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