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DESIGN NOTE

Time-resolved photon counting with digital oscilloscope

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Abstract. Photon counting by means of a digital oscilloscope controlled by a computer is presented. For many applications this system can replace commercially available gated or multichannel photon counters.

1. Introduction

Photon counting (or charged particle counting) is widely used in many fields of experimental physics, chemistry, biology, medicine and applied sciences. This method is characterized by an extremely high sensitivity, good linearity and a good signal-to-noise ratio [1]. A set-up for this type of measurement usually consists of a detector, an amplifier, a discriminator and a counter. In the case of measurements on light various types of photomultipliers or avalanche photodiodes are used as the detector, whereas for charged particle counting dynode electron multipliers, channeltrons or channel plates are used. The output pulses produced by these detectors are characterized by FWHM times of 10^{-10}–10^{-8} s and amplitudes of 10^{-5}–10^{-2} V on a 50 Ω load. In order to eliminate pulses caused by detector noise the signal is discriminated after amplification. Pulses are then registered by the counter. Timing of the counting provides a further increase in signal-to-noise ratio. For continuous light sources a modulation technique and synchronous counting (lock-in mode) allows for elimination of residual detector noise (black counts). When time-dependent photon fluxes are investigated then gated counters (in boxcar mode) are commonly used [2]. Better results can be achieved with multichannel counting, since, owing to parallel registration, the time of measurements can be decreased with respect to that with boxcar counters by a factor of the channel number. Moreover, with this method it is possible to eliminate errors caused by long-duration light source instabilities.

The photon-counting technique is not a cheap one. Prices of equipment vary from £3000 for single-channel counting systems to above £4500 for multichannel analysers with 200 MHz bandwidth [2] and above £10 000 for fast models (bandwidth >1 GHz) [3]. Further costs must arise from the need for high-quality pre-amplifiers and coolers, which are usually required in order to lower detector noise.

Considerable progress has recently been made in the development of digital oscilloscopes, which have become standard laboratory equipment. The best models are characterized by a bandpass of several gigahertz and their digitizing rate can be as much as 10 GHz. Due to its high flexibility, the computer-controlled digital oscilloscope has become one of the most universal tools for processing analogue signals.

We have found that a digital oscilloscope connected to a personal computer can, in many applications, be used instead of specialized photon-counting systems. This tandem can simultaneously play the roles of pre-amplifier, discriminator and multichannel counter. The oscilloscope's vertical sensitivity (usually no better than 2 mV cm^{-1}) is sufficient to observe photon pulses from a typical photomultiplier as peaks several centimetres in height. The temporal resolution of the system is limited by the oscilloscope's bandpass and digitizing rate. For this reason both parameters should be no smaller than 100 MHz. The price of such equipment usually does not exceed £2000.

2. Experiment details

We have used photon counting for measurements of time-dependent fluorescence from highly excited caesium and rubidium atoms. The experimental set-up is presented in figure 1. Pulses from a dye laser tuned to an appropriate two-photon transition between the ground state and the $n^2\mathrm{D}_J$ state were used to excite caesium or rubidium vapour in the cell and to trigger the oscilloscope simultaneously by means of a photodiode. Atomic fluorescence corresponding to transitions to the resonant $^2\mathrm{P}_J$ states was observed in the direction perpendicular to the laser light beam. The fluorescence was detected by a photomultiplier (EMI 9708 QB) connected directly (without any pre-amplifier) to a 50 Ω input of a Hewlett-Packard oscilloscope model

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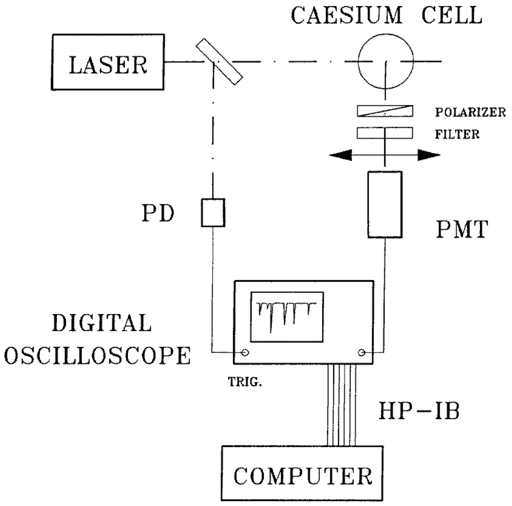

Figure 1. The experimental set-up: PD, photodiode and PMT, photomultiplier.

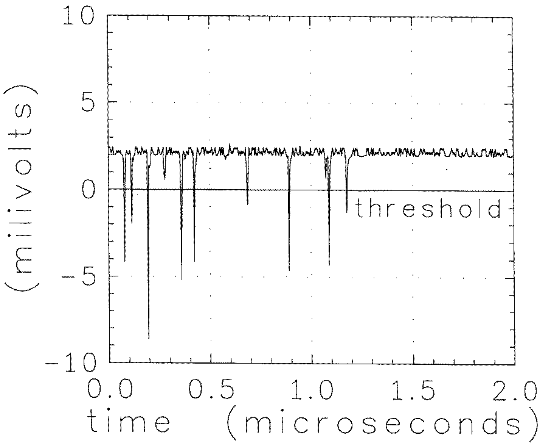

Figure 2. A typical photomultiplier output signal.

54522A. The oscilloscope was controlled from a personal computer through the HP-IB (IEEE 488) interface.

Figure 2 shows a typical waveform. The input sensitivity was 2 mV cm^{-1}, the time scale 200 ns cm^{-1} and the digitizing rate 500 Msamples s^{-1}. The waveform is composed of 512 points. The zero point on the time scale corresponds to the beginning of the trigger pulse. Small voltage fluctuations (lower than 1 mV) are caused by electrical interference. The pulses with amplitude not exceeding 2 mV are considered to be dynode noise whereas larger pulses correspond to photon pulses.

Following each trigger a signal waveform was recorded and was transferred via the interface to the computer. A simple program, which simulates the discriminator and the multichannel counter, analysed the records on-line. The software finds indices of the record points the values of which exceed the discrimination threshold and adds one to the number stored previously in the respective memory location. A photon is registered on a leading edge of the pulse. After it has been detected the acquisition in computer memory is stopped until the moment when a point in the record appears, the value of which is below the discrimination threshold (the trailing edge). In this way the end of the photon pulse is found and the next photon can be registered. Upon analysis of a certain number of detector traces it is possible to achieve in computer memory the time distribution of photons which follow the laser pulses.

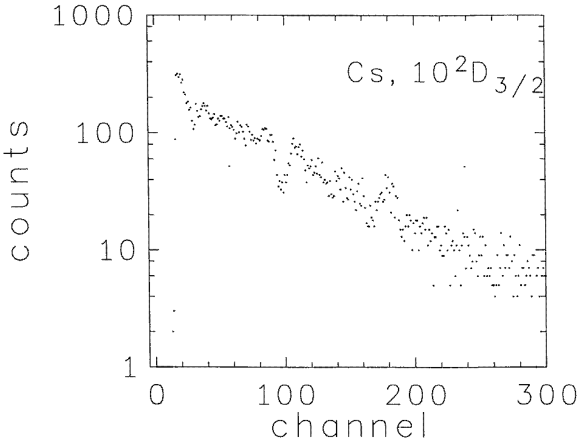

Figure 3. The fluorescence decay registered by means of multichannel photon counting using the digital oscilloscope and computer.

Since the records consist of 8 bit words (values from 0 to 255) the most convenient way to establish the discrimination level was to choose the value of 128 which corresponds to the screen central line. The discrimination voltage could then be adjusted just by changing the signal position. No window discrimination was used; that is, each pulse exceeding the threshold was registered as a photon. With a sensitivity of 1 mV cm^{-1} discrimination resolution below 0.1 mV can be achieved. Such a high precision is not available from commercial photon counting systems [2, 3] without additional amplifiers.

An example of the fluorescence decay signal is presented in figure 3 in which characteristic quantum beats [5, 6] are visible. This result was obtained with 18 000 trigger pulses. In order to achieve faster data processing the oscilloscope records were analysed in byte format as they were transferred over the HP-IB. Records of 0.5 kbyte length, at a time base of 200 ns cm^{-1}, were used to obtain a temporal resolution of 4 ns per channel. The analysing program, written in Turbo-Pascal, required only a small amount of RAM (40 kbytes) as well as a small proportion of the available CPU time. A 386–40 MHz personal computer was able to process on-line oscilloscope records of up to 2 kbytes in length at trigger frequencies up to 20 Hz. The use of longer records (up to 32 kbytes for HP 54522A) causes a proportional reduction in the trigger repetition rate. The speed limitation results mainly from the relatively slow GP-IB interface (100 kbytes s^{-1} [4]) installed in this oscilloscope.

On the other hand, the use of longer records might become necessary if the measurements were to be performed with a longer oscilloscope timebase, since in order to detect photon pulses correctly one must preserve sufficient time resolution per channel. In our opinion the photon pulse should be digitized at at least four points for it not to be lost by the sampling procedure. For the EMI 9807 photomultiplier the duration of a single-photon pulse (measured at 10% of the amplitude level) was about 17 ns so, at the time base of 2 μs and record length of 512 points, it yields a time resolution of roughly 4 ns per channel, which satisfies the above condition. In principle, at the highest digitizing rates available from this oscilloscope (2 GHz), a resolution of 500 ps per channel can be obtained.

With the photomultiplier and software used in our experiment the temporal resolution for a pulse pair in one record was limited to about 16 ns (four channels). This resolution may be too small for intense light beams. Photon counting based on pulse-threshold analysis may then give false recordings because of pulse overlapping. In order to analyse large photon fluxes another program, based on the signal integration principle, was written. The program simulates a charge-sensitive pre-amplifier and allows corrections for two-photon pulses, since their average charge is twice as large as the charge of a single-photon pulse. The software registers the photon number proportionally to the pulse charge. Yet another piece of software allows boxcar-type measurements.

3. Conclusions

A fast digital oscilloscope controlled by a computer can be successfully used for time-resolved multichannel photon counting. For many applications this equipment can replace specialized photon-counting systems provided that the trigger frequency does not exceed several tens of hertz. Due to the extremely high bandpass and digitizing rate available from the fastest digital oscilloscopes, temporal resolution of even as high as 100 ps per channel can be achieved. The great flexibility of this equipment and the possibility of direct observation of the detector's response on the oscilloscope screen make this solution very attractive, especially for development and testing of new experimental set-ups.

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