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Development of a photodetector for an analog extended fiber-optic communication line

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Abstract. Different designs of analog fiber-optic lines (FOCL) for transmitting information at different distances in different frequency ranges are considered. The peculiarities of optical analog signals transmission, which will influence its registration in the FOCL photodetector module, are noted. The format of analog signals to be transmitted over a FOCL over a distance of more than 500 km without the use of optical amplifiers was determined. A photodetector module of the type PDA 400 Thorlabs with a peak response of 0.95 A/W at 1550 nm is considered. The bandwidth of which is from DC to 10 Mhz. Response: from 800 to 1750 nm. Based on the calculation of various parameters of the FOCL and its energy balance, the requirements to the design and characteristics of the photodetector module were determined. A laboratory mockup of the photodetector module was assembled. The results of its operation as a part of the analog FOCL with different ranges of information transmission are presented.

Keywords: Analog optical signal, photodetector, laser radiation, wavelength, line width, dynamic range, registration bandwidth, signal/noise ratio

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Разработка фотоприемника для аналоговой протяженной волоконно-оптической линии связи

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Аннотация. Рассмотрены различные конструкции аналоговых волоконно-оптических линий (ВОЛС) для передачи информации на различные расстояния в разном диапазоне частот. Отмечены особенности передачи оптических аналоговых сигналов, которые окажут влияние на его регистрацию в фотоприемном модуле ВОЛС. Определен формат аналоговых сигналов, которые необходимо передать по ВОЛС на расстояния более 500 км без использования оптических усилителей. Рассмотрен фотоприемный модуль типа PDA 400 Thorlabs с пиковым откликом 0,95 А/Вт при 1550 нм. Полоса пропускания которого от постоянного тока до 10 Мгц. Отклик: от 800 до 1750 нм. На основании расчета различных параметров ВОЛС и ее энергетического баланса определены требования к конструкции и характеристикам фотоприемного модуля. Собран лабораторный макет фотоприемного модуля. Представлены результаты его работы в составе аналоговой ВОЛС с различной дальностью передачи информации.

Ключевые слова: Аналоговый оптический сигнал, фотоприемник, лазерное излучение, длина волны, ширина линии, динамический диапазон, ширина полосы регистрации, отношение сигнал/шум

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Introduction

Currently, in various optical systems photodetectors for short wave infrared (SWIR) or near-infrared region of the radiation spectrum find great application [1–8]. In some cases, their use is the only solution for obtaining accurate results in research using laser radiation [9–13], for information transmission over fiber-optic communication lines (FOCL) and much more [14–18]. A large number of different photodetectors have been developed for various designs of analog and digital FOCLs [19–21]. To calculate the parameters of digital and analog communication lines, methods have been proposed that take into account the typical conditions of information transmission. Taking into account these conditions, as well as the need to adapt the FOCL design to the required wavelength of laser radiation, a photodetector is selected and a photodetector module is developed [22, 23].

In the case of the use of FOCL to solve special problems associated with the transmission of analog signals, there are a number of features, both in the choice of the photodetector, and on the design of the photodetector module itself. These features are related to the operating conditions of the photodetector module, the frequency of transmission and form of optical signals, as well as the level of signal to noise ratio, which ensures reliable decoding of information and the recorded signal. Therefore, despite the small number of applications of analog optical signals, there are many designs of photodetector modules. This is due to the fact that the features of working with analog signals change dramatically depending on the tasks to be solved [19–25]. In most cases it is required to develop or modernize the design of photodetector module to solve new problems. One of such tasks is the transmission of telemetry information about the state of the environment along the FOCL in the power line area for distances over 500 km. In these conditions the use of optical amplifiers is excluded, since powerful spark induction on the power line, which occurs for various reasons, changes the polarization of laser radiation, which is used for pumping. This leads to distortion of information in the transmitted optical signal. During a thunderstorm the optical amplifier stops its work to ensure the functioning of the line. Therefore, optical amplifiers are not used in the transmission line system. This imposes certain restrictions on the transmitting module, because in digital FOCL the laser radiation of low power is amplified to a certain level by the optical amplifier (everything is in one transmitting module). In FOCL it is necessary to use powerful laser radiation, which has a number of features both in terms of line width and formation of information in the optical signal.

Therefore, for the new FOCL design, which is used in the transmission line system, it is necessary to develop a photodetector module, which takes into account the features of transmitted signals with information at λ = 1550 nm for long distances.

Selection of a photodetector for recording weak signals in the form of rectangular pulses with variable amplitude

The main requirement for the photoreceptor material to realize absorption at the desired wavelengths is the width of the band gap. Fig. 1 shows the absorption coefficients of various structures [22, 24, 26]. This analysis is necessary to choose a structure with maximum absorption near 1.55 µm. It is more reasonable to use $In_{0.53}Ga_{0.47}As$ based structure in the photodetector.

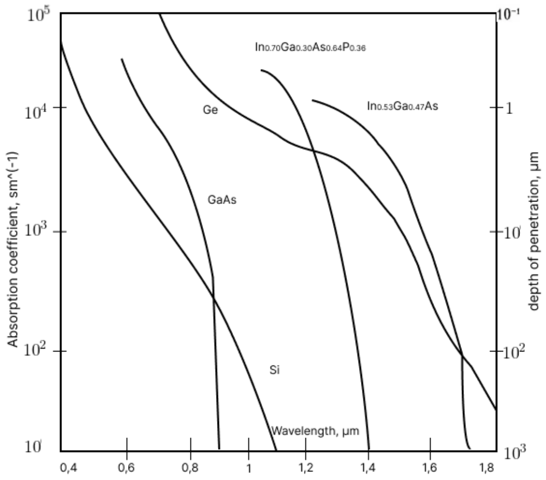

Fig. 1. Absorption coefficient of semiconductor materials

This composition has a large absorption coefficient at a wavelength of 1.55 μm and a relatively low intrinsic concentration of charge carriers. This ternary compound is lattice constant matched to InP substrates, has a bandgap width of 0.74 eV, and covers the wavelength range of 0.9 to 1.7 μm. The layer thickness of about 2 μm provides a high quantum efficiency, specifically, about 90% [19].

Analysis of the data shows that two photodiode designs with materials based on $In_nGa_{1-n}As$ and $In_{0n}Ga_{1-n}AsP$ are suitable for optical signal registration in analog FOCLs. InGaAsP structure based on InP, *n*-type substrate, highly doped. Two types of photodetectors, P-I-N and avalanche photodiodes (APD), have been mainly developed based on different combinations in terms of concentrations in these materials. These devices have a number of disadvantages and premiums in different applications depending on the tasks to be solved. As well as the design of the FOCL and the format of the signals that are transmitted over it. Fig. 2 shows the design of the analog FOCL to transmit telemetry signals over long distances from various systems installed on power lines, as well as control commands of these systems. The distances can be up to about 500 km.

In such a situation, a photodetector will receive a weak by power signal with low speed. The signal frequency will be of the order of tens of kHz. In this case the important elements in such registration will be the minimum detectable input power (NEP) of the photodiode and the spectral sensitivity. Tables 1 and 2 give the characteristics of currently produced photodiodes for comparison.

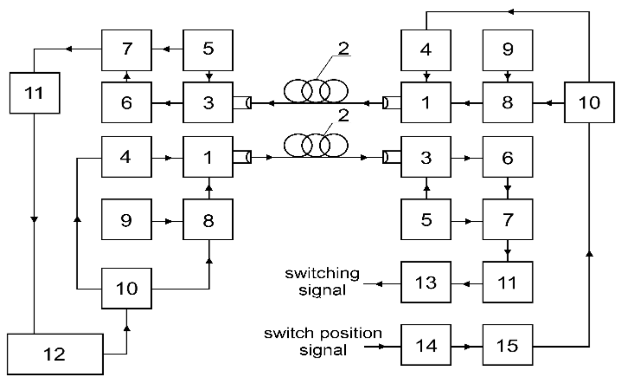

Fig. 2. Structural diagram of analog FOCL for control and monitoring of key elements: semiconductor laser *1*; optical fiber *2*; photodetector module *3*; laser power supply with direct current modulation *4*; multifunctional power supply *5*; tunable LC-filter *6*; analog-digital converter *7*; electronic key *8*; signal generator of subcarrier frequency *9*; device *10* for generation of rectangular pulse sequence; information processing device *11*, obtained using a sequence of command codes; central controller's computer *12*; device for formation of signals of the key elements *13*; switch position signal *14*

Table 1

Parameters of some commercially available *p-i-n* PDs

Material	Si	Ge	$In_{0.53}Ga_{0.47}As$	$In_{0.53}Ga_{0.3}As_{0.6}P_{0.4}$
Spectral sensitivity range, μm	0.4–1.1	0.6–1.65	1.2–1.6	1.2–1.4
Photosensitive window area, cm^2	10^{-2}	10^{-5}	n/a	n/a
Diameter of the photosensitive window, mm	n/a	n/a	0.06–2	0.06–2
Dark current, nA	1–100	100-1000	1	1
Speed, ns	< 1	0.1	0.1	0.1

Table 2

Parameters of some commercially available avalanche PDs (APDs)

Technical Specifications	Photodiodes			Avalanche photodiodes		
	FD-252			FD-317L		
Semiconductor material	Si	InGaAsP	InGaAs	Si	Ge	Ge
Spectral sensitivity range, nm	400–1100	1200–1400	1200–1600	400–1100		
Working wavelength, nm	850	1300	1550	850	1300	1550
Operating voltage, V	24	5 (10)	5 (10)	70–400	30–50	30–50
Current sensitivity, A/W	0.35	0.6–0.8	0.6–0.8	50	8–10	8–10
Dark current, nA	10	1–5	0.1–1			
Capacity, pF	5	1	1	2	< 2	< 2
Rise time, fall time, ns	5	0.15–0.3	0.1–0.2	< 2	0.3/0.6	0.5/0.7
Noise current density, AGH–0.5				$5 \cdot 10^{-13}$	$5 \cdot 10^{-12}$	$5 \cdot 10^{-12}$

The presented results allow a comparison of PD by NEP and photosensitivity *R*.

When transmitting information over long distances it is necessary to ensure energy balance in the used FOCL. In this case it is necessary to use PD with the lowest NEP and maximum R value. According to these criteria two types of PDs from Tables 1 and 2 (e.g. G12180-003A or IAG-080X) can be used for photodetector module design. The difference in these PDs between the two marked parameters is insignificant.

The primary criterion in the selection of the PD in the used analogue FOCL is its stable operation at significant temperature changes. The photodetector module used by the FOCL is placed on top of the power line and is exposed to various temperature modes. These regimes with changes in vert and precipitation can change dramatically.

Avalanche PDs (LFDs) have internal amplification, which is due to the avalanche multiplication of charge carriers in the high field region in the diode base. Photodiodes of this design have increased sensitivity. A negative quality of avalanche photodiodes is that their parameters strongly depend on temperature changes and the magnitude of the reverse voltage [27].

Therefore, it is more reasonable to use PDA P-I-N type photodetectors for photodetector module design. In the heterostructure of these photodetectors with partially depleted absorption layer (Partially Depleted Absorber) the spatial charge effect is reduced by reducing the thickness of the i-InGaAs drift layer and aligning the electron and hole fluxes in this layer. For this purpose, additional absorbing layers of InGaAs of p-type and n-type conductivity are included in the heterostructure. When PDA *p-i-n*-FD light is illuminated, photogenerated electrons are injected from the absorbing p-InGaAs layer into the i-InGaAs layer, and photogenerated holes are injected from the absorbing n-InGaAs layer. If the thickness of the n-InGaAs absorbing layer is greater than the thickness of the p-InGaAs layer, the flux of electrons is greater than the flux of holes. The advantage of p-i-n-FD PDAs is that high quantum efficiency, high photocurrent, fast response, and low thermal resistance are achieved at low reverse voltages by minimizing the spatial charge accumulation effect, short span time, and smaller drift region thickness [24, 28].

In PDA p-i-n-PDs, there are a number of limitations on the photodiode bandwidth. This problem in such PDs is solved by reducing the thickness of the absorption layer. However, such a modification of the structure will lead to a decrease in the sensitivity of the structure. In the analog FOCL used for transmission of information signals frequencies of the order of 1-10 kHz are used, so there are no significant limitations on bandwidth, which allows the thickness of the absorbing layer of the order of 2 microns less sensitive to temperature changes at its departure in the thermal stabilization system.

Photodetector module design, recorded information signals and discussion

The optical signal formed using direct modulation of laser radiation in the form of a rectangular pulse at a carrier frequency is transmitted along the optical fiber 2.

Fig. 3 shows the optical signal that comes after the transmitting laser module 1 (Fig. 2) to the input of the optical fiber 2 and after its registration by the developed photodetector module 1.

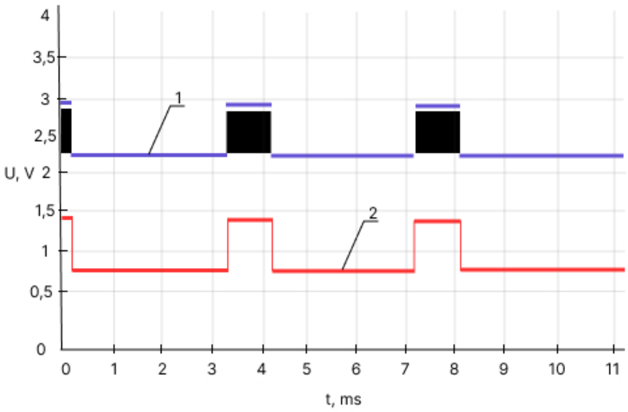

Fig. 3. Rectangular pulses for transmitting information as a sequence of command codes.
Graph 1 corresponds to the signal at the input to 2.
Graph 2 corresponds to the signal at the output of 1

Then the optical signal at a subcarrier frequency of 200 MHz is fed through the fiber 2 to the input of the photodetector module 1. At the output of the photodetector module a rectangular pulse is formed with the filling of a sinusoidal signal with a frequency of 200 MHz (Fig. 3, graph 2). The load of the photodetector is a resonant LC-filter. The filter is tuned to a frequency of 200 MHz.

After the filter the signal at the subcarrier frequency is removed from the pulse and goes to the ADC 7. Then after the ADC the signal goes to the processing device to decode the transmitted information. It should be noted that with this scheme of registration of optical signal can be carried out its registration at signal/noise ratio of the order of 4 times, when in digital fiber-optic networks it is necessary to ensure at least 20 dB.

Conclusion

The analysis of the conducted studies of sequences of rectangular pulses of different duration with different subcarrier frequencies showed the stable operation of the developed photodetector with the following characteristics: bandwidth ΔF_f = 1 GHz, NEP = 10−14 W·Hz$^{1/2}$. Placement of resonant LC-filter and ADC in the design of the developed photodetector module is one of its features of operation in conditions of power lines. This design of the photodetector module allows to register information optical signals with linear frequency modulation (LFM), which are used as subcarriers in them. This increases the base of the signal during its registration by several orders of magnitude and allows the recognition of information when the optical signal is registered below the noise level. The use of these signals in the designs of analogue fiber-optic lines is one of the future scientific directions of our development and research.

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