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Analysis of some methods for increasing the reliability of fiber-optic data transmission systems

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ABSTRACT

This article provides an overview of modern methods for increasing the reliability of fiber-optic information transmission systems. The study of reliability is an important aspect in the development of telecommunication networks, especially in the context of the growing demand for high-speed and continuous data transmission. The article examines various techniques and approaches, including improvements to physical infrastructure, monitoring and control techniques, and the use of advanced error detection and correction algorithms.

Keywords: Fiber optic systems, reliability, optical fiber, receiver and transmitter of optical signals.

Introduction

The need for growth in information flow stimulates the development of optical communications designed to increase data transfer. Technological evolution in response to growing Internet traffic is leading to the creation of high-bandwidth communication systems. Fiber-optic communication systems with data transfer rates exceeding 1 Tbit/s require more complex solutions than the use of discrete optical components. Transmission systems exceeding 1 Pb/s plan to implement a significant number of spatial channels [1]. This article provides a review of studies devoted to the analysis of factors affecting the reliability of fiber-optic information transmission systems, and discusses methods for improving their performance.

A fiber-optic information transmission system whose function is to transmit a signal with high reliability and accuracy is a set of optical devices and optical transmission lines designed for generating, processing and transmitting optical signals. The optical signal is modulated radiation from a laser or LED.

Materials and Methods

The reliability of the system naturally depends on the reliability of the individual components. A fiber-optic communications infrastructure is a system that includes an optical signal source, a fiber-optic cable, and an optical receiver. Additional components include optical amplifiers, connectors, couplers, couplers, regenerators and other passive components and active photonic devices. The reliability of a fiber-optic system is the ability of line cable components and station equipment to maintain stable and continuous operation over a certain period of time, to maintain established technical parameters within specified values.

In the field of fiber optic transmission, key technical parameters include primary standards aimed at measuring and characterizing fundamental physical parameters of fibers such as attenuation, bandwidth, and optical power levels and spectral widths [2]. Additionally, component testing standards define test procedures for fiber optic components and establish rules for equipment calibration, while system standards address methods for measuring links and networks.

In modern optical communication systems, information is transmitted using photons, making the optical source a key component in determining system performance. An optical transmitter performs the function of converting an electrical signal into an optical signal and transmitting it through an optical fiber. Devices such as LEDs and laser diodes are widely used in fiber optic systems due to their compact size and energy efficiency. Their optical output power is proportional to the electrical currents introduced into the device.

One of the main problems facing injection lasers is their reliability. Despite extensive research in this area, not all aspects of device failure mechanisms are fully understood. Laser degradation can occur either suddenly or gradually. Sudden degradation is usually caused by mechanical damage, which can lead to complete or partial failure. This process may be related to the intensity of the optical flow within the structure and, therefore, the use of a pulsed laser may limit its occurrence. However, the occurrence of sudden degradation can seriously impact the longevity and performance of the devices. Gradual degradation includes the formation of defects in the active region and degradation of current-holding junctions. These processes are usually accompanied by an increase in the laser threshold current and a decrease in its quantum output [3].

Modeling the performance of a diode laser can be done using a set of equations that describe the interaction between the carrier density (1) and the photon density (2) in the laser cavity. Analysis of these equations will help to understand the influence of various physical parameters on the static and dynamic characteristics of laser radiation [4]:

$$\frac{dN(t)}{dt} = \frac{J}{qd} - \frac{N(t)}{\tau} - 2\Gamma v_g a(N - N_0)P(t) \tag{1}$$

$$\frac{dP(t)}{dt} = 2\Gamma v_g a(N - N_0)P(t) - \frac{P(t)}{\tau_{ph}} + R_{sp} \tag{2}$$

where N(t) - carrier density, P(t) - photon density, v_g - group velocity of the light wave, d - thickness of the active layer, τ - electron lifetime, τ_{ph} - photon lifetime, J - injection current density, R_{sp} is spontaneous emission rate.

The service life of the radiation source is determined using a quantitative indicator of reliability - the average time to failure (t_F), which is based on the assumption of an exponential probability of failure:

$$P_F = \exp(-t/t_F) \tag{3}$$

where P_F - probability of failure.

To identify devices susceptible to sudden degradation, experiments are most often conducted at high temperatures and currents, called burnout or accelerated aging. This method assumes that under load, weak devices fail while others stabilize. The change in operating current at constant power serves as an indicator of degradation. The degradation rate of a laser at elevated temperature is used to estimate its lifetime and mean time to failure. These data are extrapolated at normal temperature using an Arrhenius-type relation [5]:

$$t_F = t_0 \exp(-E_a/k_B T) \tag{4}$$

where k_B - Boltzmann constant, E_a - activation energy, t_0 - constant.

The role of the communication channel is to transmit the optical signal from the transmitter to the receiver without distorting it. The durability of an optical fiber, determined by a set of characteristics, is expressed by the time during which, at given operating voltages, the probability of failure remains within acceptable limits, which depends on the length of the optical fiber, tensile strength, probability of failure, and mechanical characteristics of the optical fiber. Fiber optics theory and manufacturing experience confirm that the mechanical stress of an optical fiber is a key parameter for determining the quality of an optical cable, and for the statistical assessment of its strength, the Weibull law, written as [6]:

$$P(\sigma, L) = 1 - \exp\left[-\frac{L}{L_0}\left(\frac{\sigma}{\sigma_0}\right)^m\right] \quad (5)$$

where L - length of the optical fiber, σ_0, m are the Weibull distribution parameters, L_0 is the length of the optical fiber sample during testing, σ is the tensile strength of the fiber.

The reliability life of an optical fiber is determined by a large number of variables, and these variables differ between static and dynamic tests. For this reason, the formula for determining the average failure time often uses approximations that simplify the process of assessing reliability. The average failure time can be expressed as follows [7]:

$$t_F = \left[\left(\frac{\beta^{m_s}}{L}\ln\frac{1}{P} + \sigma_p^n t_p\right)^{\frac{1}{m_s}} - \sigma_p^n t_p\right]\sigma_\alpha^n \quad (6)$$

where L - fiber length, β - Weibull coefficient, P - probability of failure-free operation, n - dimensionless parameter of sensitivity to tensile force, σ_p - magnitude of the test stress, σ_α - test force, m_s - inertial Weibull parameter, t_p - time.

The level of protection provided by the cable sheath and protective gates at the connection points determines the mechanical reliability during operation.

The optical receiver, including a coupler, a photodetector, and a demodulator, converts the optical signal received from the optical fiber back into an electrical signal. Semiconductor photodiodes are often used as a photodetector because they are compatible with the entire system. The photodetector receives optical pulses containing information and converts them into an electrical signal, which must be a copy of the original one. The resulting electrical signal is usually weak and distorted depending on the nature of the fiber optic channel, so it is further amplified and refined before being transmitted to the output [8]. The conversion of the optical signal into an electrical signal is carried out through a reverse-biased p-n junction, where fast sensitivity, high quantum efficiency and wide bandwidth are important.

The quality of digital data transmission is assessed through indicators such as bit error rate (BER) and quality factor (Q-factor), which reflect the performance of the communication channel. In addition to BER and Q-factor, other metrics are also important, such as optical signal to noise ratio (OSNR) and error vector magnitude (EVM), which quantify the quality of the received signal [9] .

The intensive development of fiber-optic transmission systems (FOTS) of information and increasing requirements for reducing the time of fault detection lead to the need to predict possible problems in order to promptly eliminate them. Table 1 shows some types of malfunctions of fiber-optic transmission systems, the reasons for their occurrence and methods of elimination.

Table 1. Some types of failures in fiber-optic information transmission systems

Types of failures	Reasons	Methods of elimination
Physical damage to fibers	Mechanical impact, construction work, rough laying of fibers, improper laying in the ground or underground pipelines, unfavorable climatic conditions	Regular technical service, use of protective materials during installation, monitoring of infrastructure condition

Electromagnetic influences	Exposure to electromagnetic fields from electrical appliances close to optical fibers	Shielding fibers, distancing from potential sources, using optical amplifiers with high resistance to electromagnetic interference
Equipment failures	Component wear, manufacturing defects, technical failures	Regular inspection and updating of equipment, use of high-quality components, redundancy of key elements
Power issues	Failures in the energy system, power outages	Using redundant power sources
Failures in the automated control system (software)	Cyberattacks, viruses, unauthorized access	Regular software updates, use of modern antivirus protection tools, monitoring network traffic

To increase the productivity and efficiency of FOTS, it is necessary to ensure the reliability of all its components, one of which is various methods for diagnosing elements and components [10-12].

The use of an optical Brillouin scattering amplifier and an active optical filter together makes it possible to linearize the spectral characteristics of the system, which, in turn, increases the length of the regeneration section and, therefore, increases the reliability of data transmission via optical fiber [13,14]

The use of optical amplifiers and fiber lasers doped with rare earth ions leads to an increase in the signal-to-noise ratio, which makes it possible to increase the intermediate distance between regeneration points. This, in turn, reduces the need for intermediate amplifiers and regeneration equipment, which leads to an increase in the mean time between failures and the probability of failure-free operation of the fiber optic communication line [15,16].

Monitoring optical characteristics for high-quality optical signal transmission is a major challenge. These include parameters such as optical power, wavelength, dispersion, signal fading, polarization, frequency modulation, data transfer rate.

The analysis showed that machine learning algorithms are of great importance in the implementation of monitoring and control of fiber-optic communication systems. Algorithms allow you to automatically detect faults, optimize signal transmission parameters and predict possible faults. It also helps predict maintenance needs, optimize power consumption and manage data distribution across the network, resulting in lower costs and increased efficiency.

Conclusion

Analysis of methods for increasing their reliability allows us to identify the main problems and risks, as well as develop effective strategies for preventing and managing them. The use of advanced technologies and algorithms, together with monitoring and control systems, contributes to the creation of more stable and reliable data networks. However, it is important to remember that continuous development and research in this area is necessary to adapt to the ever-changing requirements and challenges facing the telecommunications industry. Only in this way can the efficient functioning of information transmission networks be ensured and the needs of users for reliable and high-speed communications can be met.

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