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Mathematical model of single quantum system
of confidential data transmit and receive

ABSTRACT

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LIST OF USED ABBREVIATIONS

FOCL – fiber-optic communication lines

APD – avalanche photodiode

APDr – avalanche photodetector

OF – optical fiber

PC – photon counter

Библиотека БГУИР

INTRODUCTION

Currently optical fiber has found widespread application in data transmission [1-4]. In some cases it is extremely important to provide transmitted data confidentiality while transmitting it using such communication channels. Channel of leakage of data transmitted through fiber-optic communication lines (FOCL) can be created by forming optical fiber (OF) macrobend [5]. Therewith unauthorized access to the data transmitted becomes possible attributed to the fact that the angle of incidence of electromagnetic wave at the core-cladding boundary becomes smaller than the angle of total internal reflection, which results in optical radiation going through both of the boundaries and a part of optical radiation at optical fiber macrobend is output to external space and registered by an unauthorized user. There are ways [5-7] which make it possible to detect data leakage channels created by forming OF macrobend but they don't allow revealing unauthorized access when outputting a small part of radiation equal not more than ten radiation photons from optical fiber during one bit transmission. In such cases, it is reasonable to transmit confidential data using single quantum communication systems where low-power optical pulses containing not more than ten photons for one bit transmission are used [8-10]. Existence of data leakage channel implemented by means of optical fiber macrobend will lead to the growth of error amount during data transmission and will decrease channel capacity.

Modern single quantum systems of confidential data transmit and receive have low data transmission rate not exceeding 50 Kbit/s [11], which narrows the range of their practical application and is limited to a greater extent by receiving modules capacity of the said systems [9].

It should be noted that it is mainly the photon counters (PC) made on the basis of silicon avalanche photodetectors (SAP) that are used as receiving modules of single quantum systems [9]. One of the main characteristics of the photon counters is detective quantum efficiency [9, 12].

It is advisable to use mathematical models of communication channels to increase communication channels capacity [13, 14]. While up to the present there are no mathematical models of single quantum systems of confidential data transmit and receive that take into account the effect which detective quantum efficiency of the photon counters has on unauthorized user detection, the purpose of this thesis was to determine the effect of detective quantum efficiency of the photon counters on the possibility to detect unauthorized user in single quantum system of confidential data transmit and receive.

Analytical review of known systems of confidential data transmit and receive

that allow to detect unauthorized access to fiber-optic communication lines automatically was carried out to achieve the purpose set; single quantum system for confidential data transmit and receive which, compared to others, doesn't require cooling of transmitting and receiving modules to extremely low temperature, which doesn't require availability of additional sources for synchronization of transmitting and receiving modules work, and which simplifies known single quantum communication systems, was developed; mathematical model of single quantum communication system containing the photon counter as a receiving module was developed and formulae which can be used to determine channel capacity of the stated communication system both in the segment between legitimate users and in the segment between legitimate transmitting side and illegitimate user were deduced; effect of OF macrobend diameter on channel capacity of single-photon communication system was experimentally researched.

The photon counters based on avalanche photodiodes FD-115L, on avalanche photodetectors with metal – resistive layer – semiconductor structure, and commercially available single-mode optical fiber G.652 were used as research objects.

Research subject was to determine what effect detective quantum efficiency of the photon counter has on channel capacity of single quantum system of confidential data transmit and receive.

GENERAL DESCRIPTION OF THE WORK

Research purposes and tasks

The purpose of this thesis is to determine the effect of detective quantum efficiency of the photon counter on possibility to detect unauthorized user in single quantum system of confidential data transmit and receive.

Achievement of the purpose set required solution of the following interconnected tasks:

1. To carry out analytical review of known systems of confidential data transmit and receive that allow to detect unauthorized access to FOCL automatically.

2. To develop single quantum system for confidential data transmit and receive which, compared to others, doesn't require cooling of transmitting and receiving modules to extremely low temperatures, which doesn't require availability of additional sources for synchronization of transmitting and receiving modules work, and which simplifies known single quantum communication systems.

3. To develop mathematical model of single quantum communication system containing the photon counter as a receiving module and to deduce formulae which can be used to determine channel capacity of the stated communication system both in the segment between legitimate users and in the segment between legitimate transmitting side and illegitimate user.

4. To research experimentally the effect of OF macrobend diameter on channel capacity of single-photon communication system.

5. To deduce formulae for rate assessment of data transmission through fiber-optic communication channel containing the photon counter with dead time.

The photon counters based on avalanche photodiodes FD-115L, on avalanche photodetectors with metal – resistive layer – semiconductor structure, and commercially available single-mode optical fiber G.652 were used as research objects.

Research subject was to determine what effect detective quantum efficiency of the photon counter has on channel capacity of single quantum system of confidential data transmit and receive.

Personal contribution of the degree-seeking student

The content of the thesis reflects personal contribution of the degree-seeking student. In coauthored work, the author participated in purposes and research objectives definition as well as in research pursuance and processing of the obtained results.

Evaluation and publication of the results

Main obtained results of the thesis were reported and discussed at XIII Belarusian-Russian scientific and technical conference “Technical Means of Data Security” (Minsk, Republic of Belarus, 2015) and XX International scientific and technical conference “Modern Communication Facilities” (Minsk, Republic of Belarus, 2015). Two abstracts of the reports were published.

Thesis structure and volume

The thesis consists of the list of used abbreviations, introduction, general description of the paper, three chapters, conclusion and reference list. Full volume of the thesis makes 53 pages of typed text. The thesis contains 12 figures on 8 pages, 1 table on 1 page. Reference list takes 4 pages and contains 34 items of used sources and the list of personal publications of the degree-seeking student consisting of two items on one page.

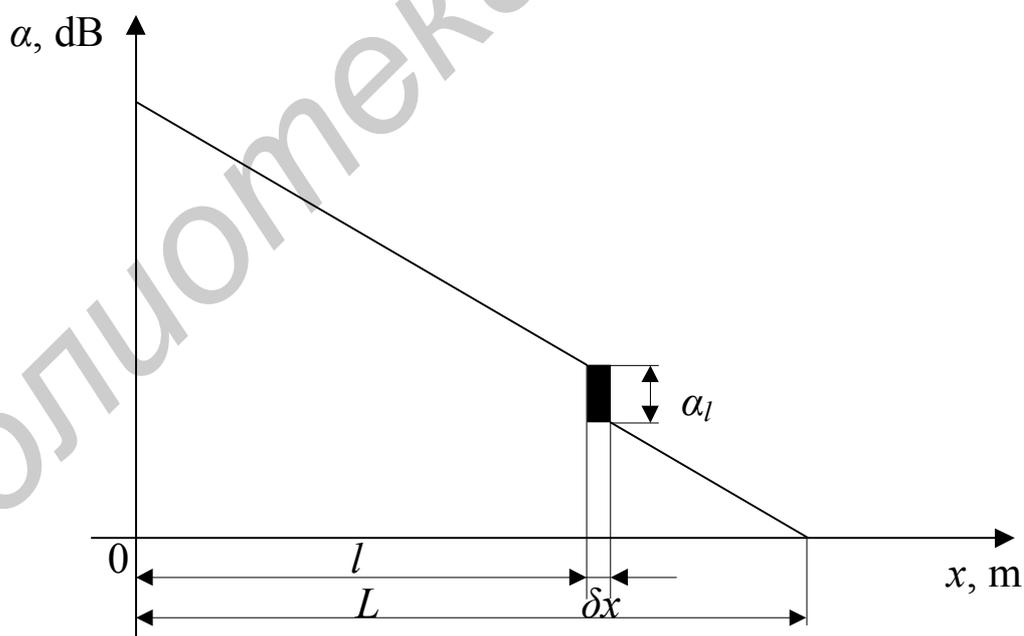
CHAPTER 1

CONFIDENTIAL DATA TRANSMIT AND RECEIVE SYSTEMS

1.1 FOCL segments with higher level of lateral radiation detection system

Currently there are systems [5-7] known for making it possible to provide fiber optic communication with control of unauthorized access to the data transmitted.

It is the system of confidential data transmit and receive which allows to identify the segments of fiber-optic communication lines having higher level of lateral radiation that is described in this paper [5]. Fiber traces, an example of which is shown at Figure 1.1, are used to implement such a system.



One segment with local insertion loss is shown:
 l – distance between the transmitter and the point with measured value of local insertion losses; δx – reflectometer resolution along optical fiber length; α_l – local insertion losses value

Figure 1.1 – Dependence of local insertion losses on optical fiber length [5]

Main constituent of insertion losses for modern fiber optic communication lines is Rayleigh scattering losses some part of which comes out through optical fiber lateral surface. Scattered radiation value along OF length is proportional to current value of attenuation ratio.

Possibility of lateral radiation detection determines potential possibility of data interception. In case if this radiation value is insufficient for reliable detection, it can be helpful to use, for example, optical fiber macrobend to increase it by several exponents. Therewith local insertion losses value will increase proportionally at the point of interception. Thus, the point of unauthorized data interception can be detected.

Firstly, local insertion loss value has to be measured with reflectometer to detect unauthorized data interception. Then the segments of optical fiber with local insertion losses have to be identified and the distance between the transmitter and the points with measured value of local insertion losses l is measured, and local insertion losses value α_i of every such a point is estimated.

Optical signal power (scattered or output together with local insertion losses) which can be brought to the receiving module of unauthorized user equals

$$W_E = K_i W_l (1 - 10^{-0,1\alpha_i}), \quad (1.1)$$

where K_i is transmission coefficient showing what part of radiation lost in FOCL went to the receiving module of unauthorized user, W_l is power of data emanation in FOCL together with local insertion losses.

On the other hand, power of optical data emanation, which is allowable at the input of unauthorized user's receiving module so that data won't be intercepted with possibility higher than the value given, will make for FOCL without quantum noise masking:

$$W_E = Q W_{thE}, \quad (1.2)$$

where Q is maximum allowable signal-to-noise ratio for unauthorized user's receiver and it provides the impossibility of data interception, W_{thE} is unauthorized user's receiver threshold sensitivity with signal-to-noise ratio equal to unity.

W_E value together with the coordinate l for FOCL with quantum noise masking equals:

$$W_E = Q \left[2eBI_p W_{rE} 10^{-0,1\alpha_l(L-l)} / (MS) \right]^{1/2}, \quad (1.3)$$

where e is electron charge, B – the band of transmitted data signals frequency, I_n – Personik integral, W_{rE} – power of optical signal at the input of unauthorized user's receiver providing required transmission quality, L – FOCL length, M – quantum masking ratio, S – transmission characteristic of fiber-optic communication system receiver.

Therewith, power of data signal together with the coordinate l makes:

$$W_l = W_{rE} 10^{-0,1\alpha_l(L-l)}. \quad (1.4)$$

Equality of the formulae (1.1) and (1.2), (1.1) and (1.3) and formula (1.4) gives the requirement on the allowable local insertion losses value for FOCL without quantum masking and with quantum masking, respectively [5]:

$$\alpha_{l_{\max 1}} = -10 \lg \left[1 - Q W_{thE} 10^{-0,1\alpha(L-l)} / (K_t W_{rE}) \right] \quad (1.5)$$

$$\text{and } \alpha_{l_{\max 2}} = -10 \lg \left[1 - Q (2eBI_p)^{1/2} 10^{-0,05\alpha(L-l)} / K_t (W_{rE} MS)^{1/2} \right] \quad (1.6)$$

A conclusion on the existence of data interception at FOCL point with the coordinate l can be made by means of comparison of measured value of α_l with the one calculated using the formula (1.5) or (1.6).

Thus, confidential data transmit and receive system [5], using FOCL testing with identification of fiber-optic communication line segments having higher level of lateral radiation and with further comparison of the obtained local insertion losses values of every such a point with allowable values to provide data security, allows to detect unauthorized user in FOCL. Herewith, accuracy of the conclusion made on the existence of an unauthorized user due to usage of the criterion, according to which measured value of local insertion losses should be considered dangerous, increases in comparison with [2, 3, 15, 16] where such a criterion wasn't used.

1.2 System of detection of slow optical radiation output through FOCL lateral surface

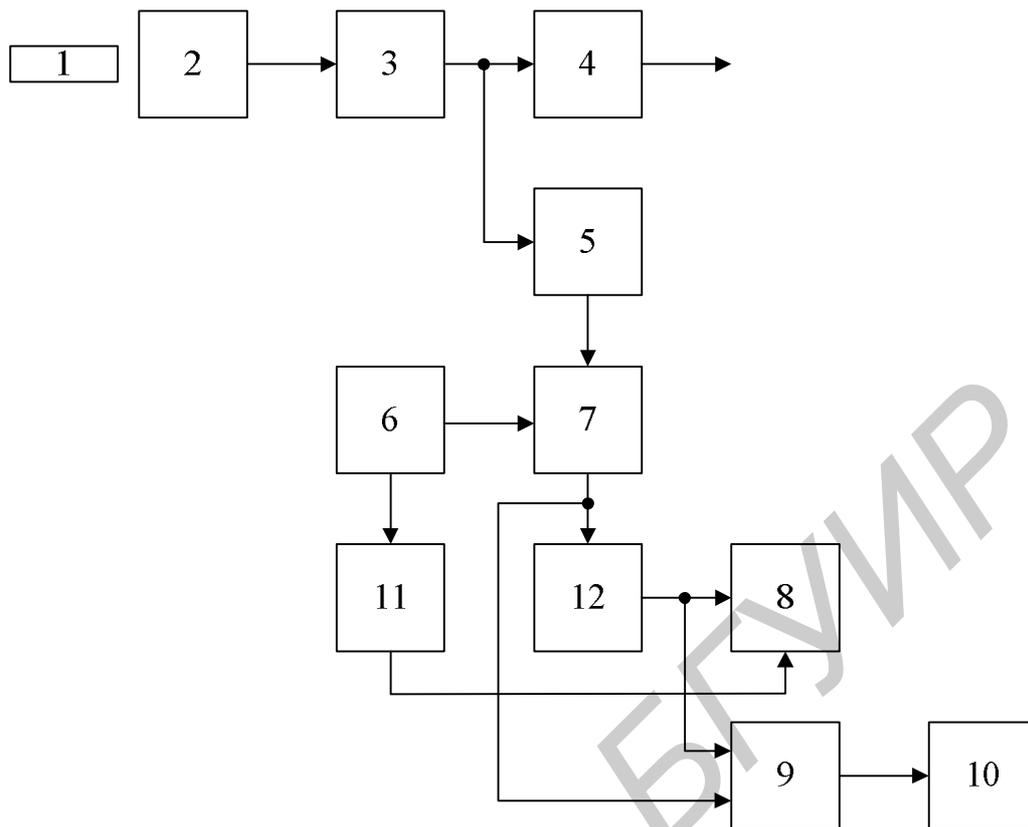
System of detection of FOCL segments with higher level of lateral radiation [5] does not allow detecting unauthorized access to fiber-optic communication line in case if slow optical radiation output through OF lateral surface is carried out. Let us consider peculiarities of its functioning.

System of confidential data transmit and receive is free from this defect [6].

There is a flowchart of the photodetector of the system of detection of slow optical radiation output through FOCL lateral surface shown in the Figure 1.2.

Photodetector calculates algebraic sum of this very signal deviation from reference level, which was obtained as a result of processing of big previous samples number and was set for a long term, alongside with the periodic comparison of control signal and the previous value (one or several). During slow extraction of optical signal power through lateral surface sum value will be negative and increasing with every count all the time. Eventually the sum will reach the set value corresponding to alert signal. Slow operating changes of parameters are random and alternating; therefore, in this case sum value will fluctuate about zero value and will not be able to reach the set value. By means of a new reference level establishment sum nullification takes place. Thus, it is slow parameter degradation caused by component ageing that is taken into account.

Photodetector function in the following way. Optical signals from fiber-optic communication line 1 are detected by photodetector 2, boosted by photocurrent amplifier 3 and goes to output through output signals shaper 4.



- 1 – fiber-optic communication line; 2 – photodetector; 3 – photocurrent amplifier;
 4 – outputsignals shaper; 5 – integrator; 6 – clock generator;
 7 – analog-digital converter (ADC); 8 – random access memory (RAM);
 9 – digital comparator; 10 – alerting device;
 11 – timer; 12 – arithmetic logic unit (ALU)

Figure 1.2 – Flowchart of the photodetector of the system of detection of slow optical radiation output through FOCL lateral surface [6].

Signals from the output of the photocurrent amplifier 3 go to the integrator input 5 from the output of which they run to the ADC input 7, where they are converted from analog form into digital. The ADC is clocked by the generator 6 signals from which come to the timer input 11. The timer measures time during which the sum calculation is carried out.

From ADC output 7 signals run to arithmetic logic unit (ALU) 12 which carries out summing up (considering the sign) of the obtained value with earlier obtained sum. The sum is saved in RAM 8. Digital comparator 9 compares current value of the signal, which came from ADC output 7, with the previous one(s) as well as the obtained sum with the given threshold value. If current value appears to be lower than the previous one(s) by a limiting value or the sum reached the given value, alerting device 10 generates alert signal.

The timer 11 counts out the interval in which zero sum in RAM 8 is set.

Slow changes in OF attenuation which will take place during the time exceeding that of current values storage will be detected for they will cause permanent sum increase (with negative sign) and result in reaching the value of alerting device actuation.

Thus, the system of detection of FOCL segments with higher level of lateral radiation [6] allows detecting unauthorized access to OF in case of gradual output of optical radiation which is impossible in the system [17]. Besides, it increases the probability of unauthorized access detection due to the detection of slow and smooth breach, carried out for a long time provided that changes in attenuation under external influence (change of environment temperature, etc.) and elements ageing will not cause false actuation [6].

CONCLUSION

The systems of confidential data transmit and receive, which function based on the assessment of lateral radiation level output from OF, were determined basing on the conducted analytical survey of literature sources. It was found out that the system of confidential data transmit and receive, which uses FOCL testing with identification of fiber-optic communication line segments with higher level of lateral radiation and further comparison of local insertion losses values of every such a point with the allowable values to provide data security, allows detecting an unauthorized user in FOCL. At the same time, accuracy of the decision taken on unauthorized user presence increases due to the used criterion according to which measured value of local insertion losses should be considered dangerous.

The system of detection of FOCL segments with higher lateral radiation level, which allows detecting unauthorized access to OF in case of gradual output of optical radiation, was analyzed. Such a system in comparison to others is characterized by quite high probability of unauthorized access detection due to the detection of slow and smooth breaches carried out for a long time provided that changes in attenuation under external influence (change of environment temperature, etc.) and elements ageing will not cause false actuation.

Mathematical model of single quantum communication system containing the photon counter as a receiving module was developed. The formulae that can be used to determine channel capacity of the system both in the segment between legitimate users and in the segment between legitimate transmitting side and illegitimate user were deduced for this communication system.

The deduced formulae for channel capacity assessment in the segment between the legitimate users take into account the probability of unauthorized output of radiation power from optical fiber $P_{\text{ПОР}}$ as well as such parameters of the photon counter as the probability of dark-pulses occurrence and detective quantum efficiency η_d . It was found out that it is possible to detect Eve's presence in quantum channel provided the value $\eta_d > 0,15$ with relative inaccuracy less than 13% and the probability of dark-pulses occurrence $P_t 10^{-6}$.

The formulae for assessment of data transmission rate through fiber-optic communication channel containing the photon counter with dead time of constant and

prolongable type were deduced. Comparison of channel capacity of the channels of fiber-optic communication, which contain the photon counter with dead time of constant and prolongable type, was performed. It was found out that demonstration of dead time effect in the photon counters causes growth of optical radiation power at which maximum value of data transmission rate is reached as opposed to the photon counters for which this effect is not demonstrated. If the number of dark-pulses registered during transmission of one data bit which is less or equals one, is average, it is rational to choose the threshold $N_{th}=2$.

The single quantum system that can be of use in quantum-cryptographic systems and can be also used to for data transmission in long distances without retransmitting the signal through fiber-optic communication line was suggested. Different time delay between the moments of optical pulse occurrence at the output of optical radiation source and pulse registration by avalanche photodiode working in photon counting mode used for the characters “0” and “1” transmission allows, as applied to single quantum communication system, transmitting the words consisting of n-number of data bits starting after sync-pulse transmission. Synchronization pulses are used to coordinate receiving and transmitting sides work. Unauthorized user or some defect in FOCL is detected by single quantum communication system due to delay increase between the pulses coming from the source on the receiving side and from the output on the transmitting side or due to the loss of optical pulse coming from the source on the transmitting side. In its turn, it will lead to the fact that the **reversible counter** will count some number of pulses after transmission of a word what indicates the loss of transmitted power in FOCL.

The single quantum communication system for confidential data transmission, which, compared to others, doesn't require cooling to extremely low temperatures, doesn't require receiving modules and additional lines to synchronize work of transmitting and receiving modules, and which simplifies known single quantum communication systems, was developed.

REFERENCE LIST

List of used sources

- 1 Slepov, N.N. Modern technologies of digital fiber-optic communication networks (ATM, PDH, SDH, SONET and WDM) / N.N. Slepov. – 2nd corrected edition. – M.: Radio i Sviaz, 2003. – 468 p.
- 2 Dmitriev, S.A. Fiber-optic technologies: modern status and new prospects / S.A. Dmitriev, N.N. Slepov. 3^d edition, revised and enlarged – M.:Technosphere, 2010. – 608 p.
- 3 Listvin, A.V. Reflectometry of optical fiber / A.V. Listvin, V.N. Listvin. – M.: LESARart, 2005. – 208 p.
- 4 Ivanov V.I. Optical digital telecommutation systems: lecture notes / V.I. Ivanov. – Samara.: PSUTI, 2011. – 2012 p.
- 5 The method of detection of fiber-optic transmission line segment with higher lateral radiation: pat. 2252405 of the Russian Federation, IPC G 01 M 11/00 / V.V. Shubin; applicant Federal state unitary enterprise Russian Federal Nuclear Center - All-Russian Research Institute of Experimental Physics – FSUE RFNC-ARIEP – No. 2003110558-28; applied 14.04.2003; published 20.05.2005 // Official journal / Russian Federal Service for Intellectual Property, Patents and Trademarks. – 2005. – No. 14. – 6 p.
- 6 The method of detection of slow optical radiation output through lateral surface of fiber-optic communication line: pat. 2251810 of the Russian Federation, IPC H 04B 10/08 / V.V. Shubin, S.I. Ovechkin, S.N. Ivchenko; applicant Federal state unitary enterprise Russian Federal Nuclear Center - All-Russian Research Institute of Experimental Physics – FSUE RFNC-ARIEP – No. 2003101467/09; applied 20.01.2003; published 10.05.2005 // Official journal / Russian Federal Service for Intellectual Property, Patents and Trademarks. – 2005. – No. 13. – 7 p.
- 7 The methods of data protection from unauthorized access in fiber-optic communication lines: pat. 2234194 of the Russian Federation, IPC H 04B 10/00 / S.N. Popov, V.V. Shubin; applicant Federal state unitary enterprise Russian Federal Nuclear Center - All-Russian Research Institute of Experimental Physics – FSUE RFNC-ARIEP – No. 4525936/09; applied 29.12.1999; published 10.08.2004 // Official journal / Russian Federal Service for Intellectual Property, Patents and Trademarks. – 2004. – No. 22. - 5 p.
- 8 Kholevo, S.A. Introduction in quantum information theory / S.A. Kholevo. – M.: MCCME, 2002. – 128 p.

- 9 Gulakov, I.R. Photodetectors of quantum systems: monograph / I.R. Gulakov, A.O. Zenevich, - Minsk: EI HSCC, 2012. – 276 p.
- 10 Blizniuk, V.V. Quantum radiation sources / V.V. Blizniuk, S.M. Gvozdev. – M.: “VIGMA”, 2006. – 400 p.
- 11 Kilin, S.Y. Quantum cryptography: ideas and practice / S.Y. Kilin; edited by S.Y. Kilin, D.B. Khoroshko, A.P. Nizovtsev. – Minsk: Belorusskaya Nauka, 2007. – 391 p.
- 12 The method of photodetector quantum efficiency determination: pat. 11775 of the Republic of Belarus, IPC(2006) G 01R 31/00 / I.R. Gulakov, A.O. Zenevich; applicant Belarusian State University. – No. a 20070871; applied 11.07.07; published 30.04.09 // Official journal / National Center of Intellectual Property. – 2009. – No. 2. – 6 p.
- 13 Sidorik V.V. Physics in computer models: study guide for the students of higher technical educational institutions / V.V. Sidorik, I.Z. Jilavdari. – Mn.: SPLLC “PION”, 1999. – 248 p.
- 14 Introduction into mathematical modeling: study guide / V.N. Ashihmin [and others]; edited by P.V. Trusov. – M.: Logos, 2005. – 440 p.
- 15 Photon // Information bulletin. [Electronic source]. – Access mode: [http://www.fotonexpress.ru/pdf/PE_i\(22\).pdf](http://www.fotonexpress.ru/pdf/PE_i(22).pdf). – Access date: 10.04.2015.
- 16 Portnov, E.L. Principles of primary networks and optical cable communication systems design: study guide for higher educational institutions / E.L. Portnov. M.: Goriachaya Liniya – Telecom, 2009. – 550 p.
- 17 Searching Full Text Patents // Secure fiber optic data transmission system. [Electronic source]. Access mode: <http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&p=1&u=%2Fnetahtml%2FPTO%2Fsearchbool.html&r=21&f=G&l=50&col=AND&d=PTXT&s1=4435850&OS=4435850&RS=4435850>. – Access date: 10.04.2015
- 18 Optical receiver with the device controlling operation of fiber-optic communication line // Patent of France No. 2568431. [Electronic source]. – Access mode: - <http://patentdb.su/3-1711341-ustrojstvo-kontrolya-opticheskoy-linii-svyazi.html>. – Access date: 10.04.2015.
- 19 Optical communication channel capacity during message transmission in separate photons / A.O. Zenevich [and others] // Electrosvyaz. – 2010. – No. 10. – P.14-16.
- 20 Avalanche photodetectors in photon counting mode for the systems of confidential data transmission / I.R. Gulakov [and others] // Vetsniksvyazi. – 2014. No. 3 (125). – P. 46-49.
- 21 Molotkov, S.N. Multiplex quantum cryptography with time encoding without interferometer / S.N. Molotkov // JETP. -2004. – v.79. – issue 79. – P.554-559.

22 Device for data transmission through optical communication channel: pat. 18621 of the Republic of Belarus, IPC (2013.01) H 04B 10/50, H 04B 10/60 / I.R.Gulakov, A.O. Zenevich, A.M. Timofeev; applicant Belarusian State University - No. a 20120683; applied 03.05.2012; published 30.10.2014 // Official journal / National Center of Intellectual Property. – 2014. No. 5. – P. 111.

23 Transmission systems and media, digital systems and networks // Characteristics of a dispersion-shifted, single-mode optical fibre and cable. [Electronic source]. – Access mode: <http://www.itu.int/rec/T-REC-G.653/en>. – Access date: 11.04.2015.

24 Transmission systems and media, digital systems and networks // Characteristics of a cut-off shifted single-mode optical fibre and cable. [Electronic source]. – Access mode: <http://www.itu.int/rec/T-REC-G.654/en>. – Access date: 11.04.2015.

25 Transmission systems and media, digital systems and networks // Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable. [Electronic source]. – Access mode: <http://www.itu.int/rec/T-REC-G.655/en>. – Access date: 11.04.2015.

26 Transmission systems and media, digital systems and networks // Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport. [Electronic source]. - Access mode: <http://www.itu.int/rec/T-REC-G.656/en>. – Access date: 11.04.2015.

27 Transmission systems and media, digital systems and networks // Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network. [Electronic source]. - Access mode: <http://www.itu.int/rec/T-REC-G.657/en>. – Access mode: 11.04.2015.

28 Gulakov, I.R. Photon counting method in Fiber-optic measurements / I.R. Gulakov, S.V. Kholondyrev. – Minsk: Universitetskoe, 1989. 256 p.

29 Optical communication channel capacity during message transmission by means of low-power signals / I.R. Gulakov [and others] // BSUIR reports. – 2009. No. 8(46). P. 22-27.

30 Goldanskiy, V.I. Indication statistics during nuclear particles registration / V.I. Goldanskiy, A.V. Kutsenko, M.I. Podgoretskiy; edited by B.L. Livshits. – M.: State publishing house of physical and mathematical literature, 1959. – 411 p.

31 Perina, Y. Quantum statistics of linear and non-linear optical phenomena: transl. from English / Y. Perina. – M.: Mir, 1987. – 369 p.

32 Study of data transmission rate through optical communication channel with the receiver based on photon counter / I.R. Gulakov [and others] // Autometry. – 2011. v. 47. – No. 4. – P. 31-40.

33 Laser transmitting device: pat. 2247452 of the Russian Federation, IPC H 01S 3/10 / A.A. Chasovskoy; applicant Chasovskoy Alexander Abramovich – No. 2003113812/28; applied 12.05.2003; published 27.02.2005 // Official journal / Federal Service for Intellectual Property, Patents and Trademarks. – 2005. No. 6. – 5 p.

34 Fiber-optic interferometer and fiber-optic piezoelectric converter: pat. 2100787 of the Russian Federation, IPC G 01J 9/02, G 02F 1/01 / V.M. Gelikonov, G.V. Gelikonov, N.D. Gladkova, V.I. Leonov, F.I. Feldstein, A.M. Sergeev; applicant Nizhny Novgorod Center for High Technologies Development, Institute of Applied Physics of Russian Academy of Sciences, GelikonovGrigoriyValentinovich, GelikonovValentinMikhailovich, Gladkova Natalia Dorofeevna, Leonov Vladimir Innokentevich, Sergeev Alexander Mikhailovich, Feldstein PhelixIsaakovich – No. 95102921/25; applied 01.03.1995; published 27.12.1997 // Official journal / Federal Service for Intellectual Property, Patents and Trademarks. – 1997. – No. 36. – 7 p.

List of publications of the degree-seeking student

1A Timofeev, A.M. Mathematical model of single quantum system of fiber-optic communication / A.M. Timofeev, Al-Dulaime Mustafa RokanKhalaf, Mohammed Jawad Ali Abdulmohsen, E.I. Shulezhko // Technical Means of Data Security: report materials of XIII International Belarusian and Russian Scientific and Technical Conference, Minsk, June 4-5, 2015 / Belarusian State University of Informatics and Radioelectronics; editorial board: L.M. Lynkov [and others]. – Minsk: BSUIR, 2015. – P. 20.

2A Timofeev, A.M. Capacity of fiber-optic communication channel for confidential data transmission / Al-Dulaime Mustafa RokanKhalaf, Mohammed Jawad Ali Abdulmohsen, V.I. Chvanov, A.P. Chemerko // Modern Communication Facilities: report materials of XX International Scientific and Technical Conference, Minsk, October 14-15, 2015 / Higher State College of Communications; editorial board: A.O. Zenevich [and others]. – Minsk, 2015. – P. 167-168.