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SHORT-RANGE NOISE RADAR WITH MICROWAVE CORRELATOR FOR THROUGH-THE-WALL DETECTION

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Abstract

The analysis of the autocorrelation function of a noise signal in a limited band of a microwave frequency range is described in the paper. On the basis of this analysis the static characteristic of the detector for object movement was found. The measurement results for the correlation function of noise signals are shown and the application of such solution in a noise radar for the precise determination of distance variations and the velocity of these changes is presented in the paper. The construction, working principle and measurement results for through-the-wall noise radar demonstrator have been presented in the paper. A broadband noise signal in microwave S frequency band has been chosen, for high sensitivity getting. The broadband noise signal together with correlation receiver provides high sensitivity and moderate range for low transmitted power level. The experimental results obtained from 2.6–3.6 GHz noise-like waveform for the signal of a breathing human are presented. Conclusions and future plans for application of the presented detection technique in broadband noise radars conclude the paper.

Keywords: Ultra wideband noise radar, Doppler radar, Microwave correlator, Human activities.

1. Introduction

Noise radars are those which use random or pseudo-random signals for target illumination and coherent detection techniques for reception of noise signals [1, 2, 3, 4, 5, 6]. A correlator receiver is a typical element entering into the noise radar. Its fundamental parameters are the following: broad signal band, low power density, and the capability to ensure high responsivity of the receiving devices using non-conventional methods [7, 8, 9, 10, 11, 12, 13]. Coherent reception needs delay lines of constant or variable parameters to be applied in the receiving systems. In the hitherto prevailing literature three fundamental correlation receiver types are present: a fully analog correlation receiver, analog-to-digital correlation receiver, and a fully digital correlation receiver [14, 15, 16, 17, 18]. In this paper, results for the operation of a microwave analog correlation receiver operating in the short-range noise radar system are presented. Measurement results for the correlation function of noise signals are shown and the application of such solution in the noise radar for the precise determination of distance variations and the velocity of these changes is also presented. There is a need to remotely detect human activities for through-the-wall detection techniques [19, 20, 21]. The microwave quadrature correlator which is used to extract human-induced Doppler frequency shift from the received signal, facilitates the identification of various human activities for anti-terrorism applications.

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2. Direct correlation detection of the noise signal

In this paper an idea of determination of a correlation function value for noise signals in a limited microwave range is shown. The analysis of the microwave correlator was carried out using the schematic diagram presented in Fig.1. Let us assume that the transmitter generates a signal in the form of noise with limited bandwidth and normal distribution with an average value equal to zero and a variance equal to σ^2. The signal generated in the transmitter can be described by the expression (1) [5], whereas waveforms at individual points of the system are described by relations (2) and (3):

$$S_N = X(t)\cos(\omega_0 t) - Y(t)\sin(\omega_0 t), \tag{1}$$

$$S_{NDL}(t) = k_1 S_N (t - T_{DL}), \tag{2}$$

$$S_o(t) = k_2 S_N\left(t - \frac{2D}{\mathrm{c}}\right), \tag{3}$$

where D is the instantaneous distance between the radar and the object, T_{DL} is the time delay in the delay line, ω_0 is the median frequency of the band occupied by the noise signal, $X(t)$ and $Y(t)$ are the independent stationary random processes with Gaussian distribution having an average value equal to zero, and k_1, k_2 are the propagation coefficients.

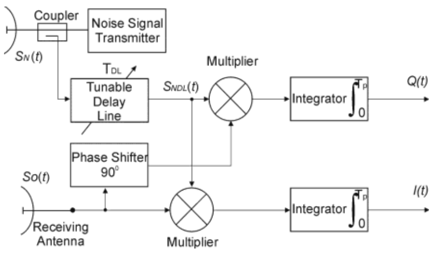

Fig. 1. Schematic diagram of the quadrature microwave correlator for noise signals.

The relation describing the instantaneous distance takes the form:

$$D = \frac{\mathrm{c}T}{2} + vt + D_m \cos(\omega_m t), \tag{4}$$

where T is the signal delay time on the radar-object-radar path, v is the radial velocity of the object, and D_m i ω_m are the amplitude and the pulsation of an additional harmonic movement of certain object parts, respectively. The object as a whole can move with radial velocity v, or stay at rest. As a result of multiplication of signals and after integration of the obtained products, the two quadrature output signals, $I(t)$ and $Q(t)$, can be expressed in the form of relations (5) and (6).

$$I(\tau,t) = A(\tau)\cos\left(\omega_0\tau + \frac{2\omega_0 vt}{\mathrm{c}} + \frac{2\omega_0 D_m}{\mathrm{c}}\cos(\omega_m t)\right), \tag{5}$$

$$Q(\tau,t) = A(\tau)\sin\left(\omega_0\tau + \frac{2\omega_0 vt}{\mathrm{c}} + \frac{2\omega_0 D_m}{\mathrm{c}}\cos(\omega_m t)\right), \tag{6}$$

where $\tau = T - T_{DL}$.
The relations (5) and (6) are the quadrature components of the correlation function for the noise signal transmitted and received by the noise radar. The complex representation of the correlation function defined in this way can be written as:

$$R(\tau,t) = I(\tau,t) + \mathrm{j}Q(\tau,t). \tag{7}$$

This results from the analysis that for the equipment designed according to the scheme presented in Fig.1, in contrast to digital processing [15, 16, 17, 18, 21], a correlation function of the noise signal in a limited bandwidth is determined.

3. Static characteristics of the movement detector

In this part the analysis of a plot of correlation function variability for a noise signal in the limited band will be performed as well as parametrization of the correlation function variables will be executed. This procedure will allow to identify the static characteristic of a movement detector. A normalized autocorrelation function of a signal in a limited band can be described by relation (8) [22], and its shape for the case when f_2 =3.4 GHz and f_1 =2.6 GHz is shown in Fig. 2.

$$r(\tau) = R(\tau)/R(0) = \frac{1}{2\pi\tau B}\left[\sin(2\pi f_2 \tau) - \sin(2\pi f_1 \tau)\right], \tag{8}$$

where $B = f_2 - f_1$ is the noise frequency band.

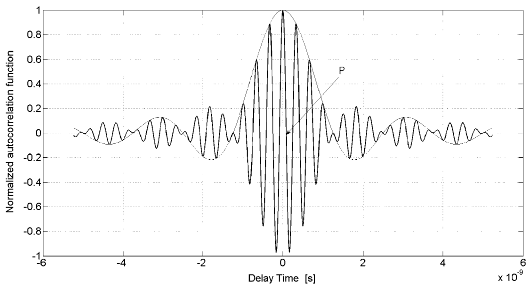

Fig. 2. The plot of normalized autocorrelation function.

It can be seen in Fig.2 that two factors – a fast varying factor and a slowly varying one – have an influence on the variability of the normalized autocorrelation function $r(\tau)$. The first factor depends on the rate of sine function changes, i.e. on variation rate of its argument, namely the $2\pi f_0\tau$ product, where $f_0 = (f_2 - f_1)/2$. The higher the median frequency of a microwave band occupied by the noise signal, the higher the variation rate of the sine function. On the other hand, the second factor is related to variations of the envelope of the autocorrelation function and next depends on the $B\tau$ product in this way that the broader the signal band – the higher the autocorrelation function envelope rate for fixed τ increments. Both factors are a function of the delay time τ. For a noise radar with microwave correlator [23, 24], the delay time depends on the momentary distance D of the detected object to the noise radar, according to the dependence:

$$\tau = 2(D - D_{\mathrm{Corr}})/\mathrm{c}, \tag{9}$$

where: D_{Corr} is the distance for which the value of mutual correlation of the signal received by the radar and the signal delayed in the fixed radar delay line corresponds to working point P, **c** is the speed of light.

The working point P can be selected in an arbitrary way on any linear part of the I and Q characteristics of the quadrature microwave correlator in the major lobe of its envelope. In this case delay time $\boldsymbol{\tau}$ can be expressed by distance or distance variation D with respect to D_{Corr}. Experiments were also conducted with the use of the correlator. In Fig.3 the measurement results of a corner reflector moving in the observation zone of the noise radar are shown. Plots in Fig.3 confirm that the voltage at the microwave correlator output is reflecting the mutual correlation function of a noise transmitted signal and the received signal reflected from the moving object.

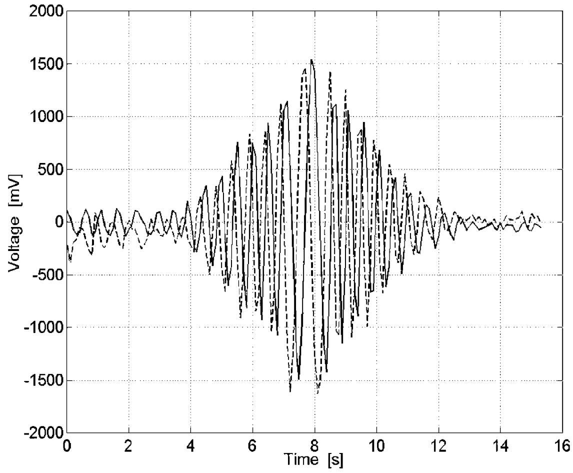

Fig. 3. The plots of voltage changes, *I* (solid line) and *Q* (broken line), at the outputs of the microwave quadrature correlator.

Taking into account the above statements, the $\tau = \tau_0 = 1/(4f_0)$ object-to-radar distance will be analyzed. This case corresponds to the point *P* in Fig.2. After expanding the function (8) into a Taylor series in the neighborhood of the point *P* we get:

$$r(\tau) \cong r(\tau_0) + \frac{dr(\tau)}{d\tau}\bigg|_{\tau=\tau_0}(\tau - \tau_0). \tag{10}$$

For narrowband noise radar systems the relation $B/(f_2+f_1) \ll 1$. After determination of the $r(\tau)$ derivative in the point $\tau = \tau_0$ and substitution $r(\tau_0) = 0$ for the accepted expansion point *P*, the expression (10) takes the form:

$$r(\tau) \cong -2\pi f_0(\tau - \tau_0). \tag{11}$$

Factor $(\tau-\tau_0) = \Delta\tau$, according to (9), depends on position variations of the object. So, the parametrization of the function (11) can be made in the following form:

$$\begin{aligned} \Delta\tau(D) &= \frac{2(D - D_{\text{Corr}})}{c} \\ U_{\text{Out}}(\Delta D) &= \alpha R(0) r(\Delta\tau) = -\frac{4\pi\alpha P_N}{c} f_0 \Delta D \end{aligned}, \tag{12}$$

where: U_{Out} is the voltage *I* or *Q* at the outputs of the microwave quadrature correlator, α is the coefficient related to the correlator system and conditions of the noise signal propagation, P_N is the power of the transmitted noise signal, and $\Delta D = D - D_{\text{Corr}}$.

Dependence (12) describes the static characteristics of the movement detector. It can be well seen that the sensitivity to variations of the detector-target distance of the noise radar with microwave correlator is proportional to variations of the median frequency of the noise signal band (the larger the median frequency - the higher the sensitivity). This property of the microwave correlator was used to construct an activity finder (locator) of living beings hidden beyond visible light stoppers. Results of measurements using this short-range noise radar are presented in section 4.

4. Experiments

A. Short-range noise radar

The block diagram and photograph of the system of a short-range noise radar are presented in Figs. 4 and 5.

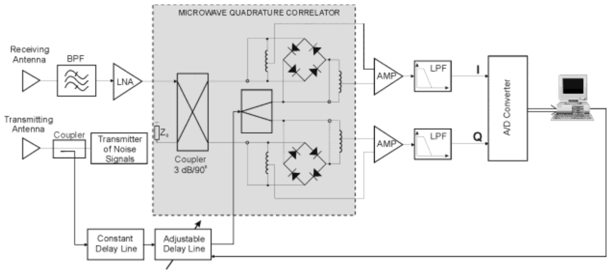

Fig. 4. Block diagram of the noise radar with a microwave correlation receiver.

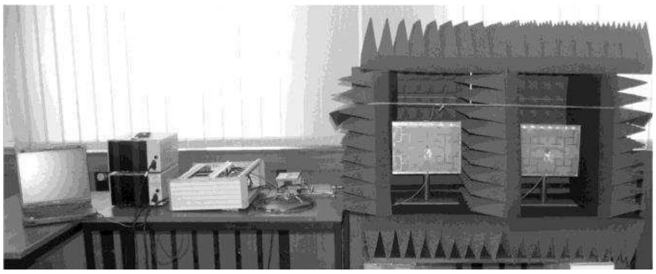

Fig. 5. Photograph of the noise radar system.

It consists of input circuits, a low-noise microwave amplifier, broadband microwave quadrature correlator, analog delay line, low-frequency amplifiers with high gain, and a system for data display. Input circuits are equipped with replaceable microwave filters made by using the NLP technique. The bandwidth of the filters could be changed from 100 MHz to 1 GHz whereas their median frequency amounts to 3 GHz. The low-noise amplifier is a broadband system with 40 dB gain and a noise factor not worse than 1.5 dB. The broadband microwave quadrature correlator is a modified six-port measurement module [25]. The system consists of a power divider, a coupler, and two diode rings. The input voltages are divided into two equal parts and delivered to the diode rings with adequate phase shifts. The diode rings play the role of multiplication systems. At the output of the quadrature detector two signals, I and Q appear, described by expressions (5) and (6). These signals are next amplified in measuring amplifiers with adjustable voltage gain from 100 to 100000 V/V. The bandwidth of the correlator output signals is limited by low-pass filters. The range of changes of post-detection bandwidth varies from a fraction of a hertz up to 100 Hz. The signals prepared in this mode are then digitized in an A/D converter and sent to a PC via an USB link. The PC plays the role of a data collection and processing system. A medium-power noise generator is the noise radar transmitter. The microwave noise generator is based on a semiconductor primary noise source and a set of amplifiers and microwave filters. Thus the noise signal source operates on a median frequency of f_0 = 3 GHz with a 3 dB bandwidth of B = 1 GHz width and a spectral power density of G_n = –82 dBm/Hz.

B. Measurements of human breathing

Measurement results carried out using the noise radar described in 4.A are presented in this subsection. Measurements were performed according to the scheme shown in Fig. 6.

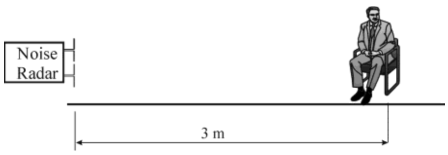

Fig. 6. Set-up diagram for the human breathing measurement.

The lung volume expansion and contraction is used for this measurement. The lung volume change causes a chest movement. This movement is successfully detected by the noise radar. This can be modeled as a harmonic wave whose amplitude ΔD corresponds to the maximum rise of the chest and the frequency corresponds to the frequency movement of inspiration and expiration.

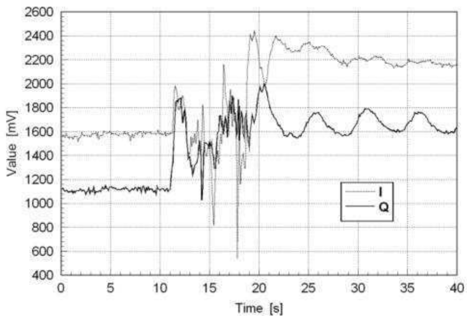

Fig. 7. The plots of the voltage changes at the I and Q outputs of the microwave quadrature correlator for signals from human activity.

The measurement results are presented in Fig. 7. A man with regular breathing, sitting on a chair was used as the object for the tests. From Fig. 7. it is clear that using the analog microwave correlator circuit, the activity of the living being can be detected, thus neglecting complicated digital signal processing. In the first period (0-11 s), only static objects in the zone were present. The quadrature signals have nearly constant values for this case. In the second period (11-19 s), one person was let into the measurement zone. He was allowed to move his hands and legs. This caused rapid changes of the output quadrature signals that were registered. In the third period (19-40 s), the person sat on the chair with motionless hands and legs. The periodical changes corresponding to the breath frequency were registered.

Using the correlator circuit, the internal correlation function structure information is not lost. For example, for the center frequency of 3 GHz the wavelength is 10 cm in the open air, so the distance of the tested object to the radar at 2.5 cm gives the output correlator voltages in the full range of the minimum to the maximum values. This method was used for activity detection of the living organism.

C. Through-the-wall detection of human breath

Measurements were performed as shown in Fig. 8. The plot of the voltage variable component at output Q of the microwave correlator is presented in Fig. 9 for the observation of an area behind a wall of 120-mm thickness consisting of bricks and concrete.

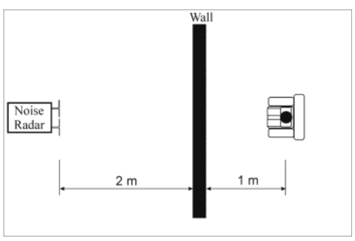

Fig. 8. Set-up diagram for through-the-wall detection of human breathing.

In this method a person whose steady breathing was detected was made to sit on a chair. As can be seen in Fig. 9, the following situations can be distinguished during the observation: the phase of steady breathing from 0 to 18 s and from 38 s to 50 s, the phase of absence of breathing which started from 18 s to 26 s without any reserve of air in the lungs, the phase of intense breathing from 26 s to 38 s, and the phase of absence of breathing which began with the drawing of air into the lungs that lasted from 53 s to 59 s.

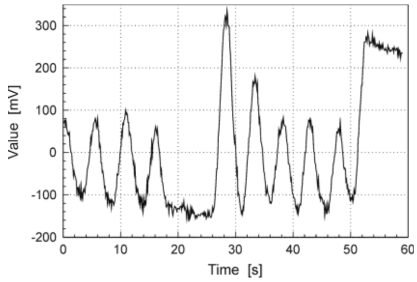

Fig. 9. Plot of the voltage changes at the output *Q* of the microwave quadrature correlator for the signal from human activity.

It can be seen that even insignificant changes in the distance of a human chest from the radar, caused by breathing, are very well identified by the noise radar. So, it can be used as a localizer of living beings present behind screens for visible and infrared light.

5. Conclusions

The suggested method of analog correlation detection allows to construct radars which make precise measurements of velocity and distance possible. The method uses analog correlation detection in the microwave band, in contrast to processing of the received signal in the primary band. This allows to precisely detect a movement using an internal structure of the correlation function of a noise signal. The suggested design of a noise radar can be used, among others, for monitoring the activities of living beings displaying, for instance, movements of the individual parts of their bodies. Noise radars are characterized by a "pin-type" indeterminate function. Therefore, the distance and Doppler frequency can be precisely and unambiguously determined by means of these radars. Potential applications of short-range noise radars are as follows: anti-collision radars [26], protection of objects, detection of movement, recognition and penetration of inaccessible objects, penetration of objects hidden in shallow soil layers, and detection of living beings in inaccessible areas [20, 27]. For very high frequencies in the microwave range the simple analog systems of the correlative detector can be used, because a digital realization of the autocorrelation function for these frequencies is very difficult. The frequency range of noise radars covers an interval from 100 MHz to hundreds of GHz, and this is only a technological limitation at the current stage of electronics development. The future plans of the authors will focus on application of the presented concept of broadband microwave correlation in the design and development of selected types of short-range noise radars.

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