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THE SAMPLER OF THE VIDEOPULSE GEORADAR

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The given work is devoted to the theoretical analysis of noise characteristics and distortions of the sampler with the bandwidth 1 GHz and sensitivity 1 mV made according to the bridge diode circuit. The results of test measurements of the sampler working setup are given in the work.

1. Introduction

The modern approach to the practical solution of problems of videopulse subsurface sounding requires improvement of the technique of receiving and processing the sounding signals of nano- and subnanosecond duration. The most important problem is the problem of precise determination of time and amplitude parameters of the wideband sounding signal. The measurement accuracy of these characteristics is one of the most important factors influencing the operation efficiency of the whole radar system.

For precise determination of time-amplitude characteristics of videopulse signals of nanosecond duration radiated by georadars it is necessary to use ultrawideband samplers with the bandwidth 1 GHz providing conversion of sounding signals with the rise (decay) time of the order of 1 ns.

Generally high-speed samplers are made according to the classical circuit without feedback [1] and include the following functional parts: the switch circuit (sampling gate), strobe generator (sampling gate control section), stretcher (storage capacitor) with the buffer repeater and compensating and amplifying circuits.

At present samplers with high frequency transistors as elements of the switch circuit are widely used in radar equipment. But such circuits do not satisfy requirements to up-to-date videopulse georadars both in bandwidth and dynamic [1].

As it is know from [1-5] it is possible to extend the bandwidth and simultaneously the sampler dynamic range by using the sampling gate with high-speed diodes.

From the known sampling gate circuits [4, 6-9] such as: one-diode circuits, balanced two-diode circuits, balanced bridge circuits and transistor circuits in the sampler with the bandwidth 1 GHz it is more preferable to use the sampling gate bridge circuit. Its merits are the high input resistance eliminating the influence on a previous cascade, small signal distortions during conversion, the high sensitivity and stability. The circuit demerit is the complexity of identical diode pairs matching. However, diode bridges are produced in lots at present and it simplifies the problem.

The following strobe generator circuits are well-known: circuits with tunnel diodes, with the Gunn diodes, with charge-storage diodes with series and parallel connection, and also avalanche transistor circuits [1, 10-14]. From the specified circuits the circuit with parallel-connected charge-storage diodes is the most suitable as a strobe generator for the sampler with the balanced bridge circuit of the sampling gate. The merit of this circuit is the simplicity of the short voltage step forming and power-supply noise compensation due to the specific connection of the output transformer.

The buffer repeater is the most suitable as a stretcher for the sampler. The given repeater exerts the smallest influence on signal stretching and is well matched with following cascades.

The results of development of the high-speed sampler with the sampling gate built according to the bridge circuit, the strobe generator with series-connected charge-storage diodes and voltage stretcher with the buffer repeater.

2. Noise and Stray Parameters of the Sampling Gate

The measuring system sensitivity and boundary bandwidth are determined by the internal noise level. So, first of all, it is necessary to determine the noise level at the sampler output. The sampler circuit is shown in Fig. 1.

The energy spectrum of noise sources is described by the expression [6]

$$w = \frac{A_f I_{rev}^2}{\omega} R_{eq} + 2qI_{rev}R_{eq} + 4kTR_{eq}\,, \quad (1)$$

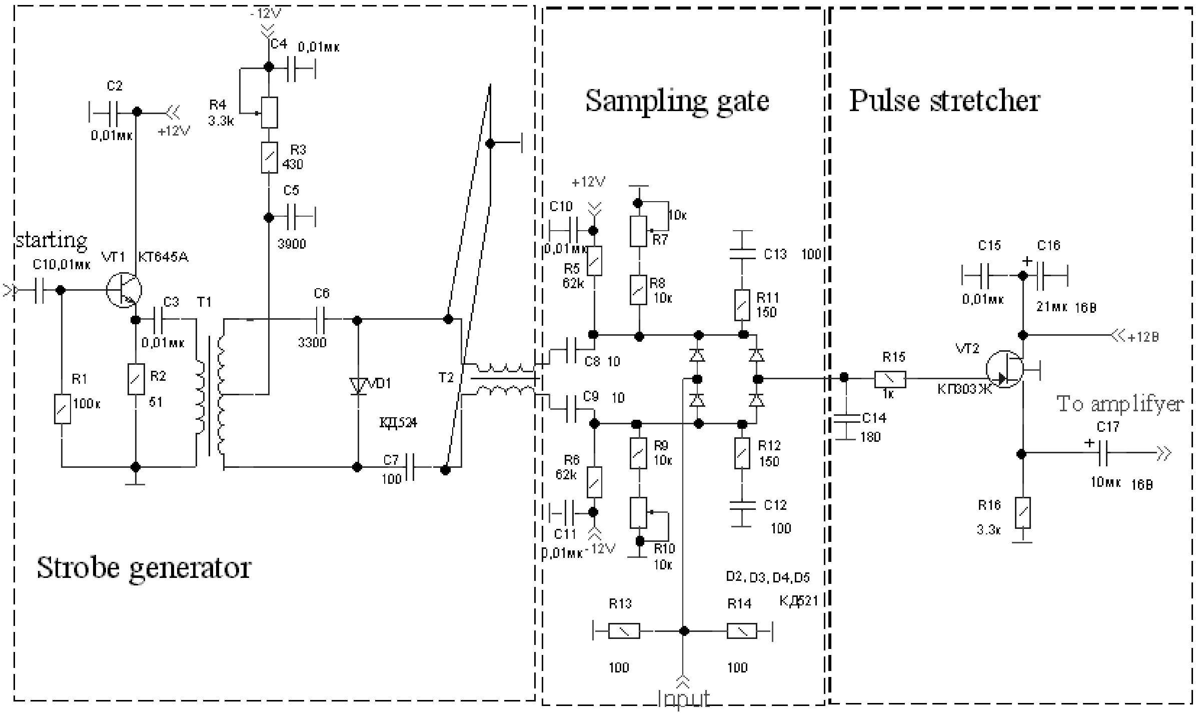


Fig. 1. *The sampler circuit*

where $R_{eq} = \dfrac{R_\partial R_{in}}{R_\partial + R_{in}}$, R_∂ is the differential resistance of the non-conducting diode, R_{in} is the input resistance of the buffer amplifier, A_f is the flicker noise factor, q is the elementary charge, k is the Boltzmann constant, ω is the frequency, I_{rev} is the diode reverse current, T is the equivalent noise temperature. At that the noise-voltage dispersion is:

$$\sigma_u^2 = \frac{A_f I_{rev}^2}{\pi} \ln\left(1 + \frac{\Delta\omega}{\omega_1}\right) R_{eq}^2 + 2qI_{rev}R_{eq}^2\Delta\omega + 4kTR_{eq}^2\Delta\omega, \qquad (2)$$

where $\Delta\omega$ is the frequency band, in which the noise is calculated, ω_1 is the lower bound of the bandwidth.

In the second members of the formulas (1) and (2) the first term describes the diode flicker noise, the second one – the shot noise, and the last one – the thermal resistance noise. Due to the fact that the circuit with balanced diode inclusion is used in the sampler the thermal noise (30 μV), noise of the sampling gate input load and also charge-storage diode noise contribute in a smaller way than the noise of the sampling gate diodes. Therefore, the shot and flicker noise of diodes is the most essential for the bridge circuit. Their amplitude at the sampler output amounts to 340 μV. Consequently, the resultant noise level of the sampler doesn't exceed 341 μV.

The waveform transfer accuracy by the sampler is determined by the level of distortions appearing due to the influence of the stray inductive and capacitive diode parameters. These parameters appear in the equations (3) and (4) describing the time conversion of a signal in the following way:

$$\begin{aligned} &L_1C_1\frac{d^2u}{dt^2} + R_1C_1\frac{du}{dt} + u = u_{sp}(t) - E \\ &\quad\text{for}\quad -E \le u_{sp}(t) - E < 0; \\ &L_1C_1\frac{d^2u}{dt^2} + \left(R_1C_1 + L_1\frac{dF}{du}\right)\frac{du}{dt} + u + \\ &\quad + R_1F(u) = u_{sp}(t) - E \\ &\quad\text{for}\quad u_{sp}(t) - E \ge 0; \end{aligned} \qquad (3)$$

$$\begin{aligned} &L_2C_2\frac{d^2v}{dt^2} + R_2C_2\frac{dv}{dt} + u = u_s(\Theta, t) \\ &\quad\text{for}\quad t < t_1 \\ &L_2C_2\frac{d^2v}{dt^2} + (R_2C_2 + L_2g(t))\frac{dv}{dt} + \\ &\quad + v\left[1 + R_2g(t) - L_2\frac{dg(t)}{dt}\right] = u_s(\Theta, t) \\ &\quad\text{for}\quad t_1 \le t \le t_2 \end{aligned} \qquad (4)$$

where $F(u)$ is the equation of voltage-current characteristic of series-connected diode junctions, $L_1 = L_{SG} + L_D$, L_{SG} is the inductance of the strobe generator output, L_D is the inductance of the sampling gate diode leads, $R_1 = R_{SG} + R_B$, R_{SG} is the strobe generator resistance, R_B is the diode base resistance, C_1 is the diode capacitance including the average junction capacitance C_D, $u_{sp}(t)$ is the time dependence of the strobe pulse voltage, E is the cutoff voltage of the sampling gate diodes, t_1, t_2 is time of diode opening and closing, $u_s(\Theta,t)$ is the expression describing the signal in the coordinate system, in which the time coordinate origin coincides with the strobe pulse arrival time [5], $g(t) = \frac{dF(u)}{du}$ is the time dependence of the diode differential conductance, where u is the solution to the equation (3), $L_2 = L_S + L_D$, L_S is the inductance of the signal generator output, $R_2 = R_S + R_B$, and R_S is the signal generator resistance, for the bridge circuit of the sampling gate $C_2 = C_1$.

The converted signal amplitude at the time interval Θ is calculated by the formula:

$$P(\Theta) = \frac{1}{C_H}\int_{t_1}^{t_2} i(\Theta,t)\,dt\,. \qquad (5)$$

Integration is performed in the time interval $[t_1,t_2]$, when the bridge diodes are conducting. The charge current of the storage capacitor C_H composed of the current in the sampling gate diodes and current arising owing to the signal passage through the diode junction capacitance is described by the expression:

$$i(\Theta,t) = g(t)v(\Theta,t) + C_2\frac{dv(\Theta,t)}{dt}\,. \qquad (6)$$

If to transform the expression (5) taking into account (6) we will obtain:

$$P(\Theta) = Ucon + U_C \qquad (7)$$

where $Ucon = \frac{1}{C_H}\int_{t_1}^{t_2} g(t)v(\Theta,t)\,dt$ is conditioned by the diode conduction, and $U_C = \frac{1}{C_H}\int_{t_1}^{t_2} C_2\frac{dv(\Theta,t)}{dt}dt$ is conditioned by the signal passage through the junction capacitance.

As it follows from (7) the conversion is a sum of two terms. The first term is $Ucon$ conditioned by the diode conduction. The second one is U_C conditioned by the signal passage through the junction capacitance of the sampling gate diodes. It is U_C that is the cause of the waveform distortion during conversion because the time dependence of the first term repeats the time dependence of the converted signal, and the second term depends on time as the time derivative of the applied signal.

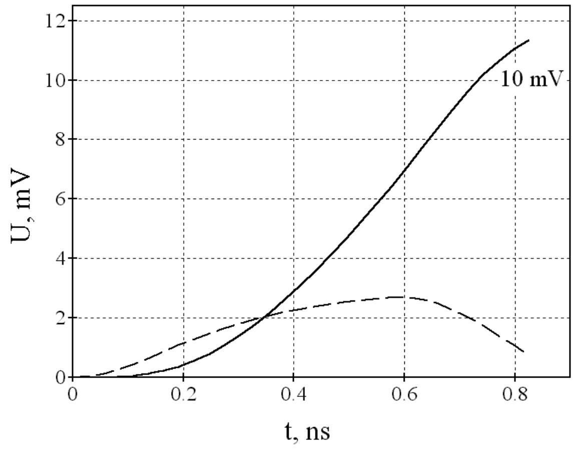


Fig. 2. *The converted voltage step with the amplitude 10 mV; the dashed line shows a signal part passed through the diode capacitance*

Fig. 2 shows the time dependence of each component (7) in case that the input signal is the voltage step with the amplitude 10 mV. In this case the converted signal is a transient response of the sampler $U(t) = P(\Theta)$ [6], which determines the sampler speed and distortions of the converted signal. The sampler speed is characterized by the rise time of the transient response, which is 0.5 ns in the given case and that indicates the possibility of signal conversion, which rise (decay) time is more than 0.5 ns. It is enough to convert georadar signals, the rise (decay) time of which has a duration of the order of 1 ns.

To estimate distortions by the transient response is possible by analyzing the contribution of $Ucon$ and U_C. It is clearly seen from the figure that the peak amplitude of the converted signal component conditioned by the signal passage through the junction capacitance of the sampling gate diodes is at the point in time 0.6 ns and reaches about a half of the converted signal amplitude at this time.

After charging the junction capacitances of the sampling gate diodes the charge current of these capacitances drops practically to zero. It happens about 1 ns after the signal arrival. Later on the diode current is conditioned only by the diode conduction current component. So the waveform distortions during conversion are almost absent.

Fig. 3 shows the time dependence of the ratio $U_C/Ucon$. This dependence characterizes waveform distortions during conversion. The higher the ratio $U_C/Ucon$ the bigger the capacitive current contribution and the more significant the distortions.

As it is seen from the figure when applying the voltage step to the sampler input the ratio $U_C/Ucon$

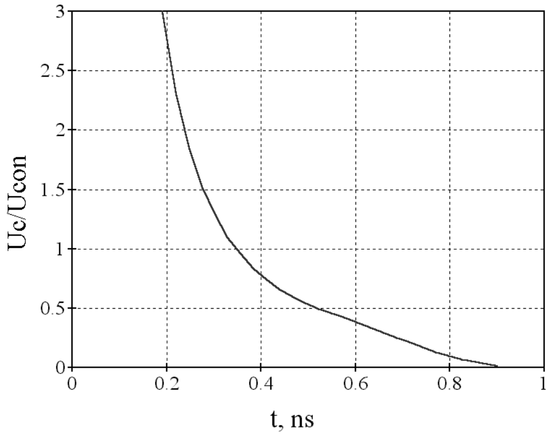


Fig. 3. *Dependence of the ratio $U_C\,/\,Ucon$ on time*

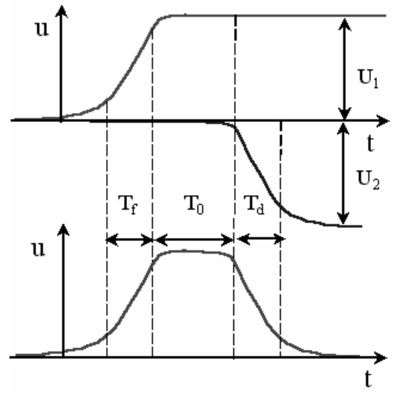


Fig. 4. *The strobe pulse forming in the short-circuited line*

decreases rapidly and it is equal practically to zero already at 0.9 ns. So waveform distortions during conversion are observed in the time interval from 0 to 0.9 ns. Later on the distortions are negligible.

It is possible to shorten the time interval, where distortions take place, by using diodes with lower junction capacitance and also applying "servo" feed-backs and enclosing by them the sampling gate and buffer amplifier [1]. However, as it is seen from Fig. 3, 1 ns after the signal arrival the contribution of the junction capacitance is small. It means that the influence of the diode junction capacitance can be ignored for signals, which spectrum occupies the bandwidth less than 1 GHz.

Thus, these calculations indicate the possibility of creating the sampler, at which output the noise level will be less than 1 mV and the conversion error (taking into account the influence of stray parameters of the sampling gate) at the bandwidth boundary will be no more than $0{,}2u \pm 1\ mV$.

3. The Sampler

It is necessary for signal conversion with the cutoff frequency in the spectrum 1 GHz that the strobe pulse duration at the level when the sampling gate diodes become conducting will be no more than 0.25 ns [15]. To obtain these parameters we should select carefully the operating mode of the strobe generator and set an appropriate voltage shift of the bridge diodes.

3.1. An Optimum Operation Mode of the Strobe Pulse Generator

The strobe generator operates in the following way. The starting pulse with rise time of the order of 3 ns and the amplitude 10 V is applied to the input of the matching emitter repeater with the high-frequency transistor VT1. From its output pulses comes through the transformer to the diode peaker. The diode КД524Б operating in the charge storage mode is used in the diode peaker circuit as an active element. Characteristics of КД524Б satisfy completely basic requirements to the strobe generator diodes. This diode has the low stray inductance and capacitance and also the low direct resistance what permits to form the current step of nanosecond duration.

A strobe pulse is formed by the short-circuited line [6]. A part of the voltage step U_1 (Fig. 4) passes through the balanced transformer and forms the pulse leading edge. Another part U_2 passes through the short-circuited line and after reflection it forms the pulse droop. So, the short pulse is formed after passing through the long line.

To received a pulse with duration $T_f + T_0 + T_d$, at the shaper output it is necessary that $T_f + T_0 = 2L/v_u$, where v_u is the electromagnetic wave velocity in the line, and L is the length of the short-circuited line. For $T_f = 0.25$ ns, $T_0 = 0$ ns, $T_d = 0.25$ ns, $v_u = c/\sqrt{\varepsilon}$, and for teflon $\sqrt{\varepsilon} = 1{,}5$ we obtain $L = 2.5$ cm.

At the current step the charge-storage diode has the low resistance [8, 11], and is badly matched with the high-resistance load being the diode sampling gate in this case.

The balanced broad-band transformer T2 (Fig. 1) with the input resistance 50 Ohms and output resistance 20 Ohms was used to match resistances of the strobe generator and sampling gate in the investigated sampler. Besides the sampling gate diodes with the lowest differential resistance were selected. In the given case we succeeded in selecting a set of diodes with a differential resistance of the order of 20 Ohms.The measurements show that the amplitude of strobe pulses decreases with their duration. It is conditioned on the one hand by attenuation in the balanced line and on the other hand by the arrival time of the reflected signal U_2. On condition that

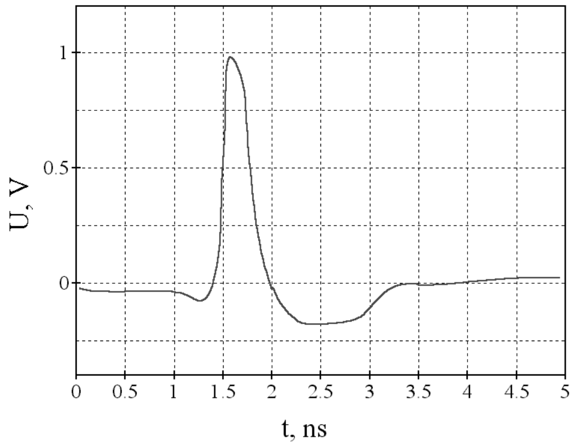


Fig. 5. *The strobe pulse oscillogram with duration 0.25 ns, at the level* $0.5\ U_{\max}$

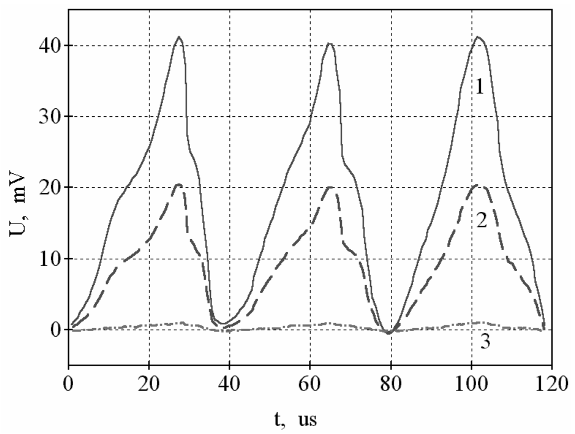


Fig. 6. *Distortions:*
1 – at complete bridge unbalancing;
2 – at diode selection;
3 – at the cutoff voltage tuning to 0.3 V

$T_0 = 0$, the sooner the reflected signal arrives, the sooner U_1 combines with U_2. Therefore an input pulse with the amplitude 10 V and duration 1 μs is needed to form a strobe pulse with the amplitude 1 V and duration 0.25 ns at the level 0.5 $U_{\max}$ (Fig. 5).

The obtained pulse satisfies completely the requirements to strobe pulses of the georadar sampler, both in amplitude and duration.

3.2. Sampling Gate. Tuning and Testing.

The diodes D2-D5 of the КД514А type with the total capacitance of each diode less than 0.9 pF were used in the sampler made according to the balanced bridge circuit. The diodes were selected in pairs in resistance. The working point shift in the diode characteristic is set by controlling the trimming resistors R7 and R10 of the voltage divider. The shift value determines the sampling time that in its turn determines the sampler working bandwidth.

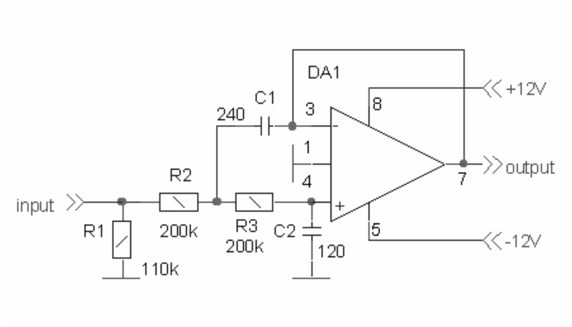


Fig. 7. *The afterfilter circuit*

Failing a signal at the sampling gate input the diode bridge is balanced and the charge value of the storage capacitance doesn't change. At applying the investigated signal to the sampler input the bridge becomes unbalanced, and the capacitance C14 is charged by the diode difference current proportional to the signal amplitude at the input. When the strobe pulse stops acting the capacitance C14 is discharged through the preamplifier input resistance.

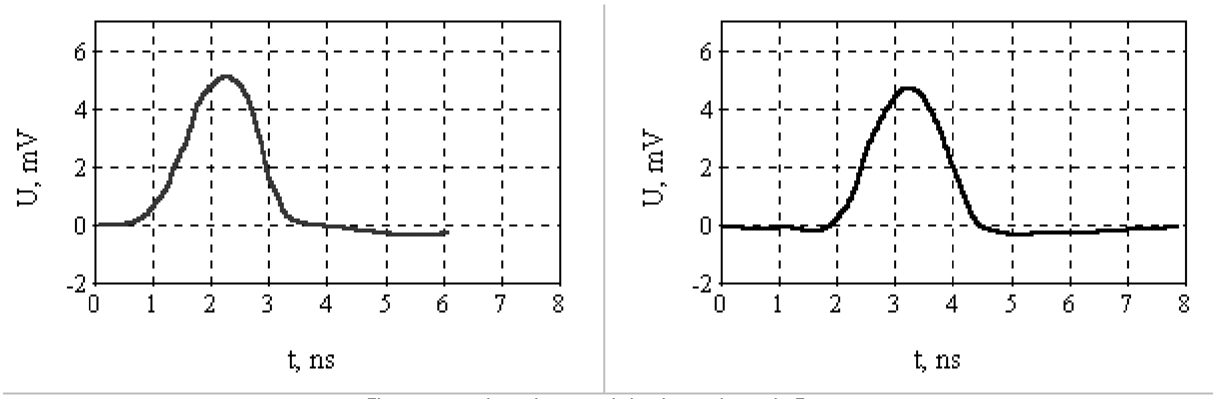
The sequence of R11, C13 and R12, C12 imitates the sampling gate load at closed bridge diodes. The voltage in them is applied to the buffer amplifier input in the antiphase with the stray signal of the direct leakage through diode capacitances. Thus, the undesirable distortions are compensated.

In the sampling gate bridge circuit the distortions during signal conversion are caused both by stray parameters of the sampling gate diodes, such as: junction capacitances, and by the bridge unbalance. As a result of their "complex action" the sawtooth voltage arises at the sampler output Fig. 6.

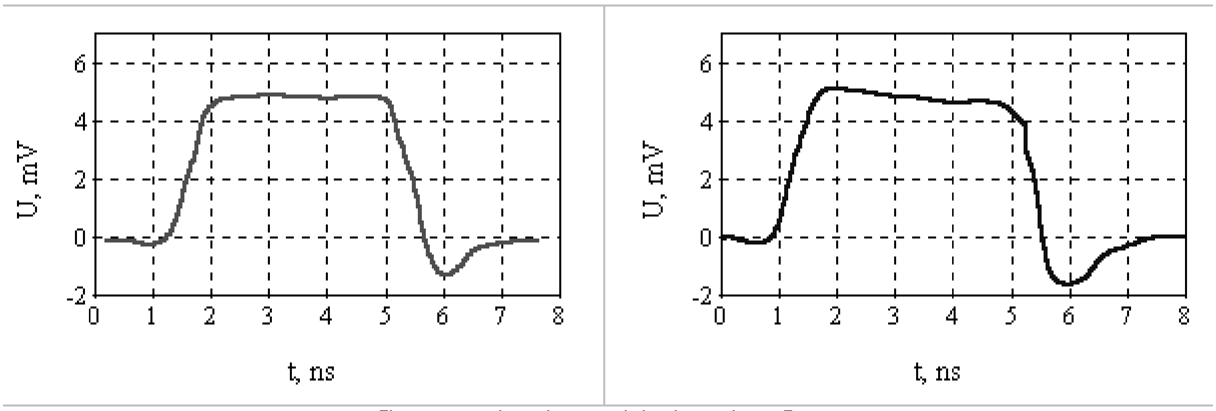
In order to eliminate this sawtooth voltage we should select carefully the sampling gate diodes trying for the identity of their parameters and tune the cutoff bridge voltage. In that way it is possible to decrease the sawtooth voltage amplitude down to 1 mV.

In the given sampler the stray sawtooth voltage period is 40 μs (the lower frequency limit in the spectrum is 25 kHz). As the converted signal spectrum is from 0 to 20 kHz it became possible to filter the signal. For that it is necessary to use the compensating filter of low frequencies (Fig. 7).

The compensating filter is made with the operational amplifier КР140УД8А. The filter boundary frequency is determined by the sequences R2, C1 and R1, R2, C2. The application of this filter reduces the amplitude of the stray sawtooth voltage by more than 10 dB. At that the converted signal shape replicates the signal shape at the sampler input.



Converted pulses with duration 1.5 ns.



Converted pulses with duration 5 ns.

Fig. 7. *Comparison of signal conversion by samplers of the oscilloscope C1-70 (left column) and georadar (right column)*

The comparative oscillograms of converted signals obtained by the georadar (right) and oscilloscope C1-70 (left) are shown in Fig. 8.

As the figure shows the duration of each pair of converted pulses is almost the same. Differences are only in amplitude in the pulse midband width, that is caused by the peculiarity of the low-frequency amplification path of georadar.

4. Conclusions

The shown in this work estimation of the influence of the sampling gate and strobe generator parameters on noise characteristics of the sampler indicates the possibility of constructing a sampler with sensitivity of the order of 341 μV in the working frequency bandwidth up to 1 GHz. Besides, it has been determined that at the given stray parameters of the circuit elements the inaccuracy of sampler measurements at the frequency upper boundary is $0,2u \pm 1\ mV$.

The strobe generator used in the sampler with a short-circuited line of 2.5 cm allowed us to obtain strobe pulses with the 0.25 ns duration at the level $0.5\ U_{\max}$ and amplitude 1 V. Moreover, the sampling gate setting features related with cutoff diode voltage installation. The cutoff voltage decreases down to 0.3 V and that allowed us to decrease signal distortions in the sampling gate conditioned by the bridge unbalance, from 20 mV to 1 mV.

The distortion in the sampler caused by the non-identity of the sampling gate diode parameters and influence of the junction capacitance has been eliminated by the compensating filter insertion.

The experimental check of calculation results has shown that the sampler sensitivity is not lower than 1 mV in the working bandwidth up to 1 GHz. The sensitivity can be increased by using high-identical diode pairs of the sampling gate and also by applying servo feedbacks. The working bandwidth of the sampler can be also expanded first of all by decreasing the junction capacitance of the sampling gate diodes and also by decreasing their stray parameters: lead inductance and capacitance.

Control measurements have shown both the amplitude and time linearity of signal conversion, and that permits us to use the developed design of the sampler in up-to-date videopulse radars for subsurface sounding.

References

1. M.E. Gryaznov, M.L. Gurevich, Yu.A. Ryabinin. Measurement of pulse parameters (in Russian). Moscow, Radiosvyaz, 1991.
2. G.N. Vdovin, L.V. Duhovskiy, V.E. Trenev. Questions of radioelectronics. Series VI. 1968, №.3, pp.16-17 (in Russian).
3. Yu.A. Ryabinin. Questions of radioelectronics. Series VI. 1965, №5, p.40 (in Russian).
4. Yu.A. Ryabinin. Questions of radioelectronics. Series VI. 1967, №2, p.26 (in Russian).
5. Yu.A. Ryabinin. Questions of radioelectronics. Series VI. 1970, №5, pp.36-44 (in Russian).
6. Yu.A. Ryabinin. Sampling oscillography (in Russian). Moscow, Sov. radio, 1972.
7. V.E. Staroselskiy, V.E. Suetinov. Proc. Inst. High Ed. Radioelectronics. 1981, **24**, №8, pp.10-18 (in Russian).
8. Yu.A. Ryabinin. Questions of radioelectronics. Series VI. 1974, №3, p.81 (in Russian).
9. V.E. Goryachev. Questions of radioelectronics. Series VI. 1970, №3, pp.7-14 (in Russian).
10. D.Yu. Eydukas. Devices and experiment technology. 1968, №4, p.107 (in Russian).
11. Ye.N. Butorin, Ye.A. Sorokin. Questions of radioelectronics. Series VI. 1967, №2, pp.30-34 (in Russian).
12. V.E. Staroselskiy, V.E. Suetinov. Proc. Inst. High Ed. Radioelectronics. 1972, **15**, №8, p.1051 (in Russian).
13. V.E. Staroselskiy, V.E. Suetinov. Questions of radioelectronics. Series VI. 1972, №3, pp.3-4 (in Russian).
14. V.E. Staroselskiy, V.E. Suetinov, A.T. Kozlov. Proc. Inst. High Ed. Radioelectronics. 1981, **24**, №12, pp.49-50 (in Russian).
15. Technical brief. Delta-time accuracy: the good, the bad, and the worst case. Tektronics. Inc, 2000, pp.4-5.

СТРОБОСКОПИЧЕСКИЙ ПРЕОБРАЗОВАТЕЛЬ ВИДЕОИМПУЛЬСНОГО ГЕОРАДАРА

В.П. Рубан, П.В. Холод

В работе представлен теоретический анализ шумовых характеристик и искажений стробоскопического преобразователя с полосой пропускания 1 ГГц и чувствительностью 1 мВ, построенного по мостовой диодной схеме. Приведены результаты тестовых измерений макета преобразователя.

СТРОБОСКОПІЧНИЙ ПЕРЕТВОРЮВАЧ ВІДЕОІМПУЛЬСНОГО ГЕОРАДАРА

В.П. Рубан, П.В. Холод

У роботі представлений теоретичний аналіз шумових характеристик та спотворень стробоскопічного перетворювача з полосою пропускання 1 ГГц та чутливістю 1 мВ, побудованого за мостовою діодною схемою. Наведено результати тестових вимірювань, проведених за допомогою макета перетворювача.