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Detection of picosecond laser pulses with nanosecond time resolution by use of analogue-to-digital converters

G. NIBLER, A. PENZKOFER, W. BLAU
Naturwissenschaftliche Fakultät II — Physik, Universität Regensburg, 8400 Regensburg, Federal Republic of Germany

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A photodetector–analogue-to-digital converter system with 1.8 ns rise and decay time is described. The photodetector waveform is fanned-out with power splitters and sampled with high-speed analogue-to-digital converters. The system is used to detect picosecond light pulses from a mode-locked Nd-glass laser with nanosecond time resolution.

1. Introduction

The detection of light signals with nanosecond and subnanosecond resolution is generally performed with fast photodetectors and high-speed oscilloscopes or transient digitizers (for a review, see [1]). Here we describe the use of high-speed analogue-to-digital converters (ADCs) to register photodetector waveforms with nanosecond time resolution. The input waveform is fanned-out to 16 equal signals using power splitters. The signals are time delayed by fixed increments with coaxial cables (50 Ω impedance) of increasing length. They are inputted to 16 synchronously gated channels of two ADC Camac modules. The delayed waveforms are shifted across the closing gate window. The ADCs accumulate the input signals within the time gate. The contents of the channels are read out by a computer. The differences of counts between adjacent channels represent the time-resolved waveform (differentiation of integrated signal).

The system is inexpensive compared with other computerized waveform digitizers with nanosecond time resolution. Up to 11 ADC waveform detection units may be installed in one Camac crate and operated by one minicomputer. The system is applicable to time-resolved detection of nanosecond signals. Subnanosecond signals are broadened to a half-width of 2.3 ns (FWHM). Nonrepetitive and repetitive waveforms up to a rate of 10 kHz (depending on computer speed) can be measured.

The device is used to measure light pulses from a mode-locked Nd-glass laser [2–4]. In these measurements the time resolution is increased by numerical data deconvolution.

2. Experimental system

The experimental set-up is shown in Fig. 1. A mode-locked Nd-phosphate glass laser generates a train of picosecond light pulses. An electro-optical switch selects a single pulse from the train [5]. The separated pulse (duration 6 ps, wavelength 1.055 μm) is detected with photocell PD (Valvo, type XA 1003, rise time < 0.2 ns).

The photodetector signal of positive polarity enters the power splitter PS1 (Mini-Circuits, type ZFSCJ-2-1, frequency range 1–500 MHz [6]) and is split into two equal 180° out-of-phase outputs (output voltage $|V_{out}| = V_{in}/\sqrt{2}$). The positive output signal is inverted by a transformer, INV, (core Ferroxcube FXC 3B from Valvo) and triggers a gate pulse generator (LeCroy NIM model 821 quad 100 MHz discriminator, rise and decay time ≃ 1.7 ns). The negative output signal of PS1 is divided into two equal outputs by power splitter

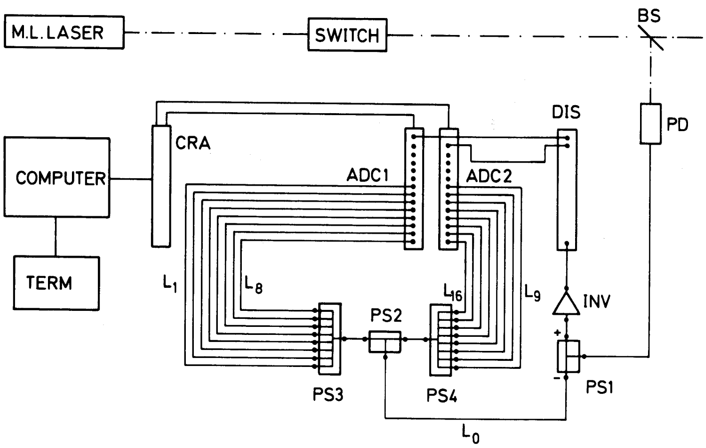

Figure 1 Experimental set-up. BS, beam splitter; PD, vacuum photocell (Valvo XA 1003); PS1, two-way 180° power splitter (Mini-Circuits ZFSCJ-2-1); PS2, two-way 0° power splitter (Mini-Circuits ZFSC-2-4); PS3 and PS4, eight-way 0° power splitters (Mini-Circuits ZFSC-8-4); INV, signal inverting transformer; DIS, discriminator (LeCroy 821); L_0, time synchronization cable; L_1–L_{16}, time delay cables; ADC1 and ADC2, analogue-to-digital converters (LeCroy 2249A); CRA, Camac crate controller; TERM, terminal.

PS2 (Mini-Circuits, type ZFSC-2-4, frequency 200 kHz–1000 MHz). Each output signal then enters an eight-way power splitter PS3 and PS4 (Mini-Circuits, type ZFSC-8-4, frequency 5–700 MHz). The 16 equal signals generated are delayed by cables L_1 to L_{16} (type RG174/U) with fixed length differences $\Delta l = l_i - l_{i+1} = 20$ cm (time separation $t_S = \Delta l/v = 1$ ns, $v = 0.66c = 20$ cm ns^{-1} signal velocity). They enter 16 channels of two high-speed ADC Camac modules (Le-Croy Camac model 2249A, charge sensitive 12-channel ADC).

Each ADC Camac module comprises 12 complete ADC units with a common gate. The input signal charges a capacitor while the gate is open. The analogue-to-digital conversion is performed by the Wilkinson rundown method whereby the discharge period (constant discharge rate) of the capacitors is measured with counters [7, 8]. The conversion time of 60 μs limits the repetition rate of the modules. The sensitivity is 0.25 pC/count, which corresponds to 1.25×10^{-11} V s/count for 50 Ω cables.

A gate pulse of -1.3 V and 40 ns duration is applied to both ADC modules from the discriminator. The time synchronization between gate pulse and signal input is adjusted by the length of cable L_0 (type RG213/U, $l_0 = 9$ m in our case). The jitter of this time synchronization is negligibly small (<0.3 ns).

The digitized contents N_i of the ADC channels are presented by a minicomputer (Dietz model 621). The pedestal signals $N_{D,i}$ (counts without input signal) of the channels are adjusted to about 40 counts (cable L_0 disconnected and PS2 terminated with a 50 Ω resistor).

The various ADC channels are calibrated to equal sensitivity by measuring the accumulated counts when all waveforms fall completely into the gate width. For this purpose a shorter cable L_0 of length $l_0 = 6$ m is used. This calibration corrects small variations in sensitivity of the channels and slight signal losses in the cables of different length.

The temporal operating principle is illustrated in Fig. 2 where a waveform consisting of two pulses is shifted across a rectangular (idealized) gate window. The waveforms S_1 and S_2 (on cables L_1 and L_2) arrive at channels 1 and 2 after the gate is closed and no signal is accumulated, i.e. $N_{S,1} = N_{S,2} = 0$ ($N_{S,i} = N_i - N_{D,i}$). For the waveforms 3 to 7, one pulse lies within the gate width and is registered. On channels 8 to 16 the two input pulses arrive within the opening time of the gate and are accumulated. The differential quotients of signal counts $C_i = (N_{S,i+1} - N_{S,i})/t_s$ of adjacent channels represent the time-resolved waveform. The time resolution is limited by the separation $t_s = 1$ ns of consecutive sampling points and the closing time $t_c \approx 2$ ns of the ADCs (internal gates of ADCs close when the voltage pulse drops below -600 mV [7]). The broadening effect of t_c is not shown in Fig. 2. The signal broadening by the dispersion of the cables and the power splitters is negligible.

3. Performance

The linearity of the system is tested with a second photodetector (Valvo, type XA 1003) and a

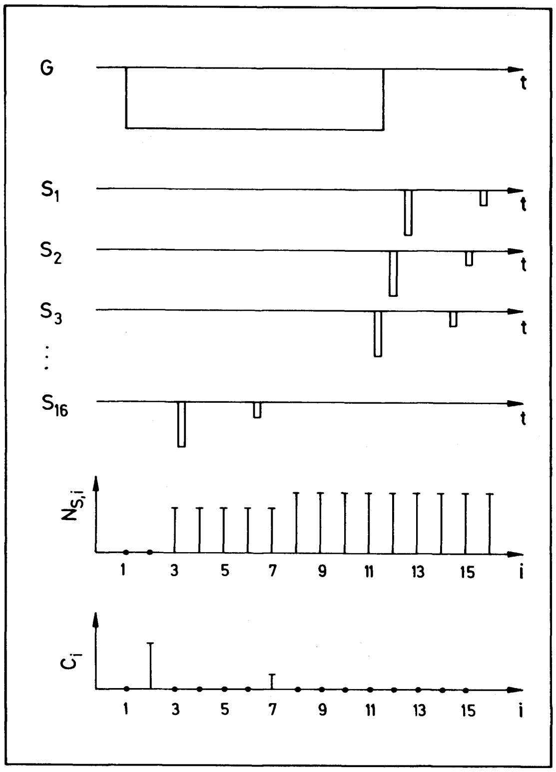

Figure 2 Temporal operating principle of waveform detection system. G, gate pulse; S_1–S_{16}, time delayed waveforms; $N_{S,i} = N_i - N_{D,i}$, accumulated signal counts of ADC channel i; $C_i = (N_{S,i+1} - N_{S,i})/t_S$, time-resolved signal height (averaged over $t_S = t_i - t_{i+1}$).

transient digitizer (Tektronix, type 7912 AD, rise time 0.5 ns, half-width 0.7 ns (FWHM)). Single picosecond light pulses enter the photodetectors. The measured signal counts of the ADC system versus the peak voltage signal of the transient digitizer are shown in Fig. 3.

Curve 1 (full circles) depicts the accumulated signal counts $N_S = N - N_D$ when cable L_0 is connected directly to one of the ADC channels. The linearity is limited by the 10-bit resolution of the ADC and the slight saturation of PSi above 700 counts. Curve 2 (open circles) represents the accumulated counts in channel 16. At a fixed input voltage the accumulated counts are reduced by a factor of 0.2 (the theoretical lossless voltage reduction is $V_{out} = V_{in}/\sqrt{16}$). The digitized signal saturates for $N_{S,16} > 250$ due to the limited power ratings of the power splitters. Curve 3 (triangular point) shows the peak height $C_p = \max(C_i)$ of the waveform versus oscilloscope peak voltage. C_p is linear up to a peak height of $C_p = 90$ counts/ns.

The time resolution of the ADC sampling system is shown in Fig. 4. A single picosecond light pulse enters the photodetector PD. The difference signals between adjacent ADC channels $C_i = (N_{S,i+1} - N_{S,i})/t_s$ are calculated and cubic spline interpolated (for description and computer program see [9]). The curve is normalized to one. The rise and decay time (10% to 90%) of this res-

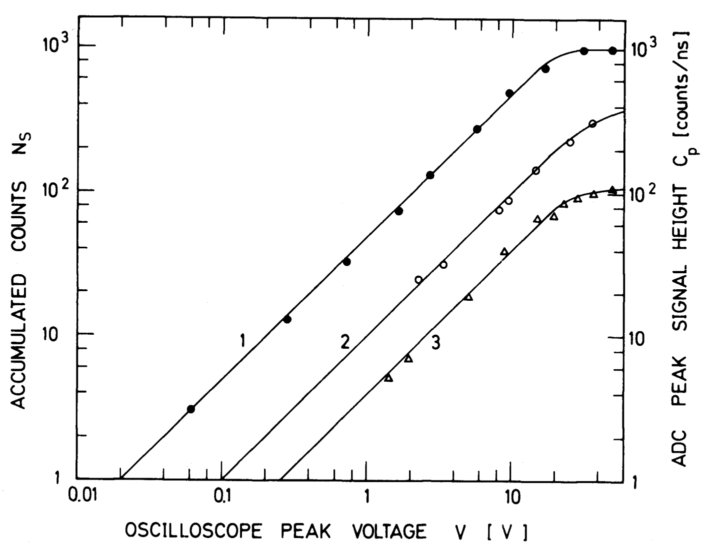

Figure 3 Linearity of ADC system. Gate width, 40 ns. Curve 1 (full circles), accumulated ADC counts versus oscilloscope peak voltage. Cable L_0 of Fig. 1 is directly connected to an ADC channel. Curve 2 (open circles), accumulated ADC counts $N_{S,16}$ of channel 16. Curve 3 (triangles), peak height C_p of time-resolved waveform.

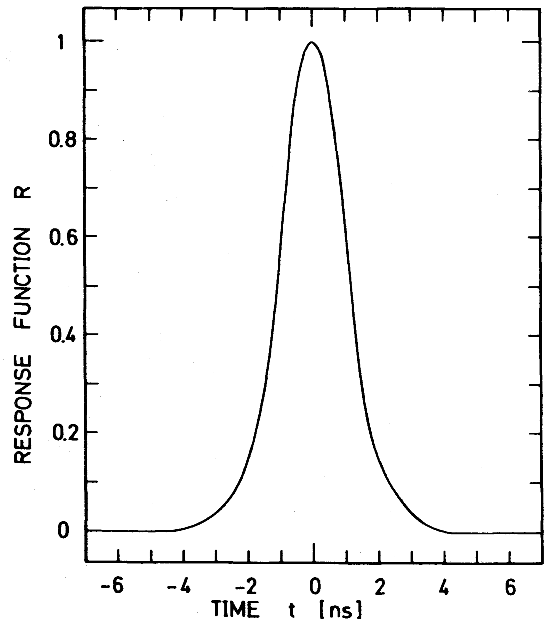

Figure 4 Cubic spline interpolated response function $R(t)$ of waveform measuring system (input pulse width < 0.5 ns).

ponse function $R(t)$ is 1.8 ns. Its half-width is $t_H = 2.3$ ns (FWHM).

The ADC waveform detection system is used to monitor picosecond light pulses of a mode-locked Nd-glass laser behind an electro-optical switch (opening time 10 ns, see Fig. 1). Since double or multiple pulses may occur within the observation time, time-resolved signal detection is necessary. The applied photodetector ADC system does not replace the photodetector oscilloscope system for the display of whole picosecond pulse trains since its time window is only 15 ns.

Fig. 5 shows a typical read-out at the terminal for a single picosecond input pulse. The 15 directly determined C_i values ($i = 1$ to 15) are increased to 29 values (time distance 0.5 ns) by spline interpolation. A histogram of the detected signal is plotted. The peak position, peak height and half-width of the pulses are calculated and recorded.

The time resolution of the detection system is increased by numerical deconvolution. Since

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 1.0    1.00   **
 1.5    7.40   ********
 2.0   19.00   ********************
 2.5   38.02   ***************************************
 3.0   55.00   ********************************************************
 3.5   59.75   ************************************************************
 4.0   51.00   ****************************************************
 4.5   31.97   *******************************
 5.0   15.00   ****************
 5.5    9.36   **********
 6.0   10.00   ***********
 6.5    7.18   ********
 7.0    3.00   ****
 7.5    1.26   **
 8.0    2.00   ***
 8.5    3.98   ****
 9.0    5.00   ******
 9.5    3.27   ****
10.0    0.00   *
10.5   -0.82   *
11.0   -1.00  **
11.5    0.53   *
12.0    4.00   *****
12.5    3.94   ****
13.0    3.00   ****
13.5    4.04   *****
14.0    5.00   ******
14.5    3.35   ****

PEAK POSITION:   3.425 ns
PEAK HEIGHT:     59.751 counts/ns
Halfwidth:       2.275 ns
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Figure 5 Computer read-out. Column 1, time in nanoseconds; column 2, signal height in counts/ns.

sophisticated mathematical deconvolution techniques are difficult to apply to noisy, convoluted waveforms [10], a simple reduction method is applied for multiple picosecond light pulses. Light pulses that are separated more then 4 ns do not overlap and are clearly resolved.

Two pulses with a time distance between 3 and 4 ns are deconvolved by the following procedure: (a) the position t_m of the highest pulse and the signal height $C(t_m)$ are interpolated; (b) the contributions of the highest pulse $C_m(t_i) = C(t_m)R(t_i - t_m)$ at the positions t_i ($i = 1$ to 29) are subtracted from the waveform, and (c) the peak height and position of the residual waveform are determined.

Measured ADC waveforms for two picosecond light pulses with a time separation of less than 3 ns are deconvolved with sufficient accuracy in the following way: (a) the time positions t_l and $t_u (t_l < t_u)$, where the signal has a height of 0.4 times the peak value, are determined by linear interpolation ; (b) the positions $t_a = t_l + t_H/2$ and $t_b = t_u - t_H/2$ ($t_H = 2.3$ ns) are calculated (t_a and t_b represent good estimates of the time positions of the pulses); (c) the pulse heights $C'(t_a)$ and $C'(t_b)$ are calculated from the measured (linear interpolated) heights $C(t_a)$ and $C(t_b)$ by solving the linear equation system:

$$C(t_a) = C'(t_a) + R(t_a - t_b)C'(t_b)$$

$$C(t_b) = R(t_b - t_a)C'(t_a) + C'(t_b).$$

Picosecond light pulses that are separated by $t_b - t_a \geqslant 1$ ns are well reconstructed.

4. Conclusions

The waveform measuring system described allows one to register signals with nanosecond time resolution. The eight free channels of the two 12-channel ADC modules are used in our experiments to integrate signals from further photodetectors and photomultipliers. Signals from photodiodes and photomultipliers with a negative output signal are connected directly to the ADCs without inverters.

The time resolution of the system is adjustable to the requirements of experiment by changing the time increment t_s between the fanned-out waveforms. The sampling points may be increased by cascading further power splitters to obtain a higher number of waveform replica and by coupling more ADC modules. If no Camac crate with controller is available, the Camac ADC modules may be interfaced directly to a computer.

Acknowledgement

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