The article describes a system of power transmission via fiber-optic cable, which allows the supply of power to sensors and other electronic devices of ultra-low power located in places of mining workings, for which the mandatory requirement is fire safety. The developed system will allow to replace the application of copper conductors. The result of this research is the developed laboratory bench that allows measuring the current and voltage parameters in the photodetector branch. The equivalent generator method has been used, as well as the known circuit laws with two dedicated nodes for an active two-terminal network. When analyzing the literature, the existing scientific achievements, and discoveries in the field of research, an own concept of research has been formed that is different from foreign analogs. During the experiment, the studies have been performed when the photodetector was in the short circuit, idle mode, and connected to a high-resistance load. Based on the results obtained, current-voltage characteristics (CVC) and histograms have been built using a radiation source (laser) with a power of 10 and 30 mW. The parameters and technical characteristics of the irradiated silicon crystal and the radiation source have been given. The obtained electrical power has been determined using the known laws of electrical engineering, including the Ohm law. To process the experimental data, there has been used quadratic interpolation of the function, the results of the root-mean-square approximation, and there has been carried out the regression analysis. Absolute and relative errors have been calculated. The Student coefficient has been determined with a confidence interval of 0.95. Based on the results of the study, the efficiency of the power transmission system has been determined

Keywords: power source, optical fiber, photovoltaics, photoelectric effect, light wave, energy transfer

UDC 681.586.5
DOI: 10.15587/1729-4061.2023.289775

POWER SUPPLY VIA FIBER-OPTICAL CONDUCTOR FOR SENSORS OF MINE WORKING MONITORING SYSTEM

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Received date 11.08.2023
Accepted date 20.10.2023
Published date 30.10.2023

***How to Cite:** Mekhtiyev, A., Dunayev, P., Neshina, Y., Alkina, A., Aimagambetova, R., Mukhambetov, G., Kirichenko, L., Kazambayev, I. (2023). Power supply via fiber-optical conductor for sensors of mine working monitoring system. Eastern-European Journal of Enterprise Technologies, 5 (5 (125)), 15–23. doi: https://doi.org/10.15587/1729-4061.2023.289775*

1. Introduction

In the modern world, mining products are the most important in the industry, making this industry relevant. However, it is worth noting that operation in the objects of mine workings is dangerous. Due to natural and manufactured impacts, cave-ins and collapses occur, which are regular and lead to injuries and death of workers. Moreover, cave-ins and collapses in places of mine workings occur due to high concentrations of methane-air mixtures. One of the causes of the ignition of methane-air mixtures is the destruction of electric cables. As a possible solution to this problem, electric power transmission systems with the help of optical fiber are considered. Optical fiber will allow the combination and use of one fiber-optic cable for information and electricity transmission. It thus will reduce the number of control cables that work with sensors. Also, a great advantage of fiber-optic cable is the absence of sparks during destruction, which causes the ignition of methane-air mixtures. Optical fiber will also allow the creation of various monitoring systems, which will be low-voltage equipment.

The idea of using optical fiber (OF) as a power conductor has been actively developed over the past ten years, from hypotheses to prototypes. Scientists from technologically developed countries, such as the USA, Japan, Europe, and China, are solving the critical problem of power transmission via OF to modernize power transmission systems in mines in the future with the prospect of replacing metal conductors with optical ones, making power lines safe.

Nevertheless, the application of the technology did not spread as it was not popular due to the low power efficiency and as promising technology quite expensive and unavailable for mass application. However, with the development of the sensor technology it became necessary to supply the instruments with continuous power without interruptions. In future it can even be used for two purposes as the sensor and as power supply system.

2. Literature review and problem statement

According to the literature analysis, there are studies on power transmission via OF. The paper [1] presents research results on the operation of high-performance optical power converters with wavelength ranges of 800–830 nm, 960–990 nm, and 1500–1600 nm, shown to enable new power-over-fiber or power-beaming applications. Different variants of absorber layers have been used for different spectral ranges. For devices with wavelengths of 960–990 nm, InGaAs absorber layers with a band edge around 1025 nm were used, and for wavelengths of 1500–1600 nm, an InGaAs grating matched with InP was used. The authors increased output power from <1 W to a power class at ~3 W and another class at >20 W. But there were unresolved issues related to data transmission, only power. This approach was used in [2]. The paper demonstrates a power converter based on gallium arsenide, where an optical power supply line with a power of 6.2 watts with integrated optical data transmission is considered. The line supports two expected voltage levels of 3.3 and 5 V at the specified power. The main problem is the data transmission rate because the maximum output power was obtained only at a data transmission rate of 1.2 kbps. When higher data rates are used, the output power and signal quality are significantly reduced, which makes simultaneous power and power transfer in this research impractical. Similar studies are presented in [3], where data were transmitted at a data rate of 1 kbit/s with a constant electrical power transfer of 5.5 W and an output voltage of 3.3 V. The maximum data rate of 600 kbit/s was achieved with a constant transmission of 4 W of electrical power.

The article [4] presents research material that describes photonic energy converters designed for efficient conversion of monochromatic (laser or LED) light into electricity. These devices consist of several *p-n* junction diodes arranged in a tandem configuration and connected in series. The problem is the sufficient complexity of the equipment used, which increases the cost of the power transmission system. In [5, 6] ultrahigh efficiency in the architecture of the vertical epitaxial, heterostructure and tunnel diodes with a high current density for multi-junction photovoltaic devices on InP substrates are considered. However, these devices have low efficiency and high cost, which makes relevant research impractical. A way to overcome these difficulties can be to change the approach, such as the photodetector interconnection scheme used in [7]. The study considers series and parallel connection of photodetectors. The use of multiple lasers with optimized current matching is justified. However, in the proposed stepwise approach, the epitaxial layer's thickness and the processing cost increase when the required photovoltage is obtained.

Another approach to improve the efficiency of the photonic converter is presented in [8], where the introduction of a distributed Bragg reflector structure and optimization of the surface electrodes of GaInP converter elements are proposed. A distributed Bragg reflector structure was implemented between the back surface field layer of n-AlInP and the buffer layer of n-GaAs. This method improved conversion efficiency by 46.0 % at 1.1 W/cm^2 irradiation and 43 % at 3–17 W/cm^2 laser power. The main disadvantage of using Bragg gratings is the high cost of fabrication, maintenance, and the presence of wavelength shifts caused by temperature and deformation. Articles [9, 10] present the results of studying AlGaAs gradient waveguides for power converters of various GaAs lasers, which can be used in the future to supply low-power, ultra-low-power electronic devices. So far, these studies are limited only to laboratory studies, and industrial application has yet to be planned. A new photoconverter device that can generate a 12 V output voltage is proposed in [11]. The designed photoconverter consists of a plurality of vertically arranged p-n junctions. These junctions are connected in series through tunnel junctions with high peak currents. In this case, the thickness of each p-n junction is optimized to ensure the coordinated generation of photocurrent in each junction and absorption of the required amount of light, making it possible to obtain a uniform output photocurrent. The authors have compared the proposed photoconverter with a conventional transformer-based power supply. Experiments showed that the optical converter is more resistant to conducted electromagnetic interference but requires a more active heat sink at a total volume of 14 cm^3.

A higher output voltage of 14 V was obtained in [12], where the approach of using 6, 8 and 12 junction photovoltaic cells was used.–The devices under consideration were designed to match the current for different wavelengths of light: the 6 junction was designed for 825 nm, while the 8 and 12 junction were designed for 850 nm. All three device heterostructures have a similar structure but have different numbers of layers and thicknesses. The layer thicknesses were adjusted for each device's required current. Experimental results showed 65 % to 70 % photovoltaic conversion efficiency. However, the device characteristics remain relatively insensitive to some current differences between junctions. Studies in [13] showed the possibility of obtaining an even higher output voltage of 23 V. The main disadvantage is the small photovoltaic conversion efficiency. In this study, it was possible to achieve 60 % efficiency only at 3 V. A way to solve the low-efficiency problem may be to use photon recycling for the back reflector in the GaAs/AlGaAs heterojunction inverse structure. This approach has been used in [14]. Also in addition to this method, the most suitable resonance in the optical resonator was selected to reduce losses. This allowed to achieve a photovoltaic conversion efficiency of 68.9 %. The disadvantage is the increased complexity of the design.

In [15], the authors designed and fabricated an integrated 100 GHz bandgap photodetector with a working photodiode with a single running carrier and a pseudomorphic transistor amplifier with high electron mobility, which performed the functions of photon energy generation and 100 GHz RF signal conditioning. Using orthogonal frequency division multiplexing (OFDM), 16 quadrature amplitude modulation (16-QAM), and 92 GHz intermediate frequency a bit error rate (BER) of 10^{-3} is achieved at 12 Gbit/s data transmission rate. Crosstalk is problematic when transmitting radio signals and power over optical fiber through multicore fiber. In [16], a data rate of 0.5 Gbit/s was obtained at a BER of 10^{-3} for a 2-meter laser link. The obtained values of the output voltage are not specified in the paper, which does not allow to judge the practical applicability of the study. Also, semiconductor development studies are underway to achieve better performance and reliability of high power and brightness semiconductor laser diodes used in the considered optical fiber power transmission systems [17]. Having studied the above sources can conclude that the energy transmission channel is of low efficiency. Accordingly, cost-reduction and searching for new solutions to improve the efficiency of power transmission is a relevant scientific issue that requires searching for new technical and high-tech solutions.

Therefore, it can be concluded that the development of this technology will allow in the future to provide reliable power supply to low-power automation devices, sensors, micro-drives and other electronic devices with high requirements for isolation, noise immunity and with full galvanic isolation. This technology will be in demand in the aerospace, defense, mining and oil and gas industries. This energy transfer technology eliminates the use of metal conductors and does not create a risk of explosion or fire. Moreover, it is worth noting that simultaneous transmission of electricity and information is also possible. This is especially promising for fiber-optic sensors. The basis of this research is the accumulated material of the preliminary studies aimed at studying the properties of light wave propagation along the OF, on the basis of which the main hypothesis [18–20] was formed.

3. The aim and objectives of the study

The aim of the study is to develop a prototype of the energy transmission system by fiber-optic cable for the power supply for sensors of the mine workings monitoring system. The solution of the task will allow the use of optical fiber not only for data transmission but also for power transmission for low-power sensors located in mining mines. In addition, optical fiber has such advantages as noise immunity, explosion, and fire safety, unlike electrical cables.

To achieve this aim, the following objectives are accomplished:

– development of the mathematical model and mathematical justification of the creation of a fiber-optic power supply system;

– development and realization of the structural scheme of the operating laboratory sample;

– experiment with the developed operating laboratory sample and process the results.

4. Materials and methods of research

The object of the study is a laboratory sample of power supply via fiber-optical conductor, designed to conduct research on processes related to the transmission of energy through a fiber-optic conductor for the power supply of low-power consumers, sensors, micro-drives and other electronic devices, for which high requirements for insulation and resistance to electromagnetic interference are presented. The subject of the study is the process of laser radiation passing through an optical fiber, with further conversion into electricity using a photovoltaic module.

The hypothesis is the possibility of using telecommunication optical fiber of G 652 standards to transmit energy over distances of several kilometers with a power of up to 30 watts for power supply of low-power devices with a high level of isolation and a high level of protection against electromagnetic interference. This hypothesis implies that the system will have a high level of galvanic isolation, through which electromagnetic interference will not be transmitted, and high levels of explosion and fire safety indicators will be provided. The proposed hypothesis will be tested by conducting field experiments on a specially designed laboratory stand.

In this study, it was assumed that when using materials based on GaAs, an efficiency of about 40 % will be obtained, which will allow to think about the manufacture of a prototype and conduct its practical testing.

Currently, the mathematical model does not take into account the properties of the materials used in the study, as well as the energy losses associated with reflection and refraction associated with the loss of optical radiation passing through a single-mode optical fiber.

5. Results of prototype development of an energy transmission system via a fiber-optic cable for the power supply of mining monitoring system sensors

5. 1. Mathematical model and mathematical justification for the creation of a fiber-optic power supply system

In order to solve the first problem, methods from such fundamental disciplines as theoretical foundations of electrical engineering, differential and integral calculus, electronics, and quantum physics were applied.

The solution to the second problem is based on applying the laws of electronics theoretical foundations of electrical engineering [21, 22] with the use of tools such as AutoCAD CorelDraw for the design of electrical and structural circuits in order to build a laboratory bench such electronic components as transistor model KT 808A, optical fiber standard G 652, a Fluke 87V (USA) multimeter has been used as a device for measuring the circuit current with the following characteristics: current measurement error ±(0.2 %+2), maximum resolution 0.1 μA. The temperature has been measured using a Fluke 51 contact thermometer (Fluke, USA) with the accuracy of (0.05 %+0.3 °C) and an industrial Smart Sensor AR320 non-contact thermometer with the accuracy of +/–2 °C that has been used for express testing. To measure voltage, a digital oscilloscope UTD2052CEX (UNIT Hong Kong) has been used with the vertical sensitivity of 1 mV/div~20 V/div and the bandwidth of 50 MHz, with the measurement rate of 1 ms/s. The sampling rate has been 1 GS/s with the rise time ≥7 ns.

In order to solve the third problem, the methodology of the research of the experimental installation as well as the basic laws in short-circuit and no-load modes, was used.

The photodetector is a silicon plate of the *p-n* junction of the KT 808A transistor [23]. When laser radiation with the wavelength of 650 nm hits its surface, photocurrent I appears at its terminals. Photovoltaic modules $h\nu_i$ work similarly, i.e. current flows from the terminal with the negative charge (cathode) to the terminal with a large positive charge (anode), through the load resistance R_L, on which the load voltage U drops (Fig. 1).

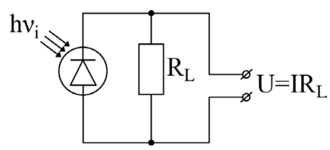

Fig. 1. Direct current generation circuit

Using the known laws of the photoelectric effect and the equations of A. Einstein, it is possible to express the forward current passing through the p-n junction in the open external circuit mode (without load resistance R_L) using the following expression [24]:

$$J_T = J_0 \cdot \left(e^{\frac{AeU}{kT}} - 1 \right), \qquad (1)$$

where J_0 – maximum current value generated by the panel; k – Boltzmann constant; T – panel temperature (Kelvin); e – elementary charge; A – coefficient depending on the semiconductor material; U – junction voltage.

Then the total current with the load turned off will be:

$$J_L = J_T - J_\Phi = J_0 \cdot \left(e^{\frac{AeU}{kT}} - 1 \right) - J_\Phi, \qquad (2)$$

since the internal current of the *p-n* junction and the photocurrent have opposite signs [25]. In the idle mode, when there is no load and the circuit is broken $J_L=0$.

The idle voltage can be expressed as:

$$U_{iv} = \frac{kT}{Ae} \cdot \ln\left(\frac{J_\Phi}{J_0} + 1 \right). \qquad (3)$$

Power P with the load R_L is:

$$P = IU = \left(J_0 \cdot \left(e^{\frac{AeU}{kT}} - 1 \right) - J_\Phi \right) \cdot U. \qquad (4)$$

Power P corresponds to the area of a rectangular with some sections J and U. At the extremal points J_{sc}, U_{iv} power $P=0$, so, the power curve $P(J, U)$ described by equation (4) will have the maximum depending on current or voltage.

By solving equation:

$$\left. \frac{dP}{dU} \right|_{J=J_{\max},\, U=U_{\max}} = 0, \qquad (5)$$

it is possible to obtain:

$$\begin{cases} J_{\max} = -\dfrac{J_\Phi}{1 + \dfrac{1}{AU_{\max}}} \approx -J_{sc}\left(1 - \dfrac{1}{AU_{\max}} \right), \\ U_{\max} = \dfrac{kT}{e} \ln\left(\dfrac{\dfrac{J_\Phi}{J_O} + 1}{AU_{\max}} \right) \approx U_{iv} - \dfrac{kT}{e}\ln\left(1 + AU_{\max}\right), \\ P_{\max} \approx J_{sc}\left[U_{iv} - \dfrac{kT}{e}\ln\left(1 + AU_{\max}\right) - \dfrac{kT}{e} \right]. \end{cases} \qquad (6)$$

The analysis of the system of equations and the CVC plot allow establishing the limitations of the parameters: $J_{\max} < J_{sc}$, $U_{\max} < U_{sc}$, $P_{\max} < J_{sc}U_{iv}$.

Based on this,

$$P_{\max} \approx (0.7 \div 0.8) \cdot J_{sc} U_{iv}. \qquad (7)$$

Hence, the experiment will be conducted in three modes with maximum load, idle, and short circuit.

5. 2. Development of the structural scheme of the experimental unit

Based on the obtained mathematical model, it is necessary to consider the structure of the developed installation (Fig. 2). First of all, it should be noted that it is recommended to divide the whole installation into three parts:

– generating part, which performs the function of primary energy generation in the form of light radiation (GP);

– the channel for energy transmission (TP);

– the receiving part, which converts the light radiation into electricity (RP).

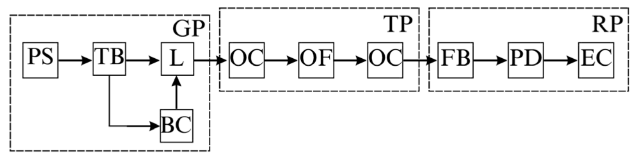

Fig. 2. Structural diagram of a prototype energy transfer device

It should be noted that it is necessary to make the generating part autonomous, i.e., able to operate without an external power source (PS). Consequently, components such as a unit that reduces voltage and converts alternating current to direct current (TB) are required to provide this function. The laser (L) is connected to the TB, to which, in turn, the battery control unit (BC) is connected, which powers the laser during power outages. Then, the light radiation is transmitted through a power transfer channel (TP) consisting of optical connectors (OC) connecting an optical fiber (OF). The light radiation is then received at a receiving part (RP), namely a light beam concentration unit (FB) collecting light from the optical fiber. Then, from the FB, the light enters a photodetector (PD), generating an electric current connected to an electric circuit (EC).

In order to investigate the behavior of light emission for long-distance energy transmission, an experimental setup was assembled (Fig. 3).

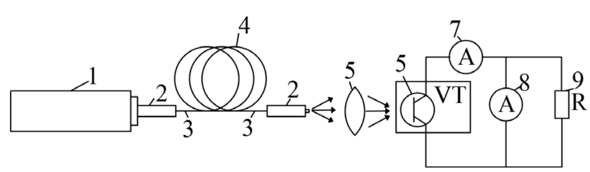

Fig. 3. Diagram of measuring the photodetector parameters: 1 – radiation source, 2 – optical connector, 3 – optical fiber, 4 – coil with optical fiber, 5 – focusing lens, 6 – photodetector, 7 – circuit current measuring device, 8 – circuit voltage measuring device, 9 – electrical load

In contrast to the prototype, laser 1 was powered directly from a battery without connection to an external power source in this case. Then, through connectors 2 optical fiber 3 with a simulated long-distance connection coil 4, the light propagation was focused through a collecting lens 5, feeding light to a photodetector 6. In order to investigate the method of energy transfer, an ammeter and a voltmeter were connected to the electrical circuit.

5. 3. Experimental studies

In the course of experiments, the current and voltage parameters have been measured only in one branch of the photodetector. The equivalent generator method has been used, as well as the known circuit laws [26] with two distinguished nodes for the active two-terminal network, which can be converted into an equivalent generator using the Taiwanen-Helmholtz theorem [27]. Power has been transferred from the active two-terminal network to the passive one that was used as a high-resistance resistor with power of 1 W.

To carry out studies, there has been r a sample pf the laboratory bench shown in Fig. 4.

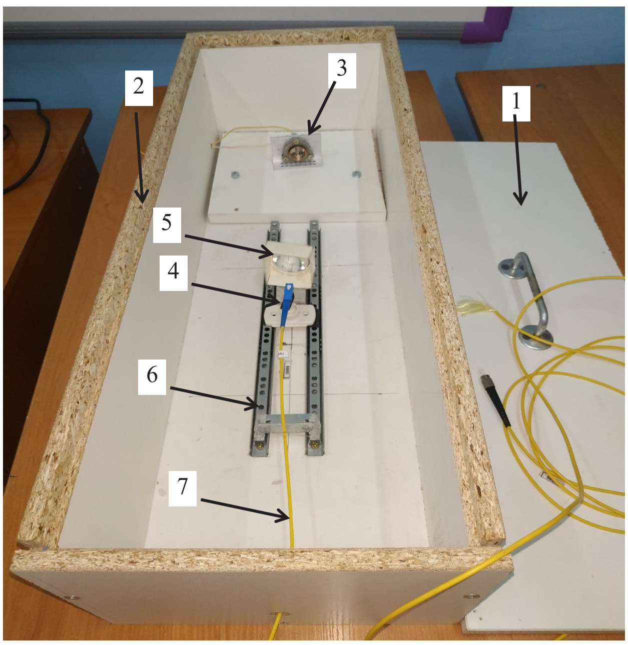

Fig. 4. Appearance of laboratory bench sample: 1 — lid; 2 — box with slots for fitting the lid; 3 — photodetector with a flint plate; 4 — optical telecommunication convector of the SC type with UPC polishing; 5 — focusing lens; 6 — guides for focusing the beam; 7 — optical fiber

In the process of developing the laboratory bench, there have been taken into account the moments that ensure the required integrity of the experiment and exclude the ingress of daylight on the silicon plate of the photocell. The box has been closed with a cover installed in special grooves, which ensures complete shading of the photodetector. To focus the radiation on the silicon plate of the photodetector, a lens with the diameter of 5 centimeters has been used that has been mounted on guide rails. This allows setting the required focal length. The optical fiber enters the box through a hole that has been closed with an opaque sealant. The wires from the photodetector come out through the side hole and are connected to the measuring instruments.

In the course of experiment, there have been carried out studies when the photodetector is in the short circuit, idle mode and is connected to a high-resistance load. Based on the results obtained, its CVC has been built, and power has been determined using the known laws of electrical engineering, including the Ohm law. The photodetector has been in the DC circuit. The radiation source was a solid-state semiconductor laser from a tester for testing fiber-optic transmission lines ONTi (China). This device is also called a visual locator with adjustable power, which varied in steps in four values: 5, 10, 20, and 30 mW. The laser is powered by lithium-ion batteries (Li-ion). The laser is red and has a wavelength of 650 nm with a deviation of no more than 5 nm. The laser pulsation was transmitted to the photodetector and recorded using an oscilloscope. Since this fluctuation is not significant, it has been excluded from the factors affecting the accuracy of the results.

In the experiment, to increase the length of the power transmission channel, a coil with a single-mode optical fiber of the G 652 standard with a length of 1200 meters wound on it has been used. The optical fiber has been terminated with an SC-type telecommunication connector with UPC polishing, from the output of which the light spot fell on the surface of the focusing lens, and then on the silicon plate of the photodetector. Standard FC/SC telecommunications connectors and adapters of the same type have been used to connect the coil and the radiation source. During the experiments, the temperature of the silicon crystal has not practically exceeded the air temperature in the room and has been in the range of 23–25 °C. The silicon wafer has been naturally cooled and placed on a copper heatsink. The laser operation mode has been short-term; therefore, no heating of the optical circuit elements has been observed, and the temperature has remained stable. On the basis of above, in these experiments, the temperature effect on the generation power of the photodetector has not been taken into account

An important point is establishing the efficiency of the fiber optical conductor. The calculation method is as follows: the ratio of the maximum power delivered to the load by the photodetector to the laser radiation power incident perpendicular to its working surface is taken into account:

$$\eta = \frac{V_P I_P}{P_c} \cdot 100, \qquad (8)$$

where V_P and I_p are voltage and current at the operating point, at which the maximum power delivered to the load is reached, P_c is the radiation power incident on the surface of the photodetector.

The filling factor of the current-voltage characteristic (CVC) of the photodetector (filling factor, FF) has been selected taking into account the parameters of the short-circuit current I_{sc} and the open-circuit voltage U_{iv}. It should be taken into account that for U_{iv} and I_{sc} the output power of the photodetector will be equal to zero. There has been accepted the duty cycle of the CVC equal to 0.7. In practice, the power transmission system operates with the combination of current and voltage when sufficient power is generated at the maximum radiation level and is reached at the point of maximum power MPP, which corresponds to the parameters V_p (nominal voltage) and I_p (nominal current). It is for this point that the rated power and efficiency of the photodetector are determined.

The current and voltage measurement results obtained during the experiment for radiation powers of 10 and 30 mW are shown in Table 1.

Table 1

Current and voltage measurements at 10 and 30 mW

Radiation powers, mW	Current, mA	Voltage, V
10	0.45	0
	0.45	2.1
	0.44	2.5
	0.43	2.8
	0.4	3.2
	0.38	3.3
	0.3	3.4
	0.2	3.45
	0.1	3.49
	0	3.5
30	1.185	0
	1.185	2
	1.175	2.5
	1.12	3
	1.02	3.5
	0.8	3.8
	0.6	3.9
	0.4	4
	0.2	4.1
	0	4.2

The results of voltage and power measurements are shown in Table 2.

Table 2

Power voltage measurements at 10 and 30 mW

Radiation powers, mW	Current, mA	Voltage, V
10	0	0
	1.5	0.9
	2	1.15
	2.5	1.3
	3	1.5
	3.2	1.574
	3.4	1.575
	3.6	1
	3.7	0
30	0	0
	2	2.5
	2.5	3
	3	3.4
	3.5	3.7
	3.8	3.9
	4	3.792
	4.2	2.5
	4.3	0

During the processing of the obtained measurements, a calculation was made, by which the model of the volt-ampere characteristics was determined, which are shown in Fig. 5, 6.

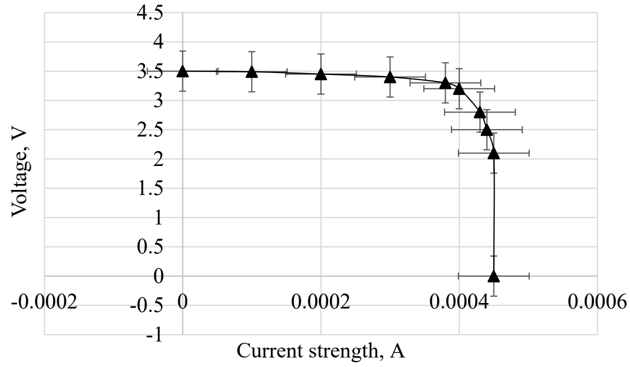

Fig. 5. CVC plot with the laser radiation power of 10 mW

Fig. 6, 7 show the graphs of the output electrical power of the photodetector at radiation powers of 10 and 30 mW. An approximation of a polynomial of the fourth degree has been performed with the derivation of the value of the approximation accuracy *R*2, the errors have been determined, and the trend line has been built.

Fig. 7, 8 show the graphs of the output electrical power of the photodetector at radiation powers of 10 and 30 mW. An approximation of a polynomial of the fourth degree has been performed with the derivation of the value of the approximation accuracy *R*2, the errors have been determined, and the trend line has been built.

The experimental data have been processed using the spreadsheet Microsoft Excel (USA), quadratic interpolation of the function (solid line) and the results of the root-mean-square approximation (dashed line). The regression analysis has been performed. The adequacy of the obtained approximations has been checked using the Microsoft Excel (USA) and Wolframalpha (USA) computer programs.

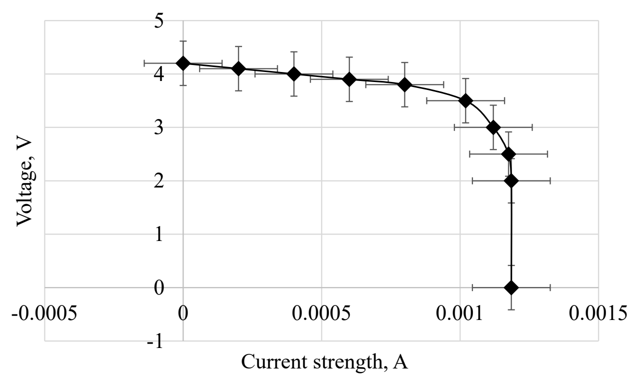

Fig. 6. CVC plot with the laser radiation power of 30 mW

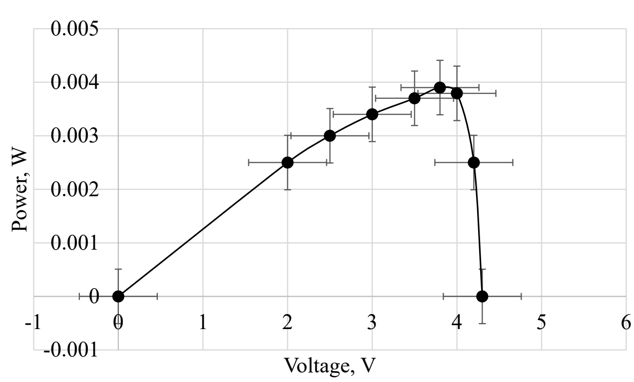

Fig. 7. CVC plot with the laser radiation power of 10 mW

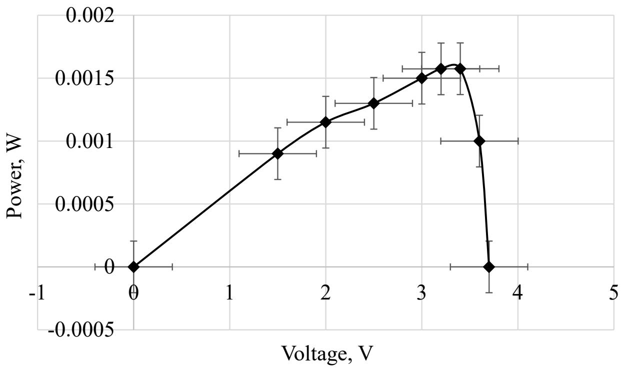

Fig. 8. CVC plot with the laser radiation power of 30 mW

The numerical study has been carried out using the Wolframalpha program (USA), which is an interactive system for processing the results of experiments and is focused on working with data arrays. The Akaike Information Criterion (AIC), which is used exclusively for selecting from several statistical models, has been taken into account. Using the program, the absolute and relative errors have been calculated, and the Student coefficient has been determined with the confidence interval of 0.95.

6. Discussion of the results of the study of power supply experimental installation via fiber-optical conductor

The obtained mathematical model allows to calculate the generated current, voltage, and power at the photodetector output using the system of equations (6). Moreover, not only the laser radiation power but also the temperature of the material itself is taken into account. Due to the obtained system of equations, it is also possible to determine the maximum power. On the other hand, the system of equations (6) allowed to prepare a methodology for determining the system's efficiency according to the parameters of short-circuit, no-load, and maximum load modes. Despite this, the disadvantage of the mathematical model is the need for more consideration of the influence of the phototransistor materials.

The proposed prototype of the developed device (Fig. 2) allows to determine the system's efficiency as a whole, analyzing the state of each component. For example, this approach allowed for the determination of a more suitable type of optical fiber during the experiment. Moreover, it was then revealed that the type of transistor used in this study has a small percentage of efficiency, in contrast to the solution of [8], where Bragg gratings are implemented in the design, where the proposed device has a more straightforward design and consequently the lower cost of the whole system. It is also worth noting that the autonomy of the proposed solution can be achieved by using special control units for the battery and the battery itself, which can be further utilized in other studies. However, the limitation of this scheme is the need for more consideration of the influence of electrical interference on the laser.

According to the study results, the efficiency of the electric power transmission system via fiber-optic conductors for the power supply of sensors in mines is determined. At laser radiation power of 10 mW, the efficiency is 15 %; at 30 mW, its value reaches 13 %, confirmed by (7), (8). The power loss during data transmission was possible to identify specific sources due to the developed scheme of both the prototype (Fig. 2) and the scheme of the experimental setup (Fig. 3). By performing several experiments, it was found that the best medium for power transmission is multimode optical fiber. It is worth noting that the obtained deviations are also explained by the fact that the mathematical model does not consider the material of the applied components. On the other hand, the maximum electric power released at the photodetector when transmitting power through the OF has been 0.001575 W in the laser operation mode of 10 mW and 0.003792 W in the laser operation mode of 30 mW. This power is not enough to power any electronic device, for example, even a low-power 12 mW LED with a current consumption of 6.5 mA and voltage of 1.86 V. There can be noted a rather low efficiency of the power transmission system through the OF. The work is at the initial stage of studies and requires further improvement in efficiency. The experiment demonstrated the possibility of power transmission through a single-mode optical fiber at a distance of 1200 meters, which is more than in [2, 16].

It can be noted that a single-mode optical fiber with a core diameter of 9 μm and cladding of 125 μm is not entirely suitable for power transmission of more than 1 W. This requires using a multimode fiber or several parallel single-mode optical fibers. Since a multimode optical fiber has a larger value of the attenuation parameters of optical radiation propagating through its core, its use will be limited to the distance within one kilometer. The use of several single-mode fibers will complicate the transmission scheme since an optical splitter will be required that will be installed at the output and the input of the fiber optical line. An optical splitter causes a certain level of power loss. Increasing the laser power will cause heating of the optical fiber at the input, which can also become a significant problem in the operation of the power transmission system. There is also the problem of focusing the beam on the surface of the photodetector using a lens since this also leads to power losses and decreases efficiency. Changing the material of the transistor from silicon to gallium arsenide will increase the efficiency by 2–2.5 times. The present study has limitations in the mathematical model, not considering the elements of the transistor. Based on the previous, to develop this research, it is necessary to finalize the power transmission system through fiber-optic conductors to provide power to sensors located in mining mines. As a result of solving the tasks set, the technology will be developed that allows developing a system for transmitting power in the form of a light wave in a wide range of lengths from 1310 to 1550 nm via a multichannel system with the power of more than 1 W over the distance of more than 30 km. The basis for the technology of transmitting power over 10 W will be laid by increasing the number of channels and photoconverters with a series-parallel circuit of their connection and stabilizing their operation using a built-in microcontroller. In this case, the information will be simultaneously transmitted from object to object. This will make it possible to develop a new generation of energy-passive systems for monitoring and controlling the technical condition of extended objects that are capable of operating in the explosive environment. The use of optical fiber for power transmission to power low-power consumers will provide a number of advantages compared to the conventional copper pair, for example, galvanic isolation, the absence of electromagnetic interference effect on the power transmission channel, the future prospect of replacing copper cables with fiber optical conductors, the absence of electrical short circuits, fire safety.

Main limitations of the use of the proposed solution is concluded in the choice of the materials, which will provide high efficiency of photovoltaic module. In practical application the system is limited by consumers' power capacity in the range from 1 to 30 W because the fiber-optic system will have limitation on the amount of the fiber optics and geometrical sizes of the cable. This system cannot be used for high power systems, for example, for high power motors, lightning systems. Mainly, the reason is concluded in that the power system via fiber-optic has low efficiency. Second main limitation is the necessity of the semiconductor materials development based on GaAs that has more advantages compared to other semiconductor materials. On the other hand, the mathematical model does not consider material of the elements that are used in the system. Therefore, the practically it can be used only with the materials that are mentioned in this research.

The results of research on the development of a power supply system based on a fiber-optical line will be presented by the authors in future joint works.

7. Conclusions

1. Using the laws of the photo effect and A. Einstein's equations, a mathematical model is developed, and creating a fiber-optic power supply system is mathematically justified. The obtained formulas are applicable to determine energy transmission efficiency over long distances. Moreover, the mathematical model itself determines parameters in short-circuit and no-load modes. However, the limitation in this case is the need to consider the materials of the electric circuit. For example, the circuit used a photodetector based on Galium Arsenide, which has several disadvantages compared to silicon ones.

2. The structural scheme of the operating laboratory sample and prototype was developed, which allows to determine the efficiency of the whole system and each of its parts separately. Thus, it is possible to monitor where the most significant losses occur easily. It should be noted that the scheme of the experimental setup differs from that of the prototype because the realization of the electrical part also requires further research.

3. Experiments were carried out on the developed laboratory stand, which showed that the efficiency of the developed laboratory setup is 15 % at a radiation power of 10 mW and 30 mW – 13 %. Based on the processed experimental results, the mathematical dependences of voltage on current power on voltage were empirically constructed. As a result, it was determined which materials were more suitable for the construction of the laboratory sample.

Conflict of interests

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

This research has is funded by the Ministry of Trade and Integration of the Republic of Kazakhstan (Grant No. BR19980899 «Development of a system for monitoring the geotechnical state of mine workings and quarries based on intelligent fiber-optic sensors»).

Data availability

Data will be made available on reasonable request.

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