Measuring the Carrier Frequency of Single Short-Duration MW Radio-Wave Pulses

Boris D. Zaitsev, *Member, IEEE*, Vladimir A. Fedorenko, Alexey V. Ermolenko, and Nikolai I. Sinitsyn, *Member, IEEE*

***Abstract*—A new method for measuring the carrier frequency of single microwave (MW) radio-wave pulse is described, which is based on its transduction to a series of echo pulses using a transversal filter. The analysis of the radio-wave pulses exhibiting constant carrier frequency or frequency modulation is shown to be both theoretically and experimentally feasible with the help of a bulk acoustic-wave delay line. A frequency meter has been developed for single short-duration 2.5–10.5-GHz radio-wave pulses, which was demonstrated to be operative under strong radio-interference conditions.**

***Index Terms*—Bulk acoustic-wave devices, frequency control, frequency measurement, microwave devices, microwave measurements, pulse measurements.**

I. Introduction

AN URGENT problem of current interest is the measurement of the carrier frequency of powerful single short-duration microwave pulses generated by relativistic electron-beam generators [1]–[3]. The available methods based on the use of a system of filters, heterodyne reception, or dispersive delay lines have a number of shortcomings.

The system of filters (a set of cutoff waveguides [4] or of microwave (MW) resonators [5] and acousto-optical spectrum analyzers [6]) permit one to assess only the amplitude spectrum of a signal. As for the phase spectrum, information about it is lost, resulting in the characteristics of frequency-modulated radio-wave pulses which are not measurable. Furthermore, the resonator's system is incapable of measuring the frequency of a radio-wave pulse whose duration is comparable to or less than the time of oscillation transition to a steady state in a separate resonator. Finally, the above frequency meters offer poor noise immunity against the low-frequency impulse radio interference which is attendant on a radio-wave pulse while operating with MW relativistic electron-beam generators [1]–[3].

The exception is provided by the heterodyne method [6] which employs a semiconductor hot-carrier-charge mixer. However, this method is successful only at a high input power (>1 GW).

As for dispersive delay lines, e.g., those on magnetostatic waves (MSW's) [7] and surface acoustic waves (SAW's) [8], they are unsuitable for analyzing signals whose frequency modulation follows a law not being known beforehand. Moreover, the frequency range of delay lines based on SAW's is restricted to 1–2 GHz. The MSW's, having more high value of the velocity than acoustic waves, do not allow a significant delay time.

Hence, a frequency meter for single and rarely recurring short-duration MW radio-wave pulses has to meet a number of specifications. They include a wide enough band and the lack of high quality-factor (Q-factor) elements in the circuit where the output response is formed. These features allow the time of transit processes to be as small as a few MW periods. Moreover, it is desired to delay an output signal for a time sufficient for the impulse radio interference to decay.

This meter unit can find realization on the base of a transversal filter [9]. In this paper, the development of a transversal-filter frequency meter is analyzed, while the results of experimental investigation of such a filter on bulk acoustic waves (BAW's) are described for the microwave band.

II. Theoretical Analysis of Operation of the Frequency Meter for Single MW Radio-Wave Pulses

The transversal filter is a two-port containing a divider, N-channels with different weight coefficient a_n and delay time $T_n = T_0 + \Delta T n$, and a summer [8]. Here, n is the channel number and $\sum_{n=1}^{N} \alpha_n^2 = 1$, T_0 is the delay time, which is common for all the channels, and ΔT is the difference in delay time values for any two adjacent channels. Signal $S_{\rm inp}$ applied to the input of this filter is divided between the channels. Then, the responses from all channels which have different amplitudes and delays are summed by the summer and form a common output signal $S_{\rm out}$.

Let us first consider a monochromatic signal $S_{\rm inp} = A_{\rm inp} \exp(j2\pi ft)$ traveling through the multichannel system. Here, $A_{\rm inp}$, f, and t are the amplitude, frequency, and time, respectively. At the output, we obtain

$$S_{\rm out} = A_{\rm inp} \exp[j2\pi f(T_0 + t)] \sum_{n=1}^{N} \alpha_n \exp(j2\pi f \Delta T n). \quad (1)$$

The gain $K(f)$ for the system under study is as follows:

$$K(f) = S_{\rm out}/S_{\rm inp} = \exp(j2\pi f T_0) \sum_{n=1}^{N} \alpha_n \exp(j2\pi f \Delta T n). \quad (2)$$

It is obvious that the values of α_n are related to $K(f)$ by Fourier transformation. We conclude that by choosing a

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particular number of channels N, as well as α_n and ΔT values, one is able to essentially derive all dependencies $K(f)$. The time of output signal formation after a lapse of time T_0 is determined by a maximum additional delay ΔTN.

When a narrow-band signal is applied to the system, whose spectrum width is many times smaller than the mean f_0 value, and its gain K_0 is measured, we can find f_0 using the known dependence $K = K(f)$. Evidently, to provide a needed measurement accuracy, the above dependence must have a sufficiently steep slope and be unique, while the time of the output signal formation must be much smaller compared to the signal duration.

Moreover, the dependence $K(f)$ must be periodic to find the values of α_n and ΔT with the help of Fourier transformation. This can be artificially achieved in the following manner. Let the function $K(f)$ be of desired shape inside the operating frequency band. Outside this band, it is defined arbitrarily, but so as to be periodic as a whole. Then, this function can be represented in the form of a Fourier series by temporal harmonics ΔTn, namely,

$$K(f) = \sum_{n=1}^{\infty} \alpha_n \exp\left(j2\pi f \Delta Tn\right) \tag{3}$$

where $\alpha_n = (1/\Delta F) \int_{-\infty}^{\infty} K(f) \exp\left(j2\pi f \Delta Tn\right) df$, $\Delta T = 1/\Delta F$, and ΔF is the function $K(f)$ period.

We think of $K(f)$ in the operating frequency band such that a specified relative measurement error for the gain $B = \Delta K/K$ produces the required relative error of frequency measurement $A = \Delta f/f$. The $K(f)$ may be conceived in the form of a piecewise-exponential periodic function [9] as shown in (4), at the bottom of this page, where m is an integer and f_1 is an arbitrary coefficient.

When passing to real measuring systems with a finite number of channels, the infinite series (3) must be truncated as follows:

$$^{N}K(f) = \alpha_0/2 + \sum_{n=1}^{N} \alpha_n \cos(2\pi f \Delta Tn). \tag{5}$$

Here, we use expansion by cosines since the function $K(f)$ is even. Calculations have shown [9] that the frequency response $K(f)$ becomes slightly pulsating, unlike the specified $K(f)$. It should be noted that increasing the number of channels yields a smaller pulsation amplitude. As the period ΔF is raised, the dynamic range of $^{N}K(f)$ variation is wider and the pulsation amplitude is greater.

Let us make some estimates. It follows from the calculations that to ensure a relative measurement error, e.g., of $A = 0.1\%$ in a frequency band of 2.5 GHz at $B = 10\%$, it is sufficient to employ a transversal filter composed of 40 channels whose gain $K(f)$ has a period $\Delta F = 20$ GHz. In this case, the time of the output signal formation after a lapse of time T_0 is smaller than 2 ns and the dynamic range lies within 100 dB. However, a MW receiver with such a dynamic range is difficult to realize in practice, especially under the conditions of strong impulse radio interference.

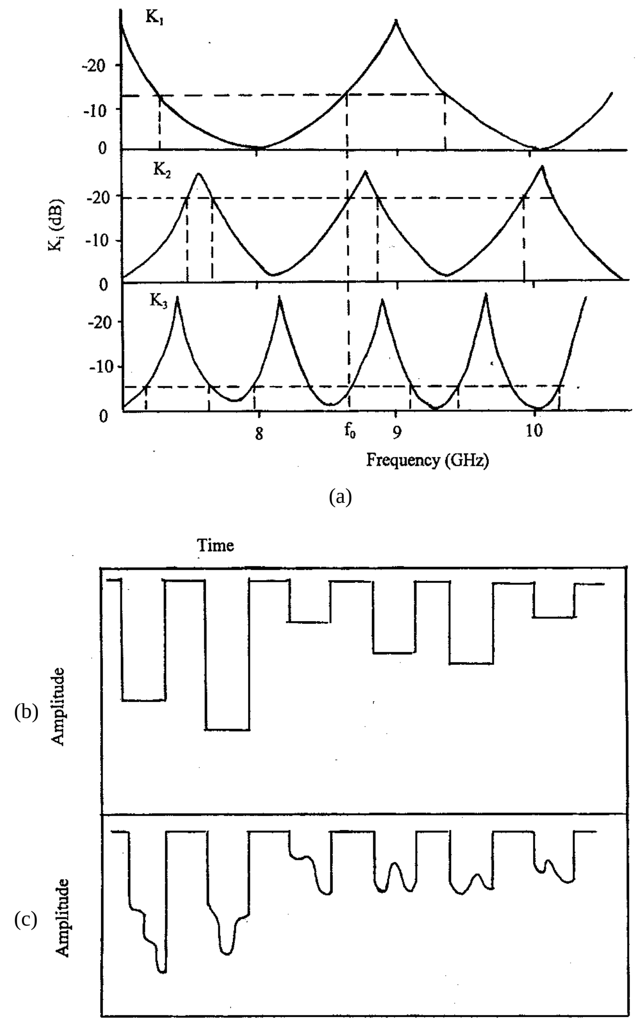

Fig. 1. Characteristics of the transversal filter. (a) Amplitude-frequency characteristics under multiple reflection conditions. (b) Series of delayed echo pulses for the input signal with a constant carrier frequency. (c) Series of delayed echo pulses for the frequency-modulated input signal.

The dynamic range of $^{N}K(f)$ variation without adversely affecting the measurement accuracy can be achieved by using a multichannel system that operates under the multiple reflection conditions. As an example, in the case of imperfect matching of the channels to the summer, the single signal under study is transduced into a series of nonoverlapping delayed echo-radio-wave pulses as the duration of the input signal $T_{\mathrm{inp}} < T_0$. Every ith echo pulse is characterized by an individual amplitude-frequency characteristic $^{N}K_i(f)$. Our calculations have shown the frequency response is to be varied within 20–25 dB to obtain the above parameters in this case [see Fig. 1(a)]. The individual dependence $^{N}K_i(f)$ may have a nonmonotonic behavior, but in the aggregate these dependencies must uniquely define the frequency. The required number of channels is lowered to 20–30 by operating the

$$K(f) = \begin{cases} [(f - m\Delta F)/f_1]^{B/A}, & f \in [m\Delta F;\ (m+1/2)\,\Delta F] \\ \{[(m+1)\Delta F - f]/f_1\}^{B/A}, & f \in [(m+1/2)\,\Delta F;\ (m+1)F] \end{cases} \tag{4}$$

transversal filter under such conditions. The time of the output response formation is thereby decreased to 1–1.5 ns; this is by an order less than for resonance systems providing the same accuracy of measurement.

The evaluations mentioned above were made under the assumption of a full decoupling between the channels. However, in real systems it is impossible to entirely eliminate mutual coupling between the channels, which implies a certain variation of the frequency responses ${}^{N}K_i(f)$. The calculated results taking into account incomplete decoupling demonstrate the decrease of the frequency band that ensures the measurement within a necessary accuracy while increasing the coupling magnitude. But if the coefficient of coupling between the channels and the summer is less than -15 dB, the variation of the frequency band and the measurement errors are negligible.

III. Measurement Technique for the Short-Duration Radio-Wave Pulse Frequency

If a narrow-band frequency-unmodulated signal with carrier frequency f_0 is applied to the input of the above system under multiple reflection, a series of delayed radio-wave pulses is produced at its output whose amplitudes are determined by the corresponding values of $K_i(f_0)$ at point f_0 [see Fig. 1(b)]. We drop a superscript N that is relevant to the number of channels in the system (and do not use it below). It is apparent that the observed echo pulses will exhibit different amplitudes; however, they will be of the same shape. Measuring the gain K_i for each echo pulse in terms of the known dependencies $K_i(f)$, one may unambiguously determine the frequency f_0 as the only value of argument f that is common for all i-indexes [see Fig. 1(a)]. Again, with such an approach, the quantity sought is measured M times, where M is the number of echo pulses. Therefore, the total error of frequency determination decreases by a factor of $\sim M^{1/2}$ with respect to a mean quadratic error.

Now, we apply a frequency modulated radio-wave pulse to the input of the system. Since the function $K_i(f)$ depends on the i-number, a series of delayed radio-wave pulses will be observed at the output which have a varying envelope shape [see Fig. 1(c)]. The distortion of the pulse shape will obviously be stronger, the greater the frequency deviation. This may be a qualitative criterion for the frequency modulation.

Thus, the use of the wide-band multichannel system with multiple reflection and delay T_i enables one not only to perform transduction of a single MW signal to a series of radio-wave pulses, but also to be informed on the change of instantaneous frequency inside the radio-wave pulse. This information is available in the form of additional amplitude modulation that differs for each echo pulse relative to the envelope of the input signal $A_{\rm inp}(t)$. To extract a knowledge of the frequency modulation law from the shape of the envelope $A_i(t)$, we partition all the echo pulses and the input signal into portions of the same duration Δt being equal in number, for which the instantaneous frequency and amplitude may be assumed to be constant. For each of these discretization intervals, we define the gain as follows:

$$K_{ij} = A_i(\Delta t_j)/A_{\rm inp}(\Delta t_j) \tag{6}$$

where $A_i(\Delta t_j)$ and $A_{\rm inp}(\Delta t_j)$ are the amplitudes of the ith echo pulse and the input signal within jth descritization interval, respectively. Then comparing the secured values of gain K_{ij} to the corresponding responses $K_i(f)$ [see Fig. 1(a)], we determine, using the above technique, the frequencies for every descritization interval. If Δf is sufficiently small, the distribution of instantaneous frequency inside the radio-wave pulse is obtained.

One is able to automatically accomplish a similar procedure of transition from analog-to-digital form with the help of a digital storage oscilloscope compatible with a computer that has dependencies $K_i(f)$ in its memory. By this means, our method permits the measurement of both the mean frequency value of narrow-band signals and the distribution of the instantaneous radio-wave pulse frequency.

IV. Realization of the Method Developed

The approach was realized for the microwave band by using, as a transversal filter, a wide-band ($\Delta f/f \sim 30\%$) acoustic delay line (ADL) on BAW's that operates under the conditions of multiple reflection. The ADL waveguides were neither acoustically uniform in attenuation nor in velocity; their reflecting edges were slightly fringe counted and near parallel (the edges are parallel only to within 15–20$''$). Such delay line can be represented as in-parallel-connected acoustic channels with different weight coefficients and delay times, i.e., as a transversal filter. The function of an oscillation divider and of summer was performed by a piezoelectric transducer for the ADL operating in the "reflection" mode or two transducers for the "transit" mode. The multiple acoustic-signal reflections by imperfectly flat reflecting edges of the waveguide, its static inhomogeneity, and diffraction divergency resulted in a strong distortion of the original flat phase front [10] (at the BAW length as long as 1–2 μm) and a great echo-pulse amplitude dependence on frequency. Fig. 2 presents the typical echo-pulse oscillograms at the output of an ADL operating in the 3-cm radio-wavelength band for various carrier frequencies. One may conclude that the envelope of the first 4–6 echo pulses is an exact and unique frequency portrait of the input signal. This is confirmed in Fig. 2(c) where two echo-pulse series are indicated, which are superimposed and differ in frequency by 0.5%. The amplitudes of echo pulses are seen to substantially differ.

Since it is impracticable to calculate the amplitude-frequency characteristics for the ADL, due to the lack of information on the nonhomogeneous properties of waveguides, the ADL's were calibrated by experimentation. To do this, the MW radio-wave pulses were applied to the ADL's input under recurring conditions at a high pulse-period-to-pulse-duration ratio from a standard generator. The frequency dependencies of the power gain were measured for every echo pulse. As an echo-pulse receiver, the amplifying circuit of traveling-wave tubes, detector, and oscillograph were used. The above dependencies normalized to the gain of the first echo pulse, i.e., relation P_i/P_1 were measured where P_i is the power of the ith pulse. These dependencies, called calibration curves, are shown in Fig. 3 for the typical 3-cm-band ADL.

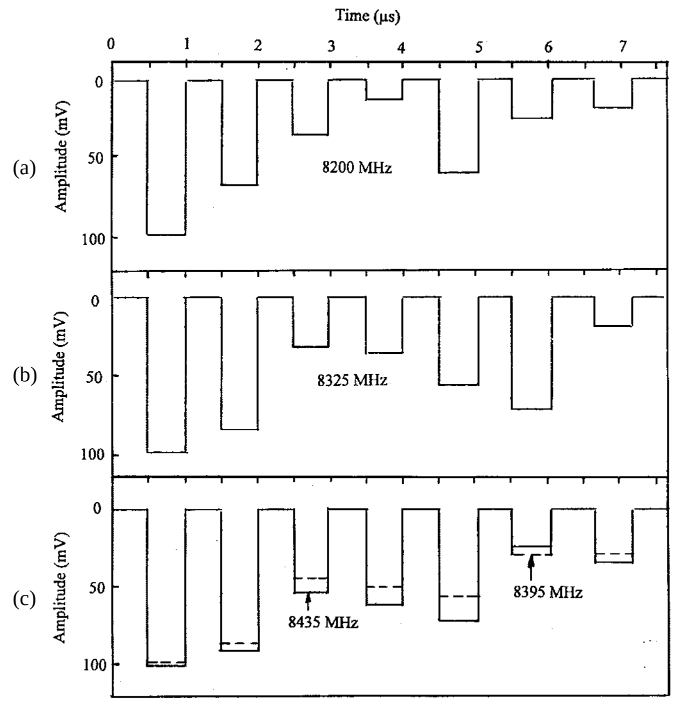

Fig. 2. A series of delayed echo pulses at the output of a typical 3-cm-band ADL for various frequencies. (a) $f = 8200$ MHz. (b) $f = 8325$ MHz. (c) $f = 8435$ and 8395 MHz.

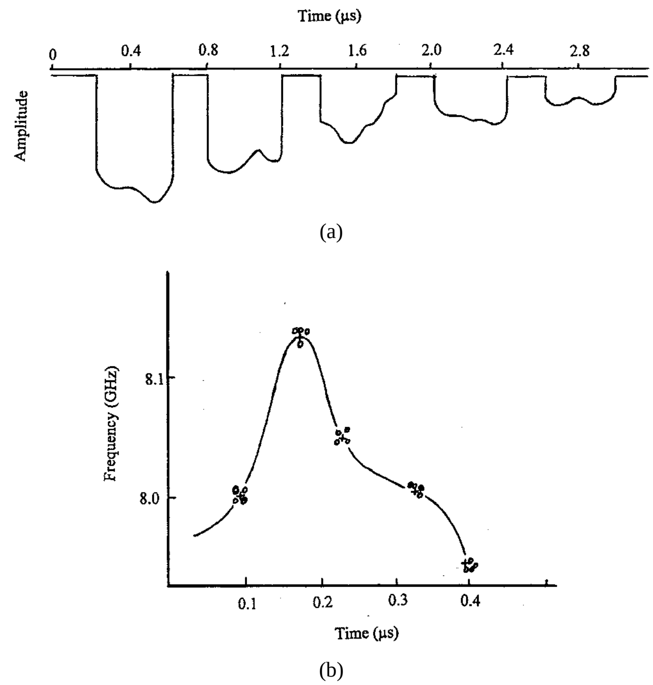

Fig. 4. Measuring results for the instantaneous frequency of an input radio-wave pulse with frequency modulation. (a) Oscillogram of delayed echo pulses. (b) Distribution of instantaneous frequency inside the radio-wave pulse measured by means of the standard wave meter (+) and the ADL (∘).

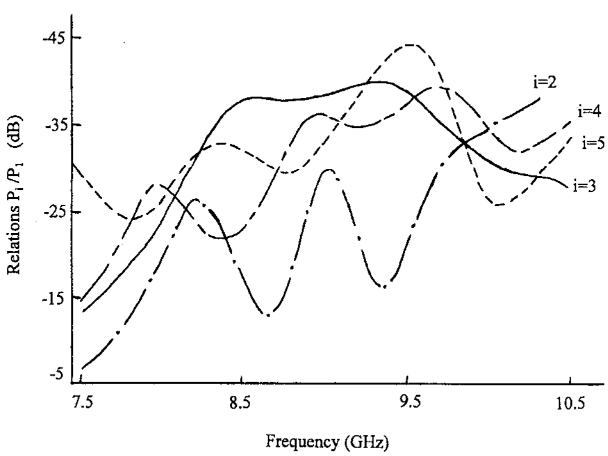

Fig. 3. Frequency dependencies of relations P_i/P_1 for the typical 3-cm-band ADL for different echo pulses.

Any series fraction consisting of four to six echo pulses can obviously be adopted for measurements. For example, under the conditions of impulse interference arising at the scan origin, one is able to carry out the measurements on the third or fourth echo pulse that exhibits a great delay. In this situation, it is more convenient to normalize the calibration curves to the power of the third or fourth echo pulse, respectively. To lessen the BAW attenuation loss in the waveguide, the ADL may be allowed to cool to the boiling point of liquid nitrogen.

As mentioned above, an additional amplitude modulation is observed for every echo pulse with respect to the input signal envelope when applying a frequency-modulated radio-wave pulse to the input of the transversal filter. Fig. 4(a) depicts the oscillogram of echo pulses from an input of 3-cm-band radio-wave pulse of rectangular shape whose frequency modulation follows the nonmonotonic law. This oscillogram was obtained using the ADL with the calibration curves indicated in Fig. 3. It is seen that the delayed pulses are shaped differently, and this qualitatively points to the frequency modulation. Using this analysis technique for frequency-modulated radio-wave pulses, the distribution of instantaneous frequency inside the pulse was defined, which is shown in Fig. 4(b). At this point, the measurement results are shown, which were obtained by means of the standard resonance wave meter with a measuring error of about ±0.05%. From this figure, we notice that the error of the instantaneous frequency determination is not in excess of ±0.3%.

V. Measurement of Operating Conditions for Relativistic MW Generators

Relying on investigation performed in the recurring mode, a measuring device has been developed and fabricated to determine the responses of single short-duration MW radio-wave pulses under the conditions of strong-impulse radio interference. This device consists of wide-band BAW ADL's, transistor amplifiers, and detectors operating in different sub-bands and, as combined, covering an operating frequency band as wide as 2.5–10.5 GHz. The errors of frequency measurement within the 2.5–7.5- and 7.5–10.5-GHz bands were smaller than ±1% and ±0.25%, respectively.

By application of this device, various operating conditions were examined for relativistic electron-beam MW generators including carsinotron, magnetron, and others. In Fig. 5, the

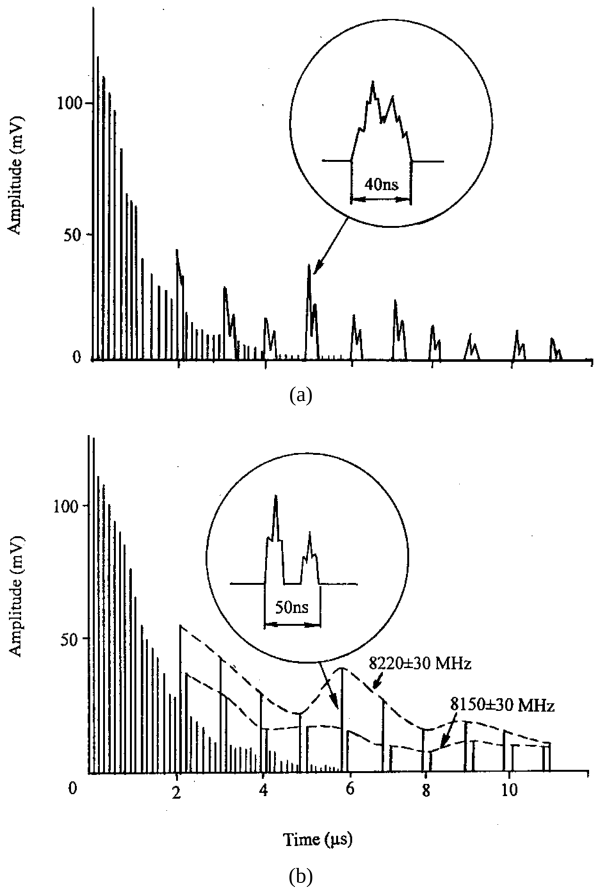

Fig. 5. Oscillograms of delayed signals at the output of the ADL for radio-wave pulses generated by a relativistic MW generator. (a) The input signal has a two peak envelope with the constant carrier frequency. (b) The input signal is composed of two pulses exhibiting different carrier frequency.

measurement results displayed are most representative of the potentials of the frequency meter developed. Fig. 5(a) shows the echo-pulse oscillogram for a typical two-peak envelope of the instantaneous power of a MW radio-wave pulse with the 30–40-ns duration. The shape of the echo pulse seems to be independent of its number. This means the absence of frequency modulation, i.e., the carrier frequency is constant along the pulse in spite of its two-peak behavior.

One of the most interesting operating conditions for relativistic electron-beam devices is generation of single series of two or three and more closely spaced short-duration MW radio-wave pulses. Unlike the methods mentioned in Section I, our method of keeping the information about phase spectrum allows us to measure the distribution of the carrier frequency for such pulses. Fig. 5(b) is a typical oscillogram of echo pulses corresponding to a double radio-wave pulse from the output of the relativistic magnetron. It is seen that amplitude envelopes for two echo-pulse series diverge due to different frequencies. These frequencies proved to be 8150 and 8220 MHz, i.e., the difference constitutes 70 MHz for a measurement error of ± 30 MHz. A low-frequency impulse radio interference of 1.5-μs duration is also visible at the scan origin of Fig. 5 that hindered the reception of useful signal. Hence, the measurements were carried out on the echo pulses with the numbers >4.

VI. Conclusion

In summary, it may be noted that the proposed method for measuring the carrier frequency of single MW radio-wave pulses can be realized not only on the ADL's, but also on coaxial, strip, or waveguide electromagnetic-wave transmission lines that operate under multiple reflection conditions.

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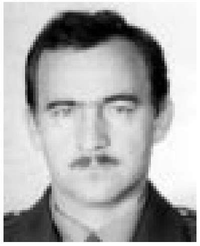

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