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Measurements of the Nonlinearity of the Ultra Wideband Signals Transformation

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1. Introduction

The linearity is one of the more difficult challenges of receiver in ultra wideband (UWB) communication systems (Green & Roy, 2003). When testing UWB receivers, one should use UWB signals as nonlinear signal distortion caused by a device dependant on the waveform of a signal.

The investigation of nonlinear distortions of UWB signals run across considerable difficulties. They are caused by a continuous spectrum of UWB signals. In this case, it is impossible to observe harmonics or intermodulation products.

In addition, application of UWB signals practically has no alternative in subsurface radars. However, such radars remain linear today. It can be explained by the same reason as stated above (difficulties in observing nonlinear transformation products). The same situation can be observed in reflectometry of wire transmission lines.

Lately Agilent Technologies Company has been using *X*-parameters (Verspecht, 1996; Verspecht & Root, 2006) in Advanced Design System (ADS) and PNA-X measuring devices. It is assumed that object characteristics depend only on the first harmonic of test signal and dc bias. Therefore, *X*-parameters are adequate only when narrow-band test signals are used. The methods described, which allow using the UWB test signals, have some failings. There is a method, which allows identifying parameters of nonlinear object model by means of testing the object by pulse signal with level sweep (Sobhy et al., 1996). However, such model includes recursive (or nonrecursive) filter and the order of this filter is prespecified. Therefore, if complexity of the object transfer function is not limited, the method is not suitable.

The equivalent gain concept (Arnstein, 1979; Arnstein et al., 1992; Chen et al., 1996) implies finding the difference between the object response and the test signal. In this case it is required that the effective width of the test-signal spectrum should be inside the horizontal segment of the frequency response of the object under test. Otherwise, it is necessary to compensate linear distortions of the test signal produced by the object. In practice, this compensation can be accomplished only for time-independent linear distortions with simple frequency dependence.

The problem of observing nonlinear transformation products of UWB signals can be solved by using the test signal with local null (or nulls) of spectrum (E. Semyonov, 2002, 2004; Lipshitz et al., 2002) or by means of rejection of narrow frequency band in the test-signal

spectrum (Snezko & Werner, 1997). In this case, it is possible to observe only nonlinear transformation products adjacent to nulls.

In the given work, we consider some examples and peculiarities of practical use of our method, which allows observing nonlinear transformation products of UWB signal against the background of a continuous spectrum of a test signal. The advantages of methods proposed (including experimental results) in comparison with the analysis of harmonics and intermodulation products are shown.

2. Method of nonlinear objects testing using ultra wideband signals

The essence of our method (E. Semyonov, 2005; E. Semyonov & A. Semyonov, 2007) is the following. The object linearly transforms signals if

$$u(t) = h(t) * x(t), \tag{1}$$

where $h(t)$ is the impulse response of the object and the equality sign indicates the identity for $x(t)$.

When investigating nonlinearity transformation of narrowband signals, usually there are points or intervals of observed frequency band for which

$$\left.\begin{array}{l} X(\omega) = 0 \\ U(\omega) \neq 0 \end{array}\right\}, \tag{2}$$

where $X(\omega)$ and $U(\omega)$ are the spectra of the test signal and the object response, respectively. In this case there is no necessity to place emphasis on identity (1) for $x(t)$. Indeed, if (2) holds at least for some ω, then it is clear that transformation of signal by an object is nonlinear, even if we take into consideration just one test impact.

Ultra wideband signals have usually a continuous spectrum. Here we can establish the nonlinearity of signals transformation using several test impact. The equality (1) should be held for all impacts (i.e., it should be identical for $x(t)$), otherwise the transformation of signals is nonlinear. Thus, at least two test signals with different waveforms and/or amplitudes are required.

The receiver is assumed to have two (reference and measurement) channels that process, respectively, the test signals generated at the generator output and the object responses. Here there is no need to use test signals with prescribed waveforms. (In particular, nonlinear signal distortions in the generator are acceptable.) This circumstance enables us to investigate, for example, the nonlinearity of signal transformation in communications systems using the fragments of real signals transmitted in these systems (including signals with nonoverlapping spectra). Test signals can be realizations of a random process.

Nonlinearity characteristic is defined by the following relationship

$$\varepsilon^*(t) = S_u[u_1(t)] - F^{-1}\left[\frac{F\{S_u[u_2(t)]\}}{F\{S_x[x_2(t)]\}}\right] * S_x[x_1(t)], \tag{3}$$

where F is the Fourier transform; F^{-1} is the inverse Fourier transform; S_u is the nonlinear operator of the measurement channel that changes the time function of the object response at the input of the receiver's measurement channel to the time function at the output of

this channel; S_x is the nonlinear operator of the reference channel; $u_1(t)$ and $u_2(t)$ are the object responses to signals $x_1(t)$ and $x_2(t)$, respectively; and the asterisk designates convolution.

When an object transforms signals linearly, and the receiver's channels are linear, $\varepsilon^*(t) \equiv 0$. If $\varepsilon^*(t) \neq 0$ at least for some values of time t, signals transformation by the object is nonlinear.

The method of nonlinear time domain reflectometry is known (Bryant, 2007), in which the series of test signals are used as well. However, only "changing the one or more pulse transmission parameter values" (such as dc bias and amplitude) is considered. The waveform of test signal remains invariable. In some cases, such restriction in a choice of test signals is inappropriate. The maximum amplitude of a nonlinear echo is usually observed at the maximum difference between amplitudes of test signals. Thus, small amplitude of the second test signal is desirable, but without energy decrease of that signal. Therefore, the waveform of the second test signal should differ from the waveform of the first. In addition, under this method (Bryant, 2007) only echo signals are registered. (The test signals generated at the generator output are not registered.) In this case, small nonlinearity of the generator should be ensured.

3. Modelling nonlinear distortion of ultra wideband signals. Virtual nonlinear impulse network analyzer

It is important to predict nonlinear distortions of signals in UWB communication and radar systems at design stage.

The task of investigation of nonlinear signals distortions should not be confused with the tasks of investigation of nonlinear objects characteristics, synthesis of nonlinear objects models and identifications of parameters of these models. Even if we have such models, we still know nothing about nonlinearity of transformation of concrete signals made by an object. Having a nonlinear model of an object, it is possible to compute its response to quite arbitrary (including UWB) signals. However, in this case it is not clear, whether the transformation of signal's waveform is caused by linear or nonlinear distortions. In fact, the investigation of nonlinear signals distortions should answer this question. Such investigation can be carried out for the experimentally registered signals or for signals calculated at a modeling stage.

Separately we note the following. Modeling nonlinear objects responses is invariably associated with using nonlinear models of these objects. However, the nonlinear distortions of signals can be selected by linear means. Moreover, a use of linear means of selection of nonlinear distortions is preferable because such means do not introduce additional nonlinear distortions to object response. As an example, we will mention the measurement of total harmonic distortion by the rejection of the first harmonic with linear band-stop filter.

If nonlinearity characteristic (3) is obtained in computer-aided design (CAD) systems as a result of modeling, then there are some peculiarities. First, we can choose the linear receiver for which $S_{x, u}(x) = x$. In this case, the nonlinearity characteristic (3) is expressed as

$$\varepsilon^*(t) = u_1(t) - F^{-1}\left\{\frac{F[u_2(t)]}{F[x_2(t)]}\right\} * x_1(t) .$$ (4)

Secondly, the object responses are computed also by CAD system (using SPICE or harmonic balance simulator). Let's express it by the formula $u(t) = S[x(t)]$, where S is the nonlinear operator reflecting the signal's transformation by object under study. Substituting this formula into (4), we obtain

$$\varepsilon^*(t) = S[x_1(t)] - F^{-1}\left[\frac{F\{S[x_2(t)]\}}{F[x_2(t)]}\right] * x_1(t) \tag{5}$$

Thirdly, the signal $x_2(t)$ can be simply shaped by CAD tools as result of a linear transformation of signal $x_1(t)$:

$$x_2(t) = h_1(t) * x_1(t), \tag{6}$$

where $h_1(t)$ is the impulse response of linear filter. Having substituted formula (6) into (5), we obtain (after transformation)

$$\varepsilon^*(t) = S[x_1(t)] - F^{-1}\left\{\frac{1}{F[h_1(t)]}\right\} * S[h_1(t) * x_1(t)]. \tag{7}$$

In fact, $F^{-1}\{1/F[h_1(t)]\}$ is the impulse response $\bar{h}_1(t)$ of some filter, which satisfies to the condition $\bar{h}_1(t) * h_1(t) = \delta(t)$, where $\delta(t)$ is the Dirac delta function. Therefore, we will represent expression (7) in the form:

$$\varepsilon^*(t) = S[x_1(t)] - \bar{h}_1(t) * S[h_1(t) * x_1(t)]. \tag{8}$$

Thus, the used CAD systems should contain: generator of test signal $x_1(t)$, nonlinear simulator (based on SPICE or harmonic balance method), linear filters with impulse responses $h_1(t)$ and $\bar{h}_1(t)$ and delay lines for superposition of object's responses to first and second test signal (these responses are consecutive).

We have developed the virtual nonlinear impulse network analyzer (Semyonov et al., 2009). "Virtual analyzer" means analyzer that is placed in the developed scheme just as other library elements. Currently its version made for AWR Design Environment. The devices for nonlinear time domain reflection (TDR_N) and transmission (TDT_N) measurements are made separate (Fig. 1a). Each device contains two control points, one of which allows the user to display the response of object and the other – the nonlinearity characteristic.
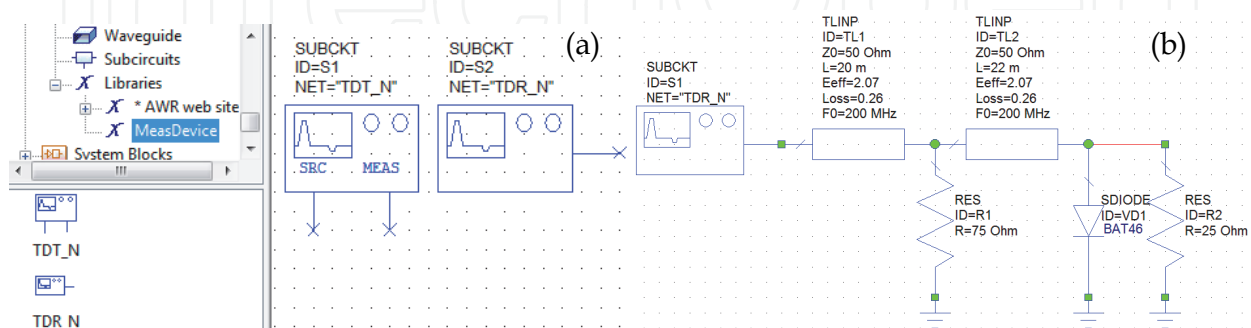

Fig. 1. Impulse time-domain transfer nonlinearity characteristic measurement device (TDT_N) and nonlinear time-domain reflectometer (TDR_N) (a); transmission line with linear (R1) and nonlinear (VD1 и R2) discontinuities (b)
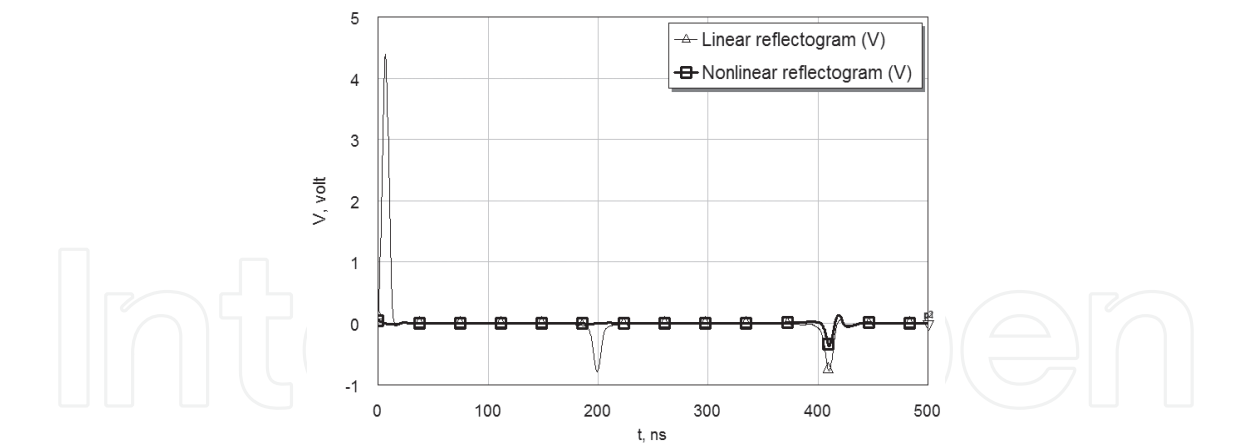
Fig. 2. The results of tests of the transmission line shown in Fig. 1b by virtual nonlinear reflectometer

Fig 1b shows the example of using developed virtual nonlinear reflectometer. It is a fragment of a window of AWR Design Environment. The transmission line with linear and nonlinear discontinuities has been used as the device under test (DUT). Fig. 2 shows the testing results of this line (thin curve is the response of network; thick curve is the nonlinearity characteristic). The extremum of nonlinearity characteristic is observed only at the moment that corresponds to the response of nonlinear discontinuity. Let's draw our special attention to the fact that nonlinearity characteristic does not contain the marks of any linear discontinuities.

4. Baseband nonlinear reflectometer R4-I-01. Wire transmission lines sounding

We have designed a baseband pulsed vector network analyzer R4-I-01 (Fig. 3a) which uses the considered investigation method of the nonlinearity of the signal's transformation (Loschilov et al., 2009). The device works under control of the ImpulseM 2.0 software (Fig. 3b).
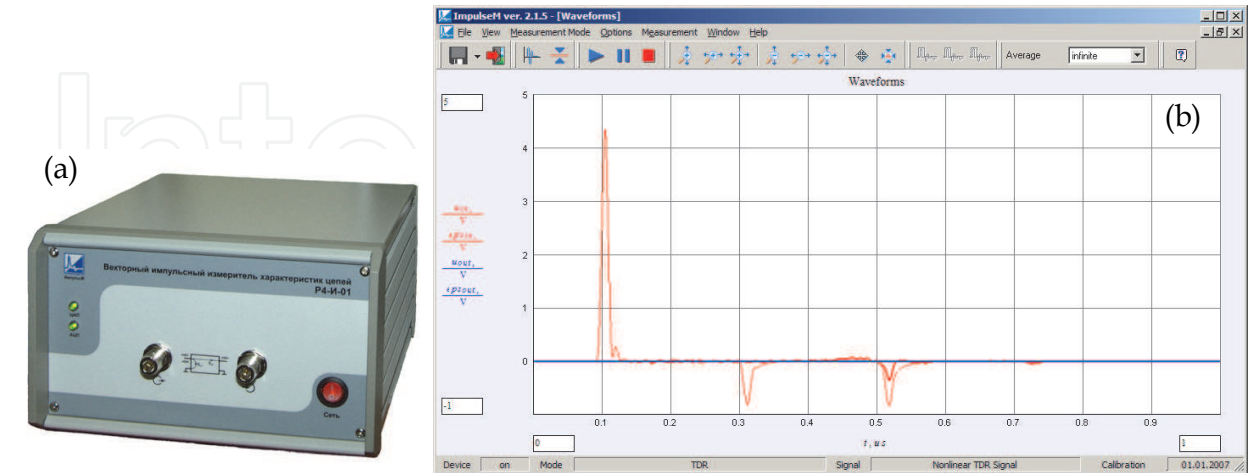

Fig. 3. Baseband pulsed vector network analyzer R4-I-01 (a) and screenshot of the main window of ImpulseM 2.0 software (b). Thin curve shows the response $S_u[u_1(t)]$ of the network which shown in Fig. 1b, thick curve shows the nonlinearity characteristic $\varepsilon^*(t)$ for this network

The device is designed for network analysis in a frequency range 0…25 MHz including wire transmission lines. The amplitude of a test signal can be set up within 0.1…5 V. The minimum pulse width is 10 ns. The detection of nonlinear discontinuities in transmission lines is possible for distance up to 400 m.

The device includes an arbitrary waveform generator (AWG), a two-channel analog-to-digital converter (ADC), a delay line and a hub for universal serial bus (USB). AWG and ADC are connected to the computer with installed software ImpulseM (through USB-hub). The registration of real obtained test signals and object responses by two-channel ADC permits nonlinear distortions of test signals by the generator. The delay line allows separating an incident and reflected wave.

An averaging of last observations of test signals $S_x[x_{1,2}(t)]$ and object responses $S_u[u_{1,2}(t)]$ can be used for noise reduction. The "Averaging" window in the main window of ImpulseM software (Fig. 3b) determines how many observations are averaged. The averaged signals are used for the calculation of nonlinearity characteristic by means of formula (3). The averaged object response $S_u[u_1(t)]$ and the nonlinearity characteristic $\varepsilon^*(t)$ are displayed on the graph (Fig. 3b).

Concerning wire transmission lines, the linear reflectometry with baseband pulse test signals allows to determine the presence of discontinuities in a transmission line, a distance from them and a type of their impedance. However, we cannot determine the nonlinearity of discontinuities. Nonlinear elements are (for example) semiconductor elements and defects of a transmission lines such as metal-oxide-metal (MOM) contacts. To investigate the nonlinearity of signals transformation by discontinuities in a transmission line, one usually use a sinusoidal test signals. However, in this case we have no information about the distance from nonlinear discontinuities. Therefore, the use of baseband pulse test signals for the investigation of signals transformation nonlinearity by discontinuities in wire transmission lines is interesting.

For example, Fig. 3b shows the response $S_u[u_1(t)]$ (thin curve) and the nonlinearity characteristic $\varepsilon^*(t)$ (thick curve) of network shown in Fig. 1b. The nonlinearity characteristic has extremum close to the response of nonlinear discontinuity. Outside of this neighborhood (including the neighborhood of the response of linear discontinuity) extremums of the nonlinearity characteristic are absent. It is possible to recognize the nature of discontinuities (linear or nonlinear) by means of the nonlinearity characteristic (3). Such
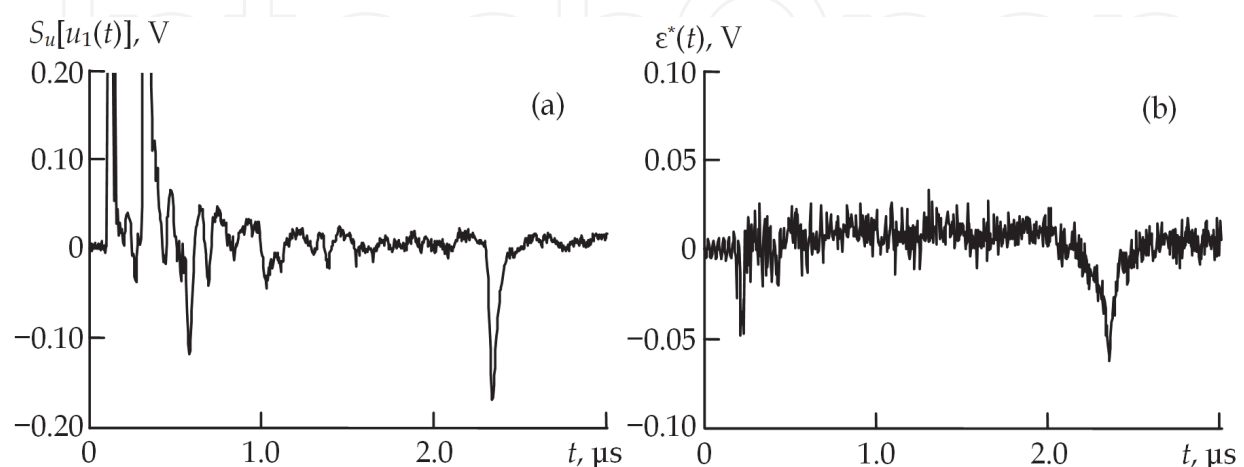

Fig. 4. Usual echo (a) and nonlinear echo (b) of metal-oxide-metal contact

possibility still remains even if the responses of discontinuities are identical (thin curve in Fig. 3b). The nonlinear response has small width. Therefore, it is possible to measure the distance from nonlinear discontinuity.

The comparison of Fig. 2 and 3b shows that results of modeling by virtual nonlinear reflectometer correlate with experimental results quite well.

Other nonlinear object, which can be in wire transmission lines, is metal-oxide-metal contact. Fig. 4 shows the example of detection of such contacts by means of device R4-I-01. We investigated the contact between the steel needle and the oxide coated steel plate. This contact was connected as a short circuit to the end of segment of TRP-0.4 cable. The length of the segment was 230 m. Fig. 4a shows the usual echo and Fig. 4b shows the nonlinearity characteristic (nonlinear echo). The MOM-contact is easily detected and its nonlinear nature is determined definitely.

In addition, we note the advantage of objects detection based on the nonlinearity characteristic.

In the presence of distributed deformations of a line, the response of this line looks like "a noise". For imitation of this quite possible situation, we use unshielded TRP-0.4 cable, which has been winded into a coil. As discontinuity, we used the BAT46 Shottky diode, which has been connected in parallel to the cable. The distance between the measuring device and the diode was 230 m. Fig. 5 shows the response (a) and the nonlinearity characteristic (b) of this network.

The amplitude of the diode response is approximately equal to the amplitude of the response from the distributed deformations of the cable (Fig. 5a). On the contrary, the nonlinearity characteristic has the clear-cut extremum corresponding to an echo-signal from the diode.
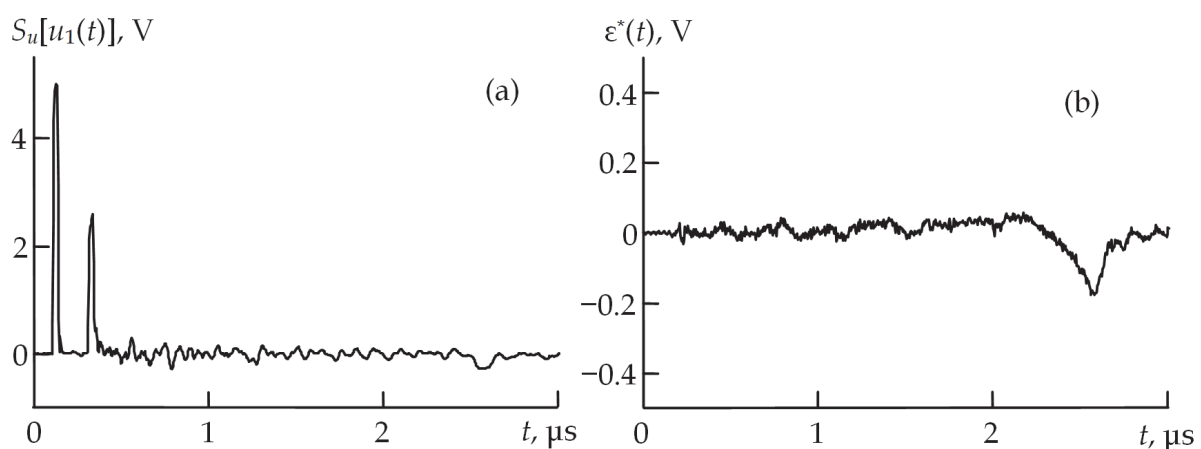

Fig. 5. The response (a) and the nonlinearity characteristic (b) of the BAT46 Shottky diode connected as a parallel discontinuity to the TRP-0.4 cable with distributed deformations

Thus, if the object under test has nonlinear properties, then an object detection based on the nonlinearity characteristic is preferable.

5. Sounding of objects by low-frequency signals with an ultra-wide relative width of spectrum

Selective detection of substances with use of their nonlinear properties is of interest. For this, the field should influence an object material. Concerning a metal, it means that the use of low-frequency signals is needed.

We've done the experimental investigations of 10-mm-dia, 1-mm-thick low-carbon-steel and aluminum disks (E. Semyonov & A. Semyonov, 2007). The objects were placed above the inductor coils with the diameter of 10 mm and at the distance of 2.5 mm from their end surfaces.

Test signal $x_1(t)$ was used in the form

$$x_1(t) = \frac{\sin(2\pi f_{up} t + \pi/2)}{2\pi f_{up} t + \pi/2} - \frac{\sin\left(2\pi f_{up} t - \pi/2\right)}{2\pi f_{up} t - \pi/2}, \tag{9}$$

where f_{up} = 24 kHz is the upper frequency limit of the spectrum of signal $x_1(t)$. The amplitude spectrum of test signal $x_2(t)$ was analogous to the amplitude spectrum of signal $x_1(t)$, and the phase spectrum of the former signal differed from the phase spectrum of $x_1(t)$ by a value that had a quadratic frequency dependence:

$$X_2(\omega) = X_1(\omega)\exp(-jd_2\omega|\omega|), \tag{10}$$

where d_2 is the coefficient that determines a decrease in the amplitude of signal $x_2(t)$ and an increase in the duration of this signal relative to the corresponding parameters of signal $x_1(t)$. The maximum voltage of pulse $x_1(t)$ applied to the transmitting coil with a resistance of 6.3 Ω was 28 V.

To compare the proposed nonlinearity characteristic and the nonlinearity characteristic that was obtained via determination of intermodulation products, a two-frequency (16 and 18 kHz) test signal was used. Its amplitude was equal to the amplitude of signal $x_1(t)$. The necessary frequency resolution was achieved through selection of the duration of the two-frequency signal such that its value was much greater than the duration of signal $x_1(t)$. At a level of 0.1 of the amplitude of the two-frequency signal, its duration was 3.9 ms. Accordingly, the energy of the two-frequency signal was greater than the energy of signal $x_1(t)$.
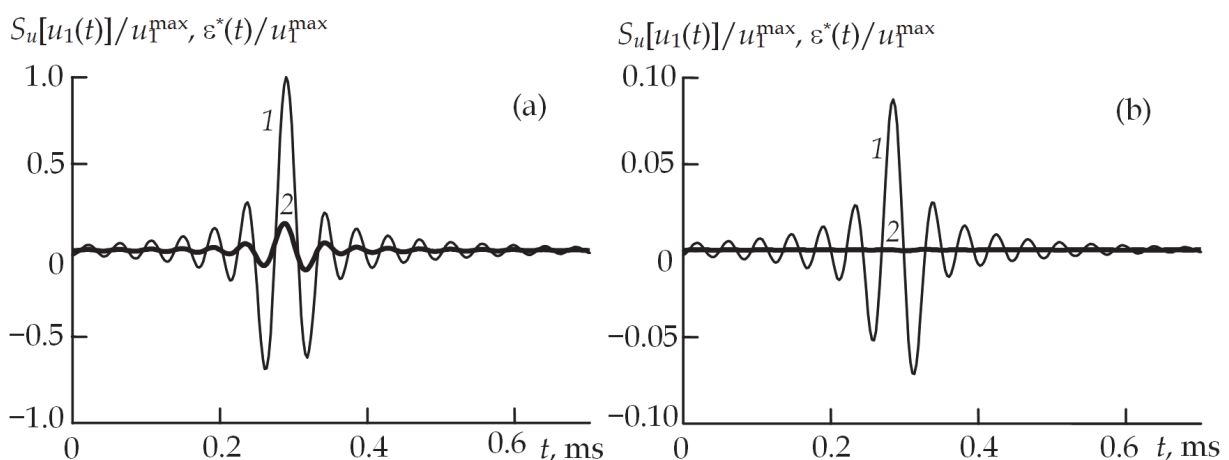

Fig. 6. Normalized response $S_u[u_1(t)]$ (curve 1) and nonlinearity characteristic $\varepsilon^*(t)$ (curve 2) of a low-carbon-steel object (a) and an aluminum object (b)

For the low-carbon-steel and aluminum objects, responses $S_u[u_1(t)]$ and nonlinearity characteristic $\varepsilon^*(t)$ are shown in Figs. 6a and 6b, where the responses of the objects and nonlinearity characteristics are normalized to amplitude u_1^{max} of response $S_u[u_1(t)]$ of the low-carbon-steel object.

We see a significant nonlinearity of signals transformation by a low-carbon-steel object, while attributes of the nonlinearity of signal transformation performed by an aluminum object were not found. Hence, the proposed nonlinearity characteristic of signals transformation can be used to obtain additional classification attributes of an object.

When the low-carbon-steel object was sensed by a two-frequency test signal with an amplitude equal to the amplitude of $x_1(t)$, the normalized amplitude of the sum of intermodulation products in the object response was 2.2%. This value is 7 times less than the normalized amplitude of nonlinearity characteristic $\varepsilon^*(t)$ that was obtained for this object, although both the sum of intermodulation products and $\varepsilon^*(t)$ can be interpreted as the residuals of the linear equation used to approximate nonlinear transformation.

Fig. 7 additionally shows this relationship (for low-carbon-steel object). Curve 1 shows the amplitude spectrum $E^*(f)$ of the nonlinearity characteristic $\varepsilon^*(t)$. This spectrum is normalized to the maximum $U_1^{\max}$ of the amplitude spectrum of the response to the signal $x_1(t)$. Curve 2 shows the intermodulation products $U_{IM}(f)$ in the response to the two-frequency signal (spectral components of the test signal are rejected). This spectrum is normalized to the maximum $U_s^{\max}$ of the amplitude spectrum of the response to the two-frequency signal. All test signals had the same amplitudes. It is clear that the normalized components of the amplitude spectrum of the nonlinearity characteristic $\varepsilon^*(t)$ is considerably greater than the normalized intermodulation products.
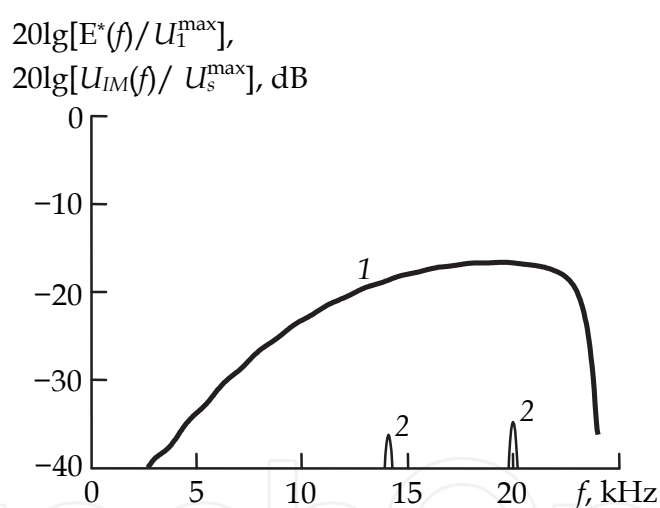

Fig. 7. The amplitude spectrum $E^*(f)$ of the nonlinearity characteristic $\varepsilon^*(t)$ (curve 1) and the intermodulation products $U_{IM}(f)$ in the response to the two-frequency signal (curve 2)

This fact means substantial increase of detection range of nonlinear detectors and radars using the considered method.

6. Problems of creation of nonlinear reflectometer with picosecond duration of test signals

If an upper frequency of measuring device exceeds 1 GHz, the formation of a pair of test signals with different forms has considerable difficulties. The upper frequency of up-to-date arbitrary waveform generators is about 10 GHz and they are very expensive. We consider the approach to solve this problem by using analog shaping of signals by passive circuits. The example of sounding of Schottky diode by the 300 ps impulse is described here.

An experimental setup for investigating the characteristics of nonlinear circuits using the considered method of nonlinear reflectometry was developed. Fig. 8 shows block diagram of the experimental setup.
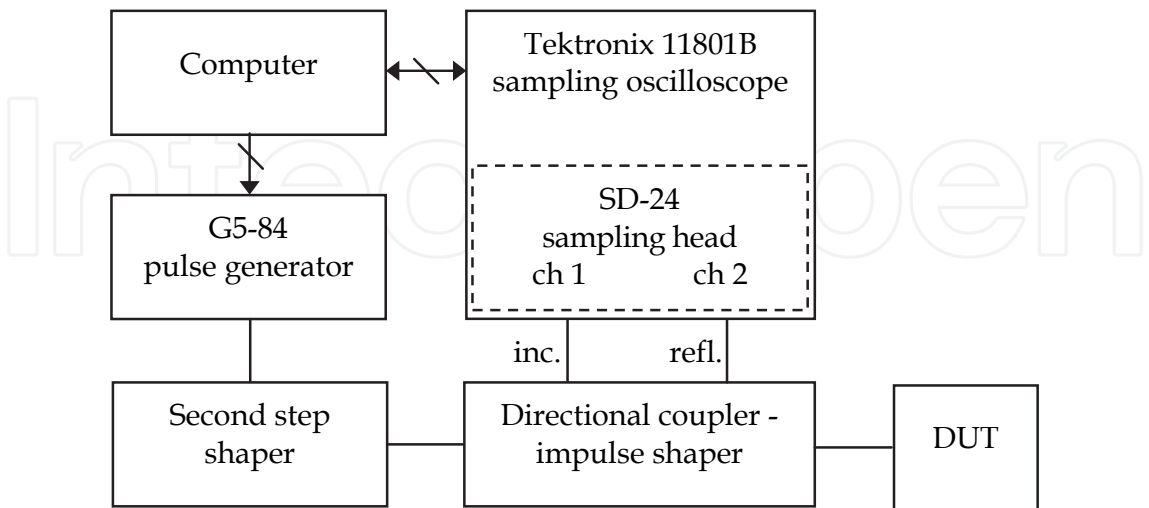

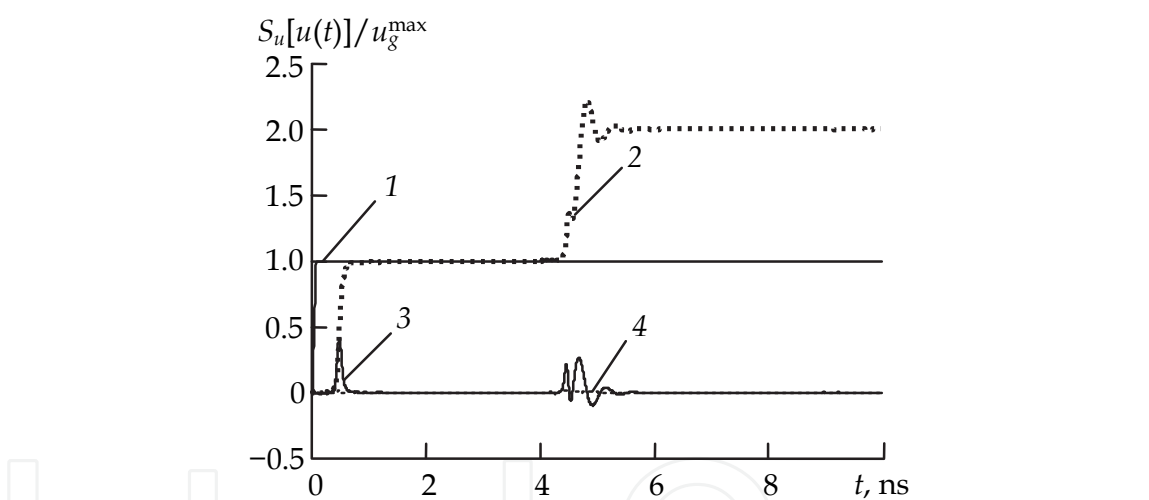Fig. 8. Block diagram of the experimental setup

Fig. 9. Examples of waveforms: *1* – G5-84 output waveform; *2* – second step shaper output waveform; *3* – experimental setup output waveform (incident wave); *4* – signal measured on channel *2* (reflected wave)

The experimental setup works as follows. The computer sets the parameters of a test signal, transfers the settings to the generator G5-84 and run generation. Fast voltage step from generator G5-84 comes to the input of the second step shaper, where forms an additional voltage step, delayed relative to the first step at some time *T* and processed by a linear circuit. After that the signal comes into a directional coupler - impulse shaper, which differentiates the input pair of steps and produces a sequence of pulses arriving at the object under test. An incident component of the test signal comes to the first channel of the sampling oscilloscope. The signal reflected from the DUT comes to the second channel of the sampling oscilloscope. The sampling oscilloscope registers the incident and reflected pulses, and transmits the data to the computer.

Fig. 9 shows some examples of waveforms at the inputs/outputs of blocks of the experimental setup.

The waveforms are presented at the matched mode on the output of the experimental setup. Fig. 9. shows the initial voltage step (curve *1*) produced by the pulse generator G5-84 (the pulse width is much larger than the observation window). After processing by the second step shaper, the signal has additional voltage step with oscillations at the front (curve *2*). Directional coupler - impulse shaper performs three functions: the differentiation of the initial signal (curve *3*); the directional separation of the signal reflected from DUT (curve *4*); the transfer of the incident signal to the first channel of sampling oscilloscope (curve *2*). All signals are normalized to the amplitude $u_g^{\max}$ of the pulse generator output signal.

The experimental investigations were performed with the use of the designed setup. Two types of objects were investigated: a linear object (the 38 Ω chip resistor) and a nonlinear object in which the microwave Schottky diode HSMS-8202 and the 51 Ω chip resistor were connected in parallel. For both objects, linear and nonlinear reflectograms were measured. Fig. 10 shows the results of the experimental investigations.
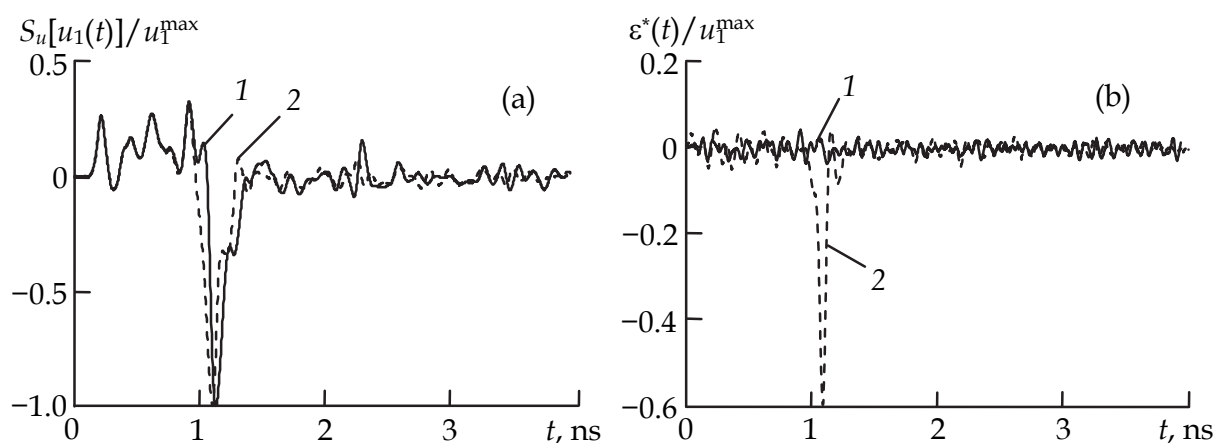

Fig. 10. Experimentally registered linear reflectograms $S_u[u_1(t)]$ (a) and nonlinear reflectograms $\varepsilon^*(t)$ (b). Curve *1* – linear object; curve *2* – nonlinear object. All signals are normalized to the amplitude of signal $S_u[u_1(t)]$

As seen from Fig. 10a, measured reflectograms of linear (curve *1*) and nonlinear objects (curve *2*) have similar forms and amplitudes. (A negative polarity of the responses indicates that the impedance of objects is lower than 50 Ω.) Comparison of the responses cannot indicate nonlinear properties of any objects.

As seen from Fig. 10b, the results obtained by nonlinear reflectometry is different for linear and nonlinear objects. Nonlinear objects trace (curve *2*) has a pronounced extremum in the neighborhood of 1.1 ns, whereas in the trace of a linear object (curve *1*) there are no extremums greater than the noise level. Extremum time position corresponds to the point of connection with a nonlinear element.

The experimental investigations performed illustrate that nonlinear reflectometry can be effectively realized at the width of incident and reflected pulses about 300 ps.

7. Measurement of nonlinearity of ultra wideband receivers

The considered method permits nonlinear distortions of test signals by the generator. Therefore, if the channel between the generator and the receiver is linear, then we measure nonlinear signals distortions only by the receiver (E. Semyonov & A. Semyonov, 2007).

In this case

$$u_{1,2}(t) = h(t) * x_{1,2}(t), \tag{11}$$

where $h(t)$ is the impulse response of this channel. If the impulse response $h(t)$ is Dirac delta function then $u_1(t) = x_1(t)$ and $u_2(t) = x_2(t)$. In this case $\varepsilon^*(t) \equiv 0$ even if transformation of signals by the receiver is nonlinear. Therefore it is necessary to choose $h(t)$ so that the signals $u_1(t)$ and $x_1(t)$ would have different waveforms and/or amplitudes. (The same apply to signals $u_2(t)$ and $x_2(t)$.)

To use the nonlinearity characteristic (3) the receiver should be two-channel. However, quite often it is required to investigate the single-channel receiver (or the separate channel of the multichannel receiver). In this case the same channel of the receiver should register signals $x_{1,2}(t)$ and $u_{1,2}(t)$ (which are the result of transformation of signals $x_{1,2}(t)$ according to (11)). This is possible, if signals $u_{1,2}(t)$ come to the same point in which signals $x_{1,2}(t)$ are registered (similarly how it occurs in reflectometers).

Thus, the channel between the generator and the receiver should contain a delay line (for consecutive transmission of $x_{1,2}(t)$ and $u_{1,2}(t)$ to receiver's input) and a linear filter which provides some difference between the waveforms of signals $u_{1,2}(t)$ and $x_{1,2}(t)$.

If we have a single-channel receiver, then $S_x = S_u = S_r$, where S_r is the operator of the investigated single-channel receiver. Therefore, the formula (3) will become:

$$\varepsilon^*(t) = S_r[u_1(t)] - F^{-1}\left[\frac{F\{S_r[u_2(t)]\}}{F\{S_r[x_2(t)]\}}\right] * S_r[x_1(t)]. \tag{12}$$

If equality (11) holds and $\varepsilon^*(t) \neq 0$ at least for some values of time t, S_r is nonlinear. (The receiver distorts the signals nonlinearly.)

Fig. 11a shows the nonlinearity of transformation of baseband pulse by the Tektronix TDS1012B oscilloscope. Here are shown: signal $S_r[u_1(t)]$ (curve *1*) and nonlinearity characteristic (curve *2*). Both curves are normalized to amplitude $u_1^{\max}$ of signal $S_r[u_1(t)]$. At the same amplitude of the test signal the harmonic distortion has been measured. Fig. 11b shows the results of this measurement. (The frequency of test signal $x_s(t)$ is 50 MHz.) Let us notice that the amplitude of the nonlinearity characteristic of baseband pulse's transformation (1%) is 5 times more than total harmonic distortion (0.2%).
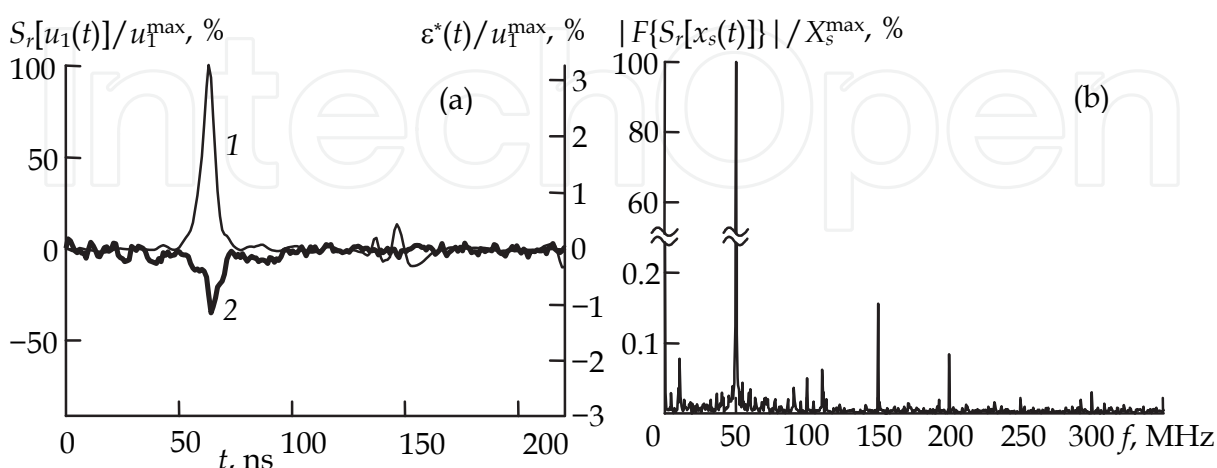

Fig. 11. Receiver-registered baseband pulse ($S_r[u_1(t)]$, curve *1*) and nonlinearity characteristic ($\varepsilon^*(t)$, curve *2*) (a). Spectrum module $|F\{S_r[x_s(t)]\}|$ of the receiver-registered sinusoidal signal (b). (Spectrum is normalized to the amplitude of the first harmonic $X_s^{\max}$.)

This example illustrates special importance of linearity in UWB receivers. Besides, it is clear that for UWB receivers testing one should use UWB signals. In nonlinear radars and nonlinear reflectometers such measurements are necessary to observe the nonlinear response of the object against the background of nonlinear distortions in the receiver (E. Semyonov & A. Semyonov, 2007).

8. Conclusion

The considered method is effective for the following tasks.
1. Investigation of devices (for example, receivers) for ultra wideband communication systems (including design stage).
2. Detection of imperfect contacts and other nonlinear elements in wire transmission lines.
3. Remote and selective detection of substances with the use of their nonlinear properties.
The main advantages of the considered approach are listed below.
1. Real signals transmitted in UWB systems can be used as test signals.
2. Nonlinear signal distortions in the generator are acceptable.
3. Measurement of distance from nonlinear discontinuity is possible.
4. Nonlinear response is several times greater than the response to sinusoidal or two-frequency signal.
The designed devices and measuring setups show high efficiency for frequency ranges with various upper frequency limits (from 20 kHz to 20 GHz).
The developed virtual analyzers provide corresponding investigations of devices and systems at design stage.

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This book has addressed few challenges to ensure the success of UWB technologies and covers several research areas including UWB low cost transceiver, low noise amplifier (LNA), ADC architectures, UWB filter, and high power UWB amplifiers. It is believed that this book serves as a comprehensive reference for graduate students in UWB technologies.

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