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Manko O.O.
Kyiv Professional College of Communication

Kunah N.I.
Kyiv Professional College of Communication

Kharlai L.O.
Kyiv Professional College of Communication

Nikiforenko K.B.
Kyiv Professional College of Communication

Konovalov O.Yu.
Kyiv Professional College of Communication

Sotnichenko Yu.O.
Kyiv Professional College of Communication

PROTECTION OF INPUT CIRCUITS OF MICROWAVE RANGE RADIO RELAY STATIONS RECEIVERS AGAINST POWERFUL IMPULSE INTERFERENCES

The principle of construction of wide-band self-controlled power limiters mm – wavelength range is proposed in the work. The operating range is considered, which includes the range of frequencies that lie between 28 GHz and 38 GHz, and which are used by 5G technology. As a basis for the constructive design of the limiter, a guide system of the H-waveguide type was chosen.

Its structural parameters have been optimized. In particular, the width of the waveguide crest and the distance between the crests are selected. It was determined that the width of the ridges and the distance between them significantly affect the parameters of the input losses in the mode of a small and large input signal. In particular, reducing the width of the ridges increases the introduced loss in the mode of a large input signal, which is a positive factor. It was determined that a similar course of the dependence of losses occurs when the distance between the ridges decreases. However, in this case there is a slight increase in losses in the small signal mode. Thus, there is an optimal ratio in relation to these dimensions that is determined in the work.

Methods for calculating the transmission characteristics (introduced attenuation) of self-controlled power limiters in the small-signal mode are provided. Ways to optimize the design of the limiter are considered. The value of the spatial interval was selected for the placement of the semiconductor elements included in the design of the limiter in the guide system of the H-waveguide. The proposed interval provides a wide operating frequency range in the low signal mode, which includes the frequencies of the 5G mobile communication technology. A similar construction of the limiter can be used in the 60 GHz frequency range, which is also used by 5G technology.

At the same time, the losses of the experimental sample in the mode of low power of the input signal at the lower frequencies of the operating range did not exceed 0.3 dB. At the upper frequencies of the operating range, losses did not exceed 1.7 dB. The transmission characteristic in the range was quite smooth. In the mode of pulsed high input power, the value of losses was of the order of 30 dB. At the same time, the signal duty cycle was in the range of 10-100.

The results of this work can significantly increase the reliability of the input circuits of microwave receivers of mm-band radio relay stations operating in a complex electromagnetic environment, namely in the presence of the influence of strong external pulse signals. Along with this, they can be used to improve the reliability of mobile networks of the new generation using 5G technology.

Key words: *guide system, losses in the mode of a low-power signal, losses in the mode of a high-power signal, diodes with a Schottky barrier, p-i-n-diodes.*

Formulation of the problem. At the current stage of communications development, intensive research is being conducted on the implementation of communication networks using the millimeter wavelength range. At the same time, the development of the millimeter wavelength range continues, using frequencies of 28 GHz, 38 GHz [1] and 60 GHz [2], which belong to the wavelength range of 5G technologies.

Given the high information throughput capacity of such networks, it is important to ensure a high level of their reliability by increasing their protection against powerful interference. One of the most important parameters of transceivers of communication networks is their immunity. Because impulse interference of significant power can damage the input circuits of receiving devices, in particular, lead to breakdown or increase the noise level of mixing diodes.

Thus, the problem of protecting the input circuits of receiving devices in the millimetres wavelength range, including radio relay stations, from powerful external interference is urgent.

Analysis of modern developments regarding protection devices for the input circuits of microwave receivers. The solution to this problem significantly increases the reliability of the equipment. Protective devices of microwave receivers prevent energy overload of their input circuits, ensuring reliable operation of elements sensitive to it – tunnel, parametric, detector and mixing diodes and microwave transistors [3]. These elements are widely used in the input circuits of microwave receivers of the millimeter range radio-relay stations and other radio-electronic devices of similar purpose. The listed elements are characterized by low levels of permissible microwave power, which are primarily related to the so-called burn-in power [4].

Thus, taking into account the practically unforeseen possibility of irradiating the microwave receiver with a high-power pulse, the problem arises of building an effective fast-acting and wide-band protective device, the function of which is to limit the microwave power falling on sensitive elements. From a functional point of view, the maximum permissible input power $P_{in\ max}$ is determined by the level of the maximum permissible power entering the output $P_{out\ max}$ (the typical value of $P_{out\ max}$ for mixers, parametric and transistor low-noise amplifiers is within 10–200 mW). However, of course, the limit of $R_{in\ max}$ is dictated by the dissipation of part of the input power in the working volume of the limiter itself. The heat dissipating ability of the semiconductor structure of the limiters, like most solid-state microwave devices, is small and rarely exceeds 1 W in continuous mode. Therefore, with an average input power of tens of watts and, even more so, several kilowatts, they tend to create highly reflective limiters, the input impedance of which in the mode of high power level is much smaller than the characteristic resistance of the transmission line Z_0 [5].

A typical solid-state protective device is a microwave module, in general n-cascade, and each cascade can be an autonomous protective device. P-i-n-diode structures are mainly used as elements that provide a high level of attenuation of a powerful input signal [6].

If synchronous and non-synchronous (random) interference of high power is received at the input of the receiver, an element sensitive to microwave power must be used as a sensor in the design of the device. The signal from the sensor is fed to the amplifier, and from the output of the amplifier – to p-i-n-diode structures. Such devices are called active, because they need to be connected to a power source for their operation. For all the advantages, active designs have a significant drawback. In the event of a power failure (in the event of an accident, planned shutdown, etc.), the receiver elements (input circuits, mixer) remain practically defenceless against high-power microwave signals, since tunnel, parametric, detector and mixing diodes and microwave transistors are sensitive to them even in a "cold" state.

It is desirable that the work of the limiter is carried out automatically and does not require external control signals to be applied to it. In this regard, so-called passive designs are more promising devices. Passive semiconductor protective devices are power limiters in which due to the automatic shift of the operating point during the rectification of incoming microwave oscillations and a sharp decrease in the resistance of the semiconductor structure, a state of high conductivity is formed in the plane of the inclusion of the diode and the incident power is intensively reflected in the direction of the source, which leads to output power level limitation.

The use of semiconductor limiting diodes made it possible to dramatically reduce the overall dimensions and mass of limiting devices [7]. The purpose of limiting diodes can be explained using the example of the simplest receiver of microwave signals with a protective limiting device (Fig. 1). Waveguide B connects antenna A to the input of amplifier E.

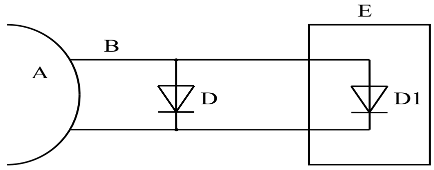

Fig. 1. Scheme of inclusion of a limiting diode to protect the receiver

The detector diode D1 is turned on at the input of the amplifier. A limiting diode D is included in the waveguide between the antenna and D1. When a weak signal arrives from the antenna, it passes through the waveguide with the limiting diode almost without attenuation. When the power of the microwave signal increases to a certain value, the attenuation will increase and part of the incident power will be reflected. The greater the incident power, the greater its part will be reflected. The reason for this microwave power limiting effect is the change in the total input resistance of the limiting diode under the action of the rectified current. A change in the total input resistance leads to a change in the transfer losses of the limiting device. This happens due to the fact that the limiting diode is, as it were, a combination of a p-i-n diode and a diode with a p-n junction. The scheme of its structure is the same as that of switching p-i-n diodes [4]. If it is necessary to reduce the limiting power threshold, instead of a limiting diode, a diode with a Schottky barrier (SBD) is used [8].

The disadvantage of circuits of protective devices (PD) on one limiting diode is a relatively low level of introduced losses (which depends on the direct current through the diode). In this regard, a rather promising schematic solution is the use of auxiliary rectifier diodes, the rectified current of which controls p-i-n diodes and limiting diodes (Fig. 2). Such a scheme is self-controlled and therefore has high reliability, in contrast to an active controlled scheme that requires synchronization signals and supply voltage [7].

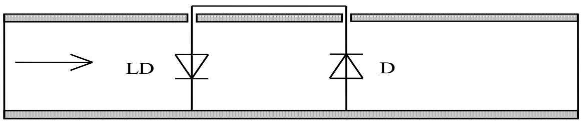

Fig. 2. Scheme of passive PD:
LD-limiting diode;
D-rectifier diode.

In this scheme, the increase in direct current is achieved by sequentially including the detector diode on the BSD in the PD. In the process of detecting the incident microwave signal, the BSD creates a rectified voltage on its contacts. This voltage plays the role of a direct bias for the limiting diode and reduces the threshold power and the limiting power, because it reduces the resistance of the diode. The use of an auxiliary diode facilitates the development of solid-state ZP, but also creates new problems. The parameters of the rectifier diode play an important role, determining the inertia of such a ZP and increasing the peak of the leakage power.

Setting objectives. Taking into account the above, it is possible to formulate general requirements, compliance with which ensures a high level of development for the protective device:

1. The protective device must be "passive", i.e. do not use an external power source and operate due to the incoming microwave signal.
2. The protective device must have a small maximum tripping power and a high switching speed (low inertia).
3. The protective device should introduce small losses in the transmission mode (ideally, they are equal to zero) and high losses in the input power limiting mode.
4. The protective device must be sufficiently broadband and resistant to high levels of microwave power.

Among the disadvantages of PD currently used is a relatively narrow operating frequency range (up to 10%), which is explained by the use of resonant elements in them. In addition, there are practically no developments of PD in mm – the range of wavelengths, although the development of this range in the direction of the application of transmission systems using 5G technology in it continues.

Thus, there are problems of creating protective devices that would meet as many of the listed requirements as possible and master new frequency ranges

Selection of the type of guide system and the principles of schematic construction of the protective device. The decisive parameter when choosing a protective device construction scheme is the operating frequency range, which in our case is determined by 5G technology and covers the entire operating range of a rectangular waveguide with a section of 7.2x3.4 mm. In such a wide frequency band, integrated gratings and other devices using impedance transformers based on transmission line segments [5] cannot be used in the PD, since these elements provide acceptable characteristics in a relatively narrow frequency band (about 5–10%).

It is obvious that the required width of the operating band of the PD can be ensured by its implementation on the basis of a regular transmission line without the use of matching resonant elements. The principle of a self-controlled microwave power limiter was used as a circuit diagram, when the energy of the detected microwave signal is used to power the control p-i-n diodes (Fig. 3). The advantages of such a schematic solution were clarified above. In this case, the PD is always in the working mode, even if the equipment is disconnected from the power source [7].

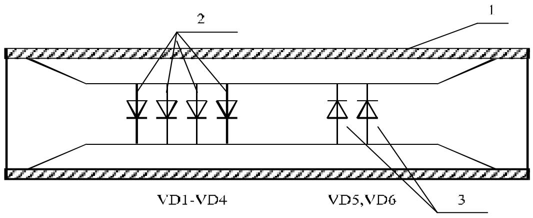

Fig. 3. PD based on a regular transmission line (H – waveguide)
1 – H- waveguide;
2 – control node on p-i-n diodes;
3 – node of detector diodes (BSD).

Losses (signal attenuation) in these schemes in the weak signal mode are determined both by losses in the active elements and by the reflection of the signal from the input of the PD due to the mismatch of the transmission line at the locations of the diodes, which occurs even in the absence of losses in the diodes. If capacitance C is included in a certain cross-section of a coordinated long line with a wave resistance ρ (Fig. 4), the reflection coefficient from this cross-section is determined by the expression:

$$r = \frac{1}{-1 + i \cdot \dfrac{2}{\omega \rho C}}, \qquad (1)$$

where ω = 2πf – is the circular frequency, *i* – is an imaginary unit.

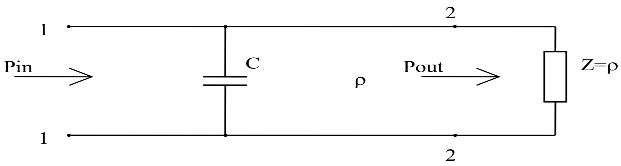

Fig. 4. Scheme of inclusion of capacitive heterogeneity in a regular transmission line

From (1), it is possible to calculate the value of the transmission coefficient of the line between sections 1-1 and 2-2 (Fig. 4):

$$\frac{Pin}{Pout} = \frac{1}{1 + \frac{1}{4} \cdot \omega^2 \cdot \rho^2 \cdot C^2}, \qquad (2)$$

and, accordingly, losses in the line:

$$L = 10\lg \cdot \left(1 + \frac{1}{4} \cdot \omega^2 \cdot \rho^2 \cdot C^2\right). \qquad (3)$$

In fig. 5 shows the dependence of losses (due to reflection) on the section of the line with capacitance C and wave resistance ρ depending on the value of C (ρ expressed in ohms, C in picofarads). It follows from the figure that to ensure losses of the order of 1 dB, it is necessary to fulfill the condition ρC ≤ 5 Ωhm×pF. Capacities of p-i-n diodes used in the millimeter range usually have a value of 0.05–0.1 pF [4] and cannot be reduced both for technological reasons and in view of the thermal regime, which determines the limit value of the microwave power that is switched. It follows from this that to create a PD with low attenuation in the weak signal mode, it is necessary to use a line with a wave resistance not higher than 50–100 Ohms.

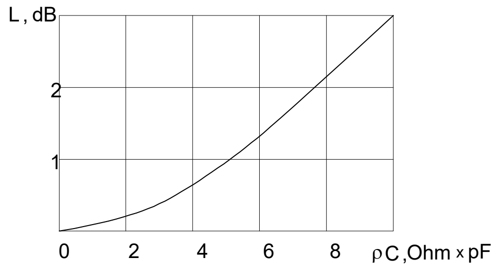

Fig. 5. Dependence of losses due to reflection on the section of a regular line with wave resistance ρ on the capacity C included in the line (ρ is expressed in ohms, C – in picofarads)

It is obvious that an ordinary rectangular waveguide is not very suitable for this purpose, since its wave resistance has a higher value. In addition, the electromagnetic wave field in it is distributed over almost the entire cross-section, while the active elements (AE) placed in the rectangular waveguide can be considered as point elements with concentrated parameters. The level of AE interaction with the electromagnetic wave in this case is quite low.

In connection with the above, the following types of lines can be considered the most acceptable for the implementation of the PD, from the point of view of ensuring sufficient heat dissipation:

1. H-waveguide, where you can mount AE on the crest of the waveguide, which will provide the necessary heat dissipation.
2. MSL – microstrip line. If holes are made in the dielectric plate at the locations of the AE, the diodes can be mounted directly on the metal plate, which will perform the functions of a heat sink.

However, MSLs have relatively high losses, and making holes in the dielectric plate is a relatively complex technological operation. Thus, the entire set of requirements for the guide system is provided by the H-waveguide.

Evaluation of parameters and calculation of characteristics of individual elements of the protective device. In order to estimate the main parameters of the PD and calculate the characteristics of its elements, it is first necessary to determine the characteristics of the regular waveguide structure and its geometric dimensions.

In fig. 6 shows the design of the H-shaped waveguide. The waveguide is formed by two symmetrically located ridges of width 2t, the distance between them is 2l. These ridges are located in a rectangular waveguide, the width of which is 7.2 mm and the height is 3.4 mm.

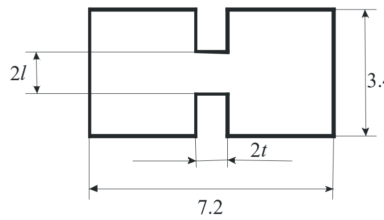

Fig. 6. Design of H-waveguide

From the results of the calculation of the parameters of the H-waveguide, it can be seen that for a crest width of 2t = 2.8 mm and a distance of 2l = 0.4 mm, the wave resistance is equal to 45.3 Ohms at the middle frequency of the range and changes little in the working frequency range (from 44.9 Ohms to 46.5 Ohms), i.e. a change wave resistance in the range is ± 1.75% of the average value. Increasing the distance 2l to the value of 2l = 0.6 mm gives a value of the wave resistance of 66.3 Ω ± 2.6%, which can lead to an increase in losses in the small-signal mode.

Control elements of PD are p-i-n diodes. The PD control node is 4 p-i-n diodes installed in a regular line with a wave resistance ρ at the same distance l from each other. The equivalent circuit of the control node is shown in Fig. 7.

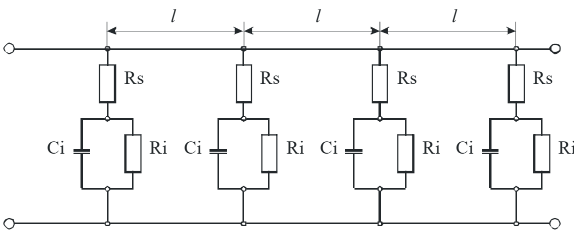

Fig. 7. Equivalent diagram of the control node

Here, Ri is the resistance of the i-layer, Ci is the capacitance of the p-i-n structure, Rs is the resistance of the low-resistance semiconductor and metal. To reduce the voltage standing wave coefficient (SWC) and increase the bandwidth, the distance l and the value of the conductance of the diodes must be chosen so that each stage produces relatively small losses and reflections in the small signal mode, and the reflection introduced by each stage must be compensated on average.

The analysis and synthesis of multi-cascade devices is based on the application of an equivalent circuit in the form of a cascade connection of concentrated inhomogeneities, the role of which is performed by controlled diodes VD1... VDn separated by phase distances Θ (4), represented on the diagram by conductivities y_1... y_n (Fig. 8).

$$\Theta = \frac{2 \cdot \pi}{\lambda} \cdot l, \quad (4)$$

where λ is the wavelength.

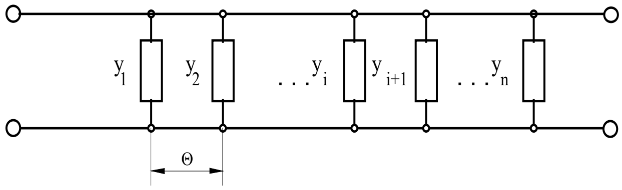

Fig. 8. Equivalent circuit of the PD control node in the form of a cascade connection of concentrated inhomogeneities

In the case of equal distances between the same diodes, matrix theory allows obtaining the ratio for the transmission coefficient of the n-cascade control unit [6].

The paper calculated the initial losses L_0 (in the small signal mode) of the PD control unit using p-i-n diodes with Rs=0, Si=0.05 pF, Ri=20 kΩ for a line with wave resistance ρ =70 Ohm. In the calculations, the distance l between the diodes was taken into account in the form of the electrical length of the line segment between the diodes at the average frequency of the range

$$\Theta = \frac{2 \cdot \pi \cdot l}{\lambda_{32}},$$

where λ_{32} – is the wavelength in the guide system at a frequency of 32 GHz.

In fig. 9 shows the dependence of the initial losses for the PD control node on the frequency under the assumption that the condition Rs=0 is fulfilled for p-i-n diodes [9]. As can be seen from the graphs, the parameter Θ determines not only the value of the initial losses, but also their change in the frequency range.

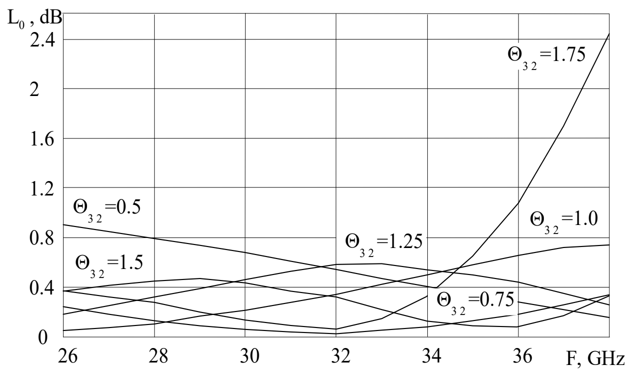

Fig. 9. Dependence of the initial losses on the frequency for the PD control node

From the given results, it follows that to ensure uniform characteristics and small values of initial attenuation in the operating frequency range, the distances between the diodes of the control unit should be selected according to the expression:

$$l \approx \frac{\lambda_{32}}{8}.$$

In our case, this value is within ~ 0.8-1 mm. For the mode of high microwave power levels, when the p-i-n diodes are open, they can be represented as a resistance R. In this case, the calculations show that the control node provides the following values of the input attenuation Lins in the power signal mode. As R changes from 2 to 8 Ohms, Lins changes from 73 to 40 dB.

As can be seen from the results of the calculation carried out in the work, the control node of 4 p-i-n – diodes in the range of the given R values provides a fairly high value of the introduced attenuation.

Thus, it is advisable to use a regular line on the H-waveguide for the construction of the PD. The uniformity of losses in the small-signal mode in this case and their value are ensured by choosing the distance between the p-i-n-diodes and the parameters of the diodes in the small-signal mode. The magnitude of the applied attenuation in the powerful signal mode is determined mainly by the resistance of the p-i-n diodes in this mode with other parameters fixed.

Conclusions. The results of the work make it possible to significantly increase the reliability of the input circuits of microwave receivers of mm-band radio relay stations operating in a complex electromagnetic environment, namely in the presence of the influence of strong external pulse signals. At the same time, they can be used to increase the reliability of new generation mobile networks using 5G technology.

As a result of theoretical and experimental research, the principles of building a self-controlled power limiter have been developed, which, unlike the existing ones, works in a wide range of frequencies (about 40%), and this allows it to be used in transmission systems of 5G technology and provides a relatively low level loss in a small signal mode with a high level of attenuation in a powerful input signal mode.

At the same time, the losses of the experimental sample in the mode of low power of the input signal at the lower frequencies of the operating range did not exceed 0.3 dB. At the upper frequencies of the operating range, losses did not exceed 1.7 dB. The transmission characteristic in the range was quite smooth. In the mode of pulsed high input power, the value of losses was of the order of 30 dB. The signal duty cycle was in the range of 10–100.

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Манько О.О., Кунах Н.І., Харлай Л.О., Нікіфоренко К.Б., Коновалов О.Ю., Сотніченко Ю.О.

ЗАХИСТ ВХІДНИХ КІЛ ПРИЙМАЧІВ РАДІОРЕЛЕЙНИХ СТАНЦІЙ МІКРОХВИЛЬОВОГО ДІАПАЗОНУ ВІД ПОТУЖНИХ ІМПУЛЬСНИХ ЗАВАД

В роботі запропоновано принципи побудови широкосмугових самокерованих обмежувачів потужності мм – діапазону довжин хвиль. Розглянуто робочий діапазон, що включає в себе область частот, які лежать в межах від 28 GHz до 38 GHz, та які використовує технологія 5G. В якості основи для конструктивної побудови обмежувача вибрано напрямну систему типу H-хвилеводу.

Проведено оптимізацію його конструктивних параметрів. Зокрема вибрано ширину гребеня хвилеводу та відстань між гребенями. Визначено, що ширина гребенів та відстань між ними *суттєво впливають на параметри внесених втрат в режимі малого та великого вхідного сигналу. Зокрема, зменшення ширини гребенів збільшує внесені втрати в режимі великого вхідного сигналу, що є позитивним фактором. Визначено, що аналогічний хід залежності втрат відбувається при зменшення відстані між гребнями. Проте, в цьому випадку має місце невелике збільшення втрат в режимі малого сигналу. Таким чином, має місце та в роботі визначене оптимальне співвідношення щодо цих розмірів.*

Надано методи розрахунку передавальних характеристик (внесеного загасання) самокерованих обмежувачів потужності в режимі малого сигналу. Розглянуто шляхи оптимізації конструкції обмежувача. Вибрано значення просторового інтервалу для розміщення в напрямній системі Н-хвилеводу напівпровідникових елементів, що входять у конструкцію обмежувача. Запропонований інтервал забезпечує в режимі малого сигналу широкий робочий діапазон частот, який включає частоти технології мобільного зв'язку 5G. Аналогічну побудову обмежувача можна використати в діапазоні частот 60 GHz, який також використовує технологія 5G.

При цьому втрати експериментального зразка в режимі низької потужності вхідного сигналу на нижніх частотах робочого діапазону не перевищували 0,3 дБ. На верхніх частотах робочого діапазону втрати не перевищували 1,7 дБ. Передавальна характеристика в діапазоні була досить гладкою. В режимі імпульсної високої вхідної потужності значення втрат складало порядку 30 дБ. При цьому шпаруватість вхідного сигналу лежала в межах 10–100.

Результати цієї роботи можуть дозволити значно підвищити надійність вхідних ланцюгів НВЧ-приймачів радіорелейних станцій мм-діапазону, що працюють у складному електромагнітному середовищі, а саме за наявності впливу сильних зовнішніх імпульсних сигналів. Поряд з цим вони можуть бути використані для покращення надійності мобільних мереж нового покоління з використанням технології 5G.

Ключові слова: *напрямна система, втрати в режимі сигналу малої потужності, втрати в режимі сигналу великої потужності, діоди з бар'єром Шотткі, p-i-n-діоди.*