Application features of micro-pixel avalanche photodetectors in the laser Doppler anemometers

V V Rakhmanov, S V Dvoynishnikov, V G Meledin, V A Pavlov and D O Semenov
Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia
E-mail: vitaly.rakhmanov@gmail.com

Abstract. The optical receiver is an essential part of any laser Doppler anemometer. Traditionally, vacuum photomultiplier tubes are used for reliable reception of weak optical radiation. However, this type of photodetector has its own drawbacks, which lead to a design complication and an increase in the cost of LDA. In this work, the characteristics of silicon micropixel avalanche photodiodes are investigated and the operation of a silicon photomultiplier as a photodetector in an LDA is tested when measuring the velocity on test benches. The possibility of using Si-PMT to receive optical signals of the laser Doppler anemometer is shown.

1. Introduction
Laser Doppler anemometers (LDA) are widely used in aerohydrodynamic studies due to high measurement accuracy, good spatial resolution and high performance for measuring pulsation characteristics of the flow [1]. The use of modern optoelectronic element base as a part of laser Doppler anemometers is an urgent scientific and technical task.

Schematically, the receiving part of the LDA is shown in figure 1. Laser beams coming out of the main lens 1 intersect in the flow and form an interference field with a given periodic structure. The scattered light from the light-scattering particle when crossing the probing optical field is collected by the main lens and, after the rotary mirror 2, is focused on the photodetector 3.

When light with frequencies \( F_L + F_M + F_D \) arrives from a light-scattering particle (where \( F_L \) is the frequency of laser radiation, \( F_M \) is the modulation frequency of laser radiation, and \( F_D \) is the frequency of the Doppler shift) to the photodetector, an electrical signal pulse with frequency \( F_M + F_D \) appears at its output. Then the signal is fed to a quadrature mixer 5, at the output of which a quadrature pair of I and Q signals with a frequency equal to \( F_D \) and a pedestal signal appear. By analyzing these signals, the velocity \( V \) of the light scattering particle can be determined.

Vacuum photomultiplier tubes (PMTs), optimized for measurements in multiphase flows with a significant solid phase concentration and protected from pulsed optical overloads, are used as standard photoconverters in LDA [2].

The photomultipliers included in the LDA allow registering the light of ultra-low intensities down to single photons. Their main advantages are: high gain \((10^5–10^8)\), sensitivity to single photons, low noise, large areas of the photodetector window (up to several dm²), and low transit time (~ 10 ns). However, they also have their disadvantages: high sensitivity to magnetic fields (shielding from magnetic fields is required), high supply voltage (1–3 kV), high requirements for stability of supply voltage, and relatively high cost.
Figure 1. Simplified diagram of LDA receiving part.

If the sensitivity to magnetic fields in a number of applications (in particular, when used in LDA) can be neglected, then the stability of the power supply is required at a level not worse than 0.1% [3], which imposes additional requirements on their use.

With the development of modern microelectronics, semiconductor analogs of vacuum PMTs have appeared. The closest analogue today is a silicon photomultiplier tube (Si-PMT) based on silicon micro-pixel avalanche photodiodes. Currently, Si-PMTs from various manufacturers are actively used in various fields of science and technology [4, 5]. However, their use as a photodetector in laser anemometry has not yet become widespread.

Modern micro-pixel avalanche photodiodes are not inferior to classical vacuum photodiodes in a number of significant parameters, and in some cases even surpass them [6]. Si-PMTs surpass vacuum PMTs in such parameters as: quantum efficiency (up to 80%), compactness (overall dimensions of microcircuits ~ 3×3×1 mm), insensitivity to the magnetic field, low operating voltage (about 30 V), low power consumption (less than 1 W together with an amplifier), and also have a significantly lower price (more than 10 times). Similar to traditional PMTs, they can operate in a single-photon mode (at low temperatures) and have a comparable gain (~10^6).

The disadvantages of silicon photomultipliers include the dependence of the dark current and gain on temperature, a relatively low recovery time (~ 100 ns at a 50 Ohm load), and small areas of the photodetector window (up to 100 mm^2). However, the temperature dependence can be leveled by bias voltage feedback, and the size of the required photodetector window in some cases does not exceed 3x3 mm, which is provided by many models of Si-PMT.

In addition, since the gain of a Si-PMT is almost linearly dependent on the excess of the breakdown voltage [7, 8], the requirements for the stability of the bias voltage of the Si-PMT are less stringent than for the stability of sources for classical PMTs, where the gain is nonlinearly dependent on the supply voltage.

One of the most significant drawbacks of the Si-PMT is its high recovery time. Since the recovery time depends on the load resistance [6], then using special amplifier circuits with low input impedance, one can hope to reduce it to ten nanoseconds. Then the maximum modulation frequency of the detected light flux will be ~100 MHz. Therefore, in applications where it is not required to register velocities in excess of 100 m/s, the Si-PMT data can be successfully applied.
This work is devoted to the analysis of scientific and technical problems arising from the use of micro-pixel avalanche photodiodes in laser Doppler anemometers.

2. Problem statement
To analyse the efficiency of using micro-pixel avalanche photodiodes in laser Doppler anemometers, a comparative analysis of the operation of classical and silicon photomultipliers is carried out.

The following characteristics are proposed as criteria for comparing the performance of the classic PMT and micro-pixel avalanche photodiodes in the LDA:
1. signal noise;
2. number of registered events;
3. possibility of operation near the surface.

The following test objects are chosen: a glass disc (limb) with a diameter of 120 mm with applied reflective lines, an ultrasonic air humidifier, a hydrodynamic flow from a flooded nozzle, and an aerodynamic flow after a convergent nozzle.

The glass disc allows checking the operation of the photodetector in conditions of reflection from the surface. The light signal from such an object is the signal from the reflective marks and from the glass surface between the lines. In addition, a large number of traced lines (1080 double strokes) allows obtaining a large number of recorded events per second.

The aerodynamic flow from the air humidifier allows checking the operation of the photodetector in conditions close to ideal with a large number of light-scattering particles.

When measuring the velocity of the hydrodynamic flow from a submerged nozzle, it is planned to check the sensitivity of the photodetector when working with natural light-scattering particles in tap water.

And when measuring the air flow, of great interest is the number of registered events from clean air without introducing additional reflective particles into the flow.

To solve this problem, a test bench was assembled based on a laser Doppler anemometer.

3. Laboratory layout
A KETEK PM3325-WB micropixel silicon photomultiplier is used to test the performance of the Si-PMT as part of the LDA.

The declared gain of the microcircuit is \(~ 1 \cdot 10^6\), the breakdown voltage is 24.9 V, the number of pixels is 13920, and the recovery time is 80 ns (at a load of 50 Ohms).

![Functional circuit of the Si-PMT as part of LDA.](image)

The functional diagram of the Si-PMT connection is shown in figure 2. Battery power is used to reduce interference level and noise from the bias voltage source Vbias. In this circuit, the load resistance of the silicon multiplier is the input resistance of the amplifier stage with a common base. In the used circuit, it is equal to 4 ohms. This allows the recovery time to be reduced to acceptable values.
A HAMAMATSU PHOTONICS K.K type R6358-10 photomultiplier is also applied to compare the signal from various measurement objects. The typical gain is about $3.5 \cdot 10^6$, the maximum supply voltage is -1250 V, and the electron avalanche transit time is 15 ns. This photomultiplier is connected according to the same scheme as the Si-PMT in order to ensure that the measurement conditions are the same.

Both photodetectors are installed in the layout LDA LAD-08L (Novosibirsk) (figure 3).

Velocity measurements are carried out on three different objects with two photodetectors: a glass disk with applied reflective marks, an aerodynamic flow after a convergent nozzle, and a hydrodynamic flow from a submerged nozzle.

To reduce the scatter of the measured parameters, the data are recorded alternately from two photodetectors on one test object. Then the object is changed to the next one and the data from two photodetectors are recorded again. The Si-PMT bias voltage is controlled by the UNIT-T UT890C portable voltmeter. And the voltage at the vacuum photomultiplier is controlled by standard LAD-08L.

Figure 3. Model LDA LAD-08L. 1 – main lens, 2 – rotary mirror, 3 – photodetector.

4. Experimental results

The signal noise level was checked on all test objects. The results of the signal-to-noise ratio SNR at the output of the quadrature mixer are presented in table 1. The arithmetic mean value of the signal amplitude during the measurement time equal to 60 s was used as the signal amplitude $A_{signal}$. The amplitude of the noise was estimated as the amplitude of the $A_{noise}$ signal in the absence of Doppler bursts.

|          | Glass disc | Humidifier | Submerged jet | Air flow |
|----------|------------|------------|---------------|----------|
| PMT      | 22         | 22         | 20            | 26       |
| Si-PMT   | 14         | 10         | 22            | 19       |

The signal-to-noise ratio SNR was calculated as:

$$SNR = 20 \log_{10} \left( \frac{A_{signal}}{A_{noise}} \right).$$

It can be seen from the table that for almost all modes of operation, the signal-to-noise ratio is higher for vacuum PMT. And only for a hydrodynamic flow, the signal obtained with the Si-PMT slightly exceeds the signal from the vacuum PMT in this parameter. This may be explained by the fact...
that the particle flux was not high and avalanche breakdowns had time to dissipate. The worst result for the Si-PMT was when a humidifier was used. This is due to the fact that the stream of particles was very dense (reminiscent of fog) and as a result, stray light from the laser beams is constantly falling on the photodetector. And thus, some of the microcells were overloaded and did not work.

This experiment shows that the signal noise when working with a Si-PMT is higher than with a vacuum PMT.

For each test object, the number of registered events (the number of light-scattering particles that pass through the LDA measuring volume) per second is obtained. This parameter defines the boundaries of the measured flux pulsation frequencies and allows judging about the light sensitivity of the photodetector. The higher the sensitivity of the photodetector is, the more particles it can register.

Naturally, this parameter is also determined by the properties of the measured object. And the lower the bulk density of light-scattering particles in the stream is, the lower the number of registered events is. The measurement results are presented in table 2.

### Table 2. Number of registered events per second.

|                  | Glass disc | Humidifier | Submerged jet | Air flow |
|------------------|------------|------------|---------------|----------|
| PMT              | 12341      | 2685       | 95            | 1        |
| Si-PMT           | 14257      | 3507       | 133           | 1        |

Table 2 shows that the micro-pixel avalanche photodiode allows more events to be recorded than the classic PMT. For the disk, the excess of events is 15%, for the flow from the humidifier it is 30%, and for the submerged jet it is 40%. Only in the case of measuring the air flow without seeding with reflective particles, the number of recorded events is the same. This is due to the fact that the events physically occurred very rarely, and in this case, both photodetectors registered the passage of all possible particles.

![Figure 4. The speed measurement signal on the glass disc. Top: PMT, bottom: Si-PMT. Left: long-term implementation, right: enlarged fragment.](image)

According to the measurement results, it is clear that this sample of Si-PMT has a better light sensitivity than this sample of a classical PMT.
Another important parameter is the ability to work near the surface. For this experiment, the signal from the output of the quadrature mixer is recorded while measuring the speed on a glass disk. Such a signal contains both the useful part from the reflective strokes and the parasitic part from the disk surface between the strokes. The appearance of such signals for a Si-PMT and a vacuum PMT is shown in figure 4.

As can be seen from the shown figure, the signal from the classical PMT is less noisy. At the same time, a low-frequency component is present in the signal from the Si-PMT. The presence of a low-frequency component of the signal is due to the fact that the Si-PMT has a very high sensitivity to the luminous flux and the parasitic illumination from the disk surface is approximately 32 times higher in amplitude than the useful signal. And this signal cannot completely filter out the quadrature mixer.

To reduce this effect, it is necessary to modernize the receiving electrical part of the laser anemometer. Under current conditions, it can be concluded that when using silicon PMT as a photodetector, it is not recommended to take measurements at the surface, as this can lead to errors in the flow rate determination algorithm.

Conclusions
The paper considers the possibility of applying micropixel avalanche photodiodes in laser Doppler anemometry. A comparative analysis of efficiency of application of micro-pixel avalanche photodiodes and classical PMT in laser Doppler anemometers has been performed.

It has been experimentally established that micro-pixel avalanche photodetectors can be successfully used as part of LDA and in a number of experimental tasks functionally surpass classical PMTs. However, there are limitations in their application associated with the need for additional signal processing to reduce noise. In addition, extra procedures are required to reduce the effect on the signal of parasitic illuminations from the surfaces.

Thus, the use of micro-pixel avalanche photodetectors in the LDA is a promising direction for the development of optical devices due to the small size of the photodetector, ease of control and high sensitivity. However, further work is needed to adapt the hardware and software components of the LDA for better operation with the Si-PMT.

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