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ELECTRONICS
AND RADIO ENGINEERING

Measurement of the Radiation Frequency of a Pulsed Submillimeter-Wave Gyrotron Using Beat-Note Signals with the Harmonics of a Millimeter-Wave Frequency Synthesizer

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Abstract—A method of frequency measurements of pulse signals in the millimeter/submillimeter wavelength region, including signals with a pulse duration shorter than 10 μs and a repetition rate of 0.1 Hz, is considered. This method is based on the analysis of amplitudes of beat notes between the signal under study and radiation of a millimeter-wave frequency synthesizer. Application of this method to frequency measurements and identification of modes of a pulsed relativistic gyrotron in a configuration of a large-orbit gyrotron operating at three lower harmonics of the cyclotron frequency in the range 100–400 GHz is demonstrated. This method allows radiation-frequency measurements with an accuracy corresponding to the frequency instability during an oscillation pulse. It is shown that the method developed is also applicable to investigations of the oscillation dynamics within a single pulse.

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INTRODUCTION

To date, gyrotrons are the most powerful oscillators in the millimeter and submillimeter regions that ensure continuous and pulse oscillation power from a few watts to several megawatts [1–7]. Depending on the values of the operating voltage and magnetic field, a gyrotron can radiate at different frequencies corresponding to different eigenmodes of the resonator and cyclotron harmonics. Exciting modes at cyclotron harmonics allows the value of the operating magnetic field to be reduced considerably and makes it possible to generate coherent radiation at fixed frequencies in a wide frequency range—up to one octave or more—in a single gyrotron [5–7].

Note that, in a gyrotron with an oversized resonator, a large number of different modes, which often have close frequencies, are excited. It is important that the mode frequency depends not only on the dimensions of the resonator, the value of the magnetic field, and the number of the resonance cyclotron harmonic, but also on factors as difficult to control as the resonator manufacturing accuracy and its temperature conditions. In such a situation, precise measurement of the oscillation frequency of gyrotrons is necessary for both identification of its operating and parasitic modes and solution of problems in which it is important to ensure a definite frequency of radiation.

Note that analyzing the spectrum of submillimeter radiation is a difficult problem because of the absence of appropriate standard instruments. At present, the lower wavelength limit for the best industrial spectrum analyzers is near 1 mm [8] even if external mixers–converters are used. A higher-frequency spectrum analyzer exists [9]. However, only a few such instruments have been built and their characteristics do not allow a review spectrum of the signal under study to be measured over the entire operating frequency range.

The simplest of the widespread methods for measuring the frequency of millimeter/submillimeter radiation involve the use of an interferometer [10] or a resonator wavemeter [11]. Under favorable experimental conditions, the relative measurement error may be $<10^{-2}$ in the first case and may reach 10^{-5} in the second. In both cases, the measurement error increases considerably if the radiation under study is not monochromatic (contains signal harmonics or—which is the most complex situation—there are several frequency components with almost the same power distribution).

More precise frequency-measurement techniques are based on the mixing of the signal under study with highly stable radiation of the frequency synthesizer and discrimination of a difference signal falling within the operating range of the industrial frequency counter. The error of measuring the radiation under study is then determined by the quality of the reference signal and, if standard commercial instruments are used, amounts to $\leq 10^{-8}$ under favorable conditions. Measurements become more complex and the probability of errors increases considerably if we investigate pulsed radiation, especially when the signal is a sequence of short pulses with a large off-duty factor.

This paper presents a method that allows analysis of the spectral composition and measurements of the frequency of pulse signals in the millimeter and submillimeter ranges, including signals with pulses shorter than 10 μs and a repetition rate of 0.1 Hz. Radiation from a pulsed relativistic large-orbit gyrotron was studied. The gyrotron operated on the first three harmonics of the cyclotron frequency in the radiation-frequency range 100–400 GHz. This study of the gyrotron radiation allowed identification of the modes excited in the gyrotron's resonator upon changes in the magnetic field and the electron-beam current, accurate measurements of the radiation frequency, and observation of the oscillation dynamics within a single pulse.

MEASUREMENT TECHNIQUE

The method proposed for frequency measurements is based on the analysis of the amplitude of beat notes between the radiation of the frequency synthesizer in the range 78.33–118.1 GHz and the gyrotron signal under study. These beats arise when the above two radiations are mixed in a nonlinear element. Hence, a well-known principle of heterodyning the frequency of the radiation under study is employed in which the frequency synthesizer operates as a heterodyne. The amplitude of the signal of beats within a fixed frequency band of an intermediate–frequency amplifier (IFA) is recorded during stepwise changes in the synthesizer frequency occurring after the arrival of each radiation pulse. When the synthesizer frequency is scanned over the entire operating frequency range, an experimental record is obtained, the analysis of which allows the frequencies of coherent components of the signal under study to be determined.

The condition under which a signal of beats is observed upon mixing the radiation from the synthesizer with the radiation under study (from the gyrotron) in a nonlinear element can be written in the form

$$nf^{\mathrm{synth}} - mf^{\mathrm{inv}} = \pm f^{\mathrm{if}}, \quad (1)$$

where n and m are the numbers of harmonics of the radiation frequencies from the synthesizer and gyrotron, respectively; f^{synth} is the synthesizer frequency; f^{inv} is the gyrotron-signal frequency; and f^{if} is the frequency of the signal of beats. Sign ± in front of f^{if} corresponds to the fact that beats are observed in both cases where the synthesizer harmonic's frequency is higher or lower than the frequency of a gyrotron radiation harmonic by the value of the intermediate frequency. The two signals resulting from this process are called image channels.

Condition (1) determines the pattern of beats in the synthesizer's frequency range. The two following facts should be considered in the analysis of this pattern: (i) as synthesizer harmonic number n increases, the amplitude of beats rapidly falls and (ii) the amplitudes of beats between the harmonics of the gyrotron radiation under study having sequential numbers m and the synthesizer harmonic having the same number n are approximately equal. In addition, a detailed record of the image channels (the amplitude of the signal of beats as a function of the synthesizer frequency) during scanning of the synthesizer frequency allows determination of synthesizer-frequency harmonic number n at which beats occur. For this purpose, the relationship

$$n = \frac{2f^{\mathrm{if}}}{f_1^{\mathrm{synth}} - f_2^{\mathrm{synth}}}, \quad (2)$$

where f_1^{synth} and f_2^{synth} are the synthesizer frequencies corresponding to the center frequencies of the two image channels observed, is used. Formula (2) follows from condition (1).

The error of measuring the frequency of the signal under study at known n and m is stipulated by the accuracy at which the values of f_1^{synth} and f_2^{synth} are determined from the experimental record of the image channels. Obviously, the narrower the IFA bandwidth and the higher the valid signal-to-noise ratio in the record, the lower the error.

THE OSCILLATOR UNDER STUDY

A so-called large-orbit gyrotron (LOG) operating at the first three cyclotron harmonics was used in this work as the oscillator under study. In contrast to a conventional gyrotron, in which the axes of electron trajectories form a cylindrical surface in the resonator, all electron of the beam in a LOG rotate around a single axis coinciding with the axis of an axially symmetric electrodynamic system. In this symmetry, an ideally thin beam having no spread of the positions of the centers of electron orbits is capable of exciting only modes with azimuthal indexes coinciding with the number of the resonance cyclotron harmonic. This selection rule reduces the number of excited modes in the spectrum considerably, thereby simplifying the selective excitation of high cyclotron harmonics as compared to a similar process in a conventional gyrotron [12, 13].

The resonators that are most frequently used in gyrotrons have the form of sections of slightly irregular cylindrical waveguides. The $TE_{r,p}$ transverse electric modes, where r and p are the azimuthal and radial indexes, respectively, and the longitudinal index is typically equal to 1, have the lowest start currents in such waveguides. The frequencies of these modes in a resonator with a fixed diameter are close to the corresponding cutoff frequencies

$$\omega = \nu_{r,p} c/a, \quad (3)$$

where a is the radius of the resonator, c is the velocity of light in vacuum, and $\nu_{r,p}$ is a root of the equation $dJ_r(\xi)/d\xi = 0$ (J_r is a Bessel function). When induction B of a homogeneous magnetic field in the gyrotron's resonator changes, the cyclotron frequency of electron rotation,

$$\omega_c = \frac{e}{m_0 \gamma} B \tag{4}$$

changes as well and the modes excited in the resonator have the frequencies satisfying the resonance condition

$$\omega \approx s\omega_c, \tag{5}$$

where e and m_0 are the electron charge and mass of rest, respectively; γ is the relativistic mass factor; and $s = 1$, 2, 3 is the cyclotron-harmonic number.

The LOG under study [7] was mounted on a high voltage test bench at the Institute of Applied Physics, Russian Academy of Sciences. A preliminary calculation has shown that, at an accessible particle energy of 250 keV and with the use of conventionally shaped resonators, it can be expected that, in the submillimeter wavelength region, the third cyclotron harmonic can selectively be excited. To reduce ohmic losses in the resonator, the $TE_{3,8}$ mode with a large radial index at a frequency near 370 GHz was chosen as the operating mode. A magnetic field with an induction $B_0 = 6.5$ T was created in the resonator for exciting this mode. An electron gun formed a helical electron beam with a current of up to 3 A with a rotational-to-translational-velocity ratio of $V_\perp/V_\parallel = 1$.

According to our calculations, in addition to the operating mode, the $TE_{1,3}$ mode must be excited at a 116.45-GHz frequency in the LOG as the magnetic-field induction falls to 6.1 T; at 5.9 T, the $TE_{2,5}$ mode at a 223.01-GHz frequency should be excited at the second cyclotron harmonic. Moreover, if the electron beam is slightly shifted from the resonator's axis, several parasitic modes with azimuthal indexes differing from the numbers of the resonance cyclotron harmonics may be excited at the first three cyclotron harmonics (Fig. 1).

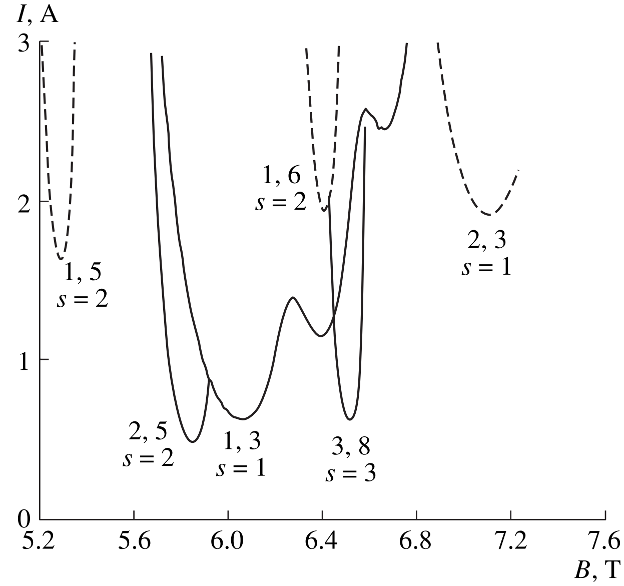

Fig. 1. Calculated start currents of the gyrotron's modes the frequencies of which were measured in this experiment depending of the magnetic-field induction. Dashed lines denote the start currents of the parasitic modes that can be excited in the range of the operating currents of the electron beam owing to a shift of the electron beam from the resonator's axis.

EXPERIMENT

Stable selective oscillation at a number of gyrotron modes resonant with the first, second, and third cyclotron harmonics was obtained in an experiment with the LOG's resonator excited by a helical beam in the magnetic field's operating range. Modes were identified on the basis of the radiation frequency, the value of the resonance magnetic field, and the results of measuring the transverse structure of the high-frequency field on the aperture of the output horn. Radiation was extracted from the gyrotron through a circular waveguide simultaneously operating as the electron collector. The radiation emerging from the output window enters a conical horn that smoothly expanded to a 50-mm diameter. The main portion of the power was absorbed in a calorimetric load. Part of radiation was diverted by a waveguide line for detection and frequency measurements.

The gyrotron radiation was preliminarily studied by a set of three waveguide filters with cutoff frequencies of 290, 157, and 100 GHz that were selected so that the first filter passed the radiation generated at the third harmonic of the cyclotron frequency, the second filter passed the second and third harmonics, and the third filter transmitted the radiations generated at the first three cyclotron harmonics. However, this simple method did not allow unambiguous identification of the excited mode and required additional measurements.

To perform precise measurements of the radiation frequency and identify modes, we used the technique of analyzing the beats between the radiations of the frequency synthesizer and gyrotron arising upon mixing these radiations across a nonlinear element. For this purpose, the portion of the gyrotron radiation diverted for measurements was mixed with the radiation of a commercial frequency synthesizer (IEM Kvarz, Nizhni Novgorod) for the range 78–118 GHz [14] with the use of a harmonic mixer–multiplier based on a Schottky diode (similar to the multiplier used in [15]) (see Fig. 2).

A signal of beats arising in the mixer was amplified at the intermediate frequency by an amplifier having a half-height passband of 300–800 MHz and a center frequency of 550 MHz. Note that the choice of the IFA's passband is determined by the width of the radiation spectrum under study and resembles the selection of the optimal bandwidth for the analysis in spectrum analyzers. A too-narrow IFA's passband allows more precise tuning to the signal under study and better determina-

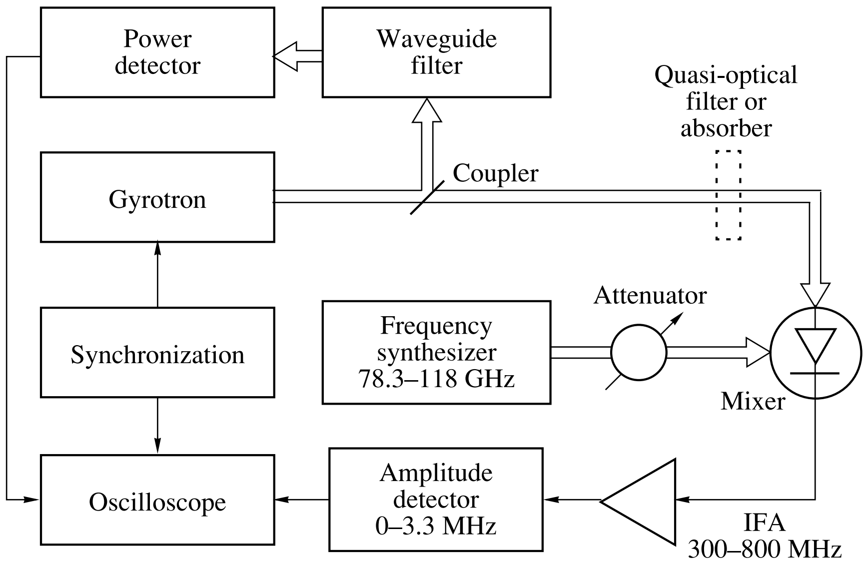

Fig. 2. Block diagram of the frequency-measuring section of the experimental setup.

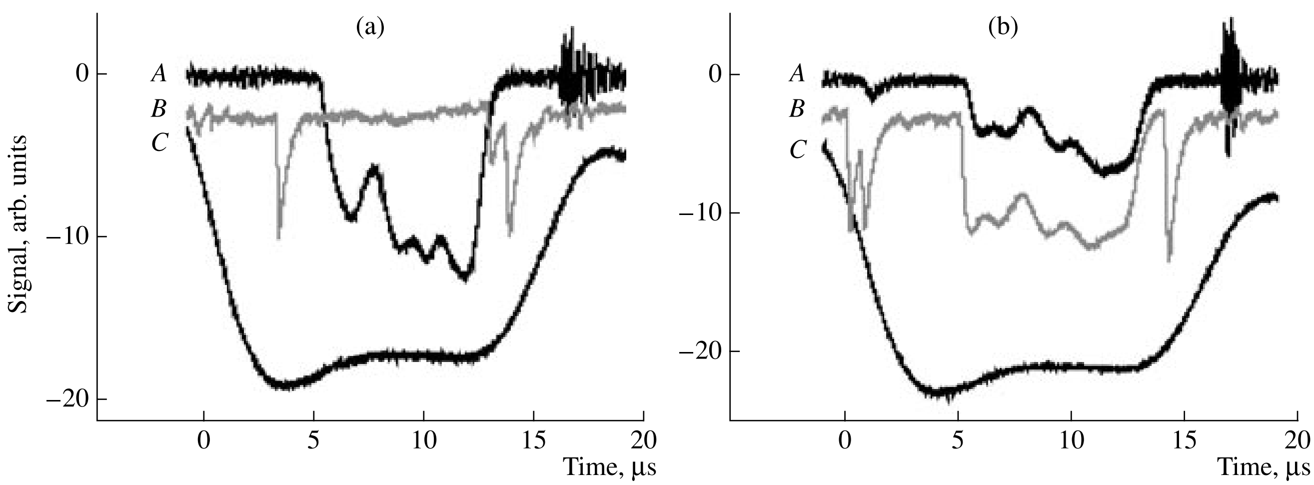

Fig. 3. Example of oscillograms of the signals recorded by an oscilloscope: (a) beyond a signal of beats and (b) at the peak of a signal of beats. Traces: (*A*) signal from the power detector, (*B*) amplitude of a signal of beats, and (*C*) accelerating voltage.

tion of its frequency; however, the passband narrowing entails smaller frequency steps during scanning of the synthesizer frequency; this increases the measurement time considerably. In addition, the IFA's passband must exceed the range of gyrotron frequency changes during a pulse.

The amplified signal of beats was detected at a time constant of 0.3 µs. The amplitude and shape of the pulse signal of beats were analyzed with a digital oscilloscope. Simultaneously with the signal of beat notes, a signal proportional to the accelerating voltage and a signal from the detector proportional to the gyrotron radiation power were applied to two other inputs of the oscilloscope, respectively (Fig. 3).

The shape of the radiation-power signal coincides well with the shape of the signal of beats at the center of the voltage pulse, thereby corresponding to generation of radiation at one of the gyrotron's modes (during a period between the 5th and 13th µs. Figure 3 shows that, at the edges of the voltage pulse, oscillations are observed at frequencies different from the fundamental oscillation frequency.

To obtain additional information, the following auxiliary elements were used in our experiments (Fig. 2): a variable (0–50 dB) attenuator placed at the synthe-

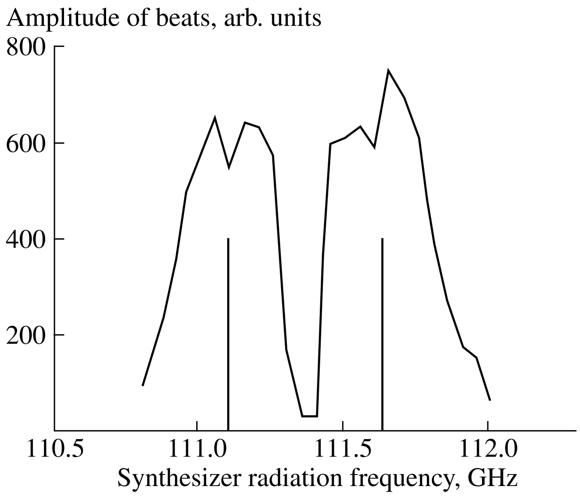

Fig. 4. Detailed record of the image channels of the signal of beats observed during the analysis of radiation from the gyrotron operating at the $TE_{2,5}$ mode.

sizer output, an absorber (~20 dB), and a quasi-optical filter [16] transmitting frequencies above 370 GHz and suppressing low-frequency radiation by 10–30 dB depending on the distance from the cutoff frequency. Attenuation of the synthesizer radiation power primarily led to a reduction of signals of beats with large numbers n. The gyrotron radiation attenuation by the absorber was aimed at protection of the mixer's diode against overheating and at the correspondence of the amplitude of the signal of beats to the dynamic range of the IFA.

In order to minimize the time of the experiment, the pattern of beats was recorded in two modes, searches and detailed measurements. In the signal-search mode, the synthesizer's frequency step is chosen such that the signal of beats falls within at least one of the image channels. The maximum step value is $\frac{\Delta f + f_{\min}}{n}$, where Δf is the width of the IFA passband, n is the synthesizer's harmonic number, and $f_{\min}$ is the lower frequency limit of the IFA range provided that $\Delta f > f_{\min}$.

In detailed measurements, the amplitudes of both channels of beats are recorded. In this case, the frequency step must be such that it were possible to determine the values of f_1^{synth} and f_2^{synth} included in (2) with an accuracy sufficient for unambiguous determination of synthesizer's harmonic number n at which beats are observed.

Figure 4 shows an example of a detailed record of image channels for a gyrotron operating on the $TE_{2,5}$ mode. The frequency synthesizer's number value corresponding to the beats observed is determined in the following way. First, the synthesizer frequency values corresponding to the signals of beats at the center frequency in the IFA passband (f^{if} = 550 MHz) are found.

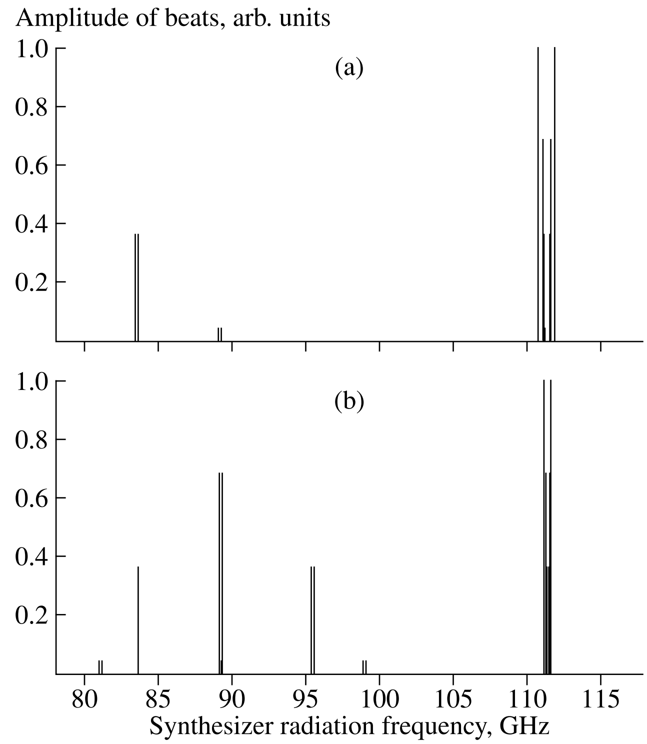

Fig. 5. Calculated patterns of beats within the operating range of the synthesizer at a frequency of the radiation under study of (a) 111.365 and (b) 222.73 GHz.

These frequencies are marked with vertical lines in Fig. 4. Substituting these frequencies into formula (2) yields a value of 2.075(80). This means that the record was made at the second harmonic of the synthesizer. The gyrotron frequency multiplied by harmonic number m and determined from formula (1) is 222.73(3) GHz. In this case, factor m may assume a value of 1 or 2. Values exceeding 2 are excluded because the gyrotron does not radiate at a frequency below a cyclotron frequency that is close to 108 GHz.

To determine the value of m, the pattern of beats observed over the entire synthesizer's frequency band must be analyzed. Figure 5 shows the patterns of beats for the analyzed signal calculated from formula (1) at frequencies of 111.365 and 222.73 GHz corresponding to the case considered for m = 2 (Fig. 5a) and m = 1 (Fig. 5b), respectively. The positions of vertical lines in the figures correspond to the synthesizer frequency values at which beats are observed at the center frequency of the IFA. The amplitudes of lines decrease with an increase in the harmonic number of the signal under study. The calculation was performed for the synthesizer's harmonics with $n \leq 20$ and harmonics of the signal under study with $m \leq 4$. Note that, during studies of the $TE_{2,5}$ mode, apart from the signal shown in Fig. 4, weak beats were observed at a synthesizer frequency close to 89 GHz and even weaker beats were observed at frequencies of 83.5 and 95.4 GHz; however, the

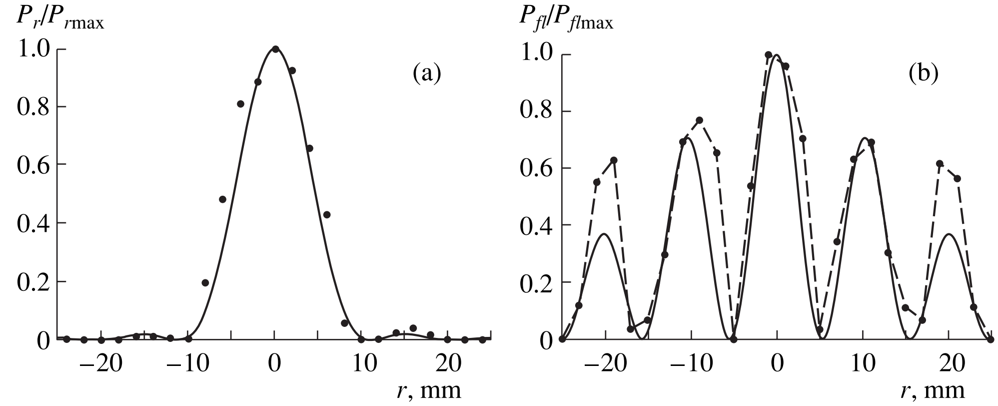

Fig. 6. Distributions of the electric field in the (a) radial and (b) azimuthal components of the $TE_{1,3}$ mode. Dots and solid lines correspond to the experiment and calculation, respectively.

image channels for these signals were not recorded in detail.

Comparing the patterns shown in Fig. 5 to the amplitudes and frequencies of the signals observed in experiments allows a radiation frequency of 111.365 GHz to be easily excluded. The signal under study with the latter frequency (Fig. 5a) would not have resulted in beats at a synthesizer frequency of about 95.4 GHz, and beats near 89 GHz would then have a lower amplitude than that of beats near 83 GHz. In contrast to Fig. 5a, the pattern of beats in Fig. 5b coincides well with the experimental data. This means that, in this experiment, the gyrotron radiation frequency was 222.73 GHz. Note that a power detector received this radiation after passing through a waveguide filter transmitting only frequencies exceeding 157 GHz, thereby additionally providing evidence in favor of the above frequency value.

The radiation from the gyrotron, which also operated on five other modes in the frequency range 115.7–371.1 GHz, was analyzed in a similar manner, and the frequencies corresponding to these modes were determined.

ANALYSIS

The main problem solved in this study was the identification of the gyrotron's operating modes using the technique of precise measurements of the mode's frequencies and their referencing to the values of the operating-magnetic-field induction. The initial referencing to the magnetic field was performed for a mode the high-power oscillation of which was observed in a comparatively wide range of 5.9–6.4 T at an electron-beam current of >0.6 A (Fig. 1). Oscillation occurred at the first cyclotron harmonic; this fact was confirmed by an assessment of the frequency with the use of cutoff waveguide filters. The exact frequency value (115.71 GHz) was determined with the technique considered here.

The comparatively low radiation frequency and a low mode of the resonator corresponding to it allowed a detailed study of the radiation-field distribution over the output-horn aperture to be performed. This distribution (Fig. 6) was obtained during displacement of the detector head with an input rectangular waveguide window of 1.2×2.4 mm along two mutually perpendicular directions running through the center of the gyrotron's output horn, the orientation of the axes of the detector's waveguide window being unchanged. The measurement results correspond well to the calculated radial and azimuthal components of the $TE_{1,3}$ mode. Three measurements, i.e., the values of the resonance magnetic field and the radiation frequency and structure, indicated the excitation of the $TE_{1,3}$ mode resonant with the first cyclotron-frequency harmonic. The difference of the measured radiation frequency from a calculated value of 116.45 GHz means that the diameter of the manufactured resonator differs from the calculated 7-mm value, being as large as nearly 7.04 mm.

After precise referencing to the magnetic field (precise calibration of the magnetic field), it was not difficult to identify the remaining modes from their radiation frequencies.

In line with the calculation, a decrease in the magnetic-field induction allowed excitation of the $TE_{2,5}$ mode at the second cyclotron harmonic, as was confirmed by frequency measurements. Radiation was passed through a corresponding waveguide filter, and the subsequent precise measurement yielded a value of 222.73 GHz, which is close to the calculated oscillation frequency (223.02 GHz) for the $TE_{2,5}$ mode.

When the field induction increased to 6.5 T, a mode was excited at the third harmonic with a radiation frequency higher than 290 GHz in the range of currents 1–2 A. A measured frequency of 371.10 GHz corresponds to the $TE_{3,8}$ mode.

The radiation-power measurements performed and comparison of the device's output characteristics with calculations also allowed the parameters of the electron

Measured and calculated frequencies of the operating (the first three modes) and some parasitic gyrotron modes

Modes	$TE_{1,3}$	$TE_{2,5}$	$TE_{3,8}$	$TE_{1,5}$	$TE_{1,6}$	$TE_{2,3}$
F_{meas}, GHz	115.71	222.73	371.10	201.10	243.57	134.95
F_{cal}, GHz	116.45	223.02	372.56	202.77	245.77	136.0

beam to be refined. The electron beam was shifted from the resonator's axis to a distance of 0.15–0.2 mm, and the spread of the transverse electron velocities in it was close to 60%. Such a beam imperfection resulted in the excitation of several parasitic modes in the ranges of operating magnetic fields and electron currents. In fact, parasitic modes at the first and second cyclotron harmonics were recorded at currents exceeding 1.5–2 A. At $B = 5.3$ T and a current >1.5 A, oscillation at the second cyclotron harmonic was observed. The measured frequency (201.10 GHz) and the resonance-magnetic-field value allowed this mode to be identified as $TE_{1,5}$. Oscillation at the next parasitic mode also occurred at the second cyclotron harmonic at 6.4 T and a frequency of 243.57 GHz, which corresponded to the $TE_{1,6}$ mode.

At $B = 7$–7.2 T and a current >2 A, oscillation of the $TE_{2,3}$ parasitic mode at a frequency of 134.95 GHz was observed at the first cyclotron harmonic. For all modes shown in Fig. 1, the measured frequencies differed from the calculated ones by a few fractions of percent (see the table).

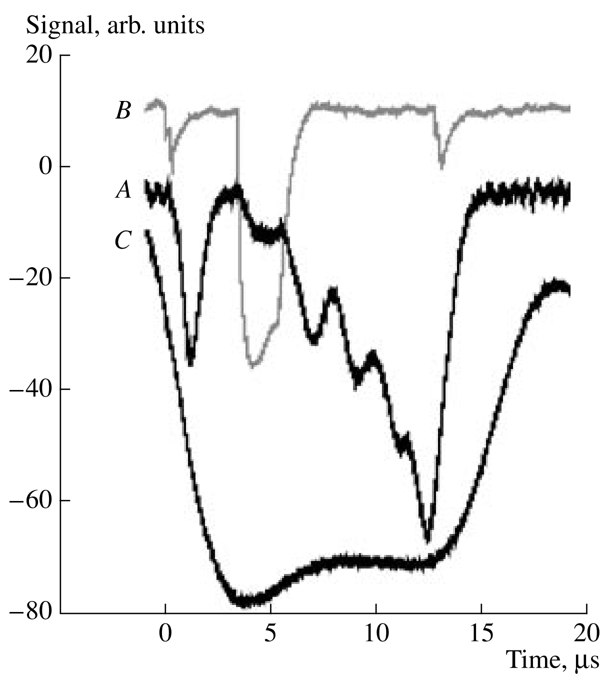

Fig. 7. Quenching of oscillation of the $TE_{2,3}$ mode and transition to another mode during a single radiation pulse, which is indicated by a signal of beats and cannot be noticed from a signal of the power detector. Traces: (*A*) signal from the power detector, (*B*) amplitude of a signal of beats, and (*C*) accelerating voltage.

As was mentioned above, a difference between the measured and calculated frequencies points to a slight difference between the actual and calculated diameters of the resonator. In this case, the frequency is equal to the eigen frequency of the resonator with an accuracy corresponding to the bandwidth of the electronic frequency tuning, which is 0.01–0.1% depending on the mode excited in the resonator.

The technique used to precisely measure the radiation frequency also allowed observation of the oscillation dynamics of various modes within a single radiation pulse. For example, for the $TE_{2,3}$ mode at a frequency of 134.9 GHz in the region of its minimum start current (Fig. 7), oscillation is observed at the top of a voltage pulse; subsequently, during a voltage decrease for 2 μs, this oscillation is quenched. This quenching can be understood from the analysis of beats, while the readings of the detector that indicates the radiation power increase until the voltage pulse terminates. It becomes clear from this that, beginning with the moment of 6 μs, oscillations occur at another mode, namely, at the $TE_{2,6}$ mode with a radiation frequency of 266 GHz excited at the second cyclotron harmonic.

CONCLUSIONS

The possibility of precisely measuring the oscillation frequency of short-pulse signals in the millimeter/submillimeter wavelength range with a large off-duty factor has been demonstrated and allowed to reliably identify the modes excited in a relativistic large-orbit gyrotron operating at the first three harmonics of the cyclotron frequency. It has also been shown that the technique presented allows the oscillation-development dynamics to be investigated within a single pulse. The capabilities of this method make it possible to use it in the analysis of radiation generated by a wide class of short-wavelength oscillators.

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