Paper

Antenna Arrays Focused on Broadband Signals

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Abstract—Broadband and ultra-wideband signals are increasingly used in modern radio systems. Traditional performance of evaluation antennas operating with narrowband signals are not always adequately reflect the characteristics of broadband antennas, at least in view of the frequency dependence of the antenna pattern. Accounting for broadband signals the antennas becomes important in the low-frequency range of the spectrum. Systems using these types of signals may include control of the atmosphere and measuring its frequency-selective properties in the range meter and decameter wavelengths. Possibility of spatial selection based on focusing of broadband signals in this case promises to implement a number of additional features. Therefore, it is important to evaluate the properties of antennas based on the spectral content of the signal, as well as taking into account the ways of its processing in the receiving equipment. Consideration features of functioning the antenna array, focused on broadband signal is devoted to this article.

Keywords—antenna array, broadband antenna, broadband signal, focusing on the broadband signals.

1. Introduction

The narrow-band antennas, often used to form the fields of radiation (or reception) in the far field, performing the required functions in a relatively small band $\Delta f/f_0 \ll 1$. These frequency boundaries of directional characteristics do not undergo significant change and are considered in analysis and synthesis of antennas for monochromatic signal with a frequency f_0. The finiteness of frequency band in these cases taking into account only when considering matching antenna feeder.

The broadband antenna is considered as antenna designed to operate in the relative frequency band $\Delta f/f_0$, amounts to no more than several tens of percent. In these cases, antennas are used in radio systems using relatively narrow-band signals. These antennas should provide radiation and reception at f_0 rearrangements carrier frequency within a desired frequency range. The behavior of antennas within the frequency band Δf is also insignificant and is not considered in estimates of the directional properties. The required broadbandness of such antennas is determined mainly as ensuring harmonization within a predetermined frequency range.

An ultra-wideband (UWB) antenna is composed of two fundamentally different groups. The first is represented by antennas with constant directivity and matching characteristics in a wide frequency band. The fundamental principles of the independence of the frequency characteristics of antennas installed in the 1950s, is well known [1]. In most practical applications, such UWB antennas are used in radio communication, sending or receiving radio signals with low or average values of the relative width of the spectrum, but with possibilities of changing its center frequency in a wide range. Special group of UWB antennas are for of radio facilities, mainly radars, with high value of the absolute width of the signal spectrum, for their part of the order of 0.5 GHz and more. These signals can be created with carrier frequencies equal centimeter or millimeter wave. The antennas providing transmitting and (or) receiving may be in the class of relatively narrow band. In those cases, where the carrier frequencies are shifted to a lower range, the antenna must be capable of operating with radio signals fractional bandwidth which

$$\frac{f_{\max}-f_{\min}}{0.5(f_{\max}+f_{\min})} \gg 1\,.$$

Antennas used in such radio facilities, have a number of significant differences from the traditional. There are currently substantial number research studies of such antennas, for example [2]–[4].

Basic fundamental difference of UWB antennas properties as part of radio facilities is that every antenna is characterized by changes in the frequency characteristics of the transmission and reception. In radio devices with a relatively narrow bandwidth such changes in the frequency band corresponding to the signal spectrum may be disregarded. For this reason, such indicators as the antenna pattern, antenna directivity are assumed constant in the frequency band signal and introduced to a monochromatic signal. For UWB radio antennas, these changes may be so significant that they cannot be neglected and it is necessary initially to reckon with the presence of a significant frequency dependence of the directional characteristics $F(\theta,\varphi,f)$. Under these conditions, it is possible to determine the directional properties of the antenna apart from the spectral composition of the emitted radio signal and a method of treatment in the receiving equipment. Therefore, the definition of the antenna pattern composed of UWB radios is ambiguous. Moreover, it is considered that in these circumstances, there may be a mismatch patterns in transmit and receive modes. The authors will illustrate the situation in a simplified presentation.

2. UWB Signals Transmitting and Receiving by Antennas

2.1. Transmit Mode

When the antenna radiates UWB signal with a spectrum $G(f)$, the intensity of the electric field in the direction (θ,φ) can be written as:

$$E(\theta,\varphi,f) = F(\theta,\varphi,f)G(f)\,. \tag{1}$$

To evaluate the integral effect is necessary to know exactly how to use the energy of the electromagnetic field in Eq. (1), which provides not enough information about the antenna already. Depending on the purpose of applying, the concept of the radiation pattern is filled with a different meaning. In some cases, in microwave technology, resulting effect may be evaluated by energy radiated signal in the direction (θ,φ):

$$\left|F_{UWB}^{TR.en}(\theta,\varphi,f)\right|^2 = \int\limits_{f_0-\Delta f}^{f_0+\Delta f} \left|F(\theta,\varphi,f)G(f)\right|^2 \mathrm{d}f\,, \tag{2}$$

where f_0 and $2\Delta f$ are the average frequency and the bandwidth of the transmitted signal.

The power of the received UWB signal can be viewed as the result of the linear filter with frequency response receiving device $K(f)$. In this case the antenna pattern in the transmission mode is defined as:

$$\left|F_{UWB}^{TR.sign}\right|^2 = \left|\int\limits_{f_0-\Delta f}^{f_0+\Delta f} F(\theta,\varphi,f)G(f)K(f)\mathrm{d}f\right|^2\,. \tag{3}$$

Difference in antenna pattern given by Eqs. (2) and (3) is evident. Also well visible is another fact – the directional properties of the antenna in the transmit mode to a certain extent depend on the properties of the receiver.

2.2. Receive Mode

The EMF is induced in the UWB antenna with a spectrum $G(f)$, and thus the radiation pattern in the receive mode, can be represented by the value $F(\theta,\varphi,f)G(f)$. The linear receiver performs the function of a weighted summation of the amplitudes of the oscillations in the band $[f_0-\Delta f, f_0+\Delta f]$ with frequency characteristics $K_{rec}(f)$. The radiation pattern in the receive mode may be determined by the resulting output of the received signal:

$$\left|F_{UWB}^{REC.sign}\right|^2 = \left|\int\limits_{f_0-\Delta f}^{f_0+\Delta f} F(\theta,\varphi,f)G(f)K(f)K_{rec}(f)\mathrm{d}f\right|^2\,. \tag{4}$$

Comparison of patterns of representations given by Eqs. (2)–(4) illustrates the well-known fact, which is treated as a contrast, in general, antenna pattern for UWB signals in the receive and transmit modes. To consider more stringent formulations the categories of antenna pattern, gain, as well as additional properties of UWB antennas as part of radio in the case of far field one can refer to article [2]–[4]. Behavior and properties of antennas in the area near the radiated field are not considered to date. In this paper some results for antenna arrays, focused on UWB signals are presented.

3. Antenna Arrays with UWB Radio Equipment

The antenna array in the near radiated field zone can be represented using a matrix model. As a partial result of these representations, it is possible to completely correct use of the current model as a linear combination of the partial patterns of array elements with weights with the physical meaning of radiating currents. For antenna arrays composed of UWB resources necessary to apply to a complete model of the array [5], [6].

Let us consider antenna array as a union of a finite number of emitters and switchgear (Fig. 1, U_f – incoming wave). For antenna arrays a matrix model with element wise account the effects of mutual coupling of emitters is sufficient, visual and convenient for practical use.

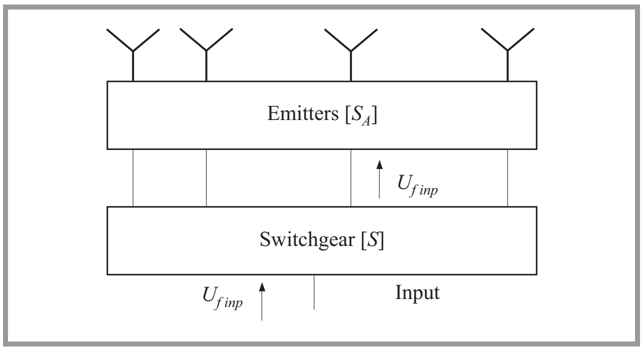

Fig. 1. Antenna array model.

According to the matrix model the distribution of the electric field generated by the emitters system in the near radiated field zone is determined by the scattering matrix of the inputs $[S_A(f)]$. The partial distribution of fields is corresponding to the antenna array element radiation pattern $e_i(x,y,z,f)$ when excited input unit incident wave in the presence of matched loads connected to the other input, and the scattering matrix switchgear $[S(f)]$.

$$[S(f)] = \begin{bmatrix} S_{11}^b(f) & S_{12}^b(f) \\ S_{21}^b(f) & S_{22}^b(f) \end{bmatrix}, \tag{5}$$

where $S_{11}^b(f)$ is an input reflection coefficient of the switchgear, $S_{21}^b(f)$ is the transmission coefficients from input to output and $S_{22}^b(f)$ is the transmission coefficients between the outputs. In addition $S_{12}^b(f) = S_{21}^b(f)$.

For a monochromatic signal with frequency f the spatial field distribution of the antenna array is represented as:

$$E(x,y,z,f) = \langle e(x,y,z,f) | U_f(f) \rangle \,, \tag{6}$$

where $|U_f(f)\rangle$ is the column vector of complex amplitudes of the incident waves at emitters entrance. Those values are determined by the properties of the emitters and the switchgear:

$$|U_f(f)\rangle = \frac{1}{E - [S^b_{22}(f)]\,[[S_A(f)]]} \, |S^b_{21}(f)\rangle \,. \tag{7}$$

Equations (6) and (7) give an accuracy sufficient for most practical purposes, to determine the strength of the electric field in the excitation input switchgear unit amplitude incident wave with frequency f. The representation for non monochromatic signal can be carried out based on the relations (2)–(4). Equations (6)–(7), together with (2)–(4) highlight the fundamental properties of the antenna consisting UWB radio: spatial distribution of the fields generated in the transmission mode and the corresponding parameters in the receiving mode depend (including the frequency dependency) of the scattering matrix dispenser. This means that these parameters cannot be identified apart from properties of the feeder devices in the array.

Accordingly, the current model of the antenna can be used only with certain assumptions. Formally, the spatial distributions of the fields produced by the antenna array in the zone near the radiated field, for each value of the frequency f. In the far field they may be determined as:

$$E(x,y,z,f) = \langle e_I(x,y,z,f) | I(f) \rangle \,, \tag{8}$$

where $\langle e_I(x,y,z,f)|$ is partial distribution of the fields of array elements defined with respect to single radiating currents in the emitter. The therm "formally" used in this case means that the properties of the array are not determined by its structural elements, but also of the declared frequency characteristics of the radiating currents $|I(f)\rangle$.

Thus Eqs. (6) and (7) together with (2)–(4) allow to determine the electromagnetic field in the near radiated field zone with used properties emitters of antenna array $\langle e(x,y,z,f)|$, $[S_A(f)]$ and the switchgear $[S(f)]$.

Subsequently, the analysis of the main differences between electromagnetic field focused using wideband signals and a monochromatic signal, use the concepts of current model taking into account the reservations made earlier in this paper.

4. Antenna Arrays

The ability to focus the radiation of the electromagnetic field in a certain region of space opens up a number of antenna technology capabilities. The task of building apertures focused, the purpose of operation and properties evaluation was in aim of many papers, for example [7], [8]. Generally, these studies examined organizations focused on the field of a monochromatic signal for coherent radiation of electromagnetic energy. In [9] the following properties of focused apertures are introduced and quantified: energy gain, stealth factor, and the dimension of the focus. Some of them, for distances up to the point of focus of 10 to 90 km, are represented in the Figs. 2 and 3.

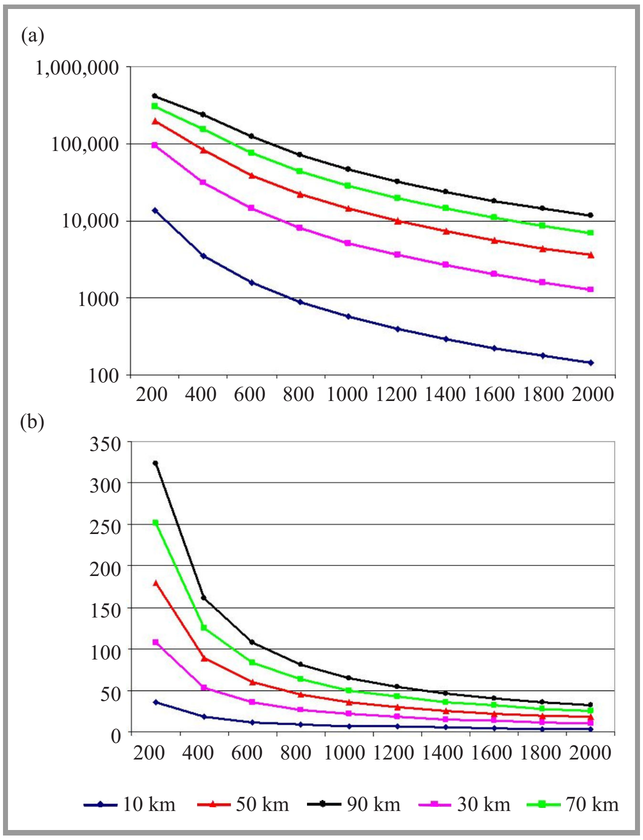

Fig. 2. The size of the area of focus: (a) lengthwise, (b) transverse. (See color pictures online at www.nit.eu/publications/journal-jtit)

The possibility of using wideband signals to solve focus problem opens up new possibilities in the construction of these systems. However, their technical implementation is determined by the properties of transmitters and receivers that work with broadband signals. Articles devoted to focusing on the UWB signals are not known to the general public. Hence, more details would be presented here.

4.1. Transmit Mode

For a discussion of the most significant properties of the focused UWB antenna arrays radio equipment, differentiating them from the case of monochromatic radiation signal, in the case of linear equidistant antenna array (Fig. 4) is considered. In such an area the representation of the electric field in the form is:

$$E_x(x,z,f) = \sum_{-N}^{N} I_n(f) e_{xn}(x,z,nd,f) \,, \tag{9}$$

$$E_x(x,z,f) = \sum_{-N}^{N} I_n(f) e_{zn}(x,z,nd,f) \,, \tag{10}$$

$$E(x,z,f)^2 = |e_x(x,z,f|^2 + |e_z(x,z,f)|^2 \,, \tag{11}$$

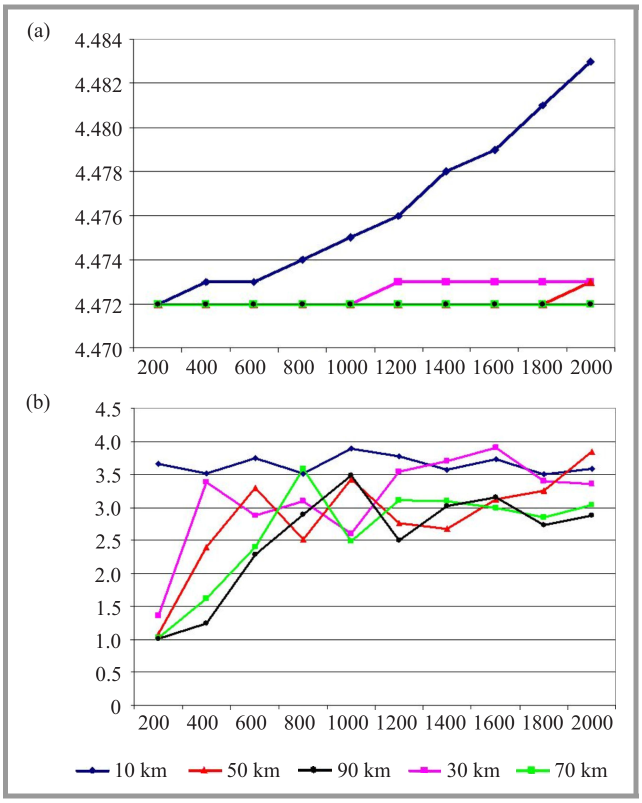

Fig. 3. Properties focused aperture coefficients: (a) efficiency, (b) secrecy.

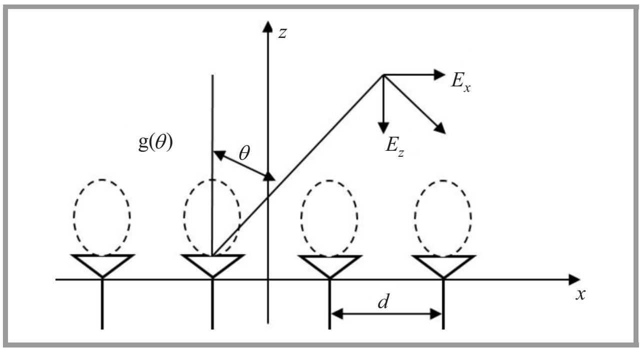

Fig. 4. Linear antenna array.

where:

$$e_{xn}(x,z,nd,f) = \\ = g\big(\theta(x,z,nd,f)\big)\cos\theta(x,z,nd)\frac{e^{jk(f)r}}{k(f)r(x)}, \qquad (12)$$

$$e_{zn}(x,z,nd,f) = \\ = g\big(\theta(x,z,nd,f)\big)\sin\theta(x,z,nd)\frac{e^{jk(f)r}}{k(f)r(x)}, \qquad (13)$$

$g(\theta)$ – the radiation pattern of the emitter

$$\arg\big(I_n(f)\big) = -k(f)r(x_0,z_0,nd). \qquad (14)$$

In many applications the most appropriate indicator of the properties of focused antenna array is the spatial distribution of the electromagnetic energy in the form given by Eq. (2). The picture of the spatial distribution of $|F_{UWB}^{TR.en}(\theta,\varphi,\Delta f)|^2$ to signal spectrum that is symmetric about the center frequency, in essential details similar repeats $E(x,z,f)^2$ at the central frequency signal spectrum is presented in Figs. 5 and 6. The most notable difference is specified for the gratings with a pitch of the order of a wavelength or more, for which there is some reduction in the far side lobes similar diffraction lobe in the antenna array pattern in the far field. In Figs. 5–6 the antenna array of 11 emitters with a pitch equal to the wavelength at the center frequency f_0 is used, radiation pattern of the element – $\cos\theta$, polarization – along the aperture, and the range of power-triangular. Focus point (0.5λ), (a) the relative bandwidth $\Delta f/f_0 = 0.01$, (b) $2\Delta f/f_0 = 0.5$.

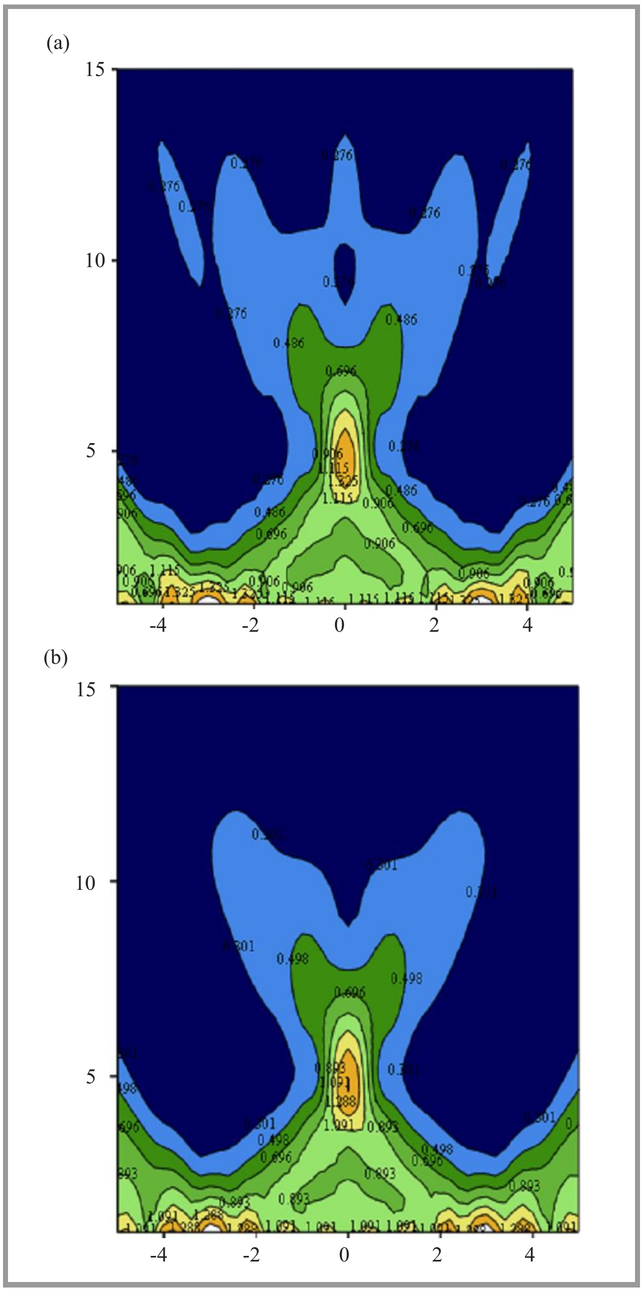

Fig. 5. Spatial distributions $|F_{UWB}^{TR.en}(\theta,\varphi,\Delta f)|^2$.

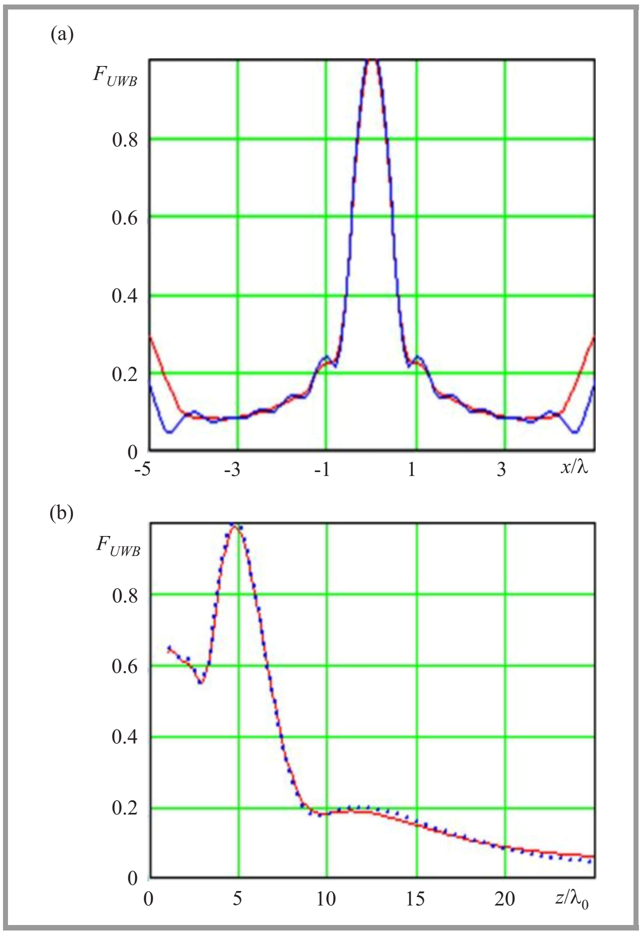

Fig. 6. Spatial distributions $|F_{UWB}^{TR.en}(\theta,\varphi,\Delta f)|^2$: (a) in a direction parallel to the aperture, (b) perpendicular to the aperture.

Thus, in a focused antenna array for broadband signals symmetric about the center frequency f_0 spectrum holds important feature: the spatial distribution of energy near the focus point substantially coincides in shape with the spatial distribution of the squared modulus of the electric field at f_0.

4.2. Receive Mode

Receiving UWB signals using multielement systems (MIMO technology) [10] can be carried out in various embodiments. In this section, the case when the antenna array is made the traditional way, and operates as part of an UWB receiver that linear filtering signals from its output (Fig. 7) is considered.

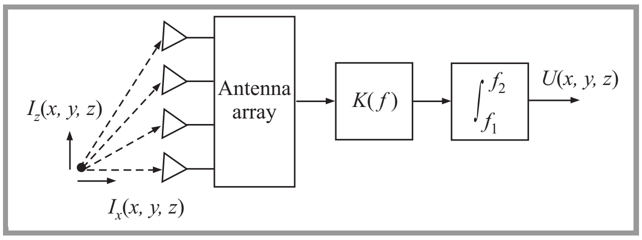

Fig. 7. Antenna array in receive mode.

For linear antenna the amplitude of the output signal $U_x(x,z)$ when receiving the radiation source with unit amplitude spectrum $G(f)$ (polarized parallel to the aperture and located at the point (x,z)) is:

$$U_x(x,z) = \int_{f_1}^{f_2} K(f)\,G(f) \sum_{-N}^{N} I_n(f)\, e_{xn}(x,z,nd,f)\,. \tag{15}$$

Similarly, for a source of polarized perpendicular to the aperture:

$$U_z(x,z) = \int_{f_1}^{f_2} K(f)\,G(f) \sum_{-N}^{N} I_n(f)\, e_{zn}(x,z,nd,f)\,. \tag{16}$$

Equations (15) and (16) characterize the spatial selectivity of the system “array plus receiver”. As can be seen from (15) and (16) directional properties depend not only on the parameters of the antenna array, i.e. array step and amplitude-phase distribution $I_n(f)$, $-N \le n \le N$, but also on the range signal $G(f)$ in the frequency band $f_1 \le f \le f_2$ and the weighting function $K(f)$.

The function defined spatial selectivity of the system in receiving mode should be different from the corresponding values for monochromatic signal at frequency f within a given band, characterized by values $E_x(x,z,f)$ and $E_z(x,z,f)$ – Eqs. (9)–(13).

Let us consider qualitatively essence of these differences, assuming that the amplitude distribution $I_n(f)$ does not depend on the frequency and phase – corresponds to the focus point $(0,z_0)$, located on the axis of symmetry of the antenna array in the direction normal to the aperture. In this case, antenna array receive only from the source of radiation polarized parallel to the aperture. The spatial characteristics of the electoral system in the receiving mode is the value of $U_x(x,z)$.

4.3. Characteristic Properties

In this subsection consideration of the characteristic properties and difference from the case radio reception focused grating monochromatic signal to conduct linear equidistant grating with a uniform frequency independent amplitude distribution is provided.

The character of magnitude changes $U_x(x,z)$ when receiving a wideband signal is characterized by a significant improvement in the focusing direction perpendicular to the aperture. Change in the plane parallel to the aperture is not so significant. The width of the main peak is located at a symmetric spectrum of the emitted signal. The side lobe levels are reduced and are almost unchanged. The noticeable decrease is in the side lobes arising from the lattice spacing a $0.7\ldots1$ wavelength at the average frequency spectrum of the signal – see Fig. 8.

The signal spectral composition is symmetric about the center frequency, as would be expected, and there has been a noticeable change in the peak width. The most significant changes are related to the side lobes levels for signals with

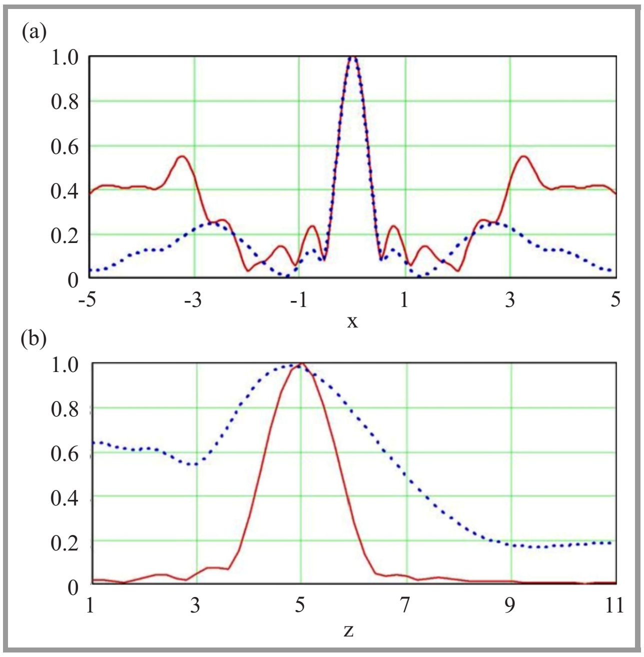

Fig. 8. The spatial dependence of the $U_x(x,z)$ amplitude for the monochromatic signal (solid line) and a wideband signal (dotted line) in the direction of: (a) a parallel aperture, (b) perpendicular to the aperture.

a predominance of high frequency components the sidelobe levels increase significantly with a slight decrease in the direction normal to the antenna – Fig. 9.

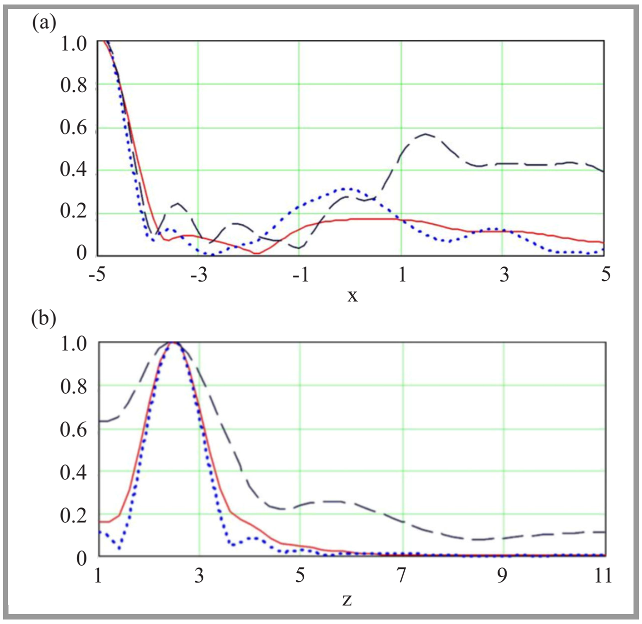

Fig. 9. Functions: (a) $U_x(x,z_0)$, and (b) $U_x(0,z)$ in a monochromatic signal (dashed line) and the signal with the spectrum of type $1-f/f_0$ (solid line) and f/f_0 (dotted line).

The type of used weight function also significantly affects the characteristic spatial selectivity. In assessing this effect it makes sense to compare the two versions of the weighting functions: $K(f)=1$ (the receiver with a uni-

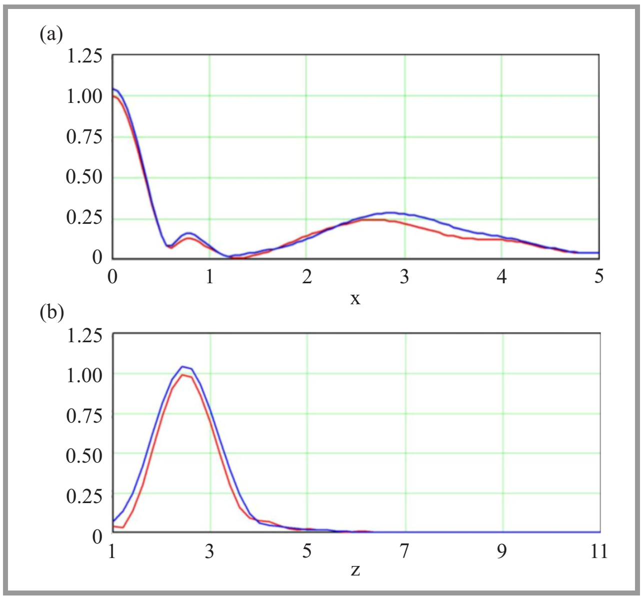

Fig. 10. Curves of: (a) $U_x(x,z_0)$ and (b) $U_x(0,z)$ for the processing of the received signal with a uniform and matched filtering.

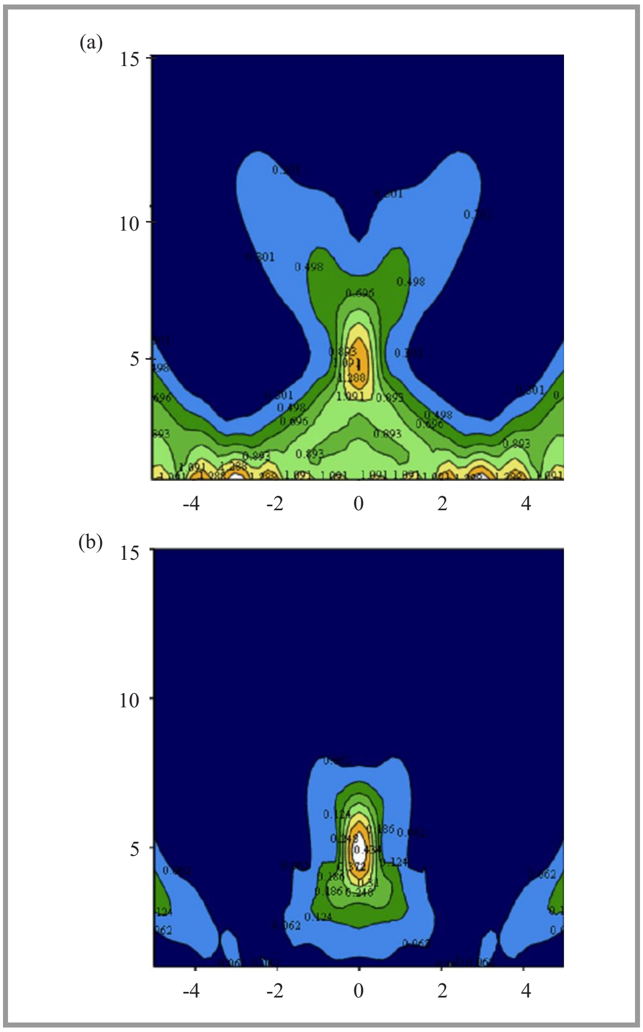

Fig. 11. Curves of: (a) $U_x(x,z_0)$ and (b) $U_x(0,z)$ for the processing of the received signal with a uniform and matched filtering.

form frequency response) and $K(f) = |G(f)|$, corresponding to the matched filtering case. As the assessment conducted under symmetric spectral function $G(f)$, the difference from the functions of spatial selectivity $U_x(x,z)$ at the uniform and consistent filtration is not observed. However, as one would expect the level of $U_x(x,z)$ is at the focal point above – Fig. 10.

5. Conclusions

To sum up, once again draw attention to the difference function, which characterizes the spatial selectivity in receiving mode $|F_{UWB}^{REC}|^2 = |U_x(x,z)|^2$ and functions $|F_{UWB}^{TR.en}(\theta,\varphi,f)|^2$, determining the spatial distribution of energy in the transmit mode. One can see, that at wide band signal, this difference can be considerable (Fig. 11).

In all cases, the antenna array consisted of 11 emitters with a uniform amplitude distribution and orientation diagrammatic form $\cos\theta$ increments of the wavelength is focused on the axis of symmetry at a distance of five wavelengths. The signal spectrum is triangular in the band of $\pm 5\%\ f_0$ (narrowband) and $\pm 25\%\ f_0$ (broadband). In the transmission mode field distribution in space – energy EMF. In receive mode, and in the same conditions, but in the assumption of the matched filter with a frequency response spectrum of the signal, and when receiving basic components of the field, i.e. antenna is oriented to receive the main components.

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