Optoelectronics and optoelectronic devices

Structural optimization of optoelectronic components in millimeter-wave radio-transmitting modules

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Abstract. The paper analyzes the effect of structure inherent to optoelectronic radio-transmitting modules of a phased array antenna (PAA) on the noise characteristics in the millimeter range (MMR) of waves. Considered are promising structures of MMR modules for generating radiation with a phased array for communication systems based on optoelectronic technologies. The promising types of photodiodes that are used to form MMR radio signals as well as the distance and physical limitations for photodetectors associated with a limited bandwidth and nonlinear response characteristics have been analyzed. Mathematical modeling of the oscillation of the output current after the optoelectronic conversion of the signal and noise characteristics of the radio-transmitting modules capable to form MMR radiation in PAA has been carried out. The analysis of the nonlinearity of the sensitivity of photodiodes in the high-frequency regions of formation of radio signals has been carried out. The necessity to structurally optimize optoelectronic components in the MMR transmission module has been shown depending on the noise characteristics of the output signal. It has been shown that fundamental studies of nonlinear characteristics and factors limiting the band of photodetectors are important tasks for further developing MMR telecommunications of the next generations.

Keywords: UTC photodiode, integration, high data rate, radio over fiber, single/multi carrier transmission, signal-to-noise ratio.

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1. Introduction

Fiber-optic transmission systems, as well as their optoelectronic components, play a key role in creating promising high-speed telecommunication systems. Fiber-optic and optoelectronic technologies not only significantly increase the telecommunication bandwidth of telecommunication systems, but also solve the problems of weak spots in the configuration of next-generation wireless networks. Fiber optic lines combine base stations of mobile communication systems and data processing centers with high bandwidth.

Optoelectronic methods are an effective solution for processing radio signals, especially in MMR [1-4]. Currently, optoelectronic technologies for generation and modulation of MMR signals with low phase noise, optoelectronic methods for controlling formation of narrowly directional radiation patterns of the phased array are the best or even the only solution [1, 5]. To solve the problem of controlling the radiation pattern of a phased array, various hybrid integration schemes can be applied. The choice of a particular circuit depends on many reasons, in particular, on the noise characteristics of the circuit elements and the structure of the circuit as a whole, which is considered in the paper.

The main components, on which the bandwidth depends, as well as the dynamic noise characteristics of the system, are optical modulators and photodetectors. Optical modulators mainly impose restrictions on the dynamic radio-frequency characteristics of optoelectronic transmitting modules, for example, on the discreteness of frequency tuning. Photodiodes must provide high output power, linearity, high throughput, and a large dynamic range free of spurious components (SFDR – spurious-free dynamic range).

Physical limitations for photodetectors are associated with a limited passband and non-linear response characteristics [1]. For *p-i-n* photodetectors, the transmission frequency limits are 60…70 GHz with an output power of up to 20 dBm. In high- speed

UTC photodiodes (Uni-Traveling-Carrier-Photodiode), the absorption region is completely doped with a *p*-type impurity, and the signal is transferred only by electrons. In these photodiodes, the method of heterodyning optical carriers from unbound (freely operating) lasers with an external resonator (ECL) yielded a radiation power close to 121.2 μW at the frequency 74 GHz [6]. At the frequency 120 GHz, the output power for UTC photodiodes is 0 dBm (1 mW). For UTC photodiodes operating at the frequencies up to 300 GHz, a maximum output power of 12 μW was achieved by the method of heterodyning optical carriers [6]. It was experimentally shown [7] that when using lasers operating in the synchronization mode and a UTC photodiode in the band up to 300 GHz, the output radio signal power, when reaching gigabit speeds, is limited to 30 dBm. As shown in [7], this limitation is associated with the noise characteristics of the output electrical signal of MMR.

Today, PDA-type photodiodes (with a partially depleted absorption layer), double depleted region (DDR) photodiodes, and various versions of UTC structure photodiodes are considered as the most promising ones. For example, in a PDA photodiode with backlight at the frequency 5 GHz, the output power of 29 dBm was achieved.

The MUTC type photodiode (a modified version of the UTC photodiode) uses absorption regions with partial doping with an impurity, which makes it similar to the photodiode of the DDR structure. Optimization of the concentration of impurities in the MUTC photodetectors allowed us to achieve an output power up to 0.75 W at the frequency 15 GHz. The highest bandwidth in high-power photodetectors is provided when a *p*-type charge is additionally formed in the collector to increase the electron drift velocity. In these devices, called NBUTC type photodetectors (near-ballistic uni-traveling-carrier – almost ballistic charge carriers), the output power close to 10 dBm at the frequency 110 GHz has been obtained.

In addition to improving the parameters of individual elements, structure optimization is used to achieve a higher output power of the high-frequency signal in the radio-photon receiving module. In particular, for single photodetectors, formation of an optical beam is proposed with the aim of more uniform distribution of incident optical power as compared with the case of direct docking with fiber. Also known are options for constructing a receiving module based on several photodetectors. For example, the following options are proposed for constructing photodetector arrays: parallel with direct summation of the photocurrents and powers of high-frequency signals, and sequential with the summation of photocurrents in the traveling wave scheme. According to this scheme, the maximum levels of RF output power from 8.9 to 5.1 dBm were achieved in [8] in the frequency range from 60 up to 120 GHz, where the balanced photodiode chip has the passband up to 80 GHz at the level of –3 dB. In addition, examples of the study of powerful balanced photodetectors in integrated design are known.

2. Structures of MMR radiation generation modules in PAA

The optoelectronic (photonic) methods for creating radiation patterns of PAA provide a wider bandwidth and lower losses as compared to electronic methods [1-3]. This makes optoelectronic control of PAA to be a solution for smart antennas in the millimeter and submillimeter ranges. However, the optoelectronic methods for PAA have serious problems associated with the integration of a high-speed photodetector with an antenna [9, 10]. This requires careful design, in which particular attention should be paid to the analysis of energy balance. The phase and amplitude control of the antenna elements must be also carried out in an efficient manner.

The various millimeter-wave services that are under development will require appropriate channel parameters and characteristics. Various optoelectronic structures that control formation of radiation from a phased array can also have different noise and dynamic characteristics. For example, to reduce interference in the channel and increase the throughput, a high antenna gain, dynamic configuration change, and an increase in the complexity of radio signal processing are required. These requirements are implemented with the system for controlling the amplitudes and phases of the phased array optoelectronic elements. Therefore, it is necessary to analyze the dependence of the noise characteristics of the signal at the output of the photodiode on the architecture of radiation formation. Shown in Fig. 1 are some options for constructing modules to form radiation of a phased array, which are proposed for promising communication systems in MMR based on optoelectronic technologies [3, 5, 7, 10].

The first two structures shown in Figs 1a and 1b allow one to organize a single-channel system for transmitting MMR signals in different ways; two subsequent structures (Figs 1c, 1d) allow organizing a multichannel system for transmitting MMR signals. An analysis of these structures will be carried out below.

3. Analysis of the noise characteristics of the radio-transmitting modules capable to form radiation of MMR in PAA

The electric current at the output of the photodiode can be represented as follows [1]:

$$I_{out,\,PD} = \Re\left|E(t)\right|^2 + I_N(t), \qquad (1)$$

where $E(t)$ is the shape of the optical signal at the input of the photodetector, $\Re$ – sensitivity of the photodetector, $I_N(t)$ – noise Gaussian component of the current at the output of the photodiode.

One of the effective optoelectronic methods for generating and tuning the frequency in MMR is optical heterodyning. In this case, the MMR frequency f_{RF} signal is obtained as the difference of the optical spectral

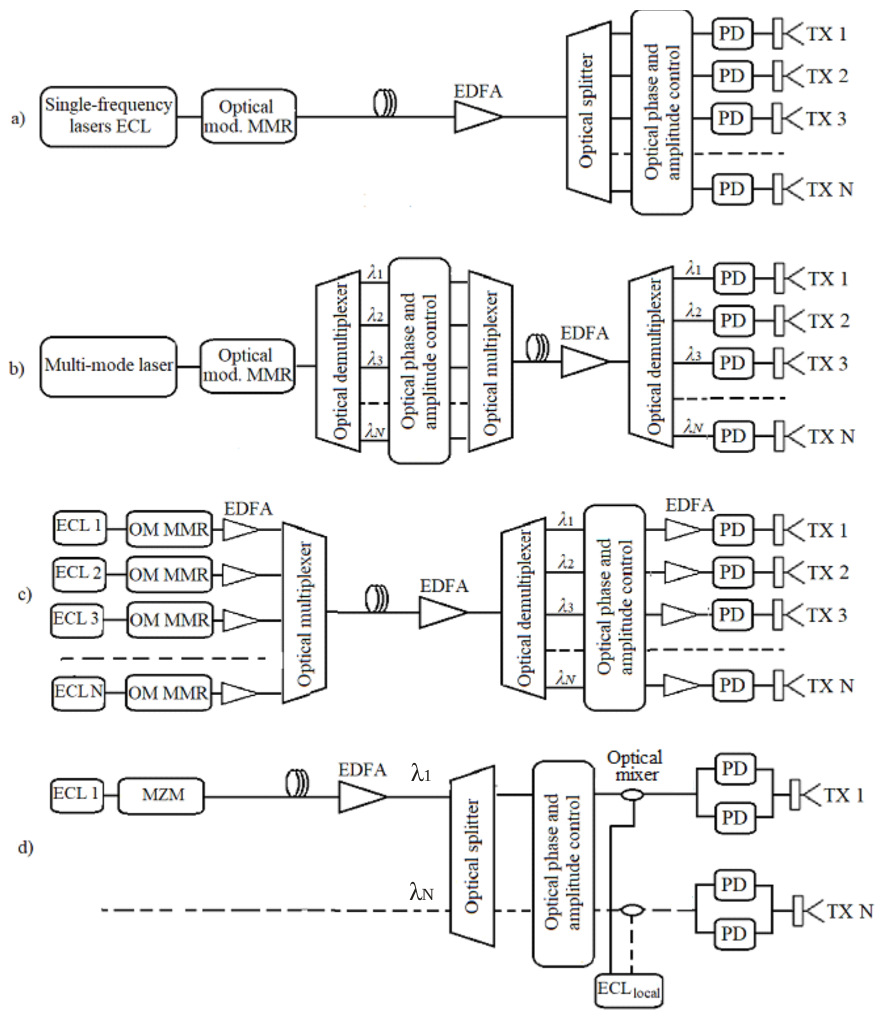

Fig. 1. Modules structure options for formation of MMR radiation in PAA based on: (a) a single-frequency laser, (b) a multi-frequency laser, (c) several laser generators, (d) several laser generators with optical local oscillators and balanced photodetectors.

components. The radio-frequency signal obtained as a result of the beating of two optical modes with the frequencies $f_{opt,1}$ and $f_{opt,2}$, then $f_{RF} = |f_{opt,1} - f_{opt,2}|$ has the form:

$$E(t) = E_{01}(t)\times$$
$$\times \exp\left[i\left(2\pi f_{opt,1}t + \varphi_1(t)\right) + m(t)E_{02}(t)\exp(i)\left(2\pi f_{opt,2}t + \varphi_2(t)\right)\right] \quad (2)$$

where $E_{01}(t)$ and $E_{02}(t)$ are the amplitudes that take into account the intensity of fluctuations, $m(t)$ is a complex modulating signal. This allows one to modulate both amplitude and phase, the quadrature components $\varphi_1(t)$ and $\varphi_2(t)$ are phase fluctuations of both fields, which have the form of a Wiener process.

After filtering the radio-frequency components, the waveform, if using Eqs (1) and (2), takes the form:

$$I_{out,\,PD} = \Re E_{01}(t)E_{02}(t)|m(t)|\cos\times$$
$$\times\left[2\pi f_{RF} + \varphi_m(t) + \Delta\varphi(t)\right] + I_N(t), \quad (3)$$

where $|m(t)|$ and $\varphi(t)$ are the amplitude and phase of the modulating signal $m(t)$, accordingly, $\Delta\varphi(t) = \varphi_1(t) - \varphi_2(t)$.

The current $I_{out,\,PD}$ can be implemented both to control the beam (control the direction of maximum radiation θ_{max}) and to form a given width of the antenna pattern. Phase adjustment can be performed using the differential delay τ. For linear PAA, the condition of maximum gain $\theta_{max} = \sin(2\tau f_{RF})$ [10].

The average output power of the RF signal can be defined as

$$P_{out,\,PD} = \left\langle I_{out,\,PD}\right\rangle^2 R_L \left|H_{PD}\right|^2, \quad (4)$$

where R_L is the output impedance, H_{PD} – filtering function of the photodiode circuit (time averaging is indicated by angle brackets).

The independent noise components in the optical channel can be considered as Gaussian random processes with a zero mean, and they can be summed as current sources, since they are formed during optoelectronic conversion in a photodetector [1]:

$$\sigma_{noise}^2 = \sigma_{thermal}^2 + \sigma_{shot}^2 + \sigma_{RIN}^2 + \sigma_{sig-ASE}^2 + \sigma_{ASE-ASE}^2 , \quad (5)$$

where $\sigma_{thermal}$ is the thermal noise of the photodiode, in which, in addition to the noise of photocurrent generation, it is also necessary to take into account the dark current resulting from the thermal generation of charge carriers in the absence of photon absorption; σ_{shot} – shot noise or quantum noise, representing random fluctuations in the signal due to the discrete nature of the charge; σ_{RIN} are fluctuations in the optical intensity of the laser; $\sigma_{sig\text{-}ASE}$ is the noise of the optical amplifier, in which, in addition to the noise of the amplified signal, there is also an amplified noise of spontaneous emission ASE; $\sigma_{ASE\text{-}ASE}$ – ASE noise beating with itself.

$$\sigma_{thermal}^2 = \frac{4k_B T B_{el}}{R_L} ,$$

$$\sigma_{shot}^2 = 2q\Re P_{opt} B_{el} ,$$

$$\sigma_{RIN}^2 = 10^{\frac{RIN^{DB}}{10}} P_{opt}^2 \Re^2 B_{el} ,$$

$$\sigma_{sig-ASE}^2 = 2\left(\Re \cdot G_{opt}\right)^2 P_{opt} NF_{opt} B_{el} h\nu_{opt} ,$$

$$\sigma_{ASE-ASE}^2 = \left(\Re G_{opt} NF_{opt} h\nu_{opt}\right)^2 B_{opt} B_{el} ,$$

where k_B is the Boltzmann constant; T – temperature; B_{el} – bandwidth of the signal, which is obtained after converting the optical signal into an electrical signal in the photodiode; q – electron charge; P_{opt} – average optical input power $P_{opt} = 0.5E_0(t)^2$; G_{opt} – gain of the optical amplifier; NF_{opt} – noise figure of the optical amplifier; B_{opt} – width of the spectrum of the optical amplifier; $h\nu_{opt}$ – photon energy; RIN – relative intensity noise

$$RIN = 2\left\langle P_{opt}^2(t)\right\rangle \Big/ \left\langle P_{opt}\right\rangle^2 ,$$

where the numerator is the rms distribution of the optical intensity noise, the denominator is the square of the average optical power.

Using the formulas (4) and (5), the signal-to-noise ratio (SNR) at the output of one photodiode (Fig. 1a) can be written as:

$$SNR = \frac{P_{out,\,PD}}{\sigma_{noise}^2} . \quad (6)$$

To analyze the effect of noise on PAA with several radiating elements, attention must be paid to the correlation between noise versions, which affect different characteristics of the antenna. The degree of correlation is different for various architectures, which will lead to different transmission quality. Different architectures of transmitting the MMR signal to PAA make noise contributions to the total noise of the system in different ways (Fig. 1). When using a single-frequency laser and an optical amplifier, the noise contributions are independent (Fig. 1a); the contributions of the noise of the multi-frequency laser correlate, however, the noise components of the optical amplifier and the photodiode are independent (Fig. 1b); when using several single-frequency optical generators, the noise components do not correlate (Figs 1c, 1d).

The radiation power of PAA can be expressed as follows:

$$P_{PAA}(t) = \eta \sum_{n=1}^{N} R_L i_n^2 , \quad (7)$$

η is the antenna efficiency; N – number of radiating elements of P_{PAA}; R_L – output impedance; i_n – current at the input of the emitter with the number n (for the optoelectronic method for creating radiation from PAA $i_n = I_{out,\,PD}$).

Fig. 2 shows the dependence of the signal-to-noise ratio on the number of radiating elements of PAA for various architectures of radiation formation shown in Fig. 1, calculated according to the formulas (4) to (7). The power radiated by the PAA element depends on the output power of the photodiode, therefore, it is important for the optical power incident onto the photodiode to be sufficiently high. Therefore, pre-amplification of the signal before photodiodes is applied (Fig. 1c). Balanced photodetection (Fig. 1d) eliminates the need for filtering low-frequency components and increases the dynamic range, but leads to the difficulty of configuring with PAA for a large number of elements. It is assumed that the system consists of a standard distributed feedback laser (DFB) (threshold current 15 mA, line width 1 MHz, RIN –145 dB/Hz, radiation power 10 dBm at 100 mA); an erbium amplifier with typical values of noise factor and gain of 4 dB and 20 dB, respectively; photodiode with a sensitivity of 0.6 A/W, spectral density of thermal fluctuations of the current 10^{-12} A^2/Hz, B_{el} = 10 GHz, B_{opt} = 1 MHz, R_L = 50 Ohm.

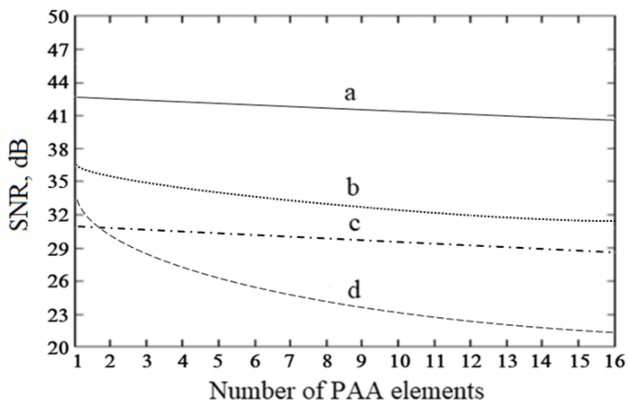

Fig. 2. The calculated dependence of the signal-to-noise ratio (SNR) on the number of radiating elements of PAA for various architectures (a), (b), (c), (d) shown in Fig. 1.

Fig. 2 shows that the noise performance is significantly different for various architectures capable to form radiation in PAA. Integration of antenna elements with high-speed photodiode is associated with problems of amplitude and phase noise. This noise is generated by the power signals of the elements and can lead to an additional change in the radiated power and fluctuations of the radiation pattern.

4. Analysis of the nonlinear sensitivity of photodiodes in high-frequency areas of formation of radio signals

The sensitivity of the photodiode $\Re$ is defined as the ratio of the photocurrent to the optical input power and can be also expressed in terms of the quantum efficiency η and the upper limit of photon absorption for a given wavelength (the photon energy must correspond to the band gap E_g):

$$\Re\left[\frac{A}{W}\right] = \frac{I_{PD}}{I_{opt}} = \frac{\eta\lambda\,[\mu\text{m}]}{1.24}. \quad (8)$$

In practice, the sensitivity of photodiodes is usually non-linear and has a limited passband. The reasons for these limitations are the final absorber thickness, carrier recombination, state of polarization of incoming light, optical reflections and losses. Capacitive-resistive (*RC*) effects and the transit time τ of the charge carrier (electron or hole) through the active region between the contacts are two critical indicators of limitation of the passband inherent to the photodiode. The linearity of characteristics of photodetectors is limited by a bandwidth of about 20 GHz. The cut-off frequency at the level of 3 dB for a photodiode with limited *RC* can be calculated using the approximate expressions [8]:

$$f_{3DB} \approx \sqrt{\frac{1}{f_{RC}^{-2} + f_\tau^{-2}}},$$

$$f_{RC} = \frac{1}{2\pi R_{eff} C_{PD}},$$

$$f_\tau = \frac{3.5\,\bar{\upsilon}}{2\pi L_{abs}}. \quad (9)$$

Here, $\bar{\upsilon}$ is the average speed of the charge carrier, L_{abs} – thickness of the absorption layer, C_{PD} – capacitance of the *p-n* junction, $R_{eff} = R_s + R_1 50\Omega/(R_1 + 50\Omega)$, R_s – series resistance, R_1 – resistance of the external load.

In telecommunication systems, photodiodes are needed to convert optical modulated signals to electrical signals at high speed. For this, photodiodes must operate with high output power and a wide passband of more than 100 GHz.

It is well known that for photodiode structures there is a compromise in performance between quantum efficiency and the bandwidth associated with the thickness of the absorbing layer. At high current densities, when electrons and holes move in opposite directions, an internal space charge field is created, which opposes the electric field of displacement. At sufficiently high levels of optical input power, the electric field induced by the space charge can be sufficiently strong to cause a collapse of the electric displacement field, which will lead to a decrease in the carrier drift velocity, a longer transit time, and, consequently, a decrease in the radio-frequency photocurrent. To eliminate the effect of space charge, photodiode structures DDR, UTC photodiode, and PDA have been developed.

In UTC photodiode, the electron propagation time has two components corresponding to a *p*-type doped absorbing layer and a lightly doped wide-gap drift layer. When applying reverse bias, the absorbing layer is in an electrically neutral state, and a strong electric field is created in the wide-gap drift layer. Therefore, using the UTC photodiode, it is possible to achieve high speed and high saturation of the output photocurrent even with a low bias voltage. The need for photon integration, as well as the demand for high bandwidth, stimulated the development of structures such as UTC based on the waveguide structure.

In waveguide photodiodes, an input optical waveguide is used, above which a thin *p-i-n* structure with a surface $S = W \cdot L$ is placed. The surface width (*W*) is related to the dimensions of the optical waveguide and remains constant. The length (*L*) can be changed and thereby the total capacitance of the *p-n* junction can be adjusted. The carriers generated by photons pass a thin absorption region perpendicular to the epitaxial layers, which provides a high bandwidth for the photodiode. In this case, a high quantum efficiency and a short carrier transit time can be simultaneously achieved. The sensitivity of a photodiode based on a waveguide structure can be represented by the expression [8]:

$$\Re_{waveguide} = \Re_{ideal}\,(1 - R_0)\,\eta_{com}\left[1 - \frac{1}{\exp(\Gamma\alpha L_{abs})}\right], \quad (10)$$

where $\Re_{ideal}$ is the sensitivity of the photodiode defined by the relation (8), η_{com} – efficiency of the input coupling, determined from the overlap integral between the optical field of the input (optical fiber) and the optical field of the photodiode waveguide structure, R_0 – reflection coefficient at the air-semiconductor interface, and Γ – directional beam retention coefficient in the absorbing layer, α – absorption coefficient.

Reducing the length of the *p-i-n* structure and the thickness of the absorbing layer decreases the equivalent capacitance and shortens the electron travel time. When decreasing the photodiode length down to 7 μm, the reduced switched-on capacitance makes it possible to achieve the bandwidth at the 25-Ohm effective load up to the frequencies of 100, 120, and 145 GHz for absorbers with a thickness of 430, 350, and 200 nm, respectively (Fig. 3) [8].

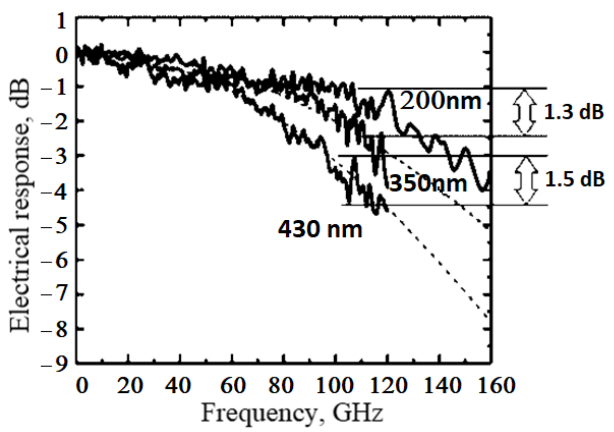

Fig. 3. The measured frequency characteristics for photodiodes with an active area of 5×7 μm^2 and different thickness of the absorbing layer (nm).

To date, high-performance waveguide photodiodes with a bandwidth well above 100 GHz have been demonstrated. Despite significant progress, there remain problems of reducing the dark current and increasing the efficiency of using the bandwidth in combination with achieving high output powers of the electric signal.

The reasons for the fluctuation in the sensitivity of the photodiode (Fig. 3) can be explained by the shot noise that together with the thermal one degrades the sensitivity of photodiode as well as other physical processes [1].

5. Discussion

The article presents the results of studying the effect of architecture chosen for the optoelectronic components of PAA as well as the nonlinearity of the PD characteristics in the MMR radio-transmitting module for the noise characteristics of the output radio signal. MMR communication systems are under development, and the main solutions for their implementation are optoelectronic technologies. However, typically only thermal noise associated with channel bandwidth is considered in radio channel energy budget models. So, for a channel width of 1 GHz with a photodiode output power of about –5 dBm, the SNR value, taking into account only the thermal noise, will reach about 60 dB. As shown in Fig. 2, during formation of radiation in PAA, SNR can take lower values (below 20 dB). Also, fluctuations in the sensitivity of photodiodes (Fig. 3) must be taken into account in noise and energy analysis. These approaches reveal the limiting factors for sophisticated signal processing techniques. They also contribute to finding optimal solutions for structural optimization of optoelectronic components in MMR radio-transmitting modules for specific tasks in telecommunication systems. Modeling the architecture of the optoelectronic components of MMR of the radio-transmitting module requires adaptive calculations based on the relationship between the parameters: radiation power, ability (limited) to control the antenna directional pattern, *etc*., with the design and noise characteristics of the transmitting module. Depending on the architecture of optoelectronic components for various tasks in telecommunications, as shown in the article in Fig. 2. The SNR can have different values with a difference of more than 20 dB. Therefore, further research is needed on the structural optimization of optoelectronic components in MMR radio-transmitting modules in terms of energy and noise characteristics for various tasks (services) of telecommunications. Also, from the analysis of the nonlinearity of the characteristics of photodiodes used to form MMR radio signals (Fig. 3). Despite the fact that waveguide PD with a bandwidth well above 100 GHz have been demonstrated, the nonlinearity of the characteristics can be more than 1.5 dB, which must be taken into account in the design calculations of PAA.

6. Conclusions

Based on the analysis of the structures of optoelectronic modules for the formation of radiation of the phased array, which are proposed for promising systems in MMD, modern types of photodetectors and their nonlinear characteristics, mathematical modeling of the output current and SNR for various options for the structures of radio transmitting modules, the following conclusions are drawn.

The characteristics of the transmitting radio module (radiation power, communication range and noise immunity) depend on the architecture of the complex and on the noise characteristics of its elements.

Solutions on the structural optimization of optoelectronic components in the MMR transmission modules depend on the specific tasks in telecommunication systems related to the signal output power, the need to control the antenna directional pattern, and the required SNR value of the output radio signal.

Fundamental studies of noise characteristics and limiting factors of optoelectronic components, first of all, PD, methods of their structural optimization in MMR radio-transmitting modules are necessary and imply promising tasks for the development of MMR telecommunications of the next generations.

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Структурна оптимізація оптоелектронних компонентів у радіопередавальних модулях міліметрових хвиль

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Анотація. У статті проаналізовано вплив структури оптоелектронних радіопередавальних модулів фазованої антенної решітки (ФАР) на характеристики шуму в міліметровому діапазоні (ММД) хвиль. Розглянуто перспективні структури модулів ММД для генерації випромінювання фазованої решітки для систем зв’язку, основаних на оптоелектронних технологіях. Проаналізовано перспективні типи фотодіодів, які використовуються для формування радіосигналів ММД, а також відстань та фізичні обмеження для фотодетекторів, пов’язані з обмеженою пропускною здатністю та нелінійними характеристиками відгуку. Проведено математичне моделювання коливань вихідного струму після оптоелектронного перетворення сигналу та шумових характеристик радіопередавальних модулів для утворення випромінювання ММД у ФАР. Проведено аналіз нелінійності чутливості фотодіодів у високочастотних областях формування радіосигналів. Показано необхідність структурної оптимізації оптоелектронних компонентів у модулі передачі ММД у залежності від шумових характеристик вихідного сигналу. Показано, що фундаментальні дослідження нелінійних характеристик та обмежувальних факторів смуги фотодетекторів є важливими завданнями для подальшого розвитку телекомунікацій ММД наступних поколінь.

Ключові слова: UTC-фотодіод, інтеграція, висока швидкість передачі даних, радіо по волокну, передача з однією/кількома несучими, відношення сигнал/шум.