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THERMOMECHANICAL INFLUENCE ON OPTICAL FIBERS DURING THE PRODUCTION AND OPERATION OF OPTICAL CABLE

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ТЕРМОМЕХАНІЧНИЙ ВПЛИВ НА ОПТИЧНІ ВОЛОКНА В ПРОЦЕСІ ВИГОТОВЛЕННЯ ТА ЕКСПЛУАТАЦІЇ ОПТИЧНОГО КАБЕЛЮ

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ТЕРМОМЕХАНИЧЕСКОЕ ВЛИЯНИЕ НА ОПТИЧЕСКИЕ ВОЛОКНА В ПРОЦЕССЕ ПРОИЗВОДСТВА И ЭКСПЛУАТАЦИИ ОПТИЧЕСКОГО КАБЕЛЯ

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Abstract. In this work the research shows that the maintenance of the mechanical integrity of optical fibers (OF) requires the determination of thermomechanical effects on OFs during the production and operation of an optical cable (OC) in order to prevent the appearance of excessive longitudinal mechanical loads on them. Generally, in the work situations are determined and analyzed in which the mechanical loads can act on optical fibers during the process of cable production and operation. It is established that due to the lower value of the thermal linear expansion coefficient (TLEC) compared with the similar parameter of optical module tube (OMT), optical fibers become considerably longer than the OMT with its contraction during cooling in production. The materials of optical module tube used in the work were polybutylene terephthalate, polyamide and polycarbonate. Calculations of the relative linear change of the OF length compared with the OMT length during its cooled showed that it significantly depends on the material of optical module tube. This causes the appearance of macrobends and may increase the value of the OF attenuation coefficient, This requires the appropriate adjustment of the speed of the sendres with the fiber coils, as well as the choice of the diameter and material of the optical module tube. On the other hand, the increase of temperature in the OC construction can lead to excessive stretching forces on the fibers which will cause the appearance of the conditions for OF rupture. This requires the consideration and creation of the necessary excess fiber length during its integration into the OMT in cable production. Research has shown that the material type of the OMT does not significantly affect on the relative linear change of the OF length compared with the length of the OC. Therefore, the way of determining the initial length of the OF in the OMT after thermal decomposition is proposed in the work, thus avoiding the appearance of excessive tensile strength.

Key words: optical cable, elements of cable construction, relative linear change of the optical fiber length, optical module tube, thermal linear expansion coefficient.

Анотація. Проведені в статті дослідження показали, що забезпечення механічної цілісності оптичних волокон (ОВ) потребує визначення термомеханічних впливів на ОВ при виробництві та експлуатації оптичного кабелю (ОК) з метою недопущення появи надмірних поздовжніх механічних навантажень на них. У статті встановлено, що через менше значення температурного коефіцієнта лінійного розширення (ТКЛР) оптичні волокна стають значно довшими за трубку оптичного модуля (ТОМ) при його усадці під час охолодження на виробництві. В якості матеріалів ТОМ у статті використовувалися полібутилентерефталат, поліамід, полікарбонат. Розрахунки відносної лінійної зміни довжини ОВ порівняно з довжиною ТОМ при охолодженні показали, що вона значно залежить від матеріалу ТОМ. Це викликає появу макровигинів та може призвести до зростання значення коефіцієнта загасання ОВ, що потребує відповідного налаштування швидкості обертання віддавачів з котушками волокна, а також вибору діаметра та матеріалу трубки ОМ. З іншого боку, підвищення температури може призвести в конструкції ОК до появи надмірних розтягувальних сил на волокна, що приведе до появи умов розриву ОВ. Це потребує необхідності врахування та створення необхідної надлишкової довжини волокна при його інтеграції в ТОМ при виробництві. Дослідження показали, що тип матеріалу ТОМ не впливає суттєво на відносну зміну лінійної довжини ОВ порівняно з довжиною ОК. Тому у статті запропоновано спосіб визначення початкової довжини ОВ в ТОМ після термічної усадки, що дозволить уникнути появи надмірних сил розтягу.

Ключові слова: оптичний кабель, елементи конструкції кабелю, відносна лінійна зміна довжини оптичного волокна, трубка оптичного модуля, температурний коефіцієнт лінійного розширення.

Аннотация. Проведенные в статье исследования показали, что обеспечение механической целостности оптических волокон (ОВ) требует определения термомеханических воздействий на ОВ при производстве и эксплуатации оптического кабеля (ОК) с целью недопущения появления чрезмерных продольных механических нагрузок на них. В статье доказано, что через меньшее значение температурного коэффициента линейного расширения (ТКЛР) оптические волокна становятся значительно длиннее трубки оптического модуля (ТОМ) при его усадке во время охлаждения на производстве. В качестве материалов ТОМ в статье использовались полибутилентерефталат, полиамид, поликарбонат. Расчеты относительного линейного изменения длины ОВ сравнительно с длиной ТОМ при охладжении показали, что оно значительно зависит от материала ТОМ. Это вызывает появление макроизгибов и может привести к росту значения коэффициента затухания ОВ, что требует соответствующей настройки скорости вращения отдатчиков с катушками волокна, а также выбор диаметра и материала трубки ОМ. С другой стороны повышение температуры может привести в конструкции ОК к появлению чрезмерных растягивающих сил на волокна, что приведет к появлению условий разрыва ОВ. Это требует необходимости учета и создания необходимой избыточной длины волокна при его интеграции в ТОМ при производстве. Исследования показали, что тип материала ТОМ не влияет существенно на относительное линейное изменение длины ОВ сравнительно с длиной ОК. Поэтому в статье предложен способ определения начальной длины ОВ в ТОМ после термической усадки, что позволит избежать появление избыточных сил растяжения.

Ключевые слова: оптический кабель, элементы и материалы конструкции кабеля, относительное линейное изменение длины оптического волокна, трубка оптического модуля, температурный коэффициент линейного расширения.

Creation of reliable, economical, easy-to-produce optical cable (OC) designs which would satisfy the requirements of their operating conditions and were able to ensure the integrity of the optical fibers (OF) and stability of their transmission parameters is the task of the cable industry. Effective technical operation of optical cables in a wide temperature range, typically from 40 °C to + 70 °C [1], requires, firstly, mechanically strong and, consequently, reliable designs. The designing and manufacturing of OC require the highest quality of materials for cable elements and take into account all physical and thermo-mechanical processes that may occur in its elements.

One of the external influencing factors in OC design is the reaction to different temperatures in the manufacturing process of the structural elements of the cable (in particular, optical fibers, tubes of optical modules (TOM), central and peripheral strength elements, protective hose, etc.) as well as the environment during operation. As a result of the difference between the values of the thermal linear expansion coefficient (TLEC) of the cable elements, under the influence of temperature in its design, there is a linear change of the lengths of these elements and therefore their tension and strained-deformed state are formed. Such an OC state can lead to the appearance of critical conditions in the OF. The extreme tensile or compressive forces due to excessive increase or decrease of the fibers length compared to the length of optical module tube (OMT) in which they are enclosed can cause unpredictable changes of the transmission parameters (attenuation and dispersion coefficient of optical signal), premature aging and failure of the entire optical fiber transmission line. These effects lead to providing a minimum service cable life 30 years becoming impossible [1].

At present, the technical and scientific literature do not fully contain the data of the thermomechanical effects on optical fibers during the production and operation of an optical cable.

In the works, for example [2 – 5], the method for determining the TLEC in a whole cable, estimation of change the relative elongation and equivalent mechanical stress of the cable design using elements with different materials under the influence of operation temperature are shown.

However, the study and determination of change of the OF length in the optical module tube of the OC design and the thermomechanical effect on optical fibers during the process of production and operation of the cable in these works were not carried out.

The purpose of this work is to substantiate the process of thermomechanical influence on the optical fibers located in the OC core during the process of production and operation of the optical cable and the provision of practical recommendations for the ensuring the mechanical integrity of the OF at the considered stages at different temperatures.

As is known, optical fibers are not manufactured in Ukraine. In the meantime, ready-made OFs of different manufacturers, and therefore with different chemical components, are placed in the optical cables core with different designs and purposes. In such conditions, the main task of cable manufacturing plants (for example, the domestic PC "PivdenKabel" and PC "Odeskabel") is turn out OC designs that would ensure the mechanical integrity of optical fibers in all modes of cable operation, as well as in its manufacturing, laying and installation.

Analyzing the state of optical fibers in the preparation of the optical module tube and in the structure of the OMT in the cable the following main situations in which the mechanical tension can be applied to the OF at the stages of OC manufacturing and operation are distinguished:

1. The placement of a beam of optical fibers into a newly-formed melt material in an OMT extruder and further cooling of the optical module (OM),

2. The effect of stretching, bending loads, etc. during the laying, installation and operation of optical cables, and

3. The effect on the optical cable the temperature of the operation zone, which causes the appearance of their tensile or compressive loads (states) in its elements, is proportional to the value of the TLEC of their materials and leads to the free transfer of the OF beam inside the OMT by reducing or increasing its excess length.

It is obvious that p. 1 and p. 3 relate to the stage of OC production in the manufacturer's plant and the subsequent exploitation of the cable, and it requires consideration of the thermomechanical influence on the OF for the design of high-quality cable products, as well the inadmissibility of the appearance of critical moments in terms of ensuring the integrity of the fibers.

Thus, at the stage of OC production, there is a melting of the material of the future structural element, which is accompanied by its subsequent contraction and, as a result, by changing the geometric dimensions (in particular, length). An example of this process is the replacement of OFs beam inside the optical module tube which formed by the molten material. After the extruder, the OF is becoming the formed TOM. The optical module passes through a cooling bath, where the OM is cooled by circulating water. In this case, the OMT material, when cooled, contracts and decreases in length. Optical fibers at cooling OMT material are placed inside the module by helicoid.

As is known from [2], under the action of temperature linear length of OC elements varies (increases or decreases in relation to the initial length) in proportion to the value of the thermal linear expansion coefficient of material by expression

$$\Delta l = l_0 \cdot \Delta T \cdot TLEC, \quad (1)$$

where Δl – absolute linear change of the element length, mm; l_0 – the initial length of the OC element, mm; ΔT – difference of temperatures, K; $TLEC$ – thermal linear expansion coefficient of the material of the OC element, K^{-1}.

The OC design should be projected taking into account the minimum interaction between the materials of the OF and other elements at the manufacturing and operation, as well as when changing their sizes under the influence of the environment with different temperatures [2].

The presence in the OC design of elements made of materials with different *TLEC* causes change in geometric dimensions of the OF, in particular its length [5].

As mentioned earlier, cooling the OM from its melting temperature of the OMT material to its coolant temperature leads to decreasing the length of the module tube. This leads to differences in the lengths of the OF, laid inside the tube, and the finite length of the OMT. In particular, due to the fact that the *TLEC* of the OMT material is greater than *TLEC* of OF in 10^2 to 10^3 times, the module tube will decrease more than the fiber. Because of an initial equity of their lengths, compression forces of optical fiber will occur and OF is placed on a helicoid. The above may result in additional losses of the transmitted optical signal due to the occurrence of significant macrobends. To eliminate such situation there is a need for determining the change of lengths of OMT and OF at cooling and consideration of the final difference of their lengths that affects the choice of material and OMT and its internal diameter.

As noted, the thermal linear expansion coefficient characterizes the relative change of the length of the OC element, depending on the temperature change [6]

$$\varepsilon = \frac{\Delta l}{l} = TLEC \cdot \Delta T \ , \qquad (2)$$

where ε – relative elongation of the OC element; Δl – absolute elongation of OC element, m; l – initial length of the cable element, m; $TLEC$ – thermal linear expansion coefficient of the cable element material K^{-1}; ΔT – change of temperature, K.

At the equality of initial lengths of OF and OMT on the input of tube, the relative change of length of optical fiber compared with optical module tube at temperature acting is determined by the expression [6]

$$\varepsilon_{\text{OF,OMT}} = \Delta TLEC_{\text{OF,OMT}} \cdot \Delta T = \left(TLEC_{\text{OF}} - TLEC_{\text{OMT}}\right)\left(t - t_0\right), \qquad (3)$$

where $\varepsilon_{\text{OF,OMT}}$ – the relative change in OF linear length compared to the OMT length ; $\Delta TLEC_{\text{OF,OMT}}$ – TLEC of optical fiber materials and OMT, K^{-1}; $TLEC_{\text{OF}}, TLEC_{\text{OMT}}$ – thermal linear expansion coefficients of OF and OMT respectively, K^{-1} ; t – estimated temperatures of environment, K; t_0 – temperature in which the initial lengths of OF and OMT are identical, K.

Table 1 shows the melting temperature of materials for the manufacture of an optical module tube [6, 7].

Table 2 shows the typical values of the *TLEC* of the materials of the OF and OMT which used in the manufacture of the optical cable [6, 7] and presents the results of calculation the relative change of the linear length of the OF compared with the length of the OM tube.

Using expression (3), defined the change of the OF length compared with the OMT length for different materials at cooled, for example, from the melting temperature of the material to 20°C. Results of calculation $\varepsilon_{\text{OF,OMT}}$ given in Table 2 for the three types of OMT material.

Table 1 – Melting temperature of materials for the manufacture of an optical module tube

Cable element	Material	Melting temperature, ° C
	polybutyleneterephthalate	> 250

Optical module tube	polyamide	> 220
	polycarbonate	> 280

Table 2 – Results of the calculation of the relative change of the OF linear length to the length of the optical module tube

Cable element	Material	TLEC , K^{-1}	Relative change of the linear length of the OF compared with the length of the OMT $\varepsilon_{OF,OMT}$, %
Optical fiber	quartz glass	$5,5 \cdot 10^{-7}$	-
Optical module tube	polybutylene terephthalate	$1,5 \cdot 10^{-4}$	3,4
	polyamide	$7,8 \cdot 10^{-5}$	1,8
	polycarbonate	$6,5 \cdot 10^{-5}$	1,5

Results of calculation $\varepsilon_{OF,OMT}$ show that with cooling of the material of the optical module tube the OF beam becomes lengthened (at an equality of initial lengths of OF and OMT), causing its compression inside the module tube and the formation of macrobends. This requires correction lengths of OF while they lay in OMT for ensuring the speed of rotation from the sender with fiber coils or by choosing a larger internal diameter of the OM tube.

The magnitude of the OF length excess, which must be created in the OMT, depends, first of all, on the magnitude of the longitudinal loading and the influence of temperature, which leads to increase or decrease of the length of the entire cable structure. At the same time in the OC design the elements are located in different state of stress, so when OC designing it is necessary to determine the total *TLEC* of the entire cable.

It is obvious that due to the difference of the *TLEC* values of the OF and OC in general, at changing the temperature their lengths will vary in different ways. Thus, optical fibers in the OC core will be subject to the forces of tension or compression when changing the temperature of the environment, similar to the situation of their integration in the OMT.

As a rule, OC construction can contains the elements with different (positive and negative) values of *TLEC*, then reaction of cable to temperature change is a complex process and requires the definition of equivalent thermal expansion coefficient of all elements of the cable $TLEC_{OC}$ in the first approximation by expression [5]

$$TLEC_{\text{OC}} = \frac{\sum_{i=1}^{n} TLEC_i E_i S_i}{\sum_{i=1}^{n} E_i S_i} \,, \tag{4}$$

where $TLEC_{\text{OC}}$ – equivalent thermal expansion coefficient of all cable elements, K^{-1}; $TLEC_i$, E_i, S_i – TLEC, K^{-1}, Young's modulus, kg/mm^2, and the cross-sectional area, mm^2, of the *i*- th element of the cable, respectively ; *n* – the number of cable elements that take mechanical loading.

To take into account the change of the length of the OF in relation to the length of the OMT, it is possible to express (3) represented in form

$$\varepsilon_{\text{OF,OC}} = \Delta TLEC_{\text{OF,OC}} \cdot \Delta T = \left(TLEC_{\text{OF}} - TLEC_{\text{OC}}\right)\left(t - t_0\right), \tag{5}$$

where $\varepsilon_{\text{OF,OC}}$ – relative linear change of the length of OF compared to length of OMT; $\Delta TLEC_{\text{OF,OC}}$ – difference of TLEC material of optical fiber and OC, K^{-1}; $TLEC_{\text{OF}}$, $TLEC_{\text{OC}}$ – thermal linear expansion coefficient of OF and equivalent *TLEC* of optical cable, respectively, K^{-1} ; *t* – calculation temperatures, K; t_0 – initial temperature, K.

In the work as an object of research the OC, which contains in its single-mode modular structure: 6 OMT, spiral-wrapped around a central fiberglass rod, covered aramid threads and protective hose is selected. The parameters and elements of such OC are given in Table 3.

As an example, in this paper a linear change of length of the OF in relation to the length of the OMT in OC, in the core of which they are located, with the parameters of the cable elements according to Table 3 and in the temperature range from -40 °C to + 70 °C, was determined. Results of calculation $\varepsilon_{\text{OF,OC}} = f(t)$ presented in the form of Table 4.

This paper studies were performed with the following assumptions:

1. Due to small values, the change of elements' size in the OC design in radial direction under the influence of temperature was not considered.
2. In OC designs the length of the OM tube and OF at temperature 20 °C were equal to each other, that is the length of the optical fiber (or beam of optical fibers) is equal to the length of the axial line of the optical module.

Table 3 – Characteristics of selected elements OC construction

№	Elements of cable design	Parameters of OC elements
1	Central strength element: – material; – diameter d_{CSE}, mm;	 fiberglass rods 2,5

	– TLEC, 1/K; – Young's module, N/mm^2	$6{,}6 \cdot 10^{-6}$ 50 000
2	Optical module tube: – diameter d_{OMT} , mm; – quantity of OMT, pcs.	 2,3 6
3	Peripheral strength element: – material; – linear density LD, dtex; – TLEC, 1/K; – the number of threads in the layer, pcs.	 aramid threads 8750 $-3 \cdot 10^{-6}$ 12
4	Protective hose: – material; – radial thickness, mm; – TLEC, 1/K; – Young's module, N/mm^2	 polyethylene 1.6 $3{,}2 \cdot 10^{-4}$ 621

Table 4 – Results of calculation of linear change of the length of OF relative to the length of the OMT in the OC at the temperature range (-40 °C...+70 °C)

№	Material of OMT	Value of value $\varepsilon_{OF,OC} \cdot 10^{-4}$, at temperature t , °C					
		-40	-20	0	+20	+50	+70
1	polybutyleneterephthalate	8,45	5,63	2,82	0	-4,22	-7,04
2	polyamide	8,44	5,62	2,81	0	-4,22	-7,03
3	polycarbonate	8,38	5,58	2,79	0	-4,19	-6,98

As shown at the bottom of the Table 4 the material type of OMT does not significantly affect to the relative change of the linear length of OF compared with the length of the OC. A minus sign in the value $\varepsilon_{OF,OC}$ indicates that at given temperature the OF that have an equally initial length with OMT, will be shorter relative to the module tube. Therefore, they will be under the action of tensile forces that can cause the appearance of microbends in the glass – the conditions for the discontinuity of the optical fiber [8]. For given materials and elements of OC design the increasing of temperature to +70 °C leads to increasing the cable length compared with OF at 0,07 %, and decreasing the temperature to -40 °C leads to decreasing of OC 0,084 %.

Analyzing the change of OF length in OMT it can be concluded that the action of positive temperature on whole OC is more critical than the action of negative temperatures due to the appearance of possibilities to OF rupture.

It follows that to prevent such forces as OC tension, which can lead to OF rupture, there is a need to create an initial excess OF length equal , for example, 0,07 %. In the real situation, the OFs are freely located inside the OMT, and in the case of longitudinal loads, they begin to move to the center of the cable, while losing their excess length. The value of such a permissible relative elongation ε_{pe}, which is provided by the free laying of the OF in the OC design, at temperature 20 °C is determined by expression, for example, in [3, 4]. Therefore, to determine initial length of OF in OMT after thermal contraction, that allow to the appearance of tensile strength, we use the expression:

$$\varepsilon_{\text{OF,OMT}} = \varepsilon_{\text{OF,OC}}(70°C) \ , \tag{6}$$

where $\varepsilon_{\text{OF,OMT}}$ – relative linear elongation of OF compared to OMT; $\varepsilon_{\text{OF,OC}}(70°C)$ – relative change of the linear length of the OF to the length of the OC at a temperature +70 ºC.

Conclusions:

1. Implemented research shows that for ensuring the mechanical integrity of OF it is necessary to determine thermomechanic influences on optical fibers during the production and exploitation of OC to prevent the appearance of emergence excessive longitudinal mechanical loads on them.

2. The results of calculations of change of OF linear length compared to the length of the OMT during the production of the cable and relative linear length of the OC during its operation allowed that:

– due to the smaller value of the *TLEC* the optical fiber becomes considerably longer than the optical module when it is contracted. This results in the appearance of macrobends and can increase the value of the attenuation coefficient, which requires adjustment of the rotation speed of the senders with OF coils, as well as the choice of the diameter and material of the OM tube;

– the effect of increasing the temperature on the finished structure of the OC can lead to excessive tensile forces on the fibers, which will cause the appearance of the conditions of the gap in agents.This requires the consideration and creation of the necessary excess fiber length when integrated into the OMT in production.

3. The proposed expression for definition the excessive length of OF in OMT that considered thermomechanical impact on fibers during production and operation of a cable and

provide the avoidance of the appearance of excessive longitudinal stretching forces on fibers and can be recommended for usage at cable manufacturing.

REFERENCES:

1. "Kerivnyctvo shhodo budivnyctva linijnyh sporud volokonno-optychnyh linij zv'jazku": KND 45-141-99.: 1999 y. [Chynnyj vid 01.02.2000]. K.: Derzhkomzv'jazku ta informatyzacii' Ukrai'ny, 2000. 150 s. – (Nacional'nij standart Ukrai'ny).
2. Larin Yu.T. "Opticheskie kabeli: metodyi rascheta konstruktsii. Materialyi. Nadezhnost i stoykost k ionizirovannomu izlucheniyu" Larin Yu.T. M.: Prestizh, 2006: 308.
3. Bondarenko O.V. "Doslidzhennja mehanichnoi' naprugy v dielektrychnomu samonesuchomu volokonno-optychnomu kabeli pid dijeju roztjaguval'nyh zusyl' ta temperatury" O.V. Bondarenko, D.M. Stepanov, O.M. Vlasov, A.F. Nazarenko. Naukovi praci Donec'kogo nacional'nogo tehnichnogo universytetu. Serija: "Obchysljuval'na tehnika ta avtomatyzacija". Donec'k, 2011. Vyp. 20 (182): 174-179.
4. Bondarenko O.V. "Vyznachennja naprugy ta strily provysannja v samonesuchomu optychnomu kabeli pid dijeju navantazhen' ta zminy temperatury pry ekspluatacii" O.V. Bondarenko, O.M. Vlasov, D.M. Stepanov Mizhnarodnyj naukovo-tehnichnyj zhurnal «Vymirjuval'na ta obchysljuval'na tehnika v tehnologichnyh procesah». – Hmel'nyc'kyj, 2011. – Vyp. № 1: 53-58.
5. Bondarenko O.V. "Metod opredeleniya temperaturnogo koeffitsienta lineynogo rasshireniya i modulya Yunga dielektricheskogo opticheskogo kabelya" Bondarenko O.V. NaukovI pratsI Donetskogo natsIonalnogo tehnIchnogo unIversitetu. SerIya «ElektrotehnIka I energetika». Donetsk, 2009. Vip. № 9 (158): 25-29.
6. Malke, G., and P. Gessing ''Volokonno-opticheskie kabeli: Osnovy proektirovanija kabelej, planirovanie sistem'' Novosibirsk: Izdatel, 1997. Print.
7. Katok V.B. Volokonno-optychni linii' zv'jazku / V.B. Katok, I.E. Rudenko, P.M. Odnorog. K.: 2016: 445.
8. Yutaka Mitsunaga , Yutaka Katsuyama , Hirokazu Kobayashi , Yukinori Ishida. Journal of Applied Physics. 1982. Vol .53, №7: 4847-4853.

ЛІТЕРАТУРА:

1. Керівництво щодо будівництва лінійних споруд волоконно-оптичних ліній зв'язку: КНД 45-141-99.: 1999 р. – [Чинний від 01.02.2000]. – К.: Держкомзв'язку та інформатизації України, 2000. – 150 с. – (Національній стандарт України).
2. Ларин Ю.Т. Оптические кабели: методы расчета конструкции. Материалы. Надежность и стойкость к ионизированному излучению / Ларин Ю.Т. – М.: Престиж, 2006. – 308 с.: ил.
3. Бондаренко О.В. Дослідження механічної напруги в діелектричному самонесучому волоконно-оптичному кабелі під дією розтягувальних зусиль та температури / О.В. Бондаренко, Д.М. Степанов, О.М. Власов, А.Ф. Назаренко // Наукові праці Донецького національного технічного університету. – (Серія: Обчислювальна техніка та автоматизація). – Донецьк, 2011. – Вип. 20 (182). – С. 174 – 179.
4. Бондаренко О.В. Визначення напруги та стріли провисання в самонесучому оптичному кабелі під дією навантажень та зміни температури при експлуатації / О.В. Бондаренко, О.М. Власов, Д.М. Степанов // Міжнародний науково-технічний журнал «Вимірювальна та обчислювальна техніка в технологічних процесах». – 2011. – Вип. № 1. – С. 53 – 58.
5. Бондаренко О.В. Метод определения температурного коэффициента линейного расширения и модуля Юнга диэлектрического оптического кабеля / Бондаренко О.В. // Наукові праці Донецького національного технічного університету. – (Серія: «Електротехніка і енергетика»). – Донецьк, 2009. – Вип. № 9 (158). – С. 25 – 29.
6. Мальке Г. Волоконно-оптические кабели: Основы проектирования кабелей, планирование систем / Г. Мальке, П. Гессинг. – Новосибирск: Издатель, 1997. – 264 с.
7. Каток В.Б. Волоконно-оптичні лінії зв'язку / В.Б. Каток, І.Е. Руденко, П.М. Одноріг. – К.: 2016. – 445 с.
8. Yutaka Mitsunaga, Yutaka Katsuyama, Hirokazu Kobayashi, Yukinori Ishida // Journal of Applied Physics. –1982. – Vol.53, №7. – P.4847-4853.

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