УДК 621.396

TERAHERTZ WAVES APPLICATION FOR RADIO LINK BUILDING WITH GIGABIT THROUGHPUT: INNOVATIVE SOLUTIONS AND RESEARCH RESULTS

T.N. NARYTNYK, G.L. AVDEYENKO, O.V.MAY

Research Institute of Telecommunications,
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
Industrialny lane, 2, Kiev, 03056, Ukraine, director@mitris.com

ВИКОРИСТАННЯ ТЕРАГЕРЦОВИХ ХВИЛЬ ДЛЯ ПОБУДОВИ РАДІОЛІНІЇ ЗВ'ЯЗКУ ІЗ ГІГАБІТНОЮ ПРОПУСКНОЮ ЗДАТНІСТЮ: ІННОВАЦІЙНІ РІШЕННЯ ТА РЕЗУЛЬТАТИ ДОСЛІДЖЕНЬ

Т. М. НАРИТНИК, Г. Л. АВДЄЄНКО, О.В.МАЙ

Науково-дослідний інститут телекомунікацій НТУУ «КПІ ім. Ігоря Сікорського»,
пров. Індустріальний, 2, Київ, 03056, Україна, director@mitris.com

Abstract. *The results of the completed studies conducted by the author's team during the 25-year period the possibilities of creating for the first time in Ukraine the real prerequisites for solving the fundamental problem of the construction of digital telecommunication systems with the use of terahertz technologies are presented. The necessity of the transition to the use of terahertz frequency range when deploying future telecom systems with ultrahigh bandwidth is shown. The main factors that lead to the emergence of fading in radio relay communication lines are considered. It is shown that in the terahertz range the greatest influence on the energy potential of the radio-relay lines is attenuating in hydrometeors and gases. It is shown terahertz frequency range areas that are most suitable for use in radio relay communication lines. The principles of formation of signal-code design are considered. Methods and new technical solutions for choosing the type of signal construction are proposed in order to achieve the best performance in wireless communication of in the terahertz range. The results of functional design, simulation and experimental research of the receiving and transmitting paths of a telecommunication system with a gigabit throughput in the frequency range 130-134 GHz are presented. A simplex digital radio relay system in the 130-134 GHz band prototype with digital modem was designed. It provides channel throughput up to 1200 Mbit/s within 1 km. The concept of creating a software-defined radio technology based on Wi-Fi, can be used in high-performance transport distribution networks of the next generation mobile communications to ensure proper transmission speeds, reliability and security. Tests of transmission of digital television standard DVB-C over the 130 GHz path were successful.*

***Keywords**. terahertz technologies**,** telecommunication systems, radio relay system, digital modem, provides channel throughput , signal-code design construction, frequency range 128 - 134 GHz, standard DVB-C.*

Анотація. *Наведено результати проведених авторами в 25-річний період завершених досліджень можливостей створення вперше в Україні реальних передумов вирішення фундаментальної проблеми побудови цифрових телекомунікаційних систем з використанням терагерцових технологій. Обґрунтовано необхідність переходу до використання терагерцового діапазону частот при розгортанні майбутніх телекомунікаційних систем надвисокої пропускної здатності. Розглянуто основні фактори, що призводять до виникнення завмирань в радіорелейних лініях зв'язку. Показано, що в терагерцовому діапазоні найбільший вплив на енергетичний потенціал радіорелейних лінії чинять затухання в гідро метеорах та газах. Виділено ділянки частот терагерцового діапазону, які найбільше за все придатні для використання в радіорелейних лініях зв'язку. Розглянуто принципи формування сигнально-кодової конструкції, запропоновано способи і нові технічні рішення для вибору виду сигнальної конструкції з метою досягнення найкращої пропускної здатності та продуктивності в каналі зв'язку безпроводової гігабітної системи передачі в терагерцовому діапазоні. Наведено результати функціонального проектування, моделювання та експериментальних досліджень приймального і передавального трактів телекомунікаційної системи з гігабітною пропускною спроможністю в діапазоні частот 130-134 ГГц. Вперше в практичному плані проведені дослідження лабораторного зразка цифрової симплексної радіорелейної системи терагерцового діапазону в складі приймального і передавального радіотракту в діапазоні частот 130-134 ГГц і цифрового модему з пропускною канальною здатністю до 1200 Мбіт/с на дальність зв'язку в нормальних умовах в межах 1 км. Показано, що запропонована телекомунікаційна система, яка реалізує концепцію створення програмно-визначених радіосистем на основі технології Wi-Fi, може високопродуктивно використовуватись в транспортних розподільчих мережах мобільного зв'язку наступного покоління із забезпеченням відповідних швидкостей передачі, надійності та захищеності. Досліджено параметри багатоканального сигналу цифрового телебачення стандарту DVB-C при його передачі через макет приймально-передавального тракту діапазону 130ГГц.*

Ключові слова: *терагерцові технології, телекомунікації, радіорелейна система, пропускна канальна здатність, сигнально-кодові конструкції, цифровий модем, діапазон частот 130-134 ГГц, стандарт DVB-C.*

INTRODUCTION

One of the trends in the development of modern telecommunications is the usage of increasingly high-frequency ranges. Since the early 1980's and to date, the terahertz range, which roughly occupy a band of radio frequencies from 0.1 to 3 THz (Figure 1), has attracted the attention of researchers.

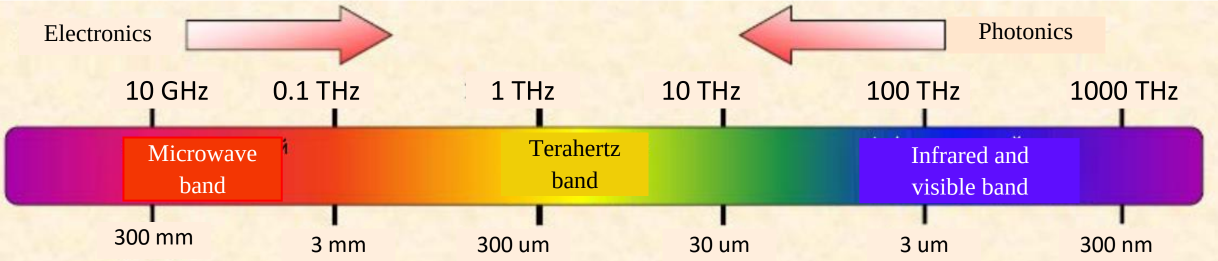


Figure 1 – Terahertz range in the electromagnetic spectrum

Terahertz range mastering contributed to development of semiconductor active elements for generating and amplification at terahertz frequencies through the use of nanotechnology, and new types of vacuum devices which operate in this frequency range.

The analysis of the activity of research and development focused in the field of terahertz technology revealed more than 7389 patents and applications which were submitted in the period from 1980 to 2017 years.

These data show that terahertz technologies are extremely broad prospects for application in various fields, and the range of areas for THz technologies application constantly expanding. The largest number of inventions were found in measurement technology, optics, telecommunications: a series of patented solutions is aimed at creating compact generators and receivers of THz-radiation, controlling devices of THz radiation (switches, modulators, phase shifters). Stable positive growth in the number of patent applications in the research area indicates that explored topics are related to the field of promising research.

One of the most promising areas of application of terahertz technologies in telecommunications linked to modern trends of development of fifth generation mobile transport distribution networks, control systems for military missions and combating terrorism which involve the exchange of large amounts of data. Services of fiber optic networks provide multigigabit volume exchange in many parts of the world. But modern telecommunications networks require similar facilities in locations where fiber access does not exist. Satellites can provide communication in remote areas, but can not fully provide the power necessary to maintain the volume of data.

This started the development of a new generation of compact wireless systems using terahertz unlicensed frequency bands distinct from the licensed frequency bands traditionally involved to transport stream transmission between macrocells.

Current trends of wireless data speed increase show that by 2020 the rate should be not less than ten gigabits per second. This issue raises the question of availability of frequency range, capable to meet the following requirements. The main feature is the increase of available bandwidth to several tens of gigahertz. It's realization at frequencies above 100 GHz and above 500 GHz fully is not possible.

In recent years, several worldwide research groups have begun to explore wireless systems at frequencies exceeding 100 GHz and above. An example is the program of Defense Advanced Research Projects Agency (DARPA) to create technologies and devices THz communication.

One of the promising new directions of our work - the creation, development and implementation of terahertz technology in telecommunications. Creating devices, systems and networks of THz band is able to radically change the principles and theoretical approaches to building 5G distribution transport networks of mobile communications and control systems for military application. In addition, there are huge prospects for their use in other areas - from aerospace and meteorology to medicine and safety.

For the first time in Ukraine In the 25-year period of was created a real precondition for solving the fundamental problem of constructing a digital high-speed noise immune communication system for wireless transmission of high-capacity data using terahertz technologies [23]. Cycle of the research includes the following areas:

- ***study features of propagation of terahertz waves in the atmosphere***
- ***implementation of the concept of software-defined radio system of terahertz range using the technology of Wi-Fi.***
- ***design of transmitting and receiving radio link, radio relay systems terahertz range***
- ***the transmission of the signal to the DVB-C signal through the transmit-and-receive link of the terahertz band***
- ***simulation of ultra wideband pulse signals transmission in terahertz range.***

1 RESEARCH OF THE PECULIARITIES OF TERAHERTZ WAVES PROPAGATION IN THE ATMOSPHERE

For the effective development of THz telecommunication systems, the knowledge of the mechanics of propagation terahertz waves in the atmosphere is extremely important, because they allow the developer to assess the degree of implementation and reliability of radio system. However, a careful study of these mechanisms has not been undertaken. Recent studies in this area were based on consideration only of individual systems (e.g. wireless networks WLAN). It is therefore extremely important in today's rapid development of equipment terahertz range of leading scientific and technical schools in the world to conduct such research, the results of which could be used to develop any wireless terahertz telecommunication system.

The above applies also to a higher range – the range of terahertz electromagnetic waves, development tools and technologies effective use is to create future communication systems of ultra-high-speed data that will be the basis for building 5G cellular networks.

Also is necessary to study the characteristics of terahertz waves propagation in the atmosphere in a wide range of frequencies for future applicatiob of the results obtained in the design of effective broadband telecommunication systems.

1.1 The features of terahertz waves propagation in the atmosphere

The authors conducted an analysis showed that in the frequency range of 30-300 GHz from known types of fading (refractive fading due to shielding effects of interferences, refractive fading of interference type, interference fading due to reflection from the heterogeneities of the troposphere layers, fading due to the shielding effect of the heterogeneities of the atmosphere layers, fading due to the effect aerial direction diagrams (for the terahertz range it is the inaccuracy of tuning the antennas, as well as the wind load on the antenna of the support), fading due to the relaxation of the radio signal by hydrometeors (rain, dry and wet snow, hail, fog, clouds), signal fading due to absorption in gases, fading signal in sand and dust storms), the most significant influence in the design are:

- fading due to signal attenuation by hydrometeors;
- signal fading due to absorption in gases (primarily water vapor and molecular oxygen);
- fading due to exposure antenna patterns.

Microwave links work at such high frequencies (especially in the terahertz range) due to high directivity antennas corresponding stations allows practically not consider interference of electromagnetic waves reflected from obstacles in the area of signal propagation, which occurs especially in the urban environment. The calculated value of the first Fresnel zone maximum radius at the center of the track with length of 5 km equals to 2.3 m at a frequency of 140 GHz and will not exceed 1.6 m at a frequency of 300 GHz and therefore it gives the right not to consider refraction interference and fading when calculating the energy budget digital microwave links terahertz range that are planned.

1.2 Attenuation of terahertz waves due to absorption of radio signal in gases

Attenuation terahertz waves in the atmosphere up to 300 GHz frequency occurs mainly due to the presence of oxygen in the air and water vapor. Other gases are making little contribution to the attenuation value of terahertz waves. In Figure 2 depicts the results of the study the dependence of the attenuation of radio frequency, conducted in 1996 by the International Telecommunication Union (ITU) under normal atmospheric parameters (temperature 15 C^0, 101.3 kPa pressure and water vapor density of 7.5 g/m^3) in close proximity to the Earth. One curve investigated the effects of oxygen (O_2 curve – dry air), the other – the influence of water vapor.

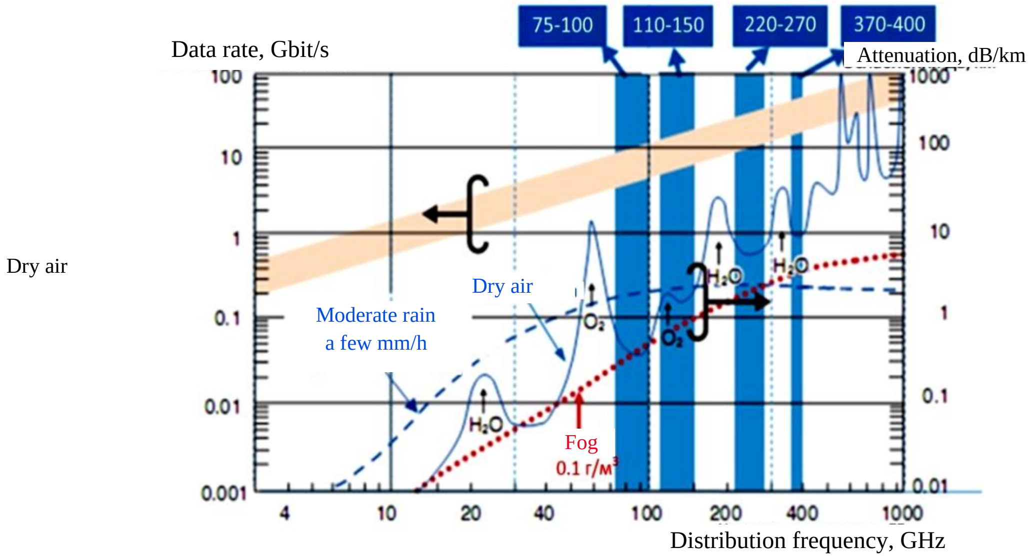


Figure 3 – Dependence of attenuation of frequencies with regard to rain

The results indicated that the attenuation peaks due to resonant interaction of radio waves with a molecule of oxygen formed in the band 50–70 GHz with a maximum frequency of 60 GHz and 118 GHz frequency. Peaks attenuation due to the interaction of electric moment of water and radio waves formed at a frequency of 22.2 GHz and 183 GHz frequency. At other frequencies observed lower attenuation values, the range between the peaks and named radio windows. In other words, selecting frequencies that are located in radio windows can significantly reduce the impact of atmospheric parameters on radio line.

1.3 Attenuation of terahertz waves due to the relaxation of radio signals by hydrometeors

Hydrometeors (precipitation) – is water in liquid or solid form, that fall down from clouds or directly from the air on the Earth's surface and objects. With clouds fall: rain, mist, snow, wet snow, cereals, hail, ice rain. From the air are: liquid raid, frost, a solid raid, hoarfrost.

Linear attenuation in the rain γ_d (dB/km) is defined by rain intensity R (mm/h) and calculated by the following formula:

$$\gamma_d = aR^b . \quad (1)$$

The coefficients a and b depend on the size distribution of water droplets. The presented models are discussed in more detail in Recommendation P.838 ITU-R.

Results computing coefficients of different intensities of rain (2.5 mm/year – light rain, 12.5 mm/hr. – moderate rain, 50 mm/hr. – showers) at 20 ° C, which are made on the basis of the proposed new functions distribution, taking into account the presence of small raindrops and experimental data sources are presented in the table 1.

Attenuation terahertz waves **in dry snow** is small. Several times increases the value of attenuation in wet snow or rain the same intensity. For comparison, experiments have shown that the frequency of 88 GHz at a distance of 1.4 km attenuation in dry snow was only 1 dB, while the wet attenuation are equal to 20 dB. The conclusion is: the contribution of snow compared with the same intensity rain negligibly small.

In the case of fog, which is characterized by a drop of water is a diameter of 0.1 mm or less, which are concentrated in a limited space and distributed by Rayleigh law, damping terahertz wave to pass 300 GHz are minor.

Table 1 – Ratio weakening γ (dB/km) for the different parameters of the atmosphere

	Type of atmosphere	Radio signal Frequency, GHz							
		30	60	90	120	140	165	250	300
1	Rain weak (1 ÷ 5 mm/h)	0.9	2.1	3.4	4.7	5.4	7.1	9.8	14.3
2	Moderate rain (5 ÷ 20 mm/h)	3.5	8.0	9.5	13.2	15.1	18.3	27.5	33.6
3	Strong rain (20 ÷ 40 mm/hour)	7.0	14.0	15.2	16.3	17.0	20.2	30.5	42.3
4	Torrential rain (40 ÷ 100 mm/hour)	17.0	28.0	30.6	33.3	35.0	38.7	45.0	53.2
5	Dry snow (10 mm/hour)	0.06	0.13	0.21	0.28	0.32	0.41	0.59	0.74
6	Wet snow (10 mm/hour)	1.7	4.9	7.7	10.7	12.4	15.3	22.8	28.7
7	Cumulus clouds strong (1.2 g/m^3)	3.5	8.0	9.5	12.9	15.1	18.9	27.5	33.2
8	Gas (oxygen)	–	15.0	0 .05	1.8	0.5	0.02	0.02	0.03
9	The gas (water vapor)	0.07	0.1	0.2	0.5	0.8	2	2.5	5.5

Based on the results of the research can be considered the most suitable and promising in the design of high-speed UWB wireless telecommunication systems are frequency bands of 110-150 GHz 220–270 GHz because it's possible to use a 40-50 GHz frequency band in order to significantly increase information capacity, increasing stealth and protection against detection and unauthorized access of transmitted information.

2 IMPLEMENTATION OF THE CONCEPT OF SOFTWARE-DEFINED RADIO IN TERAHERTZ RANGE USING WI-FI TECHNOLOGY

Among modern trends infocommunications nowadays dominated areas such as 5G, cognitive networks, big-data, optical network, green-communications, telecommunication systems terahertz range, distribution transportation mobile network and so on.

Construction of a significant part of wireless devices within these trends is based on the concept SDR- Software-defined radio. Currently known examples of implementing the concept of SDR is a unit for networks GSM, UMTS, Wi-Fi, WiMAX, etc.

The task of any telecommunication system is to achieve, within the resources allocated channel, high speed and reliability required information transfer. One of the known means of implementation of this task is to appeal to **multiposition types of modulation** and noise immunity coding. The combination of a certain type of multi-modulation and noise-immunity coding of certain parameters called code-signal design (**CSD**).

If the communication device selects an appropriate structure CSD automatically with the appropriate program and algorithm should be considered a relevant concept device **SDR**. Description appropriate for this criteria and algorithms and implementing the concept of software-defined radio terahertz range of technology-based Wi-Fi.

2.1 An example of implementing the concept of SDR in gigabit modem of telecommunications system in terahertz range

In order to implement the concept of SDR in the terahertz range telecommunication system based on Wi-Fi technology we created a gigabit modem G1, which can be used to connect geographically separated network Ethernet segments, Ethernet 10/100/1000-BaseTx. Functional Gigabit modem circuit G1 is presented on Figure 4.

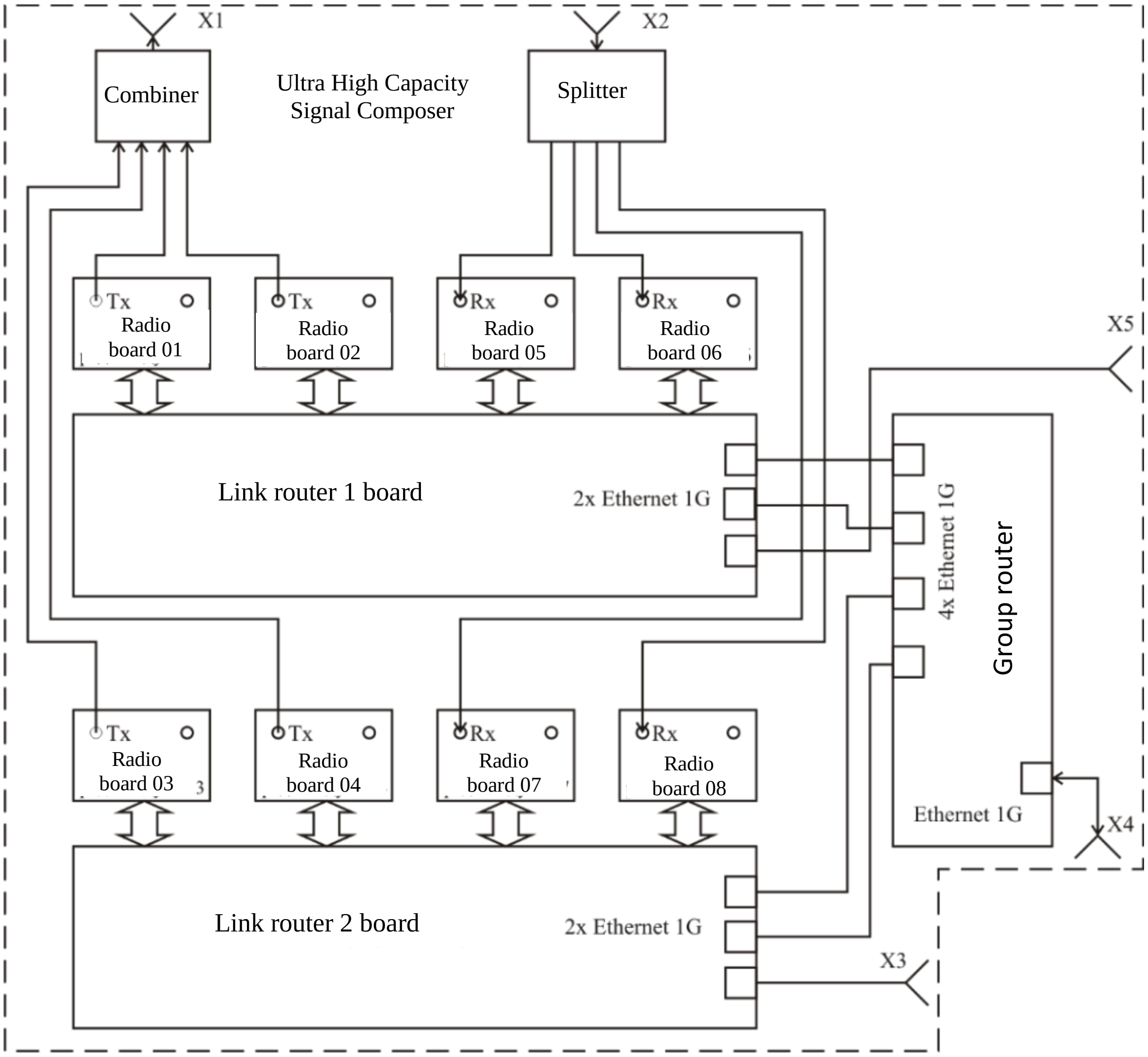


Figure 4 – Gigabit Modem Functional diagram

Key components of Gigabit Modem – channel 1 and 2 routers and router group. The input stream is automatically distributed to all the channels and further processed to form the radio spectrum in the microwave bandwidth channel.

Gigabit Modem G1 (Figure 4) made in the metal housing allows to install it in a RackMount rack or use desktop location.

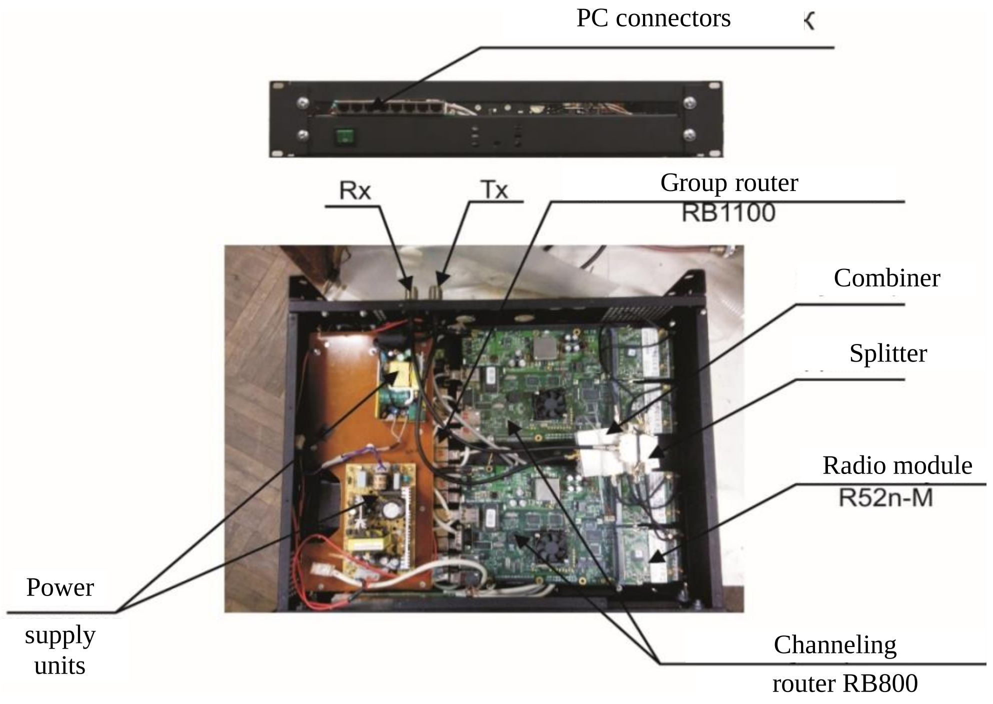


Figure 4 – Photo of Gigabit Modem G1 testbed

Main modem specifications presented in Table 2 and 3.

Table 2 – General Gigabit Modem Specifications

Name	Value
Supply voltage,	220
Interface of control modulation-demodulation mode	Ethernet 10/100 Base-Tx, RJ-45 connector
Router management interface	Ethernet 10/100/1000 Base-T, RJ-45 connector
data interface	Ethernet 10/100/1000 Base-T, RJ-45 connector
IF interface link	Coaxial, 50 Om link, N-type optional board
The central link IF frequency, MHz	2400
Bandwidth occupied by the modulated signal at maximum capacity, MHz, not greater than	40
modulation	QAM-64
Signal IF output modulator dBm	0 ... – 3
The sensitivity of the input IF demodulator dBm	– 70
The maximum allowable level of the IF signal at the input of the demodulator, dBm, not greater than	– 45
Weight modem kg, max	4

Test results of Gigabit modem G1 speed characteristics are given in Table 3.

Table 3 – Results of testing high-speed performance of Gigabit modem G1

Appropriate router	**Number of dual stream channels**	**Duplex mode**	**One direction channel capacity (Mbit/s)**	**Total bitrate for two directions (Mbit/s)**	**Operational transmission/ reception capacity (Mbit/s)**	**Total operational capacity (Mbit/s)**
rb450g	1	RX	150		116	
rb450g	1	TX	150		116	
rb450g	1	FD	150	300	85	170
rb450g	2	FD	300	600	155	310
rb750	2	FD	300	600	155	310
rb750	2	HD	300		195	
rb450g	2	RX	300		215	
rb450g	2	TX	300		225	
rb450g	4	FD	600	1200	335	670
rb750	4	FD	600	1200	335	670
rb450g	4	HD	600		415	
rb450	4	HD	600		370	

Management of each of the two channel routers by using tools WinBox – connectors X3, X5 “CONTROL MODEM” (Figure 4).

Intermediate frequency signal channel router receives the output connector X1 (Figure 4). The output signal of intermediate frequency channel routers - Connector X1 (type «N») is connected directly to the input of intermediate frequency transmitting unit terahertz range. Similarly configured path intermediate frequency signal input from the receiving unit terahertz range (connector X2). To connect to the network Ethernet, and router control group used both direct and cross UTP cable connector X4. To ensure the channel speed of 1.2 Gb/s radio link terahertz range [18-24] applied 8 transceiver Wi-Fi standard 802.11n in the range of 2,1–2,7 GHz band of 40 MHz each with channel speed 150 Mbit/s (Figure 5 and 6).

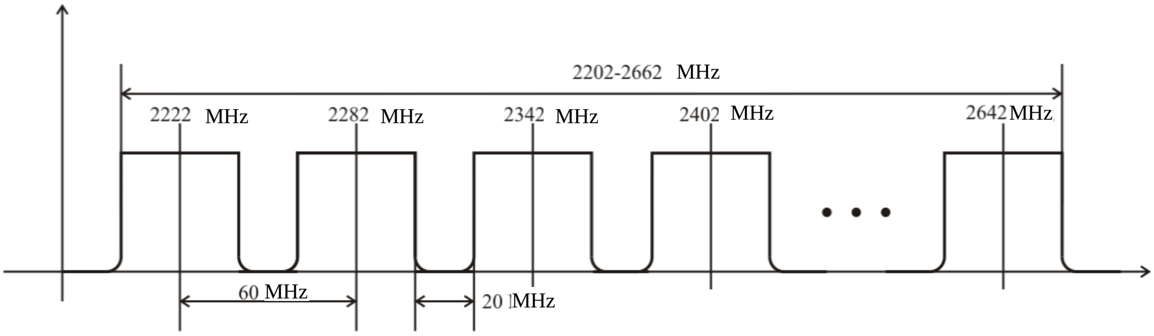


Figure 5 – Frequency Plan of Gigabit Modem

The modem uses the "dual stream" mode on the Mikrotik hardware, which uses two R52n-M receivers for one duplex radio channel, one for reception, and another for transmission. To achieve a total channel speed of 1.2 Gbit/s, four duplex channels of 150 Mbps in each direction are offered. When forming the dual stream channels which is necessary for the organization of duplex channels and increasing the efficiency of each channel, Mikrotik RB800 routers are used with four mini-PCI slots with installed Mikrotik R52n M. The access to each radio channel is provided by a separate Ethernet interface of the RB800 router.

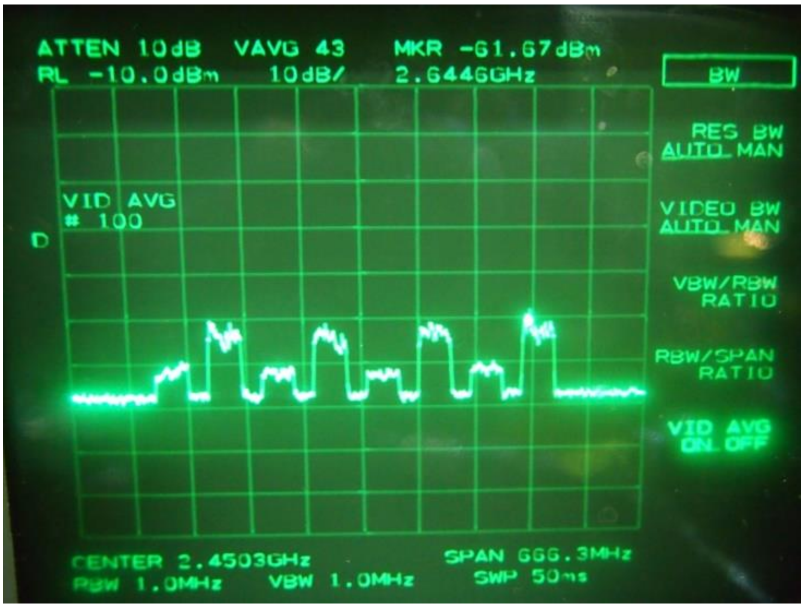


Figure 6 – Frequency response of 4-channel duplex communication channel

To combine all channels, the Mikrotik RB1100Hx2 router is used, which provides a single interface for external connection. This configuration of the modem provides high performance and claimed characteristics, while having a relatively low cost of building a gigabit modem. It is also possible to increase the channel speed of the gigabit modem to 1.2 Gb/s in each direction in case of doubling the number of kits of routers RB800 and transceivers Mikrotik R52n-M.

To issue an external 600 Mb/s aggregated channel, you must replace the RB750 Group Router with a router with a bandwidth of 1 Gbit/s or more, such as the RB450G or RB1100Hx2 provided by the modem design.

On the basis of gigabit modem G1 with set transceivers Mikrotik R52n-M and developed transmission and reception paths [25] using Wi-Fi technology, a gigabit system based on Wi-Fi technology in the range 130–134 GHz with the achievement of channel speed up to 1, 2 GB/s.

Hence such conclusions follow.

1 The principles of formation of code-signal design (CSD) for modern infocommunication systems are considered. The methods and new technical solutions for choosing the type of signal construction are proposed in order to achieve the best bandwidth and performance in the wireless communication transmission channel, where the indicator is the ratio of the signal level to the noise level at the receiver input

2 Shown gains in resource use link using CSD signal based on higher order structures and effective noise immunity block LDPC codes. Considered CSD and indicators and criteria recommended in the 802.11/n to select CSD - namely, the signal level at the receiver input. A measure of resource efficiency for selecting CSD - namely, information efficiency, showing the efficiency of resources such link as power, frequency, and time.

3 It was determined that the level of the signal at the receiver input, types of CSD and the resulting data rate PVR in the MikroTik`s equipment fully meets standards 802.11a/n.

4 An example of a technical solution that reveals the great potential protocol 802.11n, is proposed terahertz range telecommunication system. Due to the transition to the terahertz range between 100 GHz and above, it was possible to use wide bandwidth for transmission of information order of hundreds of MHz and GHz, and as a result – reach ultra-high transfer speeds.

3 DESIGNING TRANSMITTING AND RECEIVING RADIO LINK FOR RADIO RELAY SYSTEMS OF TERAHERTZ RANGE

3.1 The block diagram of the transmission and receiving link

The key elements of the radio relay system of the terahertz range are radio-electronic receiving and transmitting devices capable of generating and transmitting the required power for this frequency range modulated signals at a speed of 1 Gbit/s and receiving signals with acceptable high sensitivity.

Transmitter (Figure 7) and receiver (Figure 8) tracks constitute an analog (linear) part of the radio relay system. These tracks are built according to the heterodyne scheme and provide signaling on the track in the terahertz frequency range within the range of 130–134 GHz. The range of intermediate frequencies is 2–4 GHz. The block diagram of the transmission path is shown in Figure 1 and contains the following functional nodes: an intermediate frequency amplifier (IFA) (if necessary); frequency up converter; oscillator; band-pass filter (BPF); output power amplifier (PA) (with the possibility of purchasing components); transmitting antenna.

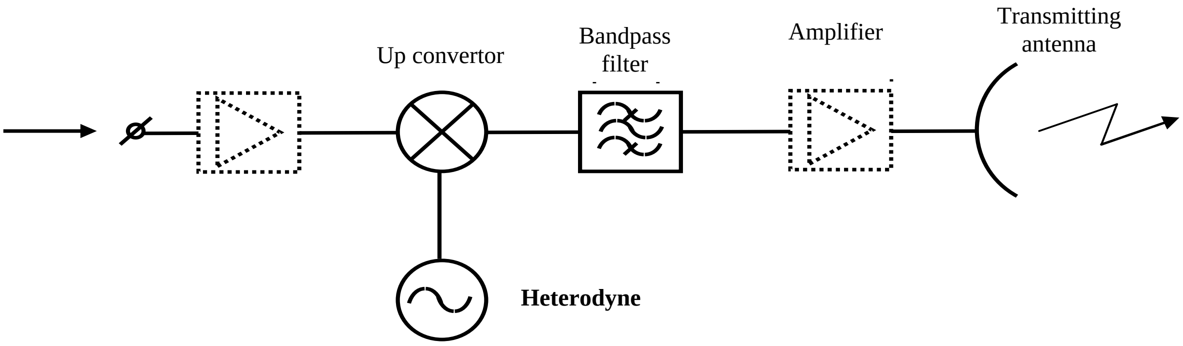


Figure 7– Block diagram of the transmission link

At the input of the transmission path, the signal is received from the group radio signal generator, and if the power of this signal is sufficient to obtain the desired signal level at the output of the converter, the scheme does not require the use of PPC.

The block diagram of the receiving path is shown in Figure 8 and consists of the following nodes: receiving antenna; Input low noise amplifier (IBC) (with the possibility of purchasing components); strip-pass filter; mixer; oscillator; intermediate frequency amplifier.

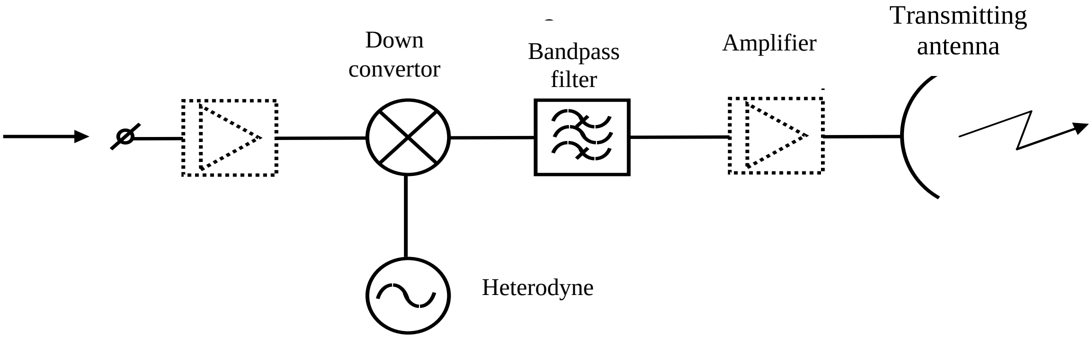


Figure 8 – The block diagram of the receiving link

The implementation of a low noise amplifier at the entrance to the receiving path is the same problem as with the power amplifier at the output of the transmitter.

3.2 Modeling and development of functional nodes of the receiving and transmitting link

3.2.1 Frequency signal transducers

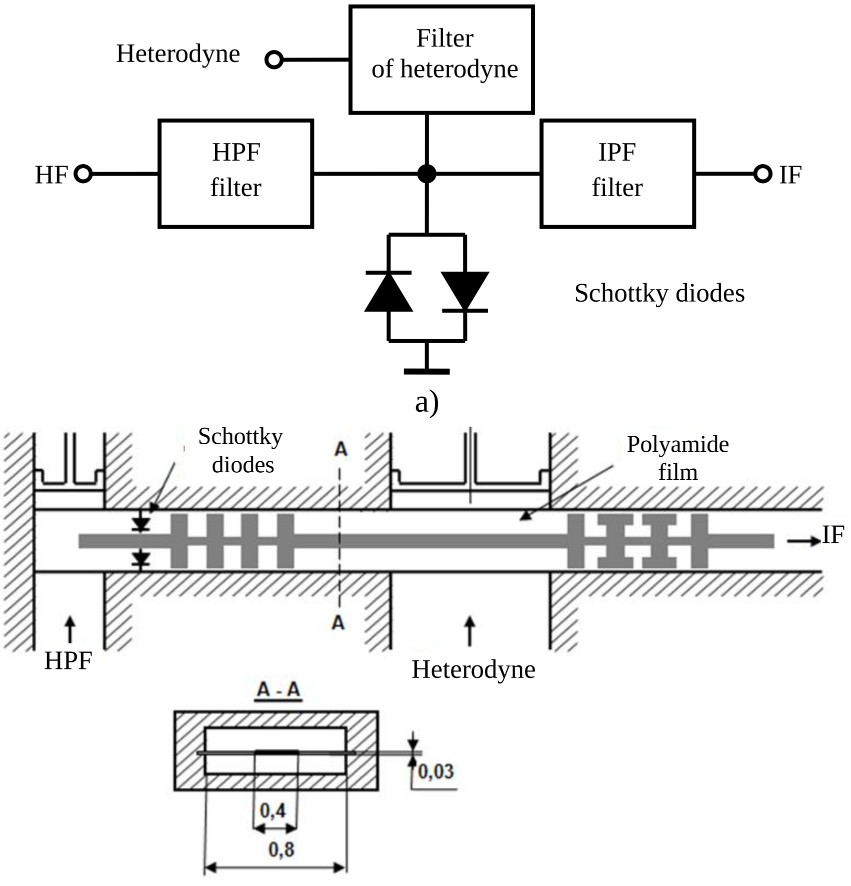
Frequency converter up and mixer operating in different modes and different functions, but have the same uniform scheme and design.

Converters have been built based on gallium-arsenide OEM Schottky diodes with beam terminals domestic production (NPP “Saturn”). These diodes cutoff frequency of 2.5 GHz, which allows them to work at least in the lower terahertz range. For electrical and design parameters developed diodes, which are not inferior to foreign analogues modern, such as gallium-arsenide diode made by Hewlett Packard.

To implement subharmonic converter circuit with pumping at half the frequency as nonlinear element used included two back-to-parallel Schottky diodes. Such forms include N-prominent resultant voltage characteristic symmetrical about the origin. This fact leads to modify the nonlinear element with a frequency greater than twice the frequency of the oscillator. Structural and constructive converter circuit shown in Figure 9.

The design of the converter contains two waveguide paths, connected by a symmetrical strip line, on which a pair of non-housing Schottky diodes are mounted. The diodes are selected according to the parameters in order to ensure the symmetry of the resulting voltage-current characteristic for qualitatively reducing the intensity of the odd harmonics of the heterodyne frequency.

Waveguide link of the channel section 1,6*0,8 mm chain is part of a high-frequency signal. This waveguide channel is transcendent for heterodyne and IF frequencies.



a)

б)

Figure 9 – Structural (a) and constructive (b) circuit of the converter

The signal of the heterodyne enters the diodes through a waveguide channel with a cross section of 3.6×1.8 mm. The channel is extraterrestrial for the IF signal, and the localization of the heterodyne from the RF signal provides a low pass filter (LPF) with a cutoff frequency of 67 GHz, executed on the strip line area between the waveguide channels.

The signal circuit of the IF is fully implemented on a symmetrical strip with a hanging lining. As a substrate, a polyimide film with a thickness of 30 μm, suspended in a rectangular channel by a cross section of 0,8×0,4 mm, prevents the occurrence of higher waveguide modes. The output LPF in the IF circuit with a cutoff frequency of 30 GHz prevents the signals of the heterodyne and the RF from penetrating into the path of the intermediate frequency. Short-circuit pistons in waveguide channels allow you to adjust the corresponding circuit of the converters.

Figure 10 shows the design of the frequency converter (mixer) with the removed upper part.

The diodes with beam terminals include a strip line with electrically conductive adhesive. In the photo (Figure 10) there are no short-acting pistons. The design of the mixer contains in its composition a preliminary amplifier of the signal of an intermediate frequency. At the output of the IF circuit, the SMA connector of the instrument type is used. The power of the heterodyne, which is required for the normal operation of the mixer, did not exceed 15 mW. The measured value of transformation losses is –11 dB, which corresponds to the best achievements of foreign analogues.

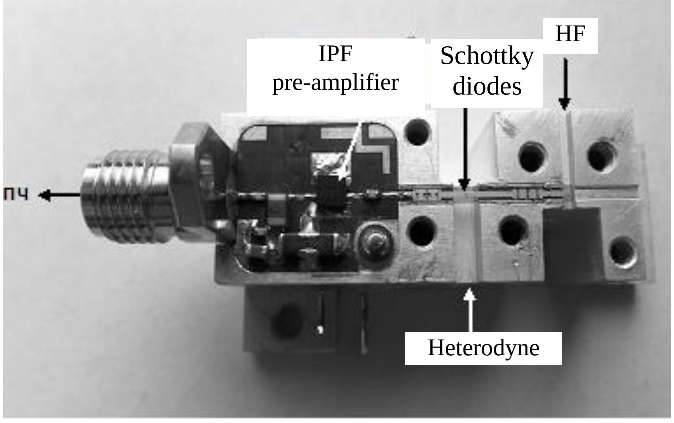


Figure 10 – Design of the frequency converter

3.2.2 High-frequency amplifier

Power Amplifier (PA) into transmitter output and low noise amplifier (LNA) at the receiver input are the functional units mainly determine the energy potential of the system.

Problems of realization of amplifiers in the terahertz range due to high operating frequencies. Advances semiconductor technology in recent years and the establishment of appropriate components offer prospects for the realization of high-quality amplifiers. Created a low noise amplifier 3 mm wavelength range is realized on the monolithic chip PIn in the frequency range 87–100 GHz while providing signal amplification to 27 dB and noise figure of 5.5 dB. The appearance of this amplifier is shown in Figure 11.

Figure 11 – Exterior amplifier 3 mm wavelength range

There are laboratory development of PA and LNA up to 300 GHz. In the coming years, the emergence of commercial amplifying chips throughout the millimeter range, which will become a real base for the construction of amplifiers in the terahertz range. Using these amplifiers in the receiver-transmitter circuit will provide reliable and high-quality transmission of the information signal over long distances.

3.2.3 Heterodyne

Heterodyne is the most complex device in the development of digital telecommunication systems in the terahertz frequency range. This is explained by the difficulty in achieving a sufficient level of power at rather high frequencies, and the need to ensure high stability of the heterodyne and low level of its phase noise.

The subharmonic circuit of frequency converters allows you to reduce the required heterodyne frequency, which somewhat facilitates the development of the heterodyne circuit, but there are stringent requirements for the stability of the heterodyne and the level of phase noise, especially in digital data transmission systems with complex types of modulation.

For the digital radio relay system of the frequency range 130–134 GHz, the chain of the heterodyne was designed for a frequency of 64.8 GHz. The construction of a heterodyne is based on the use of a highly stable quartz oscillator with a subsequent chain of multiplication and amplification stages. The gain level was set so as to provide the optimal mode of operation of multiplying cascades and the required power at the output of the heterodyne.

This principle of constructing a heterodyne is much cheaper than developing a frequency synthesizer, and filtering a signal after each multiplication stage eliminates the presence of parasitic harmonics and combinational frequencies. The block diagram of the heterodyne circuit is shown in Figure 12.

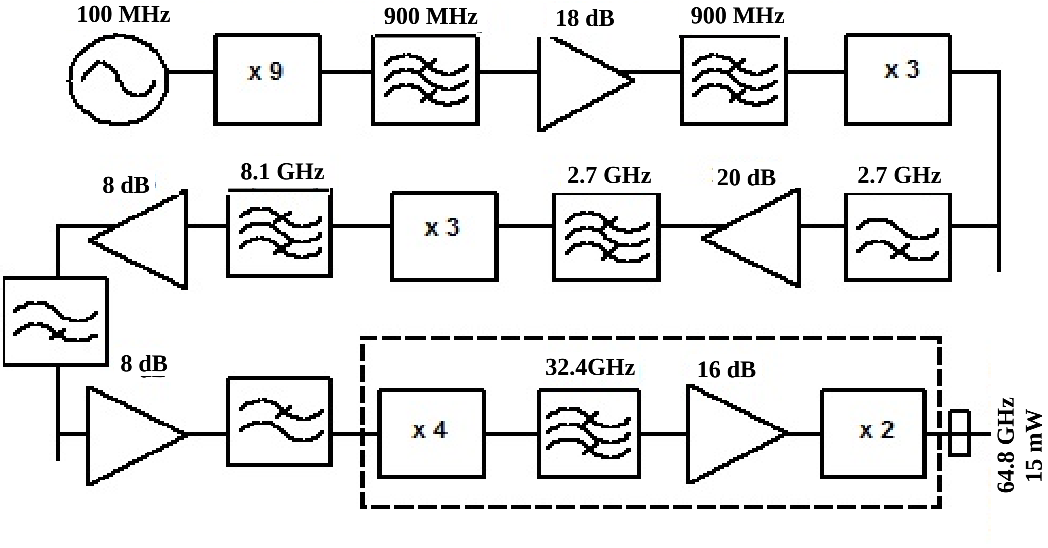


Figure 12 – Block diagram of the heterodyne circuit

A quartz oscillator of 100 MHz type CCHD-950X-25-100 from Crystek Crystals was used as a presenter with a phase noise level not higher than 143 dB when rebuilt from a central frequency of 1 kHz. Parameters of the generator that defines the main and determine the stability of the frequency and phase noise of the heterodyne.

The peculiarity of this scheme is that the first multiplication cascade made on the transistor allows one to immediately use the ninth harmonic of the frequency of the oscillating generator, namely, from 900 MHz. The signal with this frequency is amplified by 18 dB with the chip SPF5043Z and is selected by FAR-F5KA-897M50 type surface acoustic wave (SAW) filters.

Further increase of frequency to 8.1 GHz is carried out by two cascades of torusers. The first cascade in relation to the original 2.7 GHz is built on the transistor, and the second with an output frequency of 8.1 GHz on a monolithic chip HMC916LP3. At 2.7 GHz, the signal is amplified by 20 dB with the help of the TQP3M9008 chip and its filtration with the filters of the upper and lower frequencies (HF and LPF) on the lumped elements, as well as the strip pass filter (SPF) at the output of the amplifier. SPF is performed on semi-wavelength resonators on a duroid substrate (RT/Duroid 5880) with a thickness of 0.25 mm.

At 8.1 GHz, the signal is amplified by two cascades of NLB 300 chips and its filtration using LPF and HF on the lumped elements, as well as LFP made on semi wavelength elements on a 0.125 mm thick duroid lining. The results of this filter are shown in Figure 13.

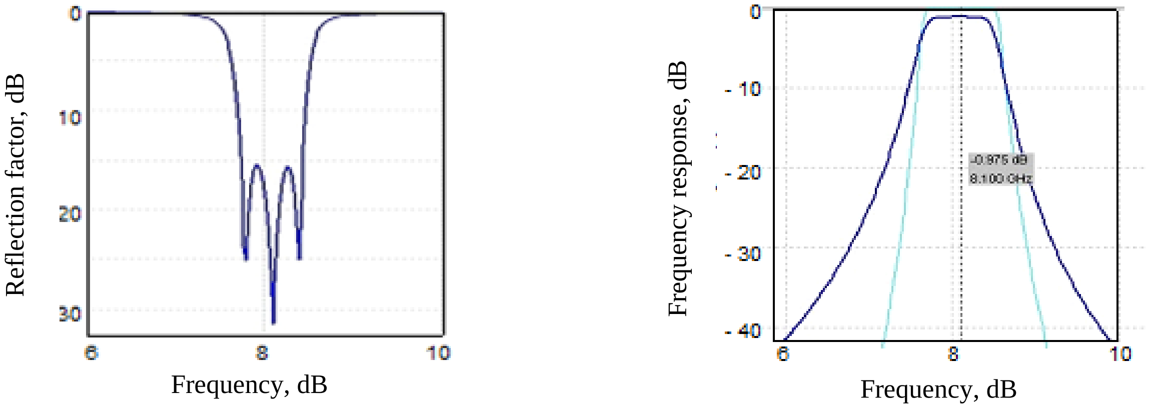


Figure 13 – The calculated frequency response and SFR of filter at 8.1 GHz

Installation of the elements of the described part of the chain of the heterodyne is shown in Figure 14. On the opposite side of the case is mounted a quartz oscillator with power supply circuits (Figure 15).

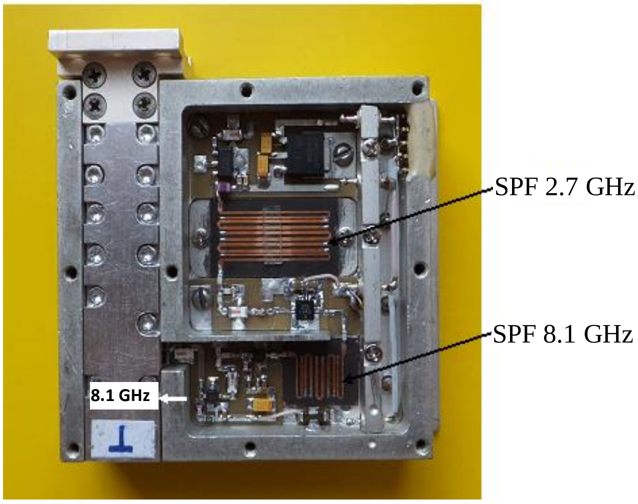


Figure 14 – Installation of the elements of the input part of the multiplication circuit in the housing of the heterodyne

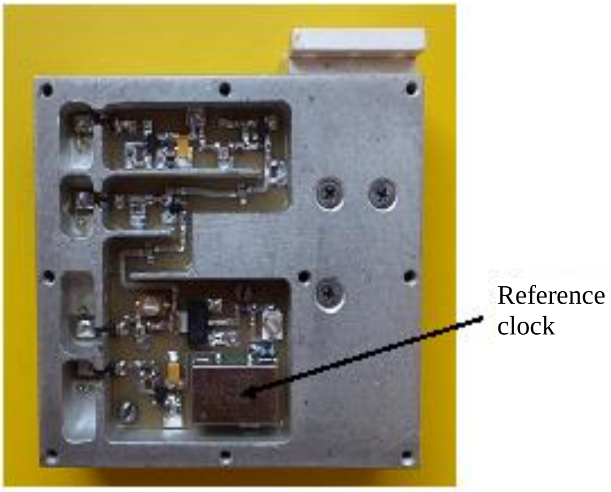


Figure 15 – The assigning oscillator is mounted on the reverse side of the housing of the local oscillator

After each multiplication stage, the quality of the signal was checked at an adequate level of power, the absence of adjacent parasitic harmonics and low level of phase noise. For example, in Figure 16 shows the measured signal spectrum at the output of the multiplication module in the frequency region of 8.1 GHz.

From Figure 16 it is seen that near the output signal with a frequency of 8.1 GHz there are no noticeable parasitic harmonics of the assigning oscillator, and the second harmonic of the output signal with a frequency of 16.2 GHz is attenuated by more than 40 dB. The output power is 7 mW, and the phase noise level does not exceed 107 dB when rebuilt from the center frequency of 100 kHz and 94 dB at rebuilding at 10 kHz.

The signal with a frequency of 8.1 GHz and a power of 11 dBm is supplied to the output more high frequency cascades of the heterodyne circuit, mounted in a separate housing, which, in turn, is built into the general housing of the heterodyne. The design of the source part of the heterodyne is shown in Figure 17.

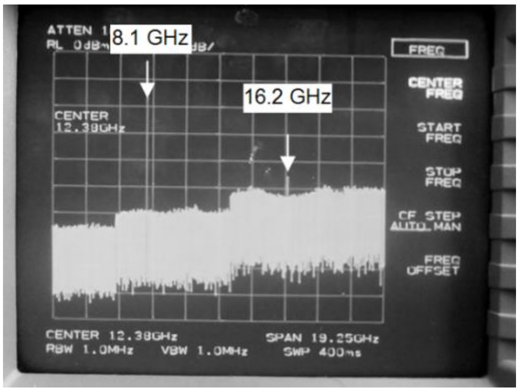


Figure 16 – Spectrum of the signal of the heterodyne circuit in the frequency region of 8.1 GHz (spectrum on the screen 19 GHz)

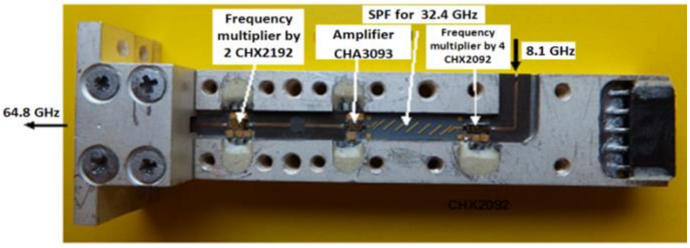


Figure 17 – Construction of the output stages of the heterodyne

The design contains a frequency multiplier of four, SPF at a frequency of 32.4 GHz, an amplifying cascade at this frequency, an output frequency doubler and a transition from a microstrip line to a waveguide channel with a cross section of 7.2 x 3.4 mm. Multipliers and amplifiers are built on the basis of corps monolithic chips. As a multiplier for four used chip CHX2092, the amplifier is based on chip CHA3093, and the output dual is built on chip CHX2192.

Monolithic microcircuits of multipliers and signal amplifiers are included in the microstrip line on a dyroid substrate with a thickness of 0.125 mm. A waveguide-microstrip transition is performed on this substrate.

Semi-resonant microstrip SPF is developed on a polycortic substrate with a thickness of 0.2 mm. For better matching of the filter with chips, fixed 3 dB absorbing attenuators are used in the form of chips included on both sides of the SPF. The measured AFC of the filter is shown in Figure 18. The appearance of the heterodyne in the housing is shown in Figure 19.

Measured values of the output power of the heterodyne for receiving and transmitting channels exceeded 15 mW, which is quite sufficient for the normal operation of the frequency converters of the receiving and transmitting paths.

Thus, as a result of the research carried out, a heterodyne was designed, manufactured and tested, which according to its indicators, in particular, in terms of output power, is not inferior to foreign analogues.

3.2.4 Intermediate frequency amplifier

An intermediate frequency amplifier circuit (IFA) includes a pre-amplifier built on the TQP3M9037 chip, as well as a main amplifier, developed on the basis of the transistor FPD6836P70 and chips HMC313. In addition to amplifying chips, the IFA scheme contains monolithic ceramic filters of the upper and lower frequencies for forming the required bandwidth of the intermediate frequency path, a resistive attenuator for matching the output filter with the transmission line, as well as secondary power supplies that form the stabilized voltage for the chips

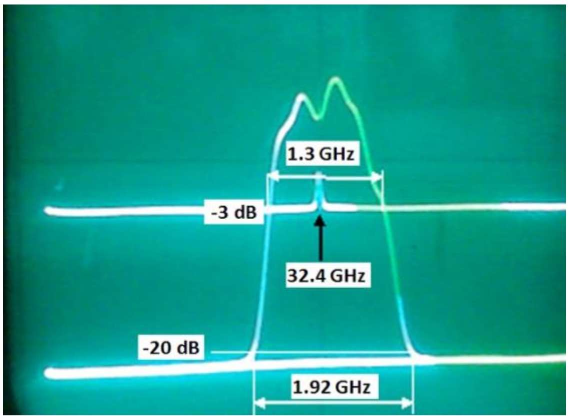


Figure 18 – Frequency response of the filter at frequency of 32.4 GHz

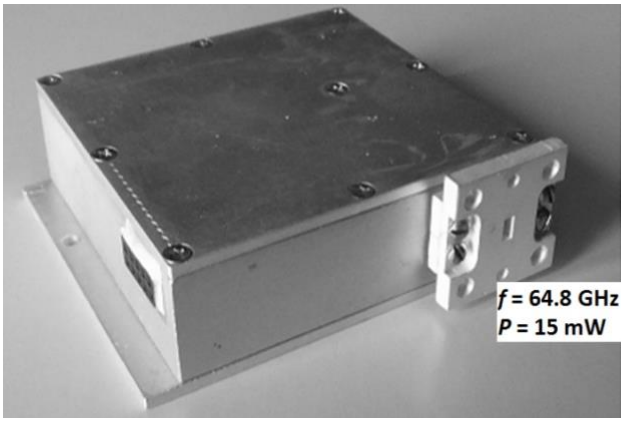


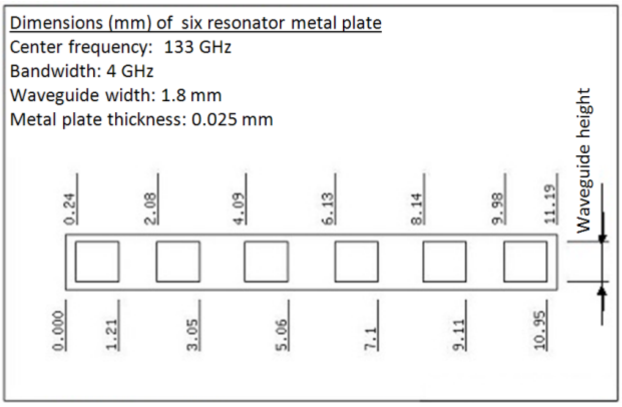
Figure 19 – Appearance of the heterodyne

The pre-amplifier is constructively integrated with the mixer to minimize the loss of a weak signal before gaining. The noise temperature of this amplifier is about 50 K and largely determines the sensitivity of the entire receiver. This is where the main signal strength is made. The full IFA gain is 47 dB.

3.2.5 High frequency bandpass filter

High-frequency bandpass filters (BPF) at the output of the transmitter and the input of the receiving link should provide a solution to the signals of the data paths, as well as sufficient suppression of the mirror channels and the signals of the heterodyne. The low magnitude of the intermediate frequency (Fpc = 2 ... 2.5 GHz) results in tight requirements for high-frequency SPFs on selectivity. The most suitable in the 2 mm wavelength range is, in terms of low losses and high selectivity, there are wave septum filters. This filter was developed as part of this project.

Structurally, the filter is a thin metal plate inserted into the E plane of the waveguide channel. The plate contains resonant windows, the relationship between which is determined by the width of their separating strips. A six-cavity filter was selected to provide sufficient selectivity. Calculated dimensions of the lamellar insert with resonant windows are shown in Figure 20. Figure 21 shows the calculated S-parameters of the six-resonator SPF, and also shows the measured frequency response of the manufactured filter



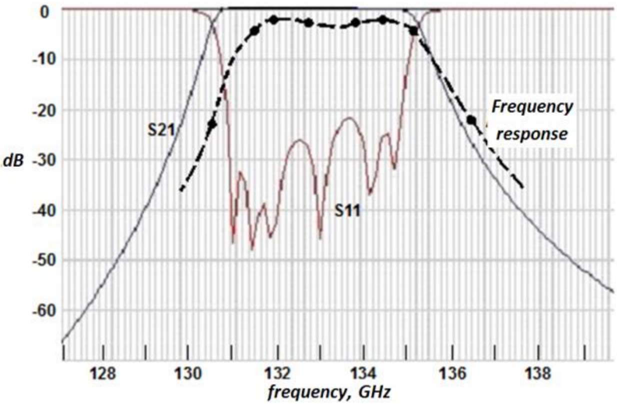


Figure 20 – Configuration and dimensions of the metal insert mounted in the E-plane of the waveguide channel

Figure 21 – Calculated S-parameters and measured frequency response of septum filter

The experimental results that we obtain show that the filter meets the requirements of selectivity, in order to ensure sufficient (by 20 dB) suppression of the mirror channel and the second harmonic of the signal of the heterodyne (129.6 GHz).

The filter loss in the terahertz frequency range of the transmitter does not exceed 4 dB, which is a satisfactory result for such high frequencies. The unevenness of the frequency response on a flat part does not exceed 2 dB.

3.2.6 Conical horn antenna

Both the transmission and the receiving tracks used a conical horn antenna with a dielectric lens concentrator. Antenna design is shown in Figure 22.

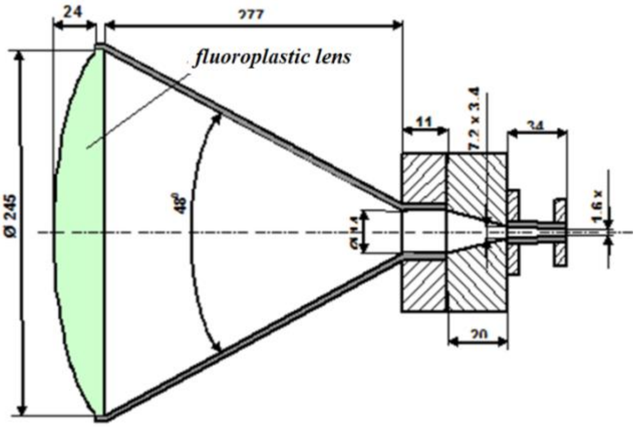


Figure 22 – Design of the horn antenna

In addition to the conical speaker, the construction contains a transition from a round waveguide to a rectangular with a cross section of 7.2×3.4 mm. An antenna connection with the transmitter or receiver path was carried out using a waveguide transition with a cross section of 7.2×3.4 mm at a cross section of 1.6×0.8 mm. The antenna's aperture is 245 mm. As a concentrator used fluoroplastic lens.

The calculations give the following characteristics of the antenna:

- Range of operating frequencies 130–134 GHz;
- Input waveguide channel with a cross section of 1.6×0.8 mm^2 ($\lambda = 2$ mm);
- Gain factor not less than 47 dB;
- The width of the direction diagram is not more than 0.60;
- SWR input in the range of 1.15.

3.2.7 Research and testing of the 130–134 GHz terahertz range wireless communication

Based on the developed functional nodes described above, the reception and transmission tracks of the radio relay system were constructed. Receiver and transmitter systems have the same constructive construction. The modular execution of individual nodes with maximum use of monolithic chips ensures compact design, as well as the convenience of its assembly and installation, as shown in Figure 23.

The links have a coaxial input (output) with SMA connectors at intermediate frequencies, and a waveguide input (output) in the channel of 1.6×0.8 mm^2 at terahertz frequencies. The appearance of the receiving (transmitting) path is shown in Figure 24.

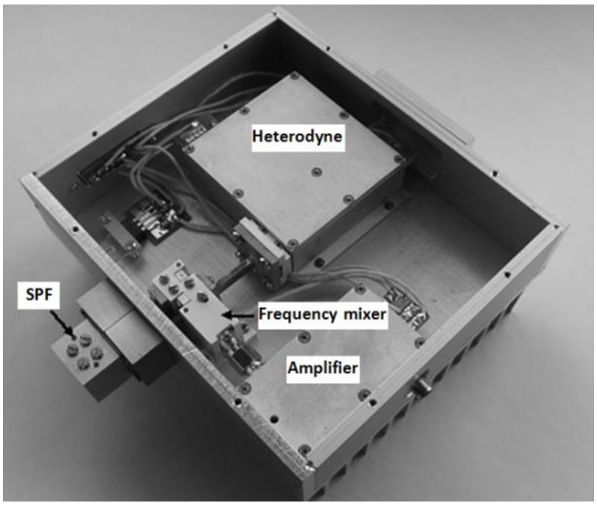


Figure 23 – Location of nodes as part of the receiving (transmitting) link

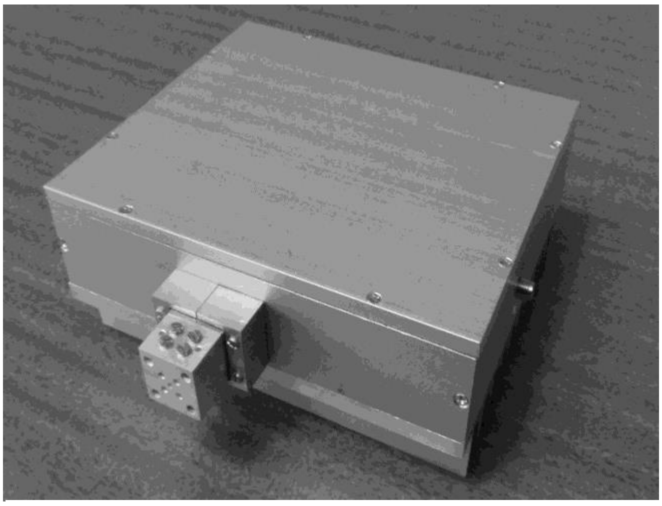


Figure 24 – Appearance of the receiving (transmitting) link

In order to ensure the qualitative work of the receiver and transmitter, secondary power sources were developed that form the necessary high voltage voltages for all nodes of the link.

The measured transverse frequency response of the transmission coefficient $K(f)$ is shown in Figure 25. As seen from the measured frequency dependence $K(f)$, the receiving and transmitting path of the terahertz range has a total transmittance of not less than 18 dB, while the unevenness of the transmission coefficient in the operating frequency range does not exceed 3 dB.

Experimental investigations of the transmission coefficient of the transmission and transmission link of the radio relay system as a whole were carried out (Figure 26).

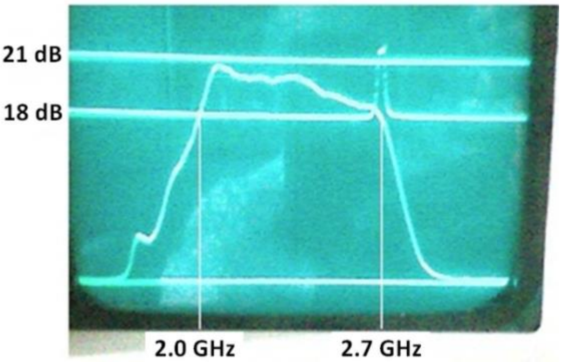


Figure 25 – Intersecting frequency response of transmission coefficient of the transmission and transmission path

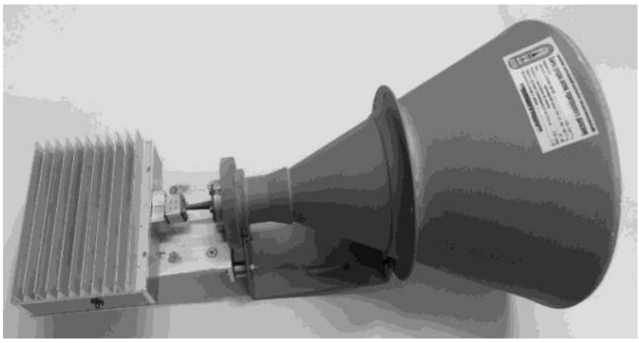


Figure 26 – Appearance of the receiving (transmitting) link

In addition, experimental research of the laboratory sample of the digital simplex radio-relay system of the terahertz range (Figure 27) was carried out consisting of: receiving and transmitting radio links in the range of frequencies 130–134 GHz, digital modems

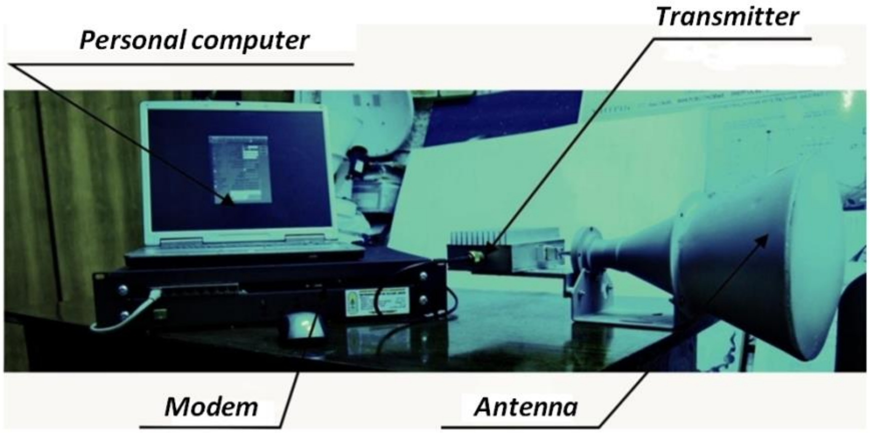


Figure 27 – Appearance of the laboratory sample of the digital simplex radio-relay system of the terahertz range

The system test was conducted in accordance with the scheme shown in Figure 28.

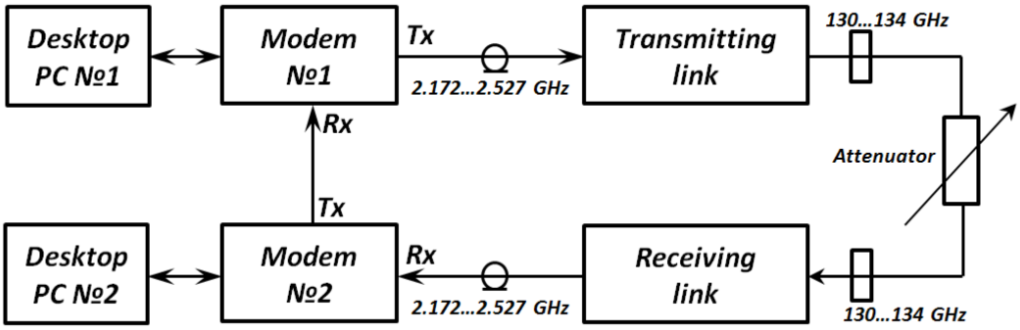


Figure 28 – Scheme of the tested telecommunication system

Experimental research of links of relay system showed the following values of key indicators in the operating frequency range:

- Noise temperature of the receiving link $T = 5000$ K;
- Output power of the transmission path $P_{\text{out}} = 40$ mW .

The following results are obtained:

- Bandwidth up to 1200 Mbps.
- The value of the probable bit errors of BER is no more than 10^{-6}.
- Range of communication in normal conditions within 1 km.
- The gain of the system is 50 dB.
- Modulation type – QAM-64.

Such conclusions can be made.

The parameters of the main nodes of the transmission and transmission path of the radio relay system in the frequency range 130–134 GHz are determined and substantiated. The structural scheme of the radio relay line in the terahertz range with a bandwidth of up to 2.4 Gbit/s has been developed and the calculated characteristics of its transmission and receive link are investigated.

On the basis of the synthesis of results, analysis of the existing electronic element base and theoretical studies, the design of the main nodes and the entire receiving and transmitting path of a telecommunication system with a gigabit bandwidth in the frequency range 130–134 GHz, consisting of: subharmonic pump frequency converters, using highly stable quasar generator with the following chain of multiplication and amplification cascades, a band-pass filter using a thin *m* plates, hand in the E plane waveguide channel 1.6–0.8 mm.

For the first time in practical terms, the main nodes of the transmission and transmission path have been manufactured and experimental research of the laboratory sample of the digital simplex and radiolabeled system of the terahertz range in the composition of the receiving and transmitting radio in the frequency range of 130–134 GHz and a digital modem with bandwidth up to 1200 Mbps has been carried out.

Created transmission and reception radio links of the terahertz range can be used for the construction of telecommunication systems and networks, including radio relay systems of direct visibility for next-generation mobile communications networks. Providing the bandwidth of the radio link of tens Gbps and more that is needed in the future may be due to the use of the terahertz wavelength range, where high transmission speeds can be provided, as well as the high reliability of the radio link at a fairly small weight and the dimensions of the receiver- transmission path and antenna system.

4 RESEARCH OF TRANSMISSION OF TELEVISION SIGNALS OF THE DVB-C STANDARD ON TRANSCEIVING LINK OF TERAHERTZ RANGE

Investigation of DVB-C multichannel digital signal parameters change during transmission through a 130 GHz transmission and transmission path model. The DVB-C standard for research was selected through the possibility of generating signals with different modulation positions (from QAM-64 to QAM-256), which made it possible to investigate the effect of the parameters of the individual nodes on the parameters of the signals transmitted through it.

For the study, an experimental installation, consisting of a transceiver, a DVB-C subsystem for DVB-C signaling subsystem, DVB-C standard signal measurement subsystem, was collected. The research was carried out in stages: one-channel, two channel and three-channel DVB-C signals were used.

The results of the study showed that the use of the lower part of the terahertz frequency band (130 GHz) with a band of 24 MHz allows the transmission of three DVB-C broadcast TV channels with a total traffic flow rate of 125 at a transceiver having a common heterodyne for the transmission and reception channel, MBit/s with high subjective quality of playback of all TV programs.

The purpose of this work is to study the change of parameters of the multichannel digital signal DVB-C standard when it is transmitted through the layout of the transmission and transmission path of 130 GHz. The DVB-C standard for research was selected through the possibility of generating signals with different modulation positions (from QAM-64 to QAM-256), which made it possible to investigate the effect of the parameters of the individual nodes on the parameters of the signals transmitted through it.

In order to study the change in the parameters of DVB-C multichannel digital TV signals during their transmission over the terahertz-band transmission and transmission path, an experimental installation, the structural scheme of which is shown in Figure 29, was collected. As can be seen from Figure 29, measurements of DVB-C signal parameters were performed at the input of the transmitter's path and at the output of the terahertz receiver's path. In this case, the output of the transmitter is connected to the receiver input by the waveguide line.

At all stages of the study the following measuring equipment was used

- ST-2 ROVER digital TV signal analyzer;
- Homecast Digital TV Receiver to the DVB-C standard connected to the Samsung TV. The receiver was used to determine the quality parameter of the DVB-C signal (Quality) in the relative percentage scale on the transmitter input and the terahertz range receiver output;
- Tuner of terrestrial and cable digital TV QBox TBS5880, which is connected to a computer via USB-cable. The tuner is designed to image signal constellation and numerical indicators of quality demodulation/decoding television signals of standard DVB-C transmitter at the input and output of the receiver path terahertz range

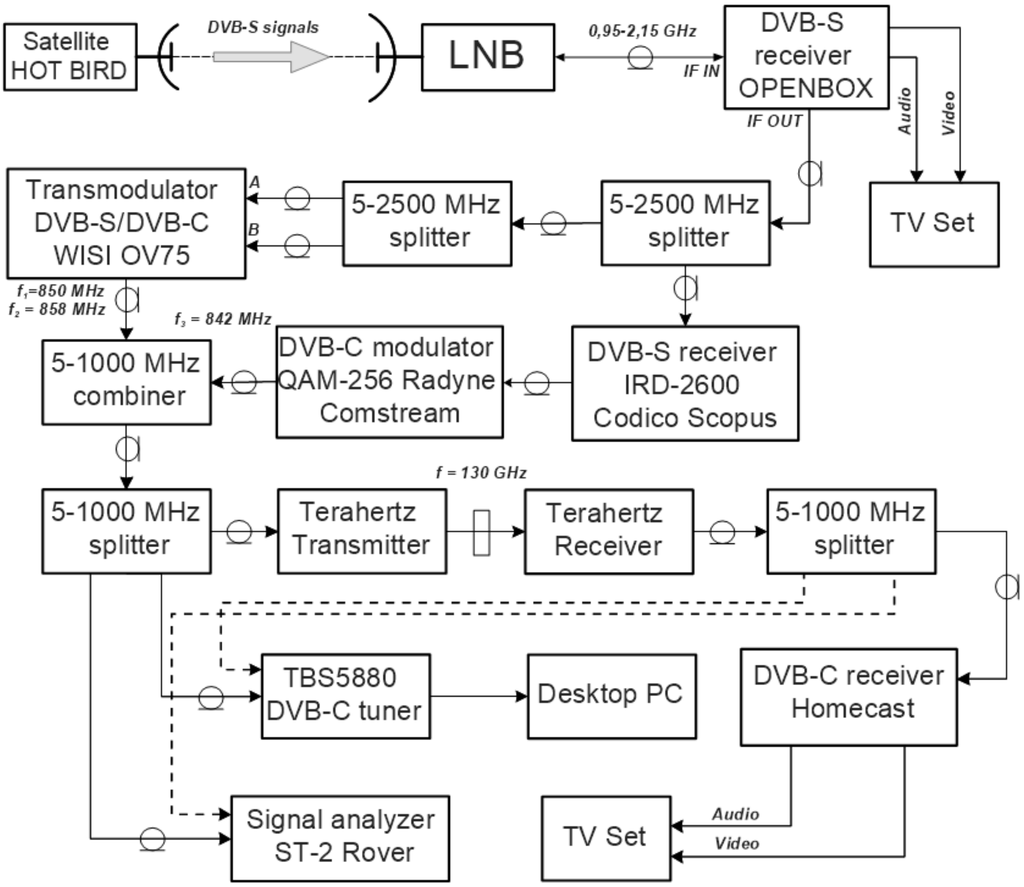


Figure 29 – The block diagram of the experimental setup for research of DVB-C multichannel digital signals

The simplified structural scheme of the terahertz range transceiver and its photo are shown in Figure 30 and Figure 31.

The ST-2 ROVER signal analyzer allows you to measure the following signal parameters of the DVB-C standard at the input of the transmitter and the receiver output of the terahertz range:

- Signal level (LEV), dBm;
- the ratio of the power of the non-volatile oscillation to the noise power (C/N), dB;
- reserve of noise immunity (N. MAR), dB;
- coefficient of unevenness of the spectrum (FLAT), dB;
- bit error rate (BER).

It should be noted that since the ROVER ST-2 signal analyzer works in emulation mode, it outputs a signal strength value of 15 dB lower than the value obtained with the TBS5880 tuner.

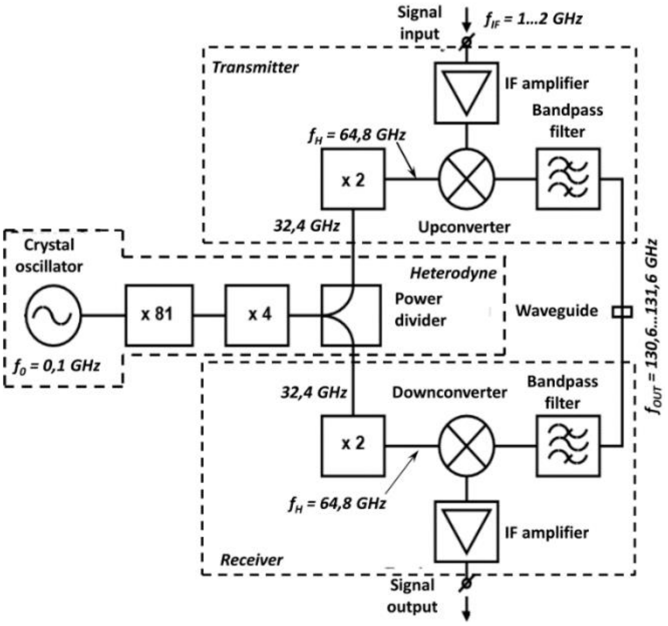


Figure 30 – A simplified block diagram of a terahertz transceiver

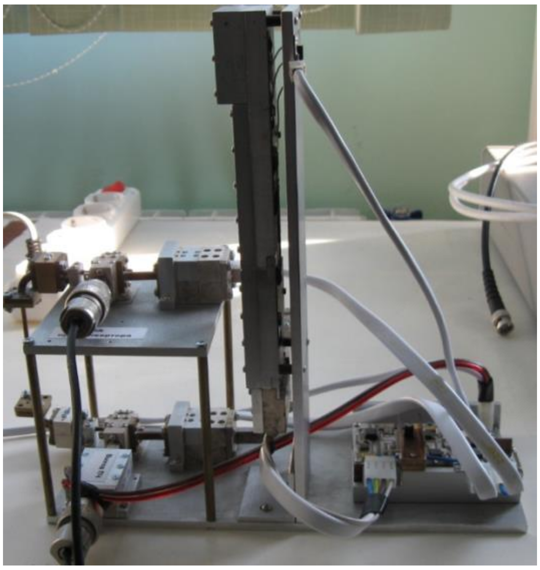


Figure 31 – Photo of the transceiver of the terahertz range

Investigation of the parameters of the multichannel signal (Figure 32) of the DVB-C digital TV on the terahertz reception and transmission line was carried out for the DVB-C three-channel signal 2. The formation of DVB-C signals was carried out using the WISI OV75 transmodulator and the QAM-256 Radyne Comstream modulator from the DVB-S standard television broadcasting signals, the parameters of which are also given in Table 4. These DVB-S signals were received on a mirror antenna with a converter from the HOT BIRD (13 E) satellite.

Table 4 – Input parameters of DVB-S digital TV signals from HOT BIRD

channel number	Input, MHz	Intermediate frequency, MHz	Symbol rate, Ksym/sec	Bit rate, Mbit/s	Modulation	FEC		Information speed Mbit/s	The width of the range, MHz
						Conv.	RS		
1	11179	1429	27500	55	QPSK	3/4	188/204	38.015	36
2	11137	1387	27500	55	QPSK	3/4	188/204	38.015	36
3	11334	1584	27500	55	QPSK	3/4	188/204	38.015	36

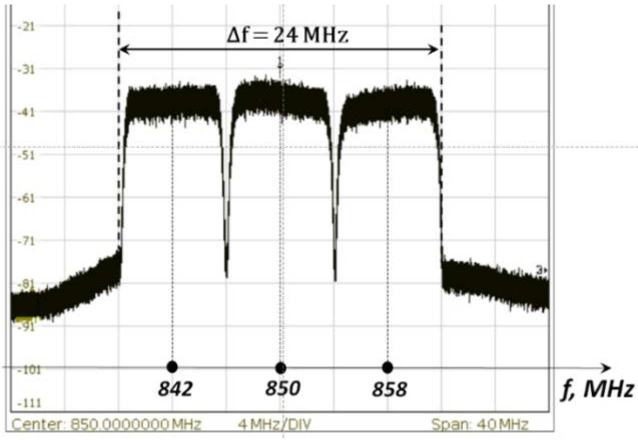


Figure 32 – Spectrum of 3 channel TV signal of DVB-C standard

Using the transmodulator and modulator, we were able to change the following parameters of the DVB-C signal modulation (QAM-16, QAM-32, QAM-64, QAM-128, QAM-256), speed (character, bit, depending on modulation and noise immunity coding)), the intermediate frequency (in the range 47–862 MHz)).

Each of the three DVB-C TV signals depicted in Figure 4.4, in turn, includes an MPEG transport stream, which transmits 5–6 TV standard definition open-access software.

Figure 33 and Figure 34 show constellation diagrams of DVB-C signals, which are inherent in all stages of the research.

From the output of the QAM Modulator RADYNE COMSTREAM QAM-256 and the output of the WISI OV75 Transmodulator (Figure 29), the television channels enter the adder, the output of which is a multi-channel (3-channel) television signal input to the input of the receiving and transmitting path of the terahertz range. The results of measuring the parameters of the DVB-C 3-channel TV signal are shown in Table 5.

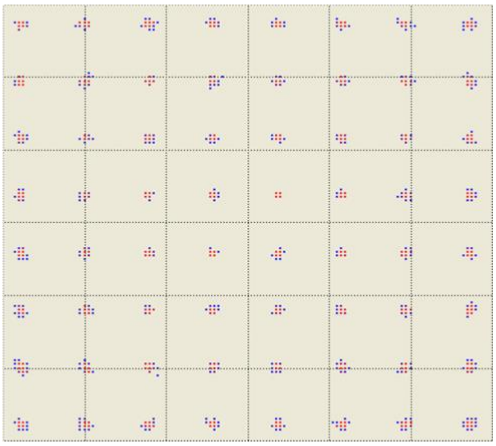


Figure 33 – Constellation diagram of DVB-C signal when modulating with QAM-64

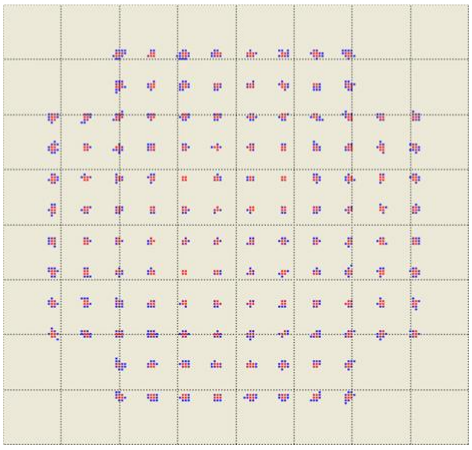


Figure 34 – Constellation diagram of the DVB-C signal when modulating with QAM-128

Table 5 – Parameters of the three DVB-C digital TV signal TV channels measured by the TBS8550 tuner

Channel indicators		The value measurements at the input of terahertz range transmitter			The value of measuring at the output of terahertz range link		
Frequency, MHz	Modulation	LEV, dBm	SNR, dB	BER	LEV, dBm	SNR, dB	BER
842	QAM–64	–51	38.6	<10–8	–60	33.71	<10–8
	QAM–128	–54	42.12	<10–8	–57	39.43	<10–8
	QAM–256	–32	38.6	<10–8	–54	36.8	<10–8
850	QAM–64	–38	38.6	10–4	–57	37.6	7 … 10^{-4}
	QAM–128	–54	43.43	<10–8	–54	39	<10–8
	QAM–256	–32	38.6	<10–8	–54	37.4	<10–8
858	QAM–64	–38	38	<10–8	–57	34.57	<10–8
	QAM–128	–54	42.12	<10–8	–54	39.43	<10–8
	QAM–256	–32	38.6	10–3	–54	36.8	$1{,}5 \cdot 10^{-3}$

Analyzing the results, it can be concluded that all parameters of the signals on average deteriorated by 4-5 dB compared with the previous experiment (the transmission of two signals DVB-C), while in the worst case when modulating QAM-256, the BER parameter by measuring the satellite tuner TBS5880 decreased, and the quality of the signal was at the level of 33-53%.

CONCLUSIONS

The results of the study of the parameters of DVB-C multichannel digital signal on the terahertz-band transmission and transmission path showed that the use of the lower part of the terahertz frequency range (130 GHz) with a band of 24 MHz allows the transmission of three channels of DVB-C TV broadcast with a general transport speed at 125 MB/s with a high subjective quality of playback of TV programs.

According to the results of the research conducted to the Plan for the use of the radio frequency resource of Ukraine (Section II) by the Resolution of the Cabinet of Ministers of Ukraine No. 838 of 05.09.2012. the radio technology of the radio relay communication has been introduced in the frequency bands 94.1 100 GHz; 102–105 GHz; 106.5–109.5 GHz; 111.8–113 GHz; 130–134 GHz; 141–148.5 GHz.

For the development of a radio link with a gigabit bandage of the terahertz range for ultrahigh-speed distribution networks, the frequency range 130–134 GHz has been selected.

New products were created and for the first time an experimental sample of digital terrestrial radio line with a gigabit bandwidth operating in the terahertz range and which can be used in ultra-high-speed distribution networks of mobile communication of a new generation for transmission and reception of digital information at speeds up to 1 Gbit/the frequency range 128–134 GHz at a range of 1 km.

There are no direct analogues at present, which can provide a significant breakthrough in the development of the telecommunications sector.

The obtained research results will also promote the development of related telecommunications sectors, in particular: radio astronomy, satellite communication, medicine, and security.

The basis for the achievement of such significant successes of our institute were ideas, knowledge and talent of its world-renowned scientists, professionals of the highest level. Along with them, the contribution to the development of terahertz technologies of telecommunications of ultrahigh-frequency semiconductor electronics is made by young people - students and post-graduate students. This is promising for the telecommunication department of the research university, which is on the threshold of a qualitative breakthrough in the field of ultrahigh-frequency terahertz technologies.

REFERENCES

1 Ilchenko M.Ye., T.N. Narytnik, A.I. Fisun, and O.I. Belous. Conception of Development of Millimeter and Submillimeter Wave Band Radio Telecommunication Systems //Telecommunications and Radio Engineering. 67(17):1549-1564 (2008)1549 ISSN 0040-2508.© 2008 Begell House, Inc. DISTRIBUTED INFORMATION AND CONTROL SYSTEMS.

2 Ильченко М.Е., НарытникТ.Н., ШелковниковБ.Н., ХристенкоВ.И. Радиотелекоммуникационные системы терагерцового диапазона // Электроника и связь. – 2011. – № 3. – С. 205–210.

3 Ilchenko M.Ye.,T.N. Narytnik, A.I. Fisun, O.I. Belous. Terahert zrange telecommunication systems / Telecommunications and Radio Engineering. – № 70(16). – 2011. – pp. 1477–1487.

4 Нарытник Т.Н., Булгаков Б.М., Кравчук С.А., Поповский В.В., Татарчук С.И. Концепция применения миллиметровых и субмиллиметровых электромагнитных волн в телекоммуникационных информационных системах /Т.Н. Нарытник, Булгаков Б.М., Кравчук С.А., Поповский В.В., Татарчук С.И. // Журнал «Радиотехника». – вып. 133. – 2003. – С. 9–19.

5 Narytnik T., A. Amro, M. Ilchenko, V.Kalinin, O. Turabi. Sub-Terahertz Low Power UWB Communication Link for WPAN. //Network and Complex Systems. – Vol 2. – No.4. – 2012. – P.45–50.

6 Ilchenko M.Ye., T.N.Narytnik, V.A.Cherepenin, V.I.Kalinin, V.V.Chapursky. Terahertz Communication System on the Base of Chaotic Noise Signals// Intern. Research Journal “Telecommunication Sciences”. –Vol. 4. – No 1, 2013.

7 Ilchenko M.Ye., T.N.Narytnik, V.A.Cherepenin, V.I.Kalinin, V.V.Chapursky. Wireless terahertz communications with spectral modulation of UWB noise signals// TELECOMMUNICATION SCIENCES. – Vol. 3. –No 2(5) July – December 2012. –pp. 39–43.

8 Ilchenko M.Ye., T.N. Narytnik , S.Ye. Kuzmin, A.I. Fisun, O.I. Belous, V.N. Radzikhovsky Transceiver for 130–134 GHZ band and digital radio relay system// Telecommunications and Radio Engineering.– vol. 72. – no 17. – 2013. – pp.1623–1638.

9 Ilchenko M.Ye.,T.N. Narytnik, R.M. Didkovsky. Clifford algebra in multiple access noise-signal communication systems// Telecommunications and Radio Engineering. – vol. 72. – no. 18. – 2013. – pp.1651–1663.

10 Ильченко М.Е., Т.Н. Нарытник, С.Е. Кузьмин, В.Н. Радзиховский. Моделирование функциональных узлов радиорелейной системы терагерцового диапазона// Электронное научное специализированное издание – журнал «Проблемы телекоммуникаций». –№ 2 (11).– 2013.– С. 95–113.

11 Ільченко М.Ю., Т.М. Наритник, Р.М. Дідковський. Принципи побудови надширокосмугової системи радіозв'язку в терагерцовому діапазоні частот на основі технології розширення спектра// Электронное научное специализированное издание – журнал «Проблемы телекоммуникаций». – Харьков, –2014. – №3 (15). – С.30–43.

12 Narytnik T.M., Ibrahim A. A., Turabi I.O.Analysis of the possibility of creating gigabit distribution networks with the using of terahertz range radio-relay lines//Electronics and Control Systems. – 2014. – № 1(39). – p.15–22.

13 Narytnik T.N. Possibilities of Using THz-Band Radio Communication Channels for Super High-Rate Backhaul//Telecommunications and Radio Engineering. – 2014. –vol.73 (15). – pp. 1361–1371.

14 Ilchenko M.Ye., V.I. Kalinin, T.N. Narytnik, R.M. Didkovsky. Potential Performance of the Communication System Using Autocorrelation Reception of Shift-Keyed Noise Signals// Telecommunications and Radio Engineering. – vol.73 (11). – 2014. – pp 955–976.

15 Ilchenko M.Ye., T.M. Narytnik, Ali Abdalla Ibrahim Idris, R.M. Didkowsky, OsamaTurabi.Theoretical and practical aspects of the use of stochastic signals in telecommunication systems// Telecommunications and Radio Engineering. – vol. 73 (20). – 2014. – pp. 31–1817.

16 Ільченко М.Ю., Кравчук С.О., Наритник Т.М. Безпроводові системизв'язку субтерагерцового та терагерцового діапазонів// Цифрові технології, 2014. – Вип. 16. – С.40–59.

17 Ільченко М.Ю., Т.М. Наритник, В.М. Радзіховський, С.Є. Кузьмін, О.В. Лутчак. Передавальний та приймальний радіотракти радіорелейних систем терагерцового діапазону// Цифрові технології. – 2015. – № 17. – С.16–29.

18 18. Наритник Т.М., О.В. Лутчак. Апаратно-програмні рішення побудови гігабітного модему для радіорелейних ліній в терагерцовому діапазоні // Цифрові технології. – №18. – 2015. – С.43–53.

19 Ilchenko M.Yu., T.M. Narytnyk, B.M. Radzikhovsky, S.E. Kuzmin, O.V. Lutchak Development of the Transmitting and Receiving Channels for Terahertz Band Relay Systems // Telecommunications and Radio Engineering. – vol. 74. – 2015. – № 11. – pp. 981–998.

20 Наритник Т.М., Лутчак О.В., Осипчук С.О. Уривський Л.О. Особливості формування сигнально-кодових конструкцій на основі технології Wi-Fi для побудови телекомунікаційних систем терагерцового діапазону // Электронное научное специализированное издание – журнал «Проблемы телекоммуникаций», Харьков. – 2015. – №2(17).

21 T.M. Narytnyk O.V. Lutchak, S.O. Osypchuk, L.O. UryvskyiCriteria and Algorithms for Shaping of the Signal-Code Sequences on the Basis of Wi-Fi Technology at Deployment of the Terahertz Band Telecommunication System// Telecommunications and Radio Engineering.Vol. 75, 2015, Number 74 (2),pp.1823–1839.

22 Наритник Т.М., Осипчук С.О. Уривський Л.О. Реалізація концепції створення програмно-визначених радіосистем терагерцового діапазону на основі технології Wi-Fi//Цифрові технології. –№18. – 2015. – С.7–20.

23 Ильченко М.Е., Нарытник Т.Н., Радзиховский В.Н., Кузьмин С.Е., Лутчак А.В. Проектирование передающего и приёмного радиотрактов радиорелейных систем терагерцового диапазона // Электросвязь. – №2.– 2016. – С. 42–49.

24 Наритник Т.М. Особливості формування сигнально-кодових конструкцій на основі технології Wi-Fi для побудови телекомунікаційних систем терагерцового діапазону/ Т.М. Наритник, О.В.Лутчак, С.О. Осипчук, Л.О.Уривський // Цифрові технології. – 2016. – № 20.

25 Ilchenko M.Ye. Simulation of functional units of the terahertz band transmitting and receiving radio systems / M.Ye Ilchenko., T.M.Narytnyk, S.V.Denbnovetsky, A.V.May, O.V. Lutchak // Telecommunications and Radio Engineering. – Vol. 75. – 2016. – No 11. – P. 1027–1039.

26 Авдєєнко Г. Л., Ільченко М.Ю., Наритник Т.М., Єрмаков А.В.Лутчак О.В. Перетворювач частоти для прийомо-передавача безпроводової телекомунікаційної системи фіксованого зв'язку терагерцового діапазону // Електронне наукове фахове видання – Журнал «Проблеми телекомунікацій». – Харків, 2017. – №1(20). – С.38-49.

27 Ильченко М.Е., Денбновецкий С.В., Нарытник Т.Н.,Лутчак А.В., Май А.В. Проектирование интегрального приёмника терагерцового диапазона частот // Електронне наукове фахове видання –Журнал «Проблеми телекомунікацій», Харків. – 2017. – №1(20). – С.57–63.

28 Наритник Т.М., Авдєєнко Г.Л. ,Бунін С.Г., Ермаков А.В., Лутчак О.В., Волков В.В. Обґрунтування частотних діапазонів для високошвидкісних безпроводових телекомунікаційних систем терагерцового діапазону// Електронне наукове фахове видання «Проблеми телекомунікацій». – №1 (20). – 2017. – Харків. – С.103–112.

29 M. Ilchenko S. Denbnovetsky,T. Narytnik, O. Lutchak,O. May,A. Fisun, O. Bilous. Design of the 290–310 GHz frequency range integral receiver // Telecommunications and Radio Engineering. – Vol.76. – 2017. – Number 15. – pp.1379–1390.

REFERENCES

1 Ilchenko, M.Ye., T.N. Narytnik, A.I. Fisun, and O.I. Belous. “Conception of Development of Millimeter and Submillimeter Wave Band Radio Telecommunication Systems.”*Telecommunications and RadioEngineering*, Vol. 67(17):1549-1564 (2008)1549, 2008 Begell House, Inc. DISTRIBUTED INFORMATION AND CONTROL SYSTEMS, ISSN 0040-2508.

2 Il'chenko, M.Ye., Narytnik T.N., Shelkovnikov B.N., and Khristenko V.I. “Radiotelekommunikatsionnyye sistemy teragertsovogo diapazona (Radio telecommunication systems of terahertz band).” *Elektronika i svyaz'*, no. 3, 2011, pp. 205–210.

3 Ilchenko, M.Ye., T.N. Narytnik, A.I. Fisun, and O.I. Belous. “Terahertz range telecommunication systems.” *Telecommunications and Radio Engineering*, vol. 70(16), 2011, pp. 1477–1487.

4 Narytnik, T.N., Bulgakov B.M., Kravchuk S.A., Popovskiy V.V., and Tatarchuk S.I. “Kontseptsiya primeneniya millimetrovyh i submillimetrovyh elektromagnitnyh voln v telekommunikatsionnyh informatsionnyh sistemah (The concept of using millimeter and submillimeter electromagnetic waves in telecommunication information systems).” *Zhurnal «Radiotekhnika»*, is. 133, 2003, pp. 9–19.

5 Narytnik, T., A. Amro, M. Ilchenko, V.Kalinin, and O. Turabi. “Sub-Terahertz Low Power UWB CommunicationLinkfor WPAN.”*Network and Complex Systems*, vol. 2, no. 4, 2012, pp. 45–50.

6 Ilchenko, M.Ye., T.N. Narytnik, V.A. Cherepenin, V.I. Kalinin, and V.V. Chapursky. Terahertz Communication System on the Base of Chaotic Noise Signals.”*Intern. Research Journal “TelecommunicationSciences”*, vol. 4, No 1, 2013.

7 Ilchenko, M.Ye., T.N. Narytnik, V.A. Cherepenin, V.I. Kalinin, and V.V. Chapursky. “Wireless terahertz communications with spectral modulation of UWB noise signals.” *Telecommunication Sciences*, vol. 3, no 2(5) July – Dec. 2012, pp. 39–43.

8 Ilchenko, M.Ye. , T.N. Narytnik, S.Ye. Kuzmin, A.I. Fisun, O.I. Belous, and V.N. Radzikhovsky. “Transceiver for 130–134 GHZ band and digital radio relay system.” *Telecommunications and Radio Engineering*, vol. 72, no 17, 2013,pp. 1623–1638.

9 Ilchenko, M.Ye.,T.N. Narytnik, and R.M. Didkovsky. Clifford algebra in multiple access noise-signal communication systems.” *Telecommunication sand Radio Engineering*, vol. 72, no 18, 2013, pp. 1651–1663.

10 Il'chenko, M.Ye., Narytnik T.N., Kuz'min S.Ye., and Radzikhovskiy V.N. “Modelirovaniye funktsional'nykh uzlov radioreleynoy sistemy teragertsovogo diapazona (Modeling the functional units of the terahertz radio relay system).”*Elektronnoye nauchnoye spetsializirovannoye izdaniye – zhurnal “Problemy telekommunikatsiy”,* no. 2 (11), 2013, pp. 95–113.

11 Íl'chenko, M.Ye., Naritnik T.M., and Dídkovs'kiy R.M. “Printsipi pobudovi nadshirokosmugovoї sistemi radíozv’yazku v teragertsovomu díapazoní chastot na osnoví tekhnologíї rozshirennya spektra (The principles of building a broadband radio system in the terahertz bandwidth based on spectrum technology).” *Elektronnoye nauchnoye spetsializirovannoye izdaniye – zhurnal “Problemy telekommunikatsiy”,* no. 3 (15), Khar'kov, 2014, pp. 30–43.

12 Narytnik, T. M., Ibrahim A. A., Turabi I.O. “Analysis of the possibility of creating gigabit distribution networks with the using of terahertz range radio-relay lines.”*Electronics and Control Systems*, no 1(39), 2014, pp.15–22.

13 Narytnik, T.N. “Possibilities of Using THz-Band Radio Communication Channels for Super High-Rate Backhaul // *Telecommunications and Radio Engineering*, vol. 73 (15), 2014, pp. 1361–1371.

14 Ilchenko, M.Ye., Kalinin V.I., Narytnik T.N., and Didkovsky R.M. “Potential Performance of the Communication System Using Autocorrelation Receptionof Shift-Keyed Noise Signals.” *Telecommunications and Radio Engineering*, vol. 73 (11), 2014, pp. 955–976.

15 Ilchenko, M.Ye., Narytnik T.M., Ali Abdalla Ibrahim Idris, R.M. Didkowsky and OsamaTurabi. “Theoretical and practical aspects of the use of stochastic signals in telecommunication systems.” *Telecommunications and Radio Engineering*, vol. 73 (20), 2014, pp. 1791–1817.

16 Íl'chenko, M.Yu., Kravchuk S.O., and Naritnik T.M. “Bezprovodoví sistemi zv’yazku subteragertsovogo ta teragertsovogo díapazonív (Sub-Terahertz and Terahertz bands Wireless Systems).” *Tsifroví tekhnologíї*, no 16, 2014, pp. 40–59.

17 Íl'chenko, M.Yu., T. M. Naritnik, V.M. Radzíkhovs'kiy, S.Ye. Kuz'mín, and O.V. Lutchak “Peredaval'niy ta priymal'niy radíotrakti radíoreleynikh system teragertsovogo díapazonu (Transmission and receiving radio paths of terahertz radio relay systems).” *Tsifroví tekhnologíї*, no. 17, 2015, pp. 16–29.

18 Naritnik, T.M., and O.V. Lutchak. “Aparatno-programní ríshennya pobudovi gígabítnogo modemu dlya radíoreleynikh líníy v teragertsovomu díapazoní (Hardware and Software Solutions for Building a Gigabit Modem for Relay Lines in the Terahertz Range).” *Tsifroví tekhnologíї*, no. 18, 2015, pp. 43–53.

19 Ilchenko, M.Ye., T.M. Narytnyk, B.M. Radzikhovsky, S.E. Kuzmin, and O.V. Lutchak. “Development of the Transmitting and Receiving Channels for Terahertz Band Relay Systems.” *Telecommunications and Radio Engineering*, vol. 74, No. 11, 2015, pp. 981–998.

20 Naritnik, T.M., O.V. Lutchak, S.O. Osipchuk, and L.O. Urivs'kiy. “Osoblivostí formuvannya signal'no-kodovikh konstruktsíy na osnoví tekhnologíї Wi-Fi dlya pobudovi telekomuníkatsíynikh system teragertsovogo díapazonu (Features of formation of signal-code constructions on the basis of Wi-Fi technology for construction of telecommunication systems of terahertz band).”*Elektronnoye nauchnoye spetsializirovannoye izdaniye – zhurnal «Problemy telekommunikatsiy»*, Khar'kov, no. 2(17), 2015.

21 Narytnyk, T.M.,O.V. Lutchak, S.O. Osypchuk, and L.O. Uryvskyi. “Criteria and Algorithms for Shaping of the Signal-Code Sequences on the Basis o fWi-Fi Technology at Deployment of the Terahertz Band Telecommunication System.” Telecommunications and Radio Engineering, vol. 75, 2015, no. 74 (2), pp.1823–1839.

22 Naritnik, T.M., S.O. Osypchuk and L.O. Urivsʹkiy “Realizatsiya kontseptsiyi stvorennya prohramno-vyznachenykh radiosistem terahertsovoho diapazonu na osnovi tekhnolohiyi Wi-Fi (Realization of conceptual development of program-based radio systems of terahertz range based on technology Wi-Fi).”Tsyfrovi tekhnolohiyi. No. 18, 2015, pp. 7-20.

23 Ilʹchenko, M.Ye., Narytnik T.N., V.N.Radzikhovsʹkyy, S.Ye.Kuzʹmin, and A.V.Lutchak. “Proyektirovaniye peredayushchego i priyomnogo radiotraktov radioreleynykh sistem teragertsovogo diapazona (Design of transmitting and receiving radio paths of terahertz radio-relay systems).” Elektrosvyaz', no. 2, 2016, pp. 42-49.

24 Naritnik, T.M., O.V.Lutchak, S.O. Osypchuk, and L.O. Urivsʹkiy. “Osoblyvosti formuvannya syhnalʹno-kodovykh konstruktsiy na osnovi tekhnolohiyi Wi-Fi dlya pobudovy telekomunikatsiynykh system terahertsovoho diapazonu (Features of formation of signal-code constructions on the basis of Wi-Fi technology for construction of telecommunication systems of terahertz band).” Tsyfrovi tekhnolohiyi, no. 20, 2016

25 Ilchenko, M.Ye., T.M.Narytnyk, S.V.Denbnovetsky, A.V.May, and O.V. Lutchak “Simulation of functional units of the terahertz band transmitting and receiving radio systems.” Telecommunications and Radio Engineering, vol. 75, no. 11, 2016, pp. 1027-1039.

26 Avdyeyenko, H. L., M.Yu. Ilʹchenko, T.M.Naritnik, A.V. Yermakov, and O.V. Lutchak.“Peretvoryuvach chastoty dlya pryyomo-peredavacha bezprovodovoyi telekomunikatsiynoyi systemy fiksovanoho zv'yazku terahertsovoho diapazonu (Frequency converter for terahertz fixed-line radio transceiver).” Elektronne naukove fakhove vydannya - Zhurnal “Problemy telekomunikatsiy”, Kharkiv, no. 1 (20), 2017, pp. 38-49.

27 Ilʹchenko M.Ye., S.V.Denbnovetskyy, T.N.Narytnik, A.V.Lutchak, A.V. May “Proyektirovaniye integral'nogo priyomnika teragertsovogo diapazona chastot (Designing an integrated terahertz frequency receiver).” Problemy telekomunikatsiy, Kharkiv, no. 1 (20), 2017, pp. 57-63.

28 Naritnik, T.M., H.L.Avdyeyenko, S.H.Bunin, A.V.Yermakov, O.V.Lutchak, and V.V. Volkov “Obgruntuvannya chastotnykh diapazoniv dlya visokoshvidkisnikh bezprovodovykh telekomunikatsiynikh system terahertsovoho diapazonu (Substantiation of frequency ranges for high-speed wireless telecommunication systems of terahertz band).”Problemy telekomunikatsiy, Kharkiv, no. 1 (20), 2017, pp. 103-112.

29 Ilchenko, M.,S. Denbnovetsky, T. Narytnik, O. Lutchak, O. May, A. Fisun, O. Bilous. “Design of the 290-310 GHz frequency range integral receiver.” Telecommunications and Radio Engineering, vol. 76, no. 15, 2017, pp. 1379-1390.