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DESIGN OF THE 290…310 GHZ FREQUENCY RANGE INTEGRAL RECEIVER

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It is developed the base structure of the 290-310 GHz range integral receiver on the basis of the frequency converter based on the metal-dielectric waveguide (10×10 mm) comprising the quasi-optical open resonator, super-dimensional metal and metal-dielectric rectangular waveguides and the micro assembly with non-linear elements. The converter allows implementation of broad operation frequency bandwidths (20 GHz and more). Introduction into the heterodyne of the quasi-optical open resonator possessing selective properties and capable of spatial summation of power allows attaining the required level of power (5…10 dBm) of the frequency converter heterodyne. The frequency converter is intended for use in the communication systems based on the terahertz range pulse ultra-wideband signals with the super-high throughput rate.

KEY WORDS*: telecommunication systems, terahertz range, integral receiver, frequency converter, heterodyne, quasi-optical open resonator, metal-dielectric waveguide*

1. INTRODUCTION

Telecommunication systems represent one of the promising spheres of application for the terahertz technologies.

Currently the rates in local area networks attained the values of 100 Gbps and 40 Gbps (100G and 40G Ethernet correspondingly), whereas 10G Ethernet is applied, in particular, in Ukraine nowadays. High Definition Television requires application of the digital channel of 1.5 Gbps and 6 Gbps. Therefore, the standards of 10G Ethernet higher are perfectly suitable for transmission of the traffic of a kind. This trend causes

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the necessity of creation of digital wireless systems capable of performing direct connection with the 10G systems [1-5].

It is noted in the report that presently we have to make a choice between high rates of data transmission (the optic fiber) and minimal delay (microwave connections). However, with the wireless terahertz technologies one can obtain minimal delay, which is commeasurable with the speed of light, with the throughput rate at the level of the optic fiber parameters. Moreover, exploring of the terahertz range would allow providing for a highly efficient communication channel with the satellites.

Insufficient element base of the solid state devices capable of generation of the required power levels (single milliwatt and more) [6-7] still remains as one of the most important problems in exploration of the 0.1…3.0 THz range.

Development and implementation of new circuitry-related solutions while creating the transceiving and antenna equipment units is a perspective trend of development for the terahertz range systems that would allow, first of all, decreasing the costs of equipment and providing for the necessary electric and power characteristics [8].

In particular, it is envisaged to develop principally new in terms of dimensions, noise protection parameters and power-efficiency terahertz range (THR) devices used for high-rate data transmission of video signals of the line-of-sight radio relay systems (RRS), transport networks of the fifth generation (5G) mobile communication and the radars with the purpose of highly precise detection and recognition of small-dimension and high speed targets.

The trend for applying THR radio waves has acquired a stable mode during recently. This is explained by the achievements in development of technically sophisticated devices and systems [9-10]. Broad operating frequency bandwidth is the most important of their advantages. Narrow patterns of the antennas in this bandwidth facilitate increasing the secrecy of communication and suppression of the interference noise, whereas the high value of gain allows decreasing the power of the transmitter and improving the weight-and-dimension characteristics of the equipment. Small weight and dimensions of the radio-electronic equipment and the THR antenna system at high rates of data transmission make them the most attractive in terms of using them as parts of the on-board equipment.

The objective of the studies is the following:

- creation and practical implementation of the frequency converter with a broad operating frequency bandwidth (20 GHz and more) for the radio relay telecommunication lines having the super-high throughput rate;
- development of the antenna-filter based on the circular metal-dielectric waveguide with the acceptable characteristics.

2. BLOCK CIRCUIT DIAGRAM OF THE INTEGRAL RECEIVER

The integral frequency converter (IFC) capable of receiving modulated signals at the transmission rates of 1 Gbps and more with the acceptably high sensitivity is the key element of the THR telecommunication line.

The block circuit diagram of the integral frequency converter (Fig. 1) includes the bandpass filter (BPF), the additional functions of which are performed by the horn lens antenna based on the circular MDW, the balance mixer (BM) on the basis of the square MDW with the cross-section of 10 × 10 mm, the heterodyne, one of the key functional elements of which is represented by the quasi-optical open resonator; and the intermediate frequency amplifier (IFA).

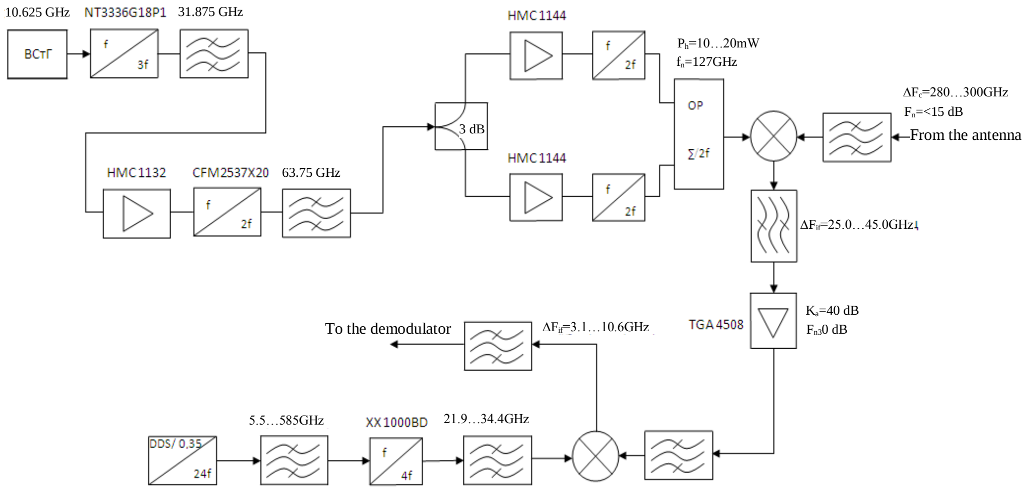


FIG. 1: Block circuit diagram of the terahertz range integral receiver

The bandwidth of the first mixer is 25.0 ... 45.0 GHz, the second - 3.1...10.6GHz.

Thus, the end-to-end bandwidth Δf = 7.5 GHz has been achieved, which makes it possible to use the already developed modem equipment.

The flexibility of the receiver circuit is in the fact that, for example, for the standard 802.11a the data transmission rate is up to 54 Mbps, the frequency range is 5 GHz or UWB, USB 2.0, the frequency range is 10 GHz and the signal processing is performed at the first and the second intermediate frequencies (see Table 1).

TABLE 1: Comparative characteristics of the ultra-wideband and other systems

Data transmission rate, Mbps	Standard	Modulation type
480	UWB, USB 2.0	PPM/other type
90	Fast Ethernet	
54	802.11a	60-QAM, 16-QAM, BPSK, OFDM
20	802.11g	60-QAM, 16-QAM, BPSK, OFDM
11	802.11b	CCK
1	Bluetooth	GMSK

The specific traffic density (Table 2) is an important characteristic of the telecommunication line.

TABLE 2: Spatial traffic density in the ultra-wideband and other systems

Standard	**Specific traffic density, Mbps m^2**
802.11b	1.0
Bluetooth	20.0
802.11a	83.0
UWB, USB 2.0	1000

Wide application of the terahertz technologies in the lines within the 0.1…3.0 THz range allows realization of the streams of up to 1000 Mbps m^2.

3. MODELLING OF FUNCTIONAL NODES OF THE INTEGRAL RECEIVER

3.1 Frequency Converter of the Signal

The balance mixer is built based on the circuit of the converter with pumping at a half of the heterodyne frequency. Two anti-parallel connected AA138-B3 Shottky diodes, the upper frequency boundary of which amounts to 300 GHz, are used as the non-linear elements.

The design of the frequency converter includes two quasi-optical super-dimensional waveguides: from the heterodyne side it is the waveguide with the cross-section of 7.2 × 3.4 mm, and from the side of the signal – the metal-dielectric waveguide with the cross-section of 10 × 10 mm. The above waveguides are joined with the micro assembly including the planar antenna, balance mixer and intermediate frequency amplifier.

Structurally, the frequency converter is executed in the form of the waveguide insert.

The conversion module parameters are provided in Table 3.

TABLE 3: Conversion module parameters

Operating frequencies range, GHz	290…315
Intermediate frequencies range, GHz	25.0…45.0
Noise factor, dB	15.0
Heterodyne signal suppression in the IF path, dB	50.0
Mirror channel suppression, dB	20.0
Heterodyne power, dBm	13.0
The power in the point of compression minus 1 dB at the heterodyne power of 13 dBm, dBm	5.0

Heterodyne phase noise, dBn/10 kHz, not more than	– 80
Frequency instability	+/– 1×10^{-7}

3.2 Balance Mixer on the Metal-Dielectric Waveguide

The balance mixer is built based on the circuit of the converter with pumping at a half of the heterodyne frequency. Two anti-parallel connected AA138-B3 Shottky diodes, the upper operating frequency boundary of which amounts to 300 GHz, are used as the non-linear elements.

Figure 2 shows: a fragment (Fig. 2(a)) of the frequency converter structure, the omnidirectional or “butterfly”-type planar antenna pattern (Fig. 2(b)) and a fragment of the BM hybrid-integral circuit (Fig. 2(c)).

The input line of the signal circuit ($\Delta F_{sign.}$) consists of a section of the metal-dielectric waveguide 10 × 10 mm and the dielectric cone.

The transmission line of the heterodyne circuit ($F_{het.}$) contains a section of the super-dimensional metal waveguide 10 × 5 mm and the dielectric lens.

Structurally, the waveguide insert comprises the balance mixer (BM) hybrid-integral circuits and the first stage of the intermediate frequency amplifier. The waveguide insert is positioned in the plane A-A (Fig. 2(a)).

A fragment of the BM topological circuit is provided in Fig. 2(c): 1 – planar antenna; 2 – strip transmission line; 3 – Shottky barrier diodes.

The planar antenna and the strip transmission line are formed on the substrate made of Duroid 5820 (the thickness is 0.127 mm, $\varepsilon = 2.2$). The Shottky barrier diodes are mounted in the planar antenna symmetry plane.

MMIC of the first stage of the IF low-noise amplifier (not shown in Fig. 2(c)) is mounted on the same substrate as above.

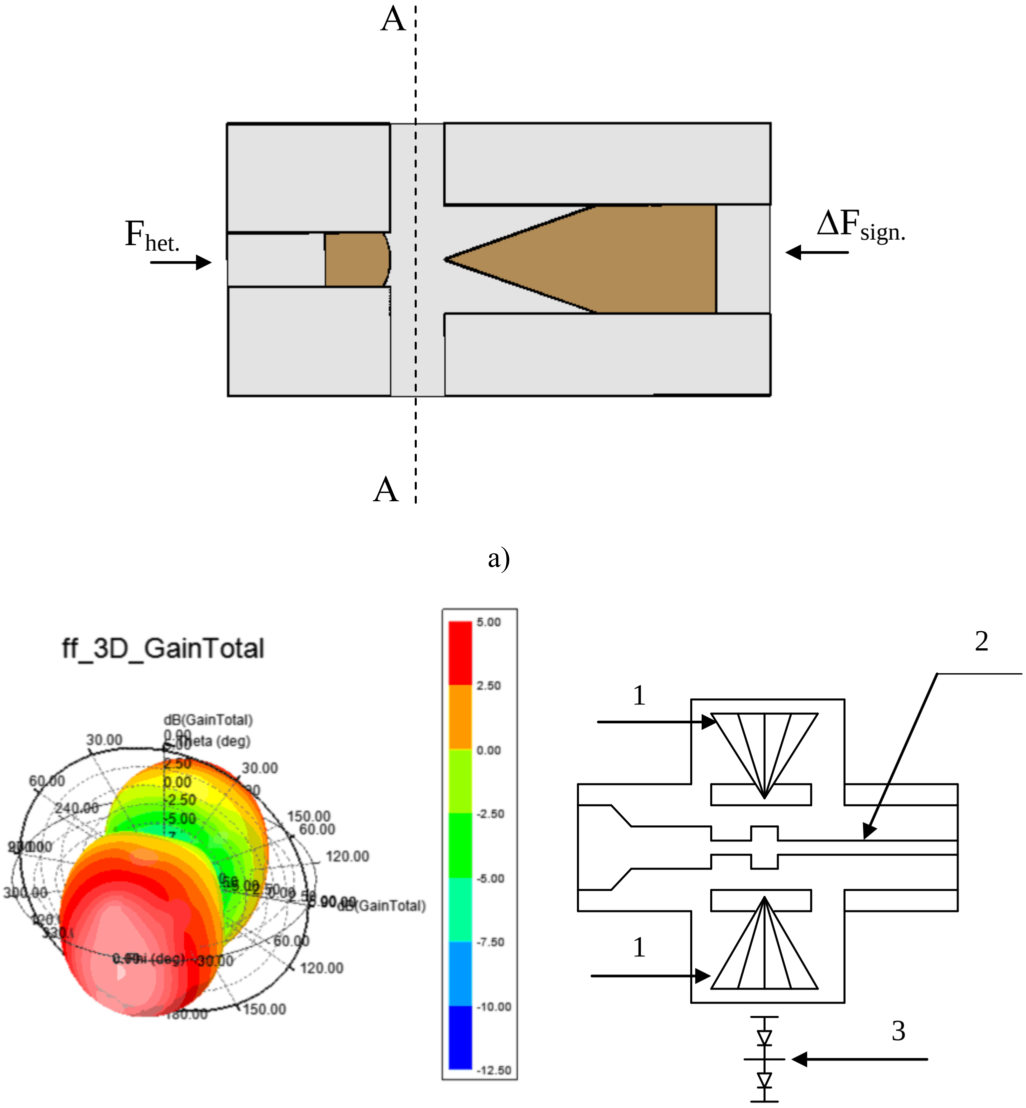
The planar antenna gain ratio in the frequency range of 290…310 GHZ amounts to 4.0 … 4.5 dB.

3.3 Heterodyne

The subharmonic circuit of the frequency converter permits decreasing the heterodyne operating frequency that facilitates, to a certain extent, the heterodyne circuit development. Nevertheless, there are preserved strict requirements set to the heterodyne stability and the phase noise level.

Introduction into the heterodyne of the quasi-optical open resonator possessing selective properties and capable of spatial summation of power allowed implementation, at the existing element base, of the heterodyne with the required level of power (10…13 dBm), phase noise (80 dB / 10 kHz) and the heterodyne frequency stability of $\pm 1 \times 10^{-7}$ [11].

Quasi-optical and combine methods were developed with the purpose to overcome basic drawbacks of the solid-state devices like small power level, and insufficient frequency stability in the short-wave domain of the millimeter and terahertz wavelength bands. Considering that the transmission lines applied at the circuit integration (the microstrip, slot and co-planar ones) lose their advantages at those frequencies due to the radiation losses, losses in the substrate and the Ohmic losses the effective power summation must be performed in the free space.



a)

b)

c)

FIG. 2: The frequency converter structure (a), the omnidirectional planar antenna pattern (b) and the bm hybrid-integral circuit (c)

It was experimentally studied at the frequency of 130 GHz the OR with the TEM_{10q} mode, which was excited with the help of two frequency multipliers and two planar aperture elements of coupling providing for matching both upon the amplitude and the phase [12,14].

The aperture element of coupling in the form of the strip slot line and the planar horn is realized upon the dielectric material – duroid 5880 having the thickness of 0.127 mm.

Basic advantage of the coupling element is that it allows separation of the matching functions upon the field and the coupling. Considering that geometrical dimensions of the aperture coupling element exceed the wavelength of the resonator operating oscillation that would exclude loss of power due to diffraction of the wave beam upon it. In this condition, the non-resonant background is also substantially decreasing.

The range between the field spot centers is equal to 10.5 mm. This range is the intra-element interval for connection of the frequency multiplier and the planar aperture coupling element circuits into OR. The dimensions of the OR mirrors are always determined by the spherical mirror because dimensions of the oscillation field spots on it are always larger than those on the plane one.

Let us set the ratio between the length and the curvature radius as $L/R = 0.5$, $R = 100$ mm, $\lambda = 2.2$ mm, $L = 50$ mm, then the field spot radius of TEM_{10q} mode on the spherical mirror is equal to 8.5 mm, the mirror diameter is 45 mm, and the OR efficiency is $\eta = 0.867$ [14,15]. The OR dimensions on the screen are the following: the diameter is 40 mm; the length is 55 mm.

The measured levels of the output powers at the outputs of OR of the transmitter and receiver amount to 13…15 dBm. The above levels of power are sufficient for normal operation of the BM of the transmitter and the transmitter up converter.

Improvement of spectral characteristics (decreasing of the frequency noise level and increasing of the generated frequency stability) is related to the problem of sparsening of the spectrum and increasing of the oscillatory system Q-factor. In the terahertz frequency band it would be more preferable to apply quasi-optical OR with diffraction gratings as mirrors. The quasi-optical solid state oscillator in the short-wave domain of the millimeter-wave band having the spherical echelette open oscillatory system is a source of highly stable electromagnetic oscillations and is intended for using as low-noise local oscillators and pumping oscillators of parametric amplifiers in millimeter and terahertz wavelength bands.

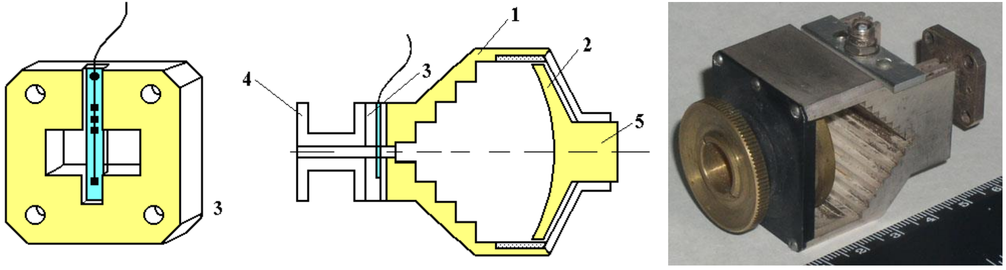
The oscillator is generated the oscillations within the 100 to 150 GHz domain at operation voltages of 15…16 V and the currents of 0.18…0.20 A. The source of oscillations is developed for fixed frequencies with the possibility of mechanical tuning of up to 0.5 GHz. The output power level attains 0.01…0.02 W. The oscillator does not require forced cooling. The weight of the device without the power source is not exceeding 0.1 kg, and its dimensions are 50 x 35 x 30 mm^3.

High stability of the oscillations are secured by using as the resonant system of the spherical-echelette open resonator having a low level of diffraction losses and high degree of spectrum sparseness both upon the longitudinal and the transverse modes of oscillations. Similar parameters of the oscillatory system are attained due to application as one of the mirrors of the *H*-polarized corner echelette reflector, which is installed under the self-collimation scheme.

Characteristics of the corner echelette OR are simulated with the help of the method suggested by L. Weinstein, in which OR is represented as a section of a two-dimensional waveguide. For the resonators with echelette and other diffraction gratings it was suggested the method of decomposition using the scattering matrices for each of the elementary sections of the two-dimensional waveguide.

The IMPATT diode is positioned in a waveguide passing through the place of joining two identical echelettes, which are positioned mirror symmetrically under the angle of 45^o to the resonator axis. One side of the waveguide is ended with a coupling slot (of the same cross-section as the waveguide), and the other side – with a load. The active element together with the disk transformer is positioned at the half-wave range from the coupling slot of the corner echelette mirror with the resonance volume. The power take-off is executed either through the coupling hole in the spherical mirror – under the "propagation-oriented" circuit – or along the waveguide path positioned in the body of the corner echelette mirror – under the "reflection-oriented" circuit. The oscillator frequency instability for 1 s is not exceeding 2×10^{-8} at the power source instability of 10^{-4} and the pulse level at the frequency of 100 Hz amounting to 0.01 V.

Proceeding to the short-wave domain of the mm-wave band called for the necessity of developing new matching and connection circuits. Specially designed new active structures made of InP were applied. The mesostructure diameter is less than 20 μm, and concentration of the carriers n and the active structure length l fulfill the condition $nl > 1 \cdot 10^{12}$ cm^{-2} that is higher that the normally used parameters. Theoretical and experimental research shows that such set of parameters results in increasing of negative impedance and rising of the frequency limit. The active structure is made of $n^+n^-n^+$ epitaxial InP films under the integrated heat removal technology with the mesostructure height of 5 μm and the diameter of 12 μm, $l = 1.6$ μm, and $nl = 3 \cdot 10^{12}$ cm^2. The contacts are formed with the help of multilayer films; the active structure is covered with the protective polyamide film, in which there are formed the contact sites, the shifting circuit and the LF filter. These technological features allow reducing parasite capacitance and inductivity of the protective case to minimum. The active structure and the shift circuits are mounted on a quartz plate with the dimensions of $0.2 \times 0.6 \times 8.5$ mm^3, which is embedded into the active module. Manufacturing of the active element and the shift and matching circuits are maximally approximated to the planar technology methods. The active module (see Fig. 3(a)) represents a standard waveguide flange with a section of the waveguide with the cross-section 2.4×1.2 mm^2, which is executed in the body of the flange with the help of the electric spark method. Figure 3(b) shows the axial cross-section of the quasi-optical solid state oscillator on the basis of Gunn diode made of InP with the corner echelette OR. The structure comprising the corner 1 and the spherical 2 mirrors, the active module 3 and the waveguide section 4 is rather simple and allows fast replacing of the active module. The echelette mirror serves as the case of the oscillator and the OR length is varied with the help of the adjusting screw mechanism 5. The oscillator operated on the basis of the reflecting resonator scheme, the operation mode of the oscillations used to be quasi-TEM_{00q}, the OR loaded Q-factor was $Q_l = 5 \cdot 10^3$. The generated power P =8…11 mW was obtained at the frequencies of 100…150 GHz. General view of the oscillator is shown in Fig. 3(c). Application of active modules based on the Gunn diodes or IMPATT diodes executed with the help of using the planar technology in an uncased option of manufacturing with the shift and matching circuits, is the most promising trend in exploring the short-wave domain of mm and submm wave bands, because those are just the kinds of a structure that incur minimal excitation into the resonant system field structure.



a) b) c)

FIG. 3: Oscillator with the spherical corner echelette OR on the Gunn diode made of indium phosphide: the diode section (a); the diode section connection with OR (b) and general view (c)

3.4 Intermediate Frequency Amplifier

Structurally, the intermediate frequency amplifier (IFA) is performed in the form of a separate unit.

The IFA circuitry consists of two loops and is built on the microchip TGA 4508 manufactured by TriQuint (Δf_{if} = 25…45 GHz; K_{gain} = 40 dB; K_n = 3.0 dB). In addition to the amplifying microchips the IFA unit contains the secondary power sources forming the stabilized voltage for the microchips.

The horn antenna based on the circular metal-dielectric waveguide.

Advancement of the telecommunication systems into the terahertz range caused the necessity of performing investigations related to creation of the horn antennas on the basis of super-dimensional waveguides. Thus, the paper [16] represents the design of the horn on the basis of the V-shaped trough waveguide.

Narrow antenna patterns with the width of single degrees or fractions of a degree can be obtained with the help of the horn lens antennas.

Electrical parameters of the horn lens antenna for the 290…310 GHz frequency range are provided in Table 4.

TABLE 4: Electrical parameters of the horn lens antenna

Frequency range, GHz	290…310
Diameter, mm	45
Length, mm	80
Gain ratio, dB	20
Coefficient of back-radiation, dB	30
SWRV/adverse loss, dB	1.2/21.0

Weight, kg	0.3

During the process of operation modelling and calculation of characteristics of the integral frequency converter are performed with the help of the following software environments – NI AWR Design Environment; ANSYS HFSS; Altair FEKO.

4. PARTICULARITIES OF THE DESIGN

The integral receiver is executed in a modular performance with maximal application of the monolith microchips providing for compact design along with convenience of its assembly and mounting.

The provide for the high-quality operation of the receiver there will be developed secondary power supply sources forming up the required stable voltages for all the nodes of the receiver.

The “end-to-end“ frequency characteristic of the receiver has total coefficient of transmission of not less than 40 dB, whereas the inhomogeneity of the coefficient of transmission is not exceeding 3 dB.

Comparative characteristics of the integral receivers are provided in Table 5.

TABLE 5: Characteristics of the terahertz range telecommunication systems

Radio system	**130 GHz**	**250 GHz**	**290…310 GHz**
Frequency, GHz	130…134	250 and more	300 and more
Frequency bandwidth, GHz	4 (up to 10)	up to 20	20 and more
Digital stream bitrate, Gbps	1,0	1.0 and more	1.0 and more
Noise factor, dB	8…10	10…12	15
Mirror channel suppression, dB	– 55	– 55	– 55
Receiving path coefficient of transmission, dB, not less than	20	20	20
Heterodyne power, dBm, not less than	10	5	3
Heterodyne phase noise, dBn/ 10 kHz	– 80	–80	– 80
Dynamic range, dB	20	20	20
Intermodulation distortions of the 3rd order, dBn	25	25	25
Frequency instability	+/– 1×10^{-7}		+/– 1×10^{-7}
Modulation	QPSK 2 QAM 16, 32, 64, 128, 256	QPSK 2 QAM 16, 32, 64, 128, 256	QPSK 2 QAM 16, 32, 64, 128, 256
Technology	InP, GaAs	InP, GaAs	InP, GaAs

5. CONCLUSIONS

The developed design of the frequency converter based on the metal-dielectric waveguide (10 × 10 mm) comprising the quasi-optical open resonator, super-dimensional metal and metal-dielectric rectangular waveguides and the micro assembly with non-linear elements allows implementation of broad operation frequency bandwidths (20 GHz and more).

Introduction into the heterodyne of the quasi-optical open resonator possessing selective properties and capable of spatial summation of power allows attaining the required level of power (5…10 dBm) of the frequency converter heterodyne.

On the basis of the developed electronic components and nodes it is designed the base structure of the integral receiver with the frequency range of 290…310 GHz having the noise factor at the level of 15 dB, which is executed in a modular performance with maximal application of the monolith microchips.

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