PHOTON COUNTING SYSTEMS FOR LASER SOUNDING OF THE ATMOSPHERE

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Some principal problems arising in the stage of design of photodetection system used for lidar studies are treated in the paper. Results of experimental investigation of the characteristics of photomultiplier tubes operating in the photon counting mode are discussed. Recommendations for use of the photomultipliers in special–purpose lidars have been given. The problems arising in the stage of design of amplitude discriminators and single–electron pulse counters are treated. Specifications of the developed photon counting systems are presented.

When solving some problems of atmospheric laser sounding, lidar signals are recorded in photon counting mode. Principal factors limiting the accuracy of measurements of the atmospheric parameters in this mode are following: low intensity of lidar signals, their wide dynamic range, external and intrinsic noise, and drift of instrumental parameters during the measurements. Account of the enumerated factors in the stage of development of photodetectors ensures a measurement error of several fractions of percent for modern specifications of lidar systems.

It is well known that for instrumental realization of the photon counting method, a series connection is used of a photomultiplier tube (PMT), amplitude discriminator of single–electron pulses (SEP), and SEP counter.[1] Moreover, a computer providing coordinated operation of system units, data recording, and processing of obtained results by given algorithms is a necessary element of a modern lidar system. Development of the photon counting system for lidar complex incorporates three stages:

– proper choice of the PMT type allowing for the specific features of the physical problem being solved and selection of a concrete specimen for operation as part of photodetection system;

– development of the amplitude discriminator allowing for peculiarities of the output PMT signals;

– development of the SEP counter for a specific physical problem.

The photon counting systems are well known which use an avalanche photodiode as a photodetector.[2] However, for operation in the visible and ultraviolet wave ranges, the photomultiplier tubes remain the most suitable devices up to now. High quantum yield (up to 30%), high photocurrent gain (10^5–10^8), low level of the intrinsic noise, and practically unlimited service life are the merits of the PMTs. Among the demerits of the PMTs are rather high supply voltages (1–3 kV), comparatively large overall dimensions, and afterpulses.

The fundamental parameters of the PMTs influencing the measurement accuracy in the photon counting mode are the quantum yield, dark–current pulse repetition rate, and drift of these parameters from their mean values during the measurement.[3] The quantum yield is considered to mean the ratio of the average number of single–electron pulses exceeding a discrimination threshold to the average number of photons striking the PMT photocathod, and the dark–current pulse repetition rate is considered to mean the average number of dark–current pulses per second exceeding the discrimination threshold.

An essential demerit of the PMT is a wide spread of the fundamental single–electron parameters from one specimen to another. So, the quantum yields of the PMTs from one batch may differ by an order of magnitude, and the dark–current pulse repetition frequency may differ by a factor of 10^3–10^4. This circumstance calls for the close study of the PMT characteristics in the photon counting mode and selection of specimens with the required single–electron parameters.

To study possible use of different PMT types in the photon counting systems, I developed an automated stand[4] to investigate the dark and light photon counting characteristics and pulse amplitude distribution as well as temporal dependence of PMT output pulse frequency after switching on the power supply and constant illumination. In all, more than 100 specimens of the following types: FÉU–71, 79, 104, 106, 130, 136, and 147 were investigated. Analysis of the obtained results allowed the procedure of selection of the single–electron PMTs to be developed and recommendations for use of different

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PMT types in special–purpose lidar systems to be given.[5] The PMT specifications are presented in Table I.

The quantum yields of the enumerated PMTs with multi–alkaline photocathodes are approximately identical, on average, and are within 1–10% (Ref. 1). Analysis of the data in Table I allows the PMT type for a specific lidar system to be selected properly. So, for example FÉU–71 is of little use for photon counting systems due to high level of the intrinsic noise. Sharp "spikes" of the dark current of FÉU–136 also renders this device unsuitable except of individual specimens.

TABLE I.

PMT type	Dark–current pulse repetition rate, pulse/s	Drift of dark current per hour, per–unit	Drift of quantum yield per hour, %
FÉU–71	> 1000	1–5	1–10
FÉU–79	> 10	1–3	1–10
FÉU–104	> 50	1–2	0.1–5
FÉU–106	> 10	1–2	0.2–5
FÉU–130	> 100	1–2	0.2–2
FÉU–136	> 50	1–100	0.2–5
FÉU–147	> 200	1–2	0.1–1

It is expedient to use FÉU–79 and FÉU–106 for recording of very weak optical signals, for example, as part of a Raman lidar for which the signal–to–noise ratio must be maximized. The FÉU–104, 106, 130, and 147 having the least drift of the quantum yields are best suited for relative and absolute measurements. In some cases, an account of the PMT design features allows the single–electron characteristics of devices to be improved and the measurement error to be reduced.[6]

The drift of the PMT supply voltage and of the discrimination threshold in the amplitude discriminator affects essentially the stability of the parameters of photodetection system. It was established experimentally that to eliminate its effect on the instrumental characteristics, it will suffice to ensure the stability of the PMT supply voltage and of the discrimination threshold no worse than 0.5% and 1% of their rated values, respectively. To supply the PMT, a modified power supply unit[7] was used in the photon counting systems developed by me. This power supply unit has the following specifications:

Range of variation of output voltage	50–3000 V
Output current	1 mA
Level of output voltage ripples,	no more than 1 V
Drift of output voltage from its rated value per hour,	no more than 0.1%.

The next stage of design of the photodetection system is the development of the amplitude discriminator allowing for the peculiarities of PMT output signals. It is well known that design capacitance of anode space and inductance of the PMT leads engender parasitic oscillations in the SEP tail. Amplitude of such oscillations attains 30% of the SEP amplitude.[1] As a result, two or three pulses appear at the discriminator output in response to the SEP. The most simple and effective way to control the parasitic oscillations is proper shaping of the bandwidth of the preliminary amplifier of PMT photocurrent pulses. It was established experimentally that for the enumerated PMT types, 25–30 MHz cut off frequency for the bandwidth allows us to smooth out the SEP shape at the amplifier output and hence to eliminate distortions caused by parasitic ringing of the PMT anode space.[8]

Based on the results of investigations of the SEP peculiarities for the indicated PMT types, the amplitude discriminator has been developed with the following specifications:

Input resistance	3–10 Ω
Conversion coefficient	no smaller than 12 mV/μA
Bandwidth at a level of 3 dB	100 Hz–30 MHz
Drift of the threshold voltage from its rated value per hour	no more than 1%
SEP duration at half–maximum at the amplifier output	15 ns
Pulse duration at the discriminator output	10 ns
Polarity and level of output pulses of the discriminator	± ECL.

When developing the SEP counters, such characteristics as the power and duration of laser pulse transmitted in the atmosphere, lasing pulse repetition rate, level of the background noise of the atmosphere and of the intrinsic noise of the photodetection system, required temporal resolution of the system, and data exchange rate between the SEP counter and computer are taken into account. I have developed four types of SEP counters[9–11] for special–purpose lidar systems. The specifications of these counters are presented in Table II.

TABLE II.

Counter type	PC2	PC3–4	PC4	PC5
Channel number	1–4	4	8	8
Strobe number in a channel	256–4096	4096	64	1024
Strobe duration, ns	80	80–320	10	10
Maximum frequency of SEP counting, MHz	10	50	50	50

The developed methods of PMT selection and the photodetection system have been introduced in five lidar complexes. They are:

– mobile Raman lidar intended for measurement of the temperature and humidity profiles and for study of aerosol–gaseous emissions at the mouths of commercial setup stacks;

– polarization lidar "Stratosfera–1M";

– Raman channel of a lidar with a receiving mirror 2.2 m in diameter intended for integrated study of the atmosphere;

– lidar with a receiving mirror 1 m in diameter intended for study of the vertical stratification of the atmospheric aerosol;

– mobile station of ecological monitoring of the atmosphere of Khabarovsk.

TABLE III.

Lidar type	Photodetector	SEP counter
Mobile Raman lidar, 1987	FÉU–104 and FÉU–79	Four–channel PC2 and PC4
"Stratosfera–1M," 1988	FÉU–130	PC3–4
Lidar with a mirror 2.2 m in diameter, 1990	FÉU–106	PC3–4
Lidar with a mirror 1 m in diameter, 1986	FÉU–130	Single–channel PC2
Mobile station, 1994	FÉU–104 and FÉU–79	PC5

Table III tabulates the employed components of the photon counting systems of different lidars and the year in which these systems went into operation. Operating experience of the developed photon counting systems included in the indicated lidars showed their high reliability and confirmed their advanced specifications.

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