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TERAHERTZ COMMUNICATION SYSTEMS FOR HIGH-DEFINITION AND ULTRA-HIGH-DEFINITION TELEVISION TRANSMISSION

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Background. The advent of HD and UHD video formats, and as a result the growing volume of accumulated and transmitted data led to the demand for higher data rate of wireless communications. THz band satisfies the main technical and economic indicators for the implementation of HD/UHD TV broadcasting networks. This papers analyzes current advancements in implementing and deploying photonic-based terahertz (THz) communication systems.

Objective. The purpose of the paper is to consider modern variants of technical implementation of transmitting and receiving devices for broadcasting of HD/UHD TV signals in the THz band.

Methods. Studying the dependence of the transmission rate of an HD/UHD video stream on the transmission distance and quality.

Results. A variant of practical implementation of a prototype of a wireless video transmission system with UHD resolution of 8K over a terahertz radio line in the 300 GHz and other frequencies of terahertz band is considered. A distinctive feature of the modern receiving device from the known is the usage of RTD as demodulators of the terahertz signal, which greatly simplifies the receiving part of the proposed wireless transmission system. It is also shown that the main problem in the construction of transmitting devices in the THz range is the formation of a highly stable THz carrier oscillation by mixing optical carriers on a photodiode, as well as obtaining the output power of this oscillation sufficient to ensure the required range of the THz transmission system.

Conclusions. The main trends and approaches to building high-speed point-to-point wireless communication links of the next generation in THz band for HD/UHD TV signals transmission are presented. The principles and approaches to the construction of receiving and transmitting devices of the THz band were revealed, as this band is one of the most promising for the development of wireless networks with data rates more than 10 Gbps.

Keywords: *High-definition (HD); ultrahigh-definition (UHD); video stream; television transmission; terahertz (THz); resonant tunnel diode (RTD).*

Introduction

Current trends in the development of digital terrestrial television networks involve the exchange of large amounts of data. This need can be addressed through the use of fiber-optic networks, which provide gigabit data rates in many parts of the world. However, given the fact that fiber-optic access is not always possible or cost-effective, the question arises of developing and using wireless telecommunications systems (networks) that could meet similar needs. In the near future we need data rates in the tens and hundreds of Gbps - at least 24 Gbps to broadcast uncompressed television data with high definition (HD) and ultra-high definition resolutions (UHD) and 100 Gbps to support 100G Ethernet [1].

Recently, there has been interest from the scientific community and development engineers in the terahertz frequency range, which contains a large frequency resource that can be used for wireless transmission of information, including uncompressed HD video with image resolution 2K (1920×1080 pixels) and UHD video with image resolution 4K (3840 × 2160 pixels) and 8K (7680 × 4320 pixels).

According to the recommendation of the International Telecommunication Union IEEE 802.15 THz band is considered to be frequencies from 300 GHz to 3 THz (wavelength range from 1 to 0.1 mm), but in the general case, this band is frequencies from 100 GHz to 3 THz (Fig .1) [2].

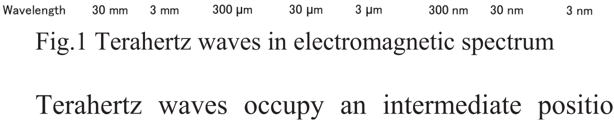

Fig.1 Terahertz waves in electromagnetic spectrum

Terahertz waves occupy an intermediate position between the millimeter and optical wavelengths. Compared to the near infrared frequency range, the THz band has a number of advantages. First, THz signals have less attenuation than infrared signals under the

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same weather conditions, such as fog. Secondly, the amplitude-phase fluctuations caused by local changes in the refractive index of the atmosphere also have little effect on the propagation of THz radiation, but limit the use of systems based on IR radiation. The described advantages are typical for the frequencies that fall into the windows of the transparency of the atmosphere, namely in the ranges of 75-100; 110-150; 200-300 and 600-700 GHz. With such wide available frequency bands, even with the simplest amplitude modulation, data rates of tens of Gbps can be achieved [3]. Also a feature of this frequency range is the narrow direction of the antenna beam, which allows you to place a large number of stations without mutual interference between them. However, there are certain problems in the development of this frequency band, namely, the technology of generation, reception and processing of data signals differs from the methods used when working with already known frequency bands. Also, currently, one of the problems is less theoretical information about the terahertz spectrum of waves and its radiation compared to microwave and infrared. Therefore exploitation and development THz band wireless communication systems is based on the capabilities of electronic devices for signal generation, processing and detection [4,8].

An analysis of the publications shows that most scientists have focused on developing and researching prototypes of wireless terahertz systems in the 100, 130, 230 and 300 GHz bands [5-7], due to the presence of “transparency windows” in these bands.

It is worth noting that the need for research and prototyping of such wireless transmission systems is due to the fact that the functionality of 6G mobile devices will go beyond the existing generation of 5G systems and will provide video transmission in 8K format with low latency and low power consumption [7] . On the other hand, since UHD video transmission speeds are very high (tens of Gbps), it is necessary to compress data when transmitting it wirelessly with a 5G system using microwaves or millimeter waves, which leads to delays and increased power consumption. Thus, the development of UHD wireless compression technology, which focuses on the 6G standard and terahertz range, is required .

Given the significant global progress in the technical development of terahertz devices, the aim of this paper is to consider the some up-to-date experimental decision for provision of wireless transmission of TV signal in HD/UHD formats.

48 Gbps wireless UHD video transmission system in the 300 GHz band

The experimental layout of this UHD (8K) video transmission system was proposed by a team of researchers from Osaka University (Japan) in conjunction with Rohm Co. , Ltd. [1]. It uses terahertz waves in the range of 300 GHz as a carrier that provides wireless transmission of 8K UHD video with a data rate of 48 Gbps within the JST project CREST “Development of an integrated technological platform of the terahertz range by combining resonant tunnel diodes and photonic crystals.

In a prototype 8K video transmission system [1], the developers configured a dual-channel terahertz transmitter (Tx) by modulating the 8K video signal output of two lasers with wavelengths in the range of 1.55 μm using a high-speed photodiode (PD) wave intensity modulator. In this case, these lasers were tuned in such a way relative to each other that the difference in their optical frequencies was in the range of terahertz waves, ie about 300 GHz (Fig. 2).

On the transmitting side of the prototype as a source of 8K video signal was used prepared and commercially available video content with full 8K resolution from Astrodesign Inc., which was formed as a four-channel signal with a stream rate of 12 Gbps in each channel, followed by two-channel signal multiplexing of 4 video streams in 2. Used with two-position amplitude manipulation on-off keing (OOK) two-channel radio signal with 24 Gbps video stream was generated.

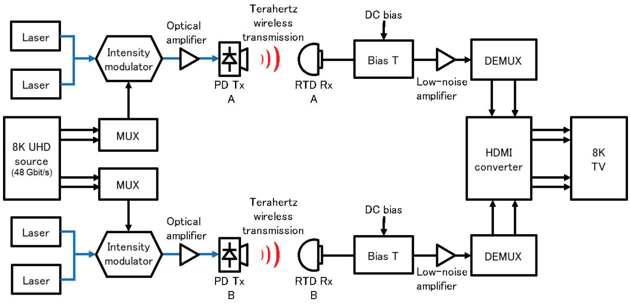


Fig.2 Block diagram of the 8K wireless video transmission system UHD in the terahertz range , which has two wireless transmission channels of 24 Gbps

On the receiving side (Fig. 2), two terahertz waves transmitted wirelessly from the corresponding terahertz transmitters were detected by sensitive coherent terahertz receivers (Rx) using resonant tunnel diodes (RTD) (Fig. 3), which acted as amplitude detectors. After that, the detected and amplified 24 Gbps video streams were demultiplexed from two channels to four 12 Gbps channels and connected to the 8K monitor via an HDMI cable. Using such a transmission system, uncompressed 8K video (equivalent to 48 Gbps) was successfully transmitted over a wireless channel in the 300 GHz band (Fig. 4).

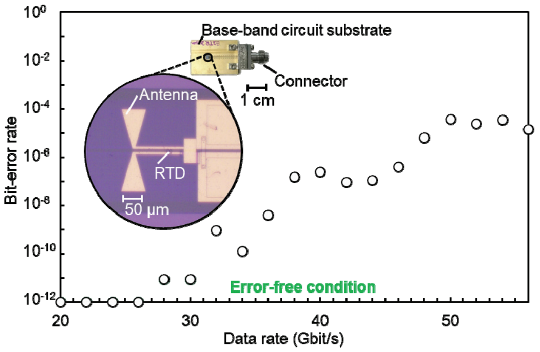


Fig.3 Photo of terahertz receiver and RTD base: the probability of bit error at 24 Gbps does not exceed 10 $^{-11}$

Fig. 4 Photo of the prototype of the 8K UHD wireless video transmission system in real time: in the foreground are two photodiode transmitters (Tx) and two RTD receivers (Rx) with an 8K TV screen in the background

Typically, experiments with ultra-high data rates in the terahertz range are performed using multi-level modulation of the QAM type using modulators / demodulators with high power consumption, and digital signal processing [5] - [7]. Experimental studies of the prototype of the 8K video transmission system proposed in [1] show the possibility of reliable use of the simplest modulation format - OOK, which greatly simplifies the circuit of the receiving device (application of direct-gain receiver) and demonstrates the capabilities of ultra-wide terahertz waves.

Six-channel integrated transmitter in the 300 GHz band with 32-QAM modulation and 17.5 Gbps bandwidth per channel

In the scientific and practical work [5] of Japanese scientists presented the development of an integrated circuit (IC) transmitter in the range of 300 GHz based on electronic technology 40 nm CMOS. This transmitter, using 32-QAM modulation, provides a bandwidth of 17.5 Gbps in each of the 6 channels with a bandwidth of 5 GHz, while covering the frequency range of 275-305 GHz (Fig.5). The total bandwidth that the transmitter IC can provide is 105 Gbps.

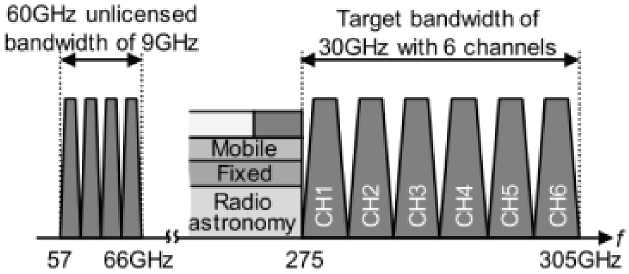


Fig.5 Frequency plan of the high-speed wireless communication system in the 300 GHz band

The block diagram of the transmitter IC are shown in Fig.6.

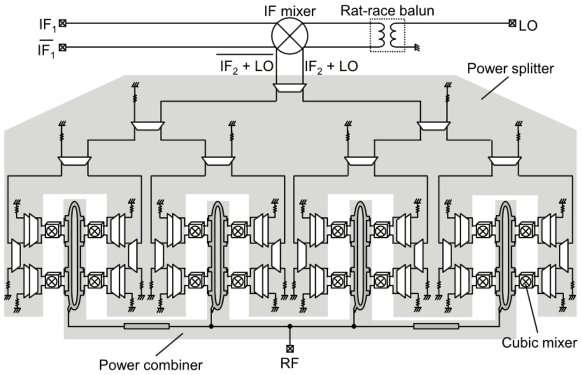


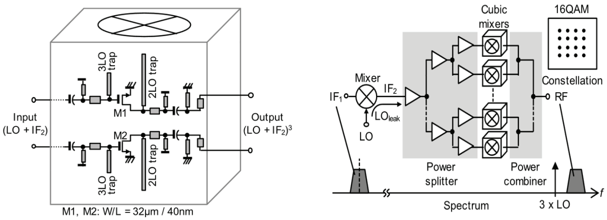
Fig.6 Schematic of the 300 GHz CMOS TX

The peculiarity of the construction of the IC transmitter (Fig.6) is the use of radio signals for the second frequency conversion with high positioning modulation (16-QAM, 32-QAM) high-line subharmonic mixers, called cubic mixers mixers) and are based on MOSFET with n-channel and maximum cut-off frequency (single gain frequency) f_{max} = 280 GHz. Due to the small gain of the transistors in the range of 275-305 GHz, to ensure a sufficient level of output power in the structure of the IC there are active power dividers.

The electrical circuit of the cubic mixer and its application for 16-QAM generation is shown in Fig.7,a,b.

Fig.8,a shows the spectrum of signals, which explains the principle of operation of the cubic mixer. From Fig.1.3, b shows that the useful signal of the cubic mixer at the output is a radio signal with a frequency

$f_{\mathrm{RF}} = 2f_{\mathrm{LO}} + f_{\mathrm{IF}_2}$ where f_{LO} – local oscillator frequency, f_{IF_2} – the second intermediate frequency of the modulated signal, which is equal to $f_{\mathrm{IF}_2} = f_{\mathrm{LO}} + f_{\mathrm{IF}_1}$, where f_{IF_1} – the first intermediate frequency of the modulated signal. For normal operation of the mixer, it is necessary that the ratio of the local oscillator power (P_{LO}) to the power of the modulated signal of the second intermediate frequency (P_{IF_2}) corresponds to the equation $P_{\mathrm{LO}} / P_{\mathrm{IF}_2} = 2$.



a) b)

Fig.7 a) Electrical diagram of the cubic mixer; b) cubic mixer application for 16-QAM generation

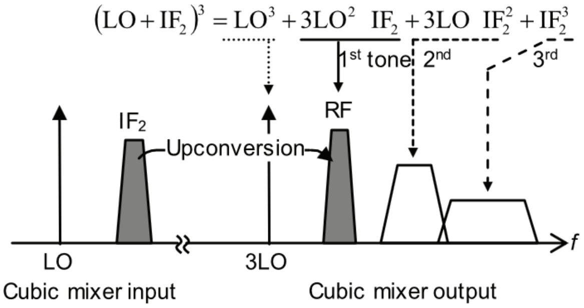


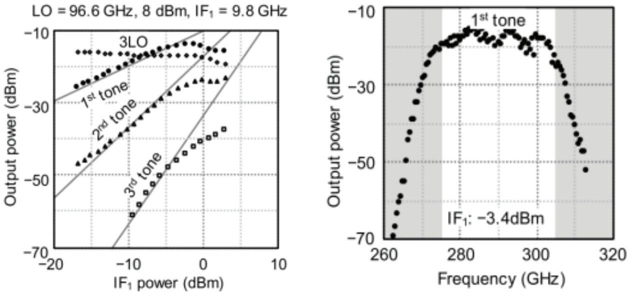
Fig.8 Operation principle of the cubic mixer.

Fig.9,a shows the measured values of the output power of the transmitter IC from the input power of the 1st intermediate frequency f_{IF_1} = 9.8 GHz at the local oscillator frequency f_{LO} = 96.6 GHz and its power P_{LO} = +8 dBm. Analysis of the dependencies in Fig.9 shows that the maximum value of the output power of the IC is $P_{\mathrm{OUT.MAX}}$ = -14.5 dBm at the input power of the intermediate frequency signal $P_{\mathrm{IF}_1} = -3,4\,\mathrm{dBm}$, i.e the loss of conversion in the IC is about 11 dB.

Fig.9,b shows the results of measuring the dependence of the output power level of the transmitter IC on the output frequency, which shows that in the frequency band 275-305 GHz, the unevenness of the output power is about 5 dB.

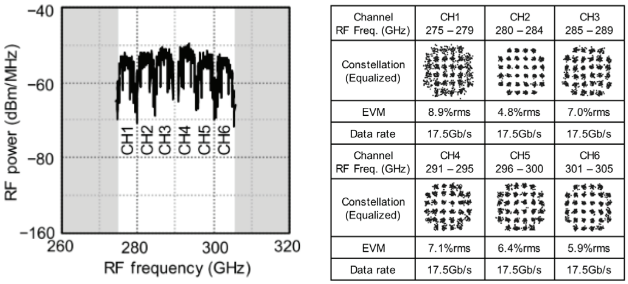
The power consumed by the transmitter IC is 1.4 watts of DC voltage.

Fig.10,a presents the spectrogram at the output of the transmitter IC, which shows the distribution of power spectral density for 6 channels with 32-QAM modulation and a symbol speed of 3.5 Gbps / channel (corresponding to a channel speed of 17.5 Gbps) channel); Fig.10,b presents the results of measuring the parameters of the constellation diagram of signals with 32-QAM modulation at the output of each of the 6 IC channels.



a) b)

Fig. 9 a) Measured dependence of the output power of the transmitter IC on the input power of the 1st intermediate frequency; b) the results of measuring the dependence of the output power level of the IC transmitter on the output frequency.



Channel RF Freq. (GHz)	CH1 275 – 279	CH2 280 – 284	CH3 285 – 289
Constellation (Equalized)			
EVM	8.9%rms	4.8%rms	7.0%rms
Data rate	17.5Gb/s	17.5Gb/s	17.5Gb/s
Channel RF Freq. (GHz)	CH4 291 – 295	CH5 296 – 300	CH6 301 – 305
Constellation (Equalized)			
EVM	7.1%rms	6.4%rms	5.9%rms
Data rate	17.5Gb/s	17.5Gb/s	17.5Gb/s

a) b)

Fig.10 a) Spectrum of a 6-channel signal with a symbol rate of 3.5 Gbps/channel; b) the results of measuring the parameters of the signal constellation diagram with 32-QAM modulation at the output of each of the 6 IC channels

Analysis of constellation diagrams in Fig.10,b shows that the worst of the 6 IC channels is the 1st (frequency band 275-279 GHz), because it corresponds to the maximum value of the modulation error vector (EVM), which is equal to 8.9%. The best is the 2nd radio channel (280-284 GHz band). It corresponds to an EVM of 4.8%. Since each of the channels has its own EVM value, each of the 6 channels will have its own noise immunity: in the 1st frequency channel it will be the worst, in the second channel - the best. Given that

EVM and signal-to-noise ratio (SNR) are related by an approximate analytical ratio

$$SNR \approx -20\lg\frac{\mathrm{EVM}(\%)}{100},\ \mathrm{dB} \qquad (1)$$

obtained a graphical relationship between EVM and SNR as a function of the frequency of the output signal of the IC transmitter (Fig.11).

Analysis of the graph in Fig.11 shows that in the frequency band 275-305 GHz SNR is at least 30 dB (approximately 30-32 dB), which is a pretty good result.

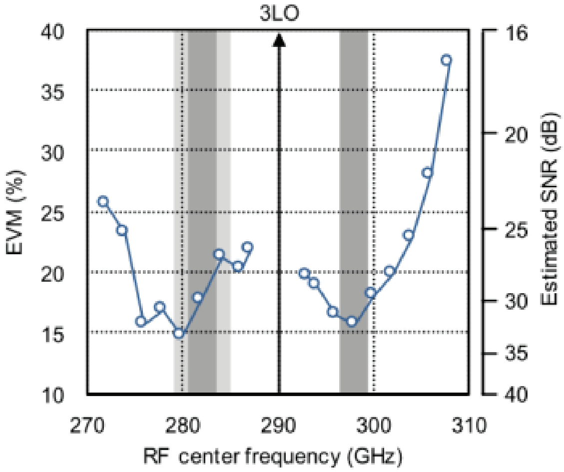


Fig.11 Graphical relationship between EVM and SNR as a function of the frequency of the output signal of the transmitter IC

Comparative characteristics of 40nm CMOS technology parameters (operating frequency, modulation, baud rate, output power) for manufacturing IC transmitter [1] with other manufacturing technologies for the terahertz range is presented in Table.1.

Table 1 - Comparative characteristics of the parameters of the IC transmitters terahertz range, manufactured by different technologies

Technology	Freq. (GHz)	Modulation	Data rate (Gb/s)	P_{out} (dBm)	P_{dc} (W)
32-nm SOI CMOS	210	OOK	20	4.6	0.24
250-nm InP DHBT	298	NA	NA	−2.3	0.45
130-nm SiGe BiCMOS	240	64QAM	1.02	7	0.54
35-nm GaAs mHEMT	240	8PSK	96	−3.5	NA
35-nm GaAs mHEMT	240	QPSK	64	−3.6	NA
130-nm SiGe HBT	314	NA	NA	−8	0.13
130-nm SiGe BiCMOS	434	ASK	10	−18.5	0.12
65-nm CMOS	260	OOK	NA	5 (EIRP)	0.69
SBD mixer	300	64QAM	0.032	−15	NA
SBD mixer	340	16QAM	3	−17.5	NA
130-nm InP HBT	630	NA	NA	−30	0.65
250-nm InP HBT	300	QPSK	50	NA	NA
65-nm CMOS	240	QPSK	16	0	0.22
40-nm CMOS	275–305 282	32QAM	17.5 × 6 30	−14.5	1.4

High speed wireless communication system in 237.5 GHz band

In [6], an experimental model of a 237.5 GHz point-to-point wireless line (SISO) was demonstrated , which combines electronic and photonic technology with a maximum data rate of 100 Gbps at a distance of 20 m when using up to three radio frequency high frequencies. For a wireless line longer than 40 m, the maximum data rate of 75 Gbps was provided by a single radio frequency carrier at a frequency of 237.5 GHz with 8-QAM modulation. Such terahertz radios can be used indoors to provide high-speed connections between mobile terminals and desktop personal computers.

Fig.12 presents a diagram of the organization of a wireless communication line with a speed of 100 Gbps to overcome an obstacle in the form of a wide river in a hard-to-reach area.

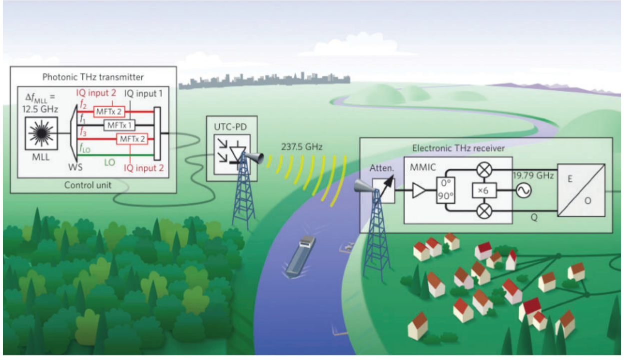


Fig.12 Option to use high-speed wireless communication line at terahertz frequencies

The principle of operation of such a radio line is as follows. The transmitter (Tx) uses terahertz photonics technology (Fig.1.7) by means of which by heterodyning frequency-synchronized laser lines (MLL) are generated spectrally pure and frequency-stable terahertz carrier oscillations. The transmitter control unit contains one laser with auto-tuning frequency and allows you to select the appropriate spectral lines for modulation of the data stream. The optical fiber transmits the modulated carriers together with the unmodulated spectral line, which acts as a remote local generator (LO), to the uni-traveling-carrier photodiode (UTC-PD) with carriers of the same type. When photomixing oscillations of the generator and modulated carriers in UTC-PD at its output are generated radio frequency signals of the terahertz range.

The terahertz receiver contains a low-noise amplifier (LNA) and a subharmonic IQ mixer with down-conversion and is implemented using a high-electron transistor (mHEMT) with a gate length of 35 nm and a cutoff frequency of more than 900 GHz. For the electronic in-phase / quadrature IQ receiver (Rx) ones can use specially designed, active millimeter monolithic integrated circuits (MMIC) with a radio frequency bandwidth of 35 GHz. Complex data is directly converted by the IQ mixer "down" into the baseband and is divided into I and Q signals.

In the technical implementation of the above principle of operation in the transmitting terahertz path using photonic technologies, one MLL source (ERGO XG laser) outputs a frequency spectrum with a frequency spacing Δf_{MLL} = 12.5 GHz. Programmable optical filter (Finisar wavehaper 4000E) selects the desired optical carrier frequencies from the MLL spectrum of the source: f_{LO} = 193.138 THz (λ_{LO} = 1,552.22 nm), the central carrier at f_1 = 193,375 THz (λ_1 = 1,550,31 nm) and two adjacent carriers at $f_{2,3} = f_1 + \Delta f_{MLL}$. The central carrier and the group of two adjacent carriers are modulated by different IQ data provided by two independent multiformat transmitters 25 MFTx1 and MFTx2.

Modulated carriers and oscillations of the local oscillator are mastered, aligned by polarization, combined and mixed on UTC-PD .

The photodiode current includes signals of three intermediate frequencies $f_{1,2,3}$ - f_{LO}, which are emitted by a horn antenna and focused by aspherical flat convex lens. In addition, the UTC- PD output current includes unwanted signals $(f_3$-$f_1)$ = $(f_1$-$f_2)$ = 12.5 GHz and $(f_3$ -$f_2)$ = 25 GHz , which are filtered by a rectangular waveguide (cut-off frequency for wave H_{10} f_c = 174 GHz) connecting UTC-PD to the antenna. UTC-PD operates with a full optical input power of +14 dBm, which leads to an average photodiode current of 6.5 mA and has an output power of -13.5 dBm for one modulated terahertz channel at f_1 -f_{LO} = 237.5 GHz. It is estimated that the phase noise of the single sideband (SSB) is optically generated carrier oscillations with a frequency of 237.5 GHz is -33.1, -66.4, -80.8 and -81.9 dBc/Hz at debug frequencies of 100 Hz, 1 kHz, 10 kHz and 100 kHz , respectively.

The receiver is equipped with a similar horn-lens antenna and is located at a distance of d = 5, 10, 20 and 40m. Beamwidth<2°, suitable for point-to-point wireless connections. The small wavelength of about 1 mm allows implementing a very compact antenna array. For frequency f = 237.5 GHz and the distance between transmitting and receiving stations d = 10 m, the attenuation in free space is about 100 dB .

After the receiving antenna, the variable waveguide attenuator of the receiving path allows adjusting the input power of the terahertz signal for the MMIC chip.

In the receiver's MMIC chip, the LNA unit provides a gain of about 30 dB and transmits the signal to the IQ mixer. The subharmonic mixer operates with a half-frequency (118.75 GHz) local oscillator signal. The local oscillator signal is formed by a chain of frequency multipliers from a synthesizer operating at a frequency of 19.79 GHz . The estimated phase noise of the local oscillator at 237.5 GHz is -44.4, -56.4, -56.4 and -78.4 dBc/Hz at 100 Hz, 1 kHz, 10 kHz and 100 kHz, respectively. The receiving IQ module is integrated in the area of the chip 2.5×1 mm^2 and packed in a waveguide module with a split unit. The packaged Rx module has a measured conversion factor of 3.8 dB and a noise figure of 10 dB. Thanks to the integrated MMIC low-noise amplifier, the receiving path works perfectly at an input power of only -32 dBm. Converted with decreasing frequency I and Q modulating signals are digitized by an analog-to-digital converter at a speed of 80 Gbytes/s (real-time oscilloscope Agilent DSO-X-93204A). Further processing includes channel alignment, carrier recovery, signal filtering and demodulation.

There are two modes of radio line operation: single-channel and multi-channel (Fig.13-14). In the first mode, UTC-PD receives two types of optical signals: only the carrier f_1 (Ch1) and oscillations of the local oscillator f_{LO} . With the help of a special generator, QPSK, 8-QAM and 16-QAM signals are generated with a baud rate of up to 25 GBaud, which corresponds to a baud rate of up to 100 Gbps (Fig.13). In the multi-channel UTC photodiode mode, two optical carriers $f_{2,3}$ (Ch2, Ch3) are additionally transmitted with fixed interval $\Delta f_{MLL.}$ = 12.5 GHz (Fig.14). In-phase pulse generation with a spectrum decreasing according to the law of elevated cosine and a rounding coefficient β = 0.35 in all 3 channels is used. The values of the symbolic speeds are 13Gbaud in Ch1 and 8 Gbaud in Ch2 and Ch3. Channel Ch1 and adjacent to it slightly overlap.

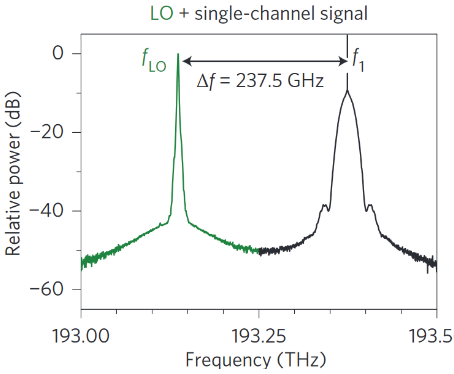


Fig.13 Optical spectra at the input of the UTC-PD for single-channel operation mode configuration

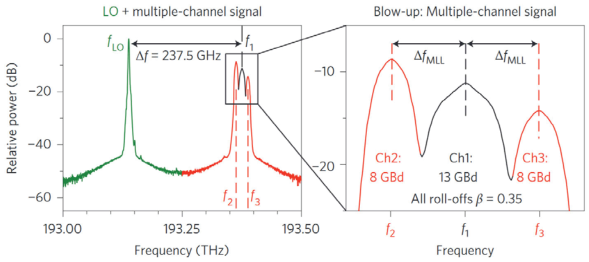


Fig.14 Optical spectrum at the input of the UTC-PD for multi-channel operation mode configuration

In the transmission path, the spectrum is adjusted by the signal generating unit to compensate for the frequency response of the UTC-PD. When using 16-QAM modulation in Ch1 channel and 8-QAM modulation in Ch2 and Ch3 channels, the total data rate is 100 Gbps .

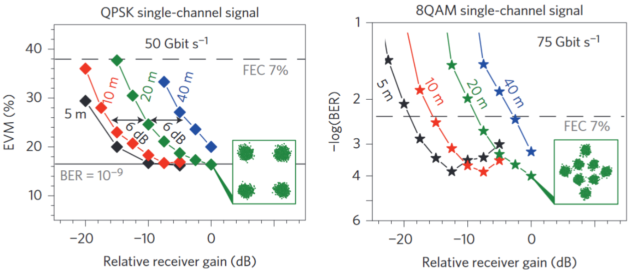
During the experiments for digital signal processing and signal quality assessment using a real-time oscilloscope (Agilent DSO-X-93204A), the obtained data were digitized and recorded. The recording time length was 80 µs. For a single channel signal of 25 Gbps , the recording length of 80 µs corresponds to a sum of 10^6 characters, i.e it was estimated approximately 4×10^6 received bits for a stream at 50 Gbps and QPSK modulation, 6×10^6 bits for a stream at 75 Gbps and 8-PSK modulation, 8×10^6 bits for 100 Gbps signal and 16-QAM modulation.

To determine the BER on the receiving side of the radio link, a pseudo-random sequence of bits of length 2^{15} - 1 was transmitted.

For low-error QPSK signals, EVM was measured instead of BER, which characterizes the effective distance of the obtained complex symbols from their ideal location on the constellation diagram. In the presence of additive gaussian white noise BER can be measured by EVM values as measured .

Fig.15,a shows the EVM flow rate of 50 Gbps for a single-channel QPSK signal for different distances of wireless transmission and depending from relative receiver transmission gain G = 1/L_{Att} , where L_{Att} - added losses of waveguide attenuator at the receiving path. The constellation diagram shows clear and understandable symbols. As the gain of the receiver increases, the EVM decreases until it is about 16% (corresponding to BER~1×10^{-9}), which can be observed for d = 5, 10 and 20 m. This threshold is due to the constant contribution of electronic noise receiver. For d = 40 m, the received signal strength is insufficient to reach this threshold EVM.

From Fig.15,a it is seen that doubling the distance requires an increase in the power of the input signal of the receiver in 4 times (6 dB). For 8-QAM and 16-QAM signals (Fig.15, b) and for distances d = 5m and 10 m BER reaches a minimum and begins to increase if the signal power at the receiver input increases. This behavior is due to nonlinearities of the MMIC chip, which affect the multi-position modulated signals. This can be seen in comparison with Fig.15,a where the QPSK signal with constant power does not show an increase in EVM compared to other modulated signals of the same power. For the 50 Gbps 16-QAM signal, the optimal BER value of 3.7×10^{-4} is obtained at a distance of more than 40 m (Fig.16). For the 100 Gbps signal with 16-QAM, the optimal BER for a distance of up to 20 m remains below the FEC limit for 7% excess. Fig.17 shows the results of EVM measurements when transmitting a signal at a speed of 58 Gbps and QPSK modulation in all channels. The central channel Ch1 at 13 Gbaud works better than the channels Ch2 and Ch3 at 8 Gbaud, because the limited bandwidth of the receiver is divided into spectra Ch2 and Ch3.



a) b)

Fig.15 Results of measuring the parameters of wireless signals transmitted in the terahertz range at a distance of 5, 10, 20 and 40 m at speeds: a) QPSK, up to 50 Gbps; b) 8-QAM, up to 75 Gbps

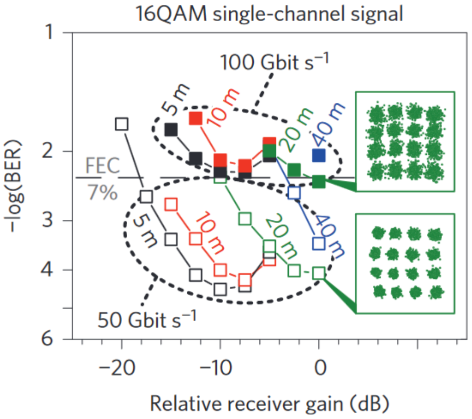


Fig.16 Results of measuring the parameters of wireless signals transmitted in the terahertz range at a distance of 5, 10, 20 and 40 m at speeds 50 Gbps and 100 Gbps with 16QAM

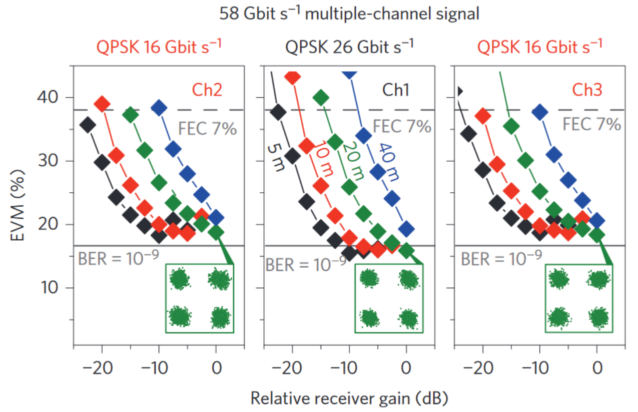


Fig.17 Results of measuring the parameters of wireless multiple-channel signal transmitted in the terahertz range at a distance of 5, 10, 20 and 40 m at speed 58 Gbps with QPSK

Horizontal solid lines in Fig.15,a and Fig.17 indicate the corresponding calculated values of BER 1× 10^{-9} .

Fig.18 shows the results for multichannel transmission at 100 Gbps, where each of the channels Ch 2 and Ch3 transmits a stream with a symbol rate of 8 Gbaud and modulation 8-QAM, and the channel Ch1 has transmits a stream with a symbol rate of 13 Gbuad and 16-QAM modulation .

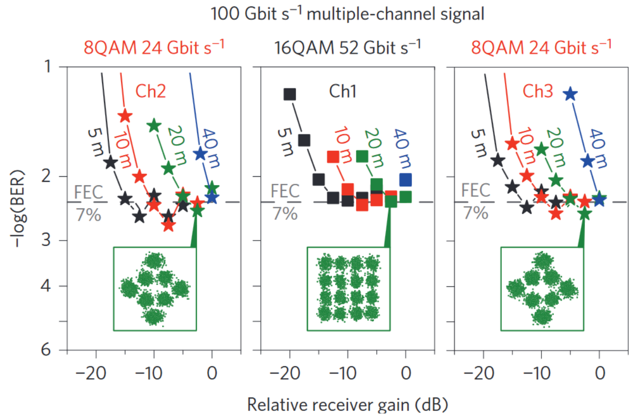
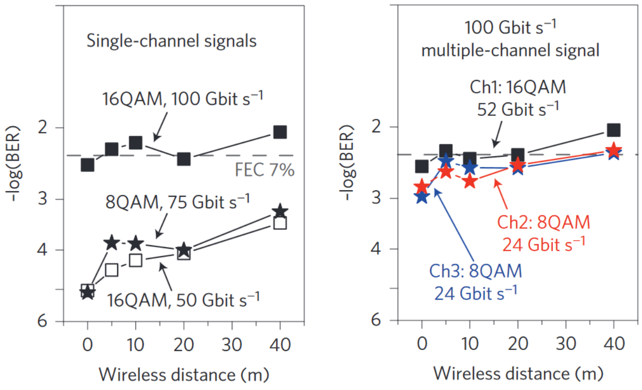


Fig.18 Results of measuring the parameters of wireless multiple-channel signal transmitted in the terahertz range at a distance of 5, 10, 20 and 40 m at speed 100 Gbps with 8-QAM and 16-QAM

Fig.19 shows the optimal BER from Fig.16 depending on the wireless transmission distance. At distances d = 5, 10 and 20 m the signal power at the receiver input is sufficient to correct errors, while the BER for d = 40 m is increased due to limited power budget.

Horizontal dotted lines in Fig.15-19 correspond to BER 4.5 × 10^{-3}. Raw BER 4.5 × 10^{-3} is the threshold for error-free transmission when using FEC with a hard decision and 7% redundancy. If the FEC decoder is working properly, the BER at the receiver output will be 1 × 10^{-15}.



a) b)

Fig.19 Indicators of the quality of data transmission over a wireless line depending on the distance

Further increase of the transmission rate to several Tbps can be achieved through the use of multiplexing with wavelength division multiplexing, frequency division multiplexing in the band 200-300 GHz and spatial multiplexing with multiple parallel MIMO connections. By using MMIC amplifiers at the output of UTC-PD and Cassegrain antennas (> 50 dBi) on both the transmitting and receiving sides, it is possible to significantly increase the distance between the corresponding stations (> 1 km).

Conclusion

Scientific and practical achievements of foreign scientists, developers and engineers demonstrate the usefulness of terahertz waves, which in turn will accelerate the research and development of ultra-high-speed transmission systems in the 6G standard.

The analysis of typical experimental samples of wireless communication systems for HD/UHD video stream transmission in terahertz range based on a combination of electronic and photonic technologies shows [5-7] that:

1) they provide ultra-high speed data transmission, usually several tens of Gbps at the bandwidth of the receiver a few units-tens of GHz ;

2) laser radiation sources are used to form highly stable optical carrier oscillations and local local oscillations ;

3) modulation of optical carrier oscillations by high-speed is carried out in the optical IQ-modulator with high position of modulation (not worse than QPSK , most often 16- or 32- QAM);

4) the formation of one or more modulated terahertz signals is carried out by photodetection in the

photodiode of the optical signal of local oscillations and optical modulated or modulated oscillations, which are shifted in frequency relative to the local oscillator frequency by terahertz (usually not less than 75-100 GHz) ;

5) maximum range of the terahertz ultrs-high speed radio link due to the limited energy potential of the radio line does not exceed 20-40 m;

6) during the generation of multi-channel terahertz radio signals for simultaneous transmission of several ultra-high-speed streams it is hard to provide complete identity the of these radio signals at output of the terahertz transmitter in terms of their energy parameters: output power and signal-to-noise ratio;

7) transmitting and receiving paths contain a significant number of optical units (filters, dividers, polarizers, phase shifters, etc.).

Thus, the combination of the appropriate type of coding and modulation in the terahertz range with further improvement of the technique of generation, transmission and reception of radio signals of the terahertz range will further help to realize transmission speeds at tens of Tbps. Also, studying the peculiarities of the radio waves propagation in the terahertz range is necessary for solving this problem.

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Терагерцові системи зв’язку для передавання телевізійних сигналів високої та надвисокої чіткості

Проблематика. Поява відеоформатів HD і UHD і, як наслідок, зростання обсягів накопичених даних призвели до потреби більш високої швидкості передачі інформації по бездротових системах зв'язку. Терагерцовий діапазон (ТГц) частот задовольняє основним техніко-економічним показникам для впровадження мереж телевізійного мовлення в форматі HD/UHD. У цій статті аналізуються сучасні досягнення у впровадженні та розгортанні терагерцових систем бездротового зв’язку на основі фотонних технологій.

Мета досліджень. Розгляд сучасних варіантів технічної реалізації передавальних та приймальних пристроїв для трансляції HD/UHD телевізійних сигналів у діапазоні ТГц.

Методика реалізації. Вивчення залежності швидкості передачі відеопотоку HD/UHD через бездротовий канал зв’язку від відстані та якості передачі.

Результати досліджень. Розглянуто варіант практичної реалізації прототипу системи бездротової передачі відео з роздільною здатністю UHD 8K по терагерцовій радіолінії в частоті 300 ГГц та інших частотах терагерцового діапазону. Відмінною особливістю сучасного приймального пристрою від відомих є використання резонансних тунельних діодів (RTD) як демодуляторів терагерцового сигналу, що значно спрощує приймальну частину пропонованої системи бездротової передачі. Також показано, що основною проблемою при побудові передавальних пристроїв у ТГц діапазоні є формування високостабільного коливання ТГц несучої шляхом змішування оптичних несучих на фотодіоді, а також отримання вихідної потужності цього коливання, достатньої для забезпечення необхідної дальності передавання системою передачі ТГц діапазону.

Висновки. Представлено основні тенденції та підходи до побудови високошвидкісних бездротових каналів зв’язку типу «точка-точка» в діапазоні ТГц для передачі телевізійних сигналів HD/UHD. Розкрито принципи та підходи до побудови приймально-передаючих пристроїв ТГц діапазону, оскільки цей діапазон є одним із найбільш перспективних для розвитку бездротових мереж зі швидкістю передачі даних понад 10 Гбіт/с.

Ключові слова: Висока чіткість (HD); надвисока чіткість (UHD); відеопотік; телевізійна передача; терагерцовий діапазон (ТГц); резонансний тунельний діод (RTD).