Ultrawideband antenna arrays based on planar combined antennas for the frequency range of 3.1-10.6 GHz

E V Balzovsky, Y I Buyanov and V I Koshelev
Microwave electronics laboratory, Institute of High Current Electronics SB RAS, Tomsk, Russia
E-mail: koshelev@lhfe.hcei.tsc.ru

Abstract. The characteristics of ultrawideband antenna arrays, the element of which is a planar combined antenna with an operating frequency band of 3.1-10.6 GHz, are studied. The results of time-domain studies for a four-element linear array, as well as for a dual polarized module consisting of 2×2 antennas, are presented. The antenna array element is a combination of electric and magnetic radiators. The combined antenna is printed on a dielectric plate with a size of 20×30 mm.

1. Introduction
Currently, many researchers are developing ultrawideband (UWB) antenna arrays capable to radiate (or record) simultaneously two orthogonal components of the electric field strength vector $E$. In an urban area or office environment, this approach allows decreasing the instability of communication link by receiving radiation of arbitrary polarization. Recording of two mutually perpendicular UWB components of the pulse field reflected from the object allows obtaining additional information about the object under study when solving recognition problems in radar [1].

For the construction of dual polarized arrays, it is promising to use arrays of crossed active dipoles [2], in which the combination of the phase centers of dipoles is provided. However, active dipoles are only receiving ones. Planar TSA-antennas are used in dual polarized arrays, operating in both receiving and transmitting modes. TSA-antennas contain a tapered slot line cut through a metal plate. The slot line is excited by an intersecting microstrip line. The combination of phase centers of TSA-antennas due to the use of crossed antennas with such a topology of the electrodes is difficult. Thus, the TSA-antennas in the array are arranged as a honeycomb structure of rectangular cross-section [3, 4]. In directions other than the normal to the array plane there is a time shift between the orthogonal components of the vector $E$. This time shift is a disadvantage of such type of arrangement of elements. The minimum distance between the elements in this case is determined by the transverse size (aperture) of the TSA-antenna, which is usually half the wavelength at the lower frequency ($\lambda_L$) of the operating band, and the longitudinal size of the antenna is equal to several $\lambda_L$ [5].

Reducing the dimension of the antenna can be achieved by using a combination of electric and magnetic radiators. Due to the selection of the necessary ratio between the moments of electric and magnetic currents [6], the reactive energy in the near zone of the antenna is minimized. Therefore, the range of matching the antenna with the feeder is expanded. When designing an antenna, electric and magnetic radiators are located in close proximity to each other. The mutual orientation of these radiators ensures the same polarization of the field irradiated by each radiator.
Combining of the radiators allows not only providing the matching in a wide frequency band, but also forming a cardioid radiation pattern. A three-dimensional UWB combined antenna with a maximum size of 0.2\( \lambda_0 \) constructed on this principle is presented in [7]. The use of the principle of combining radiators made it possible to develop a planar printed antenna for operation in the frequency range of 3.1–10.6 GHz [8]. The antenna has a transverse aperture size of 0.3\( \lambda_0 \) and in the direction of wave propagation it has a size of 0.2\( \lambda_0 \). It is of interest to use such a small-sized antenna as a part of a dual polarized array. This paper presents the results of studies of the developed combined planar antenna as a part of a four-element linear array and one cell of a dual polarized array.

2. Single antenna

The developed planar combined antenna is made by printing circuit board technology on a Rogers RO3210 dielectric plate with a dielectric constant of 10.2. The plate has dimensions of 30\( \times \)20\( \times \)1.27 mm. From one of the edges, it is equipped with an SMA connector. The geometry of the antenna electrodes is shown in Figure 1a. The direction of the main maximum of radiation is indicated by an arrow.

The antenna is a combination of radiators. The electric radiator is made in the form of a planar dipole with arms 1 and 2, the inner edges of which form a smoothly expanding slot. The magnetic radiator 3 is made as a polyhedral slot in the metal of the dipole arm 1. The input of the electric radiator is connected to the trailing edge of the plate by a slot line of variable cross-section 4. The input of the magnetic radiator is connected to the trailing edge of the plate by a slot line 5.

To increase the wave impedance of the slot line 5, a part of the dielectric is removed by means of drilled through holes. The electrical length of the slot line 4 exceeds the electrical length of the line 5 by (0.15–0.2) \( \lambda_0 \). Near the trailing edge, the slotted lines 4 and 5 form an asymmetric coplanar line. The central electrode of the coaxial connector is attached to this asymmetric coplanar line. In the metal of the dipole arm 2, a hole 6 is made, connected by a slot with the lower edge of the antenna. The slot in the arm 1 and the protrusions in the line 5 serve to ensure the matching of the antenna with the 50-ohm feeder in the upper part of the frequency range.

The antenna parameters measured in the frequency domain are given in detail in [8]. The antenna is matched with the feeder by the level of VSWR = 2 in the frequency band of 2.6–10.8 GHz. To measure the flatness of the gain and linearity of phase, two antennas were placed opposite each other at a distance of about 1 m. A vector circuit analyzer was used to measure the complex transmission coefficient of a four-pole consisting of the input port of the transmitting antenna and the output port of the receiving antenna.

In the frequency band of 2.8–9.3 GHz, the magnitude of the transmission coefficient of such a four-pole varies within \( \pm 3 \) dB. In the range of 3.1–10.6 GHz, the difference between the measured argument of transmission coefficient and the linear dependence does not exceed \( \pm 24^\circ \). The average gain is 4.13 dB. The radiation of the antenna in the direction of the pattern main lobe is linearly polarized. The polarization decoupling has a value of at least 25 dB in the range of 2.5–8 GHz and at least 15 dB in the range of 8-11 GHz, respectively. The arrangement of antennas in the linear array is shown in Figure 1b. Antennas in dual polarized array are shown in Figure 1c.

The properties of a planar combined antenna are investigated in the time domain. In the study of the transmission mode, a 0.2 ns bipolar voltage pulse generator was used to excite a single antenna. The radiated signal was recorded using a TEM-antenna and a stroboscopic oscilloscope with a band of 12 GHz. The waveform of the generator pulse is shown in Figure 2a, curve 2. The waveform of the pulse (curve 3) radiated by a three-dimensional combined antenna [9] is shown there as well. The bandwidth of three-dimensional combined antenna is much more wider and better corresponds to the spectrum of the exposing pulse than the same one of the plane antenna. The frequency spectrum of the generator pulse is wider than the bandwidth of the plane antenna under study. For this reason, distortions of the waveform are observed. The distortions represent a decrease in the first time lobe in waveform and an increase in the third time lobe in comparison with the three-dimensional combined antenna [9], in which the bandwidth more widely corresponds to the spectrum of the exciting pulse.
In order to approach the spectrum of the excited pulse as close as possible to the range of 3.1–10.6 GHz, a pulse former was simulated and manufactured. The pulse former is based on segments of open ended microstrip lines. A pulse with four time lobes was synthesized using a pulse former connected to the output of the generator. The waveform of such a pulse is shown in Figure 2b, curve 1. The waveforms of the pulses radiated by the planar antenna under study and the three-dimensional combined antenna [9] are shown in Figure 2b, curves 2 and 3, respectively.

When studying the properties of the antenna in the receiving mode, a three-dimensional combined antenna was used as a transmitting one. Figure 3a, shows the waveform of the pulses recorded by the developed planar antenna (curves 1) and by the TEM-antenna (curves 2) when the transmitting antenna is exposed to a bipolar voltage pulse. Figure 3b, shows the waveform of the pulses recorded by the same set of antennas when the transmitting antenna is excited by a pulse with four time lobes. To quantify the difference between the waveforms of two functions \( A(t) \) and \( B(t) \), the root-mean-square deviation is used:

\[
\sigma = \sqrt{\frac{\int_T (a(t) - b(t - \tau))^2 dt}{\int_T a^2(t) dt}},
\]

where \( a(t) = A(t)\sqrt{\int_T A^2(t)} \) and \( b(t) = B(t)\sqrt{\int_T B^2(t)} \) are normalized functions; \( T \) is the time interval at which the comparison is made; \( \tau \) is the time shift of \( b(t) \) relative to \( a(t) \), at which \( \sigma \) takes the minimum value. The difference in the shape of the waveforms 1 and 2 shown in Figure 3b is estimated by the numerical value \( \sigma = 0.38 \) according to the criterion mentioned above.

Directional properties of the antenna studied in the time domain. The pattern in the receiving mode of the antenna under test is defined as the angular dependence of the peak power at the matched antenna output. Figure 4 shows the pattern of the developed antenna in the receiving mode in two orthogonal planes when the transmitting antenna is excited by a pulse containing four time lobes. The azimuth angle \( \varphi \) and elevation angle \( \delta \) are counted from the direction of the main maximum of the pattern. The pattern in the transmission mode is defined as the angular dependence of the peak radiated power at the receiving point when the antenna under study is excited from the pulse generator. In this case the TEM-antenna is used as a receiving one. With the exciting pulse containing four time lobes, the patterns of the antenna in the receiving and the transmitting mode are slightly different. Figure 5 shows the angular dependence of the root-mean-square deviation \( \sigma \) calculated by expression (1) when \( A(t) \) is the recorded waveform in the pattern main lobe direction and \( B(t) \) is the recorded waveform in the arbitrary direction. It was found that \( \sigma \) does not exceed the value of 0.2 within the half-power beam width. The radiation of the developed antenna is linearly polarized. The electric field vector \( E \) is parallel to the long edge of the antenna.
Figure 2. Voltage pulse at the input of the antennas (1); a pulse radiated by a planar antenna (2); a pulse radiated by a three-dimensional combined antenna (3). Antennas are excited by a bipolar voltage pulse (a) and a pulse containing four time lobes (b).

Figure 3. Waveforms of the pulses recorded by the planar antenna (1) and TEM-antenna (2).

Polarization decoupling \( s \) is the ratio of the peak power of the main polarization signal to the peak power of the cross-polarized signal during the pulse. In the direction of the main maximum \( s \geq 25 \text{ dB} \). These data obtained during measurements in the time domain are consistent with the results of measurements in the frequency domain [8]. In the receiving mode, \( s \) of a single antenna also exceeds the value of 25 dB.

Figure 4. The pattern of the planar antenna in the \( H \)- and \( E \)-plane (curves 1 and 2, respectively).

Figure 5. Angular dependence of the root-mean-square deviation of the recorded signal waveform on the signal waveform in the main direction. \( H \)-plane (1), \( E \)-plane (2).
3. Antenna arrays

An in-phase linear array consisting of four planar combined antennas has been studied. The arrangement of elements in the array is shown in Figure 1b. The distance d between the array elements varied within the following limits: from \( d = 9 \) mm, determined by the size of the SMA connector, up to \( d = 30 \) mm. Figure 6 shows the antenna array pattern by peak power in the receiving mode at \( d = 9, 15 \) and 30 mm. These values of \( d \) correspond to \( \frac{1}{3}, \frac{1}{2} \) and one wavelength at the upper frequency (10.6 GHz) of the antenna bandwidth. A three-dimensional antenna [9] excited by a voltage pulse with four time lobes was used as a transmitting one. An increasing of the distance between the elements results in an increasing of the array directivity. The angular sector with stable waveform of the recorded pulses decreases with increasing of \( d \). Figure 7 shows the dependence of the root-mean-square deviation of the waveform of the recorded pulses in different directions in contrast with the pulse waveform in the main direction. Within the pattern width by half-power, the distortion of the pulse waveforms recorded by the array at different \( d \) does not exceed \( \sigma = 0.2 \).

The properties of the cell of the dual polarized array are studied. The location of the antennas in such an array is shown in Figure 1c. The distance between the antennas was equal to \( d = 32 \) mm, which is approximately equal to \( 0.33\lambda_L \) at the lower frequency (3.1 GHz) of the given range. Special attention is paid to the mutual influence of antennas due to reradiating energy to each other. To estimate the mutual influence of antennas in the receiving mode, the polarization decoupling \( s \) of two antenna arrays was compared. One of them is a linear in-phase array consisting of two antennas 1 in Figure 1 (c), in the absence of antennas 2. The second array is a cell of the dual polarized array, in which both antennas 1 and antennas 2 are present in Figure 1c. A three-dimensional antenna [9] excited by a bipolar voltage pulse was used as a transmitting one. The measurement results are shown in Figure 8. In the direction of the main maximum, \( s \) of the linear array has a maximum. The level of cross-polarized radiation increases with a deviation from the direction of the main maximum. For a cell of the dual polarized array, this trend persists too. The difference in the curves in Figure 8 is comparable to the measurement error, so we can conclude that the mutual influence of the perpendicular elements of the dual polarized antenna array is negligible.

![Figure 6](image1.png)

**Figure 6.** The pattern of the linear array in the \( H \)-plane at a distance between the elements \( d = 9, 15, \) and 30 mm (curves 1–3, respectively).

![Figure 7](image2.png)

**Figure 7.** Angular dependence of the root-mean-square deviation of the recorded signal waveform on the signal waveform in the main direction in the \( H \)-plane at \( d = 9, 15 \) and 30 mm (curves 1–3, respectively).
4. Conclusion
The characteristics of antenna arrays based on the planar combined antenna as an antenna element were studied. The operating frequency band of examined antenna arrays is equal to 3.1–10.6 GHz. The developed ultrawideband antenna can be used as an element of a dual polarized array with a distance between the elements equal to one-third of the wavelength at the lower frequency of the range. The planar combined antenna is designed to radiate or record orthogonal components of the electric field strength vector, as well as to work as a part of a linear antenna array with a distance between the elements equal to one-third of the wavelength at the upper frequency of the specified range.

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