Turkish Online Journal of Qualitative Inquiry (TOJQI)
Volume 12, Issue 8, July 2021: 4583 - 4590

Study of the Optical Channel Capacity from Information Receivers in the Form of a Silicone Photomultiplier Tube

ZenevichA.O.
Doctor of Technical Sciences, Professor,Belarusian State Academy of Communications, Minsk, Republic of Belarus
Belarusian State Academy of Communications, Minsk, Belarus
TashmanovE.B.
Doctor of Technical Sciences, Professor,Public Security University of the Republic of Uzbekistan
KhatamovB.B.
Doctor of Philosophy (PhD) on Technical Sciences, Public Security University of the Republic of Uzbekistan
KocherginaO.V.
Research Assistant, Belarusian State Academy of Communications, Minsk, Republic of Belarus

Abstract

The article investigates the throughput of an optical communication channel with an information receiver in the form of a silicon photomultiplier tube (Si-PMT).As a result, it was found that the highest value of the throughput corresponded to the supply voltage value equal to the breakdown voltage of the Si-PMT. It was also found that the maximum value of the throughput can be obtained for a wavelength of *470 nm*. With an increase in the energy exposure of optical pulses from *0* to $0.4 \cdot 10^{-11}$ J/cm^2, an increase in the throughput of the optical communication channel is observed. A further increase in the energy exposure of optical pulses did not lead to an increase in the transmission capacity. It was found that an increase in temperature leads to a decrease in the transmission capacity of the photodetector. the highest value of the throughput in the investigated temperature range was obtained for a temperature of *233 K*. The aim of the study is to establish the dependence of the throughput of an optical communication channel on temperature, supply voltage and wavelength of optical radiation. The results obtained can be used in the development of optical communication systems.

Key words: bandwidth, silicon photodetector, wavelength, temperature.

Introduction

At present, such data transmission technology as Li-Fi is beginning to develop [1-3]. This technology uses optical radiation in the visible range for data transmission with wavelengths from *380* to *780 nm*. [3] In this regard, the implementation of this technology requires photodetectors sensitive to optical radiation in the visible wavelength range. Vacuum photomultiplier tubes have the best sensitivity in this wavelength range. However, these photodetectors have large dimensions, high supply voltages and are quite fragile. A fairly good alternative to vacuum photomultiplier tubes are multielement avalanche photodetectors, which are called silicon photomultiplier tubes. Silicon photomultiplier tubes (Si-PMTs) have small dimensions, low supply voltage, high sensitivity in the visible region of the spectrum, and a large area of the photosensitive surface [4-6]. However, at the moment there is no information about how the characteristics of these photodetectors affect the throughput of the communication channel. This defined the purpose of this article.

Experimental setup and research technique

The objects of research were prototypes of Si-PMTs with p^+-p-n^+-structure produced by JSC "Integral" (Republic of Belarus), commercially available Si-PMT Ketek RM 3325 and ON Semi FC 30035. Figure 1 shows a block diagram of the experimental setup, on which the studies were conducted.

In the experimental setup, a white LED is used as a source of optical radiation. LED was powered from a constant voltage source PS1. With the help of LF light filters, the wavelengths of optical radiation corresponding to the visible region of the spectrum *(380 ÷ 760 nm)* were selected. After passing through the LF filter, the optical radiation was fed to the modulator M, where it was modulated by feeding rectangular electrical pulses to the control input of the modulator. The duration of electrical pulses varied from *50* to *1000 ns*, and their repetition rate was $10^4 \div 10^7$ *Hz*.

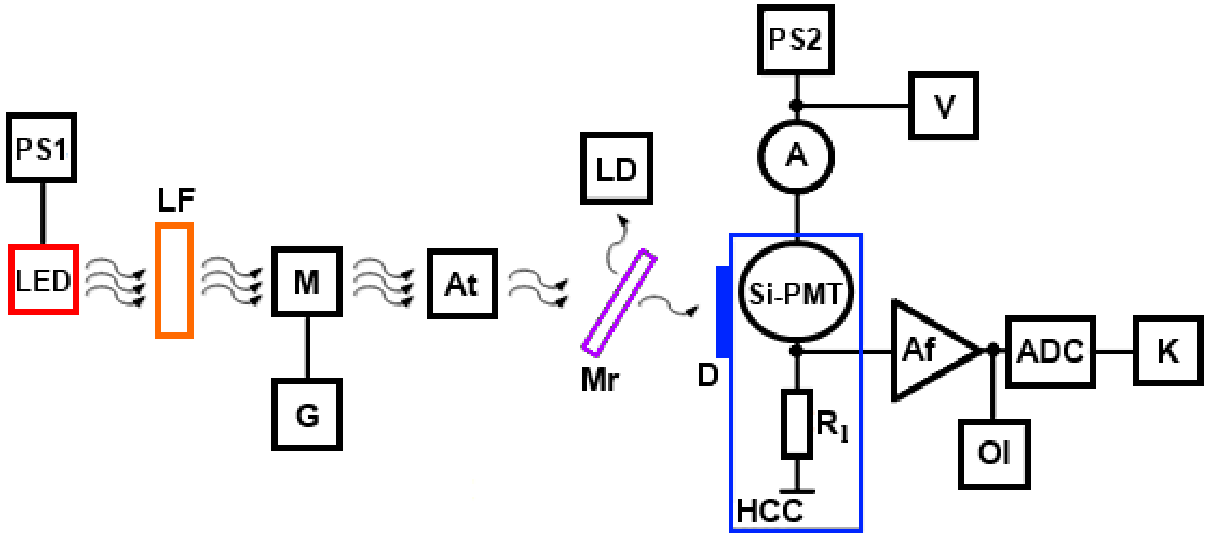

Figure 1 - Block diagram of the experimental setup:
LED – white LED; M – modulator; G – generator of rectangular pulses; LF – light filter; At. – attenuator; LD – laser dosimeter; Mr. – mirror; D – diaphragm; PS1 and PS2 – power supplies; A – ammeter; V – voltmeter; Af. – amplifier; ADC – analog-to-digital converter; K – computer; R_l – load resistance; Si-PMT – silicon photodetector; HCC – heat and cold chamber; Ol. is an oscilloscope.

During an electrical pulse at the control input of the modulator M, optical radiation enters the input of the At. attenuator. The At. attenuator was used to attenuate the power of optical radiation. The attenuation coefficient of the optical radiation power varied in the range from *1* to 10^5 *times*.

From the output of the attenuator, AT was fed to a semitransparent mirror Mr. Mirror Mr. passes *50%* of the attenuated radiation and it enters the Si-PMT through the diaphragm D, and reflects *50%* and delivers it to the laser dosimeter LD. The LD dosimeter measures the energy exposure of an optical signal.

On the Si-PMT voltage is applied from the power source PS2. The voltage applied to the Si-PMT U_{ps} controlled voltmeter V. The magnitude of the electric current flowing through Si-photomultiplier was measured by an ammeter A.

A load resistor R_l was connected in series with the Si-PMT. Under the influence of optical pulses, the electric current flowing through the Si-PMT changes. As a result, voltage pulses are formed on the load resistor R_l. These pulses are amplified by the amplifier Af. and fed to the analog-to-digital converter ADC. The type of electrical pulses at the amplifier output was monitored with an Ol. oscilloscope. Using an ADC, electrical impulses are digitized. After that, the data from the ADC output are transmitted to the computer K. The computer software allows you to calculate the average amplitude of the peak values of electrical impulses U_p and their standard deviation, the amount of noise at the amplifier output.

Diaphragm D made it possible to block the incoming pulses. If the diaphragm is closed, then ammeter A registers the dark current I_{dc}, that is, the current flowing through the Si-PMT in the absence of optical radiation. If the diaphragm is open, then the ammeter registers the total current I_{tc}, that is, the current flowing through the Si-PMT, and consisting of dark current and photocurrent.

In the course of measurements, the value of the photocurrent I_{ph} was determined, which was found as the difference: $I_{ph} = I_{tc} – I_{dc}$, where I_{tc} is the total current, I_{dc} is the dark current.

The heat and cold chamber (HCC) was used to change the operating temperature of the Si-PMT, as well as to exclude the background illumination of the photodetector. The operating temperature of the Si-photomultiplier was varied in the range from *233* to *313 K*. This temperature range was chosen, since at these temperatures, devices based on Si-photomultipliers are most often used.

By bandwidth we mean the maximum speed of information transmission over a communication channel. The capacity *S* was calculated based on Shannon's theorem [7]:

$$S = \Delta F \, log_2 (1 + \frac{U_n^2}{2\sigma^2}) \,, \quad (1)$$

where *ΔF* is the bandwidth, U_n is the mean value of the peak signal voltage, and *σ* is the root-mean-square deviation of the noise voltage.

The bandwidth was determined as:

$$\Delta F = \frac{1}{2\pi RC} \,, \quad (2)$$

where *C* is the capacitance of the Si-photomultiplier, was determined by the capacitance-voltage characteristic, R is the resistance of the photodetector.

Since the studied Si-PMTs had different breakdown voltages U_{bd}, then to compare their characteristics with each other, the overvoltage value was used, determined as follows:$\Delta U = U_{ps} - U_{bd}$.

The breakdown voltage U_{bd} was determined from the current-voltage characteristic of the Si-photomultiplier with a closed diaphragm D according to the method described in the work [8].

Measurement results and their discussion

The performed assessment by the current-voltage characteristics of the breakdown voltages of the investigated silicon photomultiplier tubes showed that they are for the highest temperature of *313 K*, in the investigated temperature range, the following values:$U_{bd} = 27,3\ V$ for Ketek PM 3325; $U_{bd} = 25,1\ V$for ON Semi FC 30035; $U_{bd} = 37,7\ V$for Si-PMT produced by JSC "Integral", respectively.A decrease in temperature led to a decrease in the value of U_{bd}. In this temperature range, the relationship between U_{bd} and T was linear. Therefore, when determining the value of ΔU for different temperatures, this dependence was taken into account. The coefficient of linear dependence between U_{bd} and T took the following values: $k = 0.010; 0.014$ and 0.017 for Ketek RM 3325, ONSemiFC 30035 and Si-PMT produced by JSC "Integral", respectively. The coefficient of linear dependence of the Si-PMT breakdown voltage on temperature k was determined as the ratio of the voltage change ΔU_{ps} to the temperature change ΔT.

The minimum value of the load resistor $R_l = 50\ Ohm$. At lower values of the load resistor for $\Delta U > 0\ V$, the current flowing through the Si-PMT becomes sufficiently large $(\geq 10\ \mu A)$ that, during long-term operation of the silicon photomultiplier tube, its thermal breakdown may occur. Also, at $R_l < 50\ Ohm$, the peak voltage of the signal formed across the load resistor was less or comparable to the standard deviation of the noise voltage.

The capacitance of the studied silicon photomultiplier tubes at supply voltages close to or exceeding them, the breakdown voltage remained constant and had the following values: $C=95;100$ and $110\ pF$ for Ketek RM 3325, ON SemiFC 30035 and Si-PMT produced by JSC "Integral", respectively. Changes in T in the investigated temperature range did not lead to a change in the capacitance of the Si-PMT.

The bandwidth remained approximately the same and equal to $\Delta F = 32\ MHz$ over the entire investigated temperature range and overvoltage range.

Figure 2 shows the dependence of the throughput of the communication channel with the Si-PMT on the overvoltage value. These dependences were obtained at a temperature $T = 293\ K$ and an energy exposure of an optical pulse $H = 10^{-11}\ J/cm^2$. The wavelength of optical radiation corresponded to the maximum spectral sensitivity, and was equal to *470 nm*. As can be seen from the obtained dependences, the highest value of the throughput of the Si-PMT S corresponded to the value $\Delta U = 0,0\ V$ and was: $S = 40; 59$ and $72\ Mbps$ for Ketek RM 3325; ON Semi FC 30035 and Si-PMT produced by JSC "Integral", respectively. Note that for other waves and temperatures, the position of the maximum of the dependence of S on ΔU does not change for all studied Si-PMTs. The highest value of throughput for all investigated overvoltages was observed for silicon photomultiplier tubes Si-PMT produced by JSC "Integral", and the lowest value was observed for Ketek RM 3325.

The highest value of the throughput corresponds to the maximum signal-to-noise ratio, which accounted for $\Delta U = 0,0\ V$ [9]. A similar relationship holds for other temperatures, wavelengths, and energy exposures.

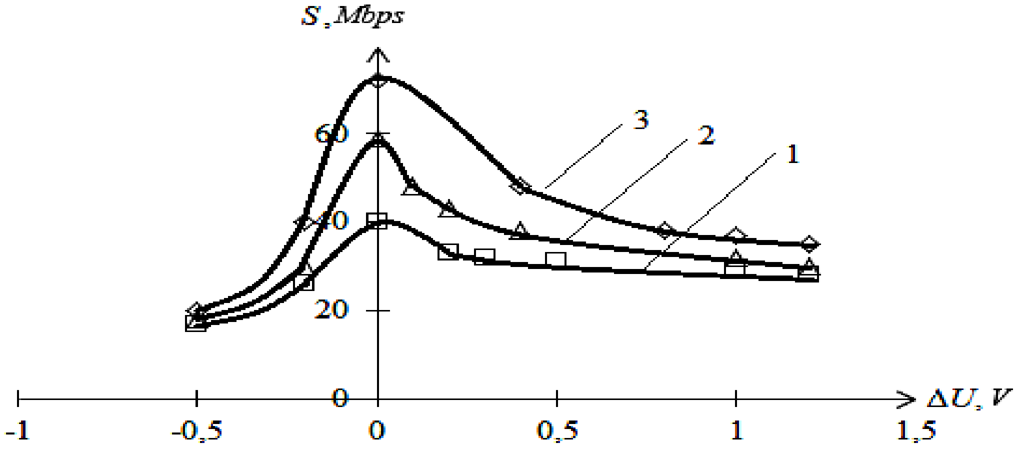

Figure 2 - Dependence of throughput on overvoltage:
1 –Ketek RM 3325; 2 – ON Semi FC 30035; 3 – Si-PMT produced by JSC “Integral”.

Figure 3 shows the dependence of the throughput of the communication channel with the Si-PMT on the wavelength of optical radiation λ. These dependences were obtained for $\Delta U = 0{,}0\ V$, energy exposure $H = 10^{-11}\ J/cm^2$ and temperature $T = 293\ K$. As can be seen from the obtained dependences, the maximum value of the throughput of the photodetectors corresponds to a wavelength of *470 nm*. As noted earlier, the wavelength of *470 nm* also accounts for the maximum spectral sensitivity of the studied Si-PMTs. For all wavelengths of the visible optical range, the highest *S* value was observed for a Si-photomultiplier produced by JSC “Integral”, and the smallest - for Ketek RM 3325. A similar dependence holds for other overvoltages and temperatures.

The dependences of the throughput of the communication channel with the Si-PMT on the energy exposure were obtained (see Figure 4). These dependences were obtained for $\Delta U = 0{,}0\ V$, wavelength of optical radiation *470 nm*, and temperature $T = 293\ K$. All of the presented dependences had two sections. On one of which there is an increase in the throughput with increasing energy exposure, and on the other, the saturation of the dependence of *S* on *H*. The increase in throughput is observed in the interval up to$H = 0.4 \cdot 10^{-11}\ J/cm^2$ for all types of investigated photodetectors. For other temperatures and overvoltages, the form of these dependences was preserved.

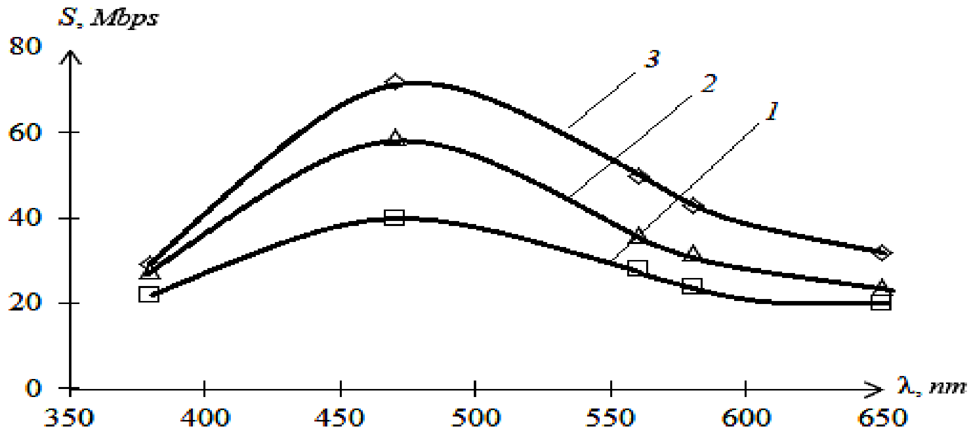

Figure 3 - Dependence of the throughput on the wavelength of optical radiation:
1 –Ketek RM 3325; 2 – ON Semi FC 30035; 3 – Si-PMT produced by JSC “Integral”.

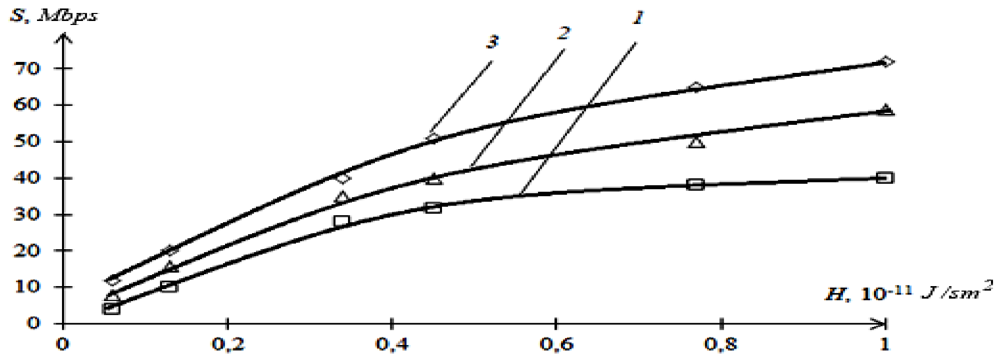

Figure 4 - Dependence of the throughput of the photodetector on the energy exposure: 1 –Ketek RM 3325; 2 – ON Semi FC 30035; 3 – Si-PMT produced by JSC "Integral".

Figure 5 shows the temperature dependence of the throughput of the photodetector. These dependences were obtained at overvoltage $\Delta U = 0{,}0\ V$, energy exposure of pulses $H = 10^{-11}\ J/cm^2$ and optical radiation wavelength of *470 nm*. As can be seen from the presented dependences, an increase in temperature leads to a decrease in the throughput of the communication channel with the Si-PMT. The highest throughput in the entire investigated temperature range was observed for the communication channels with the Ketek PM 3325 Si-photomultiplier, and the smallest - for the Si-photomultiplier produced by JSC Integral. To analyze the obtained dependences of *S* on *T*, we will use the value of $\Delta S/\Delta T$, where ΔS is the amount of change in throughput with a change in temperature ΔT. The ΔT value was determined as the difference between the highest and lowest temperature values in the investigated temperature range. Then, $\Delta S/\Delta T = -2{,}2\ Mbit/(sK)$ for Si-PMT produced by JSC "Integral", $\Delta S/\Delta T = -1{,}7\ Mbit/(sK)$ for Ketek RM 3325 and $\Delta S/\Delta T = -1{,}9\ Mbit/(sK)$ for ON Semi FC 30035. The strongest dependence of the *S* value on temperature is observed for Si-PMT produced by JSC "Integral" over the entire range of investigated temperatures, and the lowest for Ketek RM 3325. Therefore, to ensure a constant value of the channel throughput connection with Si-PMT produced by JSC "Integral" requires a higher temperature stabilization in comparison with other investigated silicon photomultiplier tubes. The nature of the presented dependence for other exposures and overvoltages is similar.

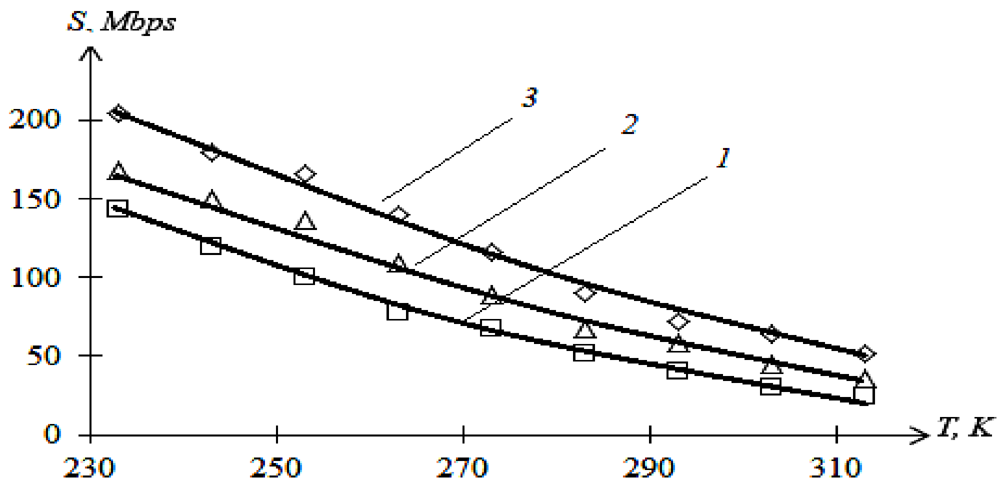

Figure 5 - Dependence of the throughput of the photodetector on temperature: 1 –Ketek RM 3325; 2 – ON Semi FC 30035; 3 – Si-PMT produced by JSC "Integral".

This behavior of the dependences of*S* on *T* can be explained by the fact that a decrease in temperature at a constant value of the energy exposure leads to an increase in the peak signal voltage and a decrease in the standard deviation of the noise voltage. So at a temperature of *233 K*, $U_p = 99$; *61* and *52 mV* and $\sigma = 15$; *7* and *4 mV* for Ketek RM 3325; ON Semi FC 30035 and Si-PMT produced by JSC “Integral”, respectively. At a temperature of *313 K*, $U_p = 51$; *28* and *25 mV* and $\sigma = 36$; *22* and *13 mV* for Ketek RM 3325; ON Semi FC 30035 and Si-PMT produced by JSC “Integral”, respectively. The increase in the peak signal voltage is associated with an increase in the gain of the Si-PMT with decreasing temperature [9]. The decrease in the root mean square deviation of the noise voltage is caused by a decrease in the thermal component of the noise [10]. All this leads to an increase in the signal-to-noise ratio. In this case, the magnitude of the frequency band practically did not change with a change in temperature.

Thus, the greatest value of the throughput was obtained at a wavelength of optical radiation of 470 nm, an overvoltage $\Delta U = 0{,}0$ *V* and a temperature of 233 K. This value was: *S = 144; 168* and *204 Mbps* for Ketek RM 3325; ON Semi FC 30035 and Si-PMT produced by JSC “Integral”, respectively.

Conclusion

It was experimentally proved that the highest value of the throughput corresponded to the value of $\Delta U = 0{,}0$ *V* for all the studied temperatures.

It was determined that the maximum value of the throughput of the Si-PMT corresponds to a wavelength of *470 nm*.

It is shown that an increase in the throughput S is observed with an increase in the energy exposure of optical pulses to $H = 0.4 \cdot 10^{-11}\ J/cm^2$ for all types of investigated photodetectors. A further increase in the energy exposure of optical pulses resulted in saturation of the dependence of *S* on *H*.

It was found that an increase in temperature leads to a decrease in the transmission capacity of the photodetector. The highest throughput in the entire investigated temperature range was observed for the Ketek PM 3325 Si-PMT, and the smallest - for the Si-PMT produced by JSC “Integral”.

It was found that the highest throughput in the investigated temperature range was obtained at an optical radiation wavelength of *470 nm*, an overvoltage $\Delta U = 0{,}0$ *V*, and a temperature of *233 K*.

References

1. Arya.V., Priya.P.,ResmaOmanakuttan, Shilby BabyLifi: The Future Technology in Wireless Communication// International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering - Vol. 4, Issue 4, April 2015. – P.2340-2343.

2. AnuragSarkar, ShalabhAgarwal. AsokeNath, Li-Fi Technology: Data Transmission through Visible Light//International Journal of Advance Research in Computer Science and Management Studies - Volume 3, Issue 6, June 2015- P.1-12.

3. LI-FI technology as an alternative to WI-FI / V. Makarenko // EKiS. New technologies. - Kiev. – 2020. - №1. – P.46-51.

4. Van Dam H. Seifert S.,Vinke R.,Dendooven P.,Löhner H.,Beekman F. J. and D. R. Schaart // Transactions on nuclear science. – 2010. – № 4. Vol.57. – P. 2254 – 2266.

5. Modi M. N.,DaieK.,Turner G. C.,Podgorski K.// Optics Express. – 2019. – № 24/25. Vol. 27. – P. 35830 – 35841.

6. Silicon photomultiplier tube. New opportunities / S. Klemin, Y. Kuznetsov, L. Filatov, P. Buzhan, B. Dolgoshein, A. Ilyin, E. Popova // Electronics: Science, Technology, Business. – 2007. – № 8 – P. 80-86

7. Shubin V.V. Information security of fiber optic systems. - All-Russian Research Institute of Experimental Physics – 2015 . –258 p.

8. I.R.Gulakov and A.O.Zenevich. PhotoReceivers of quantum systems (Minsk, UO VGKS Publ., 2012. 276 p.)

9. Temperature characteristics of silicon photomultipliers / Asayonok M.A, GorbadeyO.Yu., Zenevich A.O. // Reports of BSUIR. – 2018. - №2. – P. 54-58.

10. Investigation of the noise characteristics of silicon photomultipliers in the registration of optical pulses / MA Asayonok, AO Zenevich, OV Kochergina, EV Novikov // Problems of infocommunications. – 2020. – № 2 (12). – P. 41–46.