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Array radio imaging based on heterodyne detection with application of the continuous-wave radar technique

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A new approach to the creation of millimeter-wave radio imaging systems is proposed. This approach is based on the use of an array receiver consisting of a densely packed (pixel size of 4 mm) array of planar mixers located in the focal plane of a quasi-optical objective, with application of the frequency-modulated continuous-wave radar technique. It has been demonstrated that the implementation of the heterodyne type of reception makes it possible to increase the distance range of the array radio imaging system up to ~ 100 m while maintaining the angular resolution at the previous level.

Keywords: millimeter-wave imaging, frequency-modulated continuous-wave (FMCW) radar, focal-plane array (FPA) receiver

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The millimeter-wave radio imaging systems combine high resolution with low absorption in the atmosphere and in many other media and materials [1,2]. This is why the millimeter-wave range is in many cases optimal for radio imaging tasks.

The simplest design is inherent to receiving systems based on the principle of direct detection when only the amplitude of the radio signal is measured [3,4]. In this case, the receiver output voltage is proportional to the received signal power that quite sharply depends on distance R, being proportional to $1/R^4$. The rapid decrease in the output signal with increasing distance causes the maintenance of the distance range of the detector-type systems at the level of a few meters, which is insufficient in a number of tasks.

The heterodyne-type receivers are more sensitive; their output voltage is determined by the amplitude of the received signal mixed with the heterodyne signal. Such receivers have found wide application in radar and radio communication systems. However, the use of the heterodyne-type receivers in constructing array radio imaging systems faces serious difficulties connected with creating a densely packed array of receiving elements and with distributing the heterodyne power among a great number of elements.

In this paper, a possible case of the heterodyne-type array radio imaging system has been proposed and experimentally studied. The achievable characteristics of this system have been determined.

As the basic approach to creating the heterodyne-type array radio imaging system, the technique of continuous-wave radar with linear frequency modulation was chosen [5–7]. This approach is based on using as the heterodyne signal a part of the transmitted wave power (replica). Thuswise, the received and reference signals are coherent, which prevents the influence of the oscillator phase noise on the quality of reception. The frequency modulation makes the received and reference signals different in frequency; this is why not the constant signal but the difference-frequency signal is to be amplified at the mixer output, which is more convenient in many cases. Using the difference frequency, it is possible to determine the distance to the reflector, which enables obtaining three-dimensional image of the scene.

Fig. 1 presents a schematic picture of the system under study. As a source of millimeter waves, a W-band backward-wave oscillator is used. The oscillator power in the vicinity of the operating frequency, which is 94 GHz, is 10 mW. A sawtooth frequency modulation with the peak-to-peak amplitude $B = 576$ MHz was used. The oscillator power is

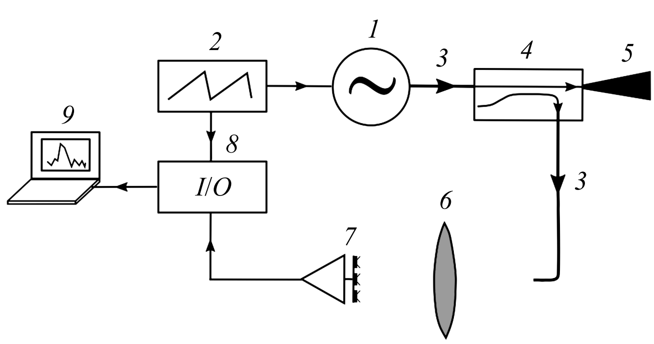

Figure 1. Schematic diagram of the heterodyne-type radio imaging system. *1* — W-band backward-wave oscillator, *2* — generator of special waveforms, *3* — metal waveguides, *4* — directional coupler, *5* — conical horn antenna, *6* — dielectric lens, *7* — three-element array receiver, *8* — input/output device, *9* — notebook.

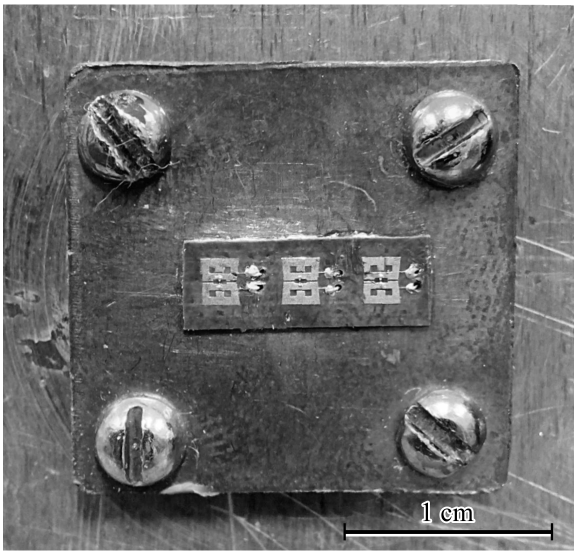

Figure 2. A photo of the high-frequency part of the three-element array receiver.

divided into two almost equal parts by using a directional coupler. One of those parts is fed to the conical horn antenna for illuminating the scene, while the other part is used as the receiver heterodyne signal. The scene image in the plane where the array receiver is located is formed by a quasi-optical objective that is an aspheric lens 10 cm in diameter [8]. The lens focal length is 100 mm. The size of the lens focal spot is about 4 mm, which complies with the size of the receiving matrix pixel. The heterodyne signal is fed to the array directly from the waveguide open end placed into the dielectric lens focus on the side of the scene. This is how the amplitude and phase uniformity of the array illuminating with the reference radiation is ensured.

To study the basic characteristics of the system being developed, an array receiver [9] consisting of three planar mixers arranged in line was used (Fig. 2). The design of each receiving element is as a whole identical to that of the single-element receiver described in [10]. The receiving element relies on a planar structure consisting in a low-barrier Schottky diode built in the modified slot antenna. The array pixel size is 4 mm in both directions. The examination of the system characteristics was preceded by its calibration during which nonuniformity of the receiving elements sensitivity, as well as nonuniformity of illuminating the receiving elements with the reference radiation, was eliminated programmatically.

The proposed radio imaging technique allows obtaining 3D scene images: the two-dimensional image is formed by the quasi-optical objective, while the information on the distances to the objects is acquired by analyzing the phase of the difference-frequency signal. Thus, it is necessary to consider two quantities characterizing the system resolution: angular resolution and radial resolution.

To study the angular resolution, two identical reflectors located equidistantly from the system objective ($R = 374$ cm) were used. Each reflector was a convex aspheric metallized surface 10 cm in diameter mounted on dielectric racks. In the initial position, two reflectors were maximally close to each other; the useful signal existed only in the central receiving element. When the angular distance between the reflectors was varied (with the step of 0.6°), the signal was transferred from the central receiving element to the lateral ones and then went beyond the array viewing angle. Two reflectors became distinguishable at the angle of 3.1° between them. In this arrangement, the amplitude at the lateral receiving elements was about $2-3$ times higher than that at the central element. Thus, the established angular resolution of the system was no worse than 3°.

The radial resolution was studied by using an almost the same arrangement of the radio imaging system and reflectors. The difference was that the reflectors were installed at the constant (minimum possible) angular distance from each other, while the radial distance between them was varied (one of the reflectors was displaced towards the radio imaging system). The experiment employed only the central receiving element. When the reflectors are closely spaced, the spectrum of the receiving element output signal contains only one line at the frequency corresponding to the mean distance to the reflectors. Beginning from a certain distance between the reflectors, the spectrum line splits into two lines, each of them corresponding to its own reflector. The reflectors were shown to become distinguishable at the radial distance of $z = 30$ cm between them. This value is in good agreement with value $\delta R = 26$ cm obtained from the commonly known relation for radial resolution of the continuous-wave radar with linear frequency modulation $\delta R = c/(2B)$ [5], where c is the light velocity in vacuum.

The distance range of the radio imaging system was studied in a long corridor. The system was installed at one end of the corridor; the reflector was moved from the system location to the opposite end of the corridor by using a mobile tripod. The experimental data were obtained along the distance of up to 40 m where the useful signal became equal to the level of signals from undesirable re-reflections mainly from the walls, ceiling and floor. Under more favorable experimental conditions, a distance range of up to 100 m (depending on the receiver noise level) may be reached.

In the described experiments, the angular resolution and distance range were studied independently: the angular resolution was measured at a short distance, while the distance range was studied in the single-element reception mode. To validate the compliance between the obtained characteristics, a demonstrative experiment was performed in which both parameters were tested simultaneously: the experiment was devoted to distinguishing a small object against the background of a large one at a distance of several tens of meters.

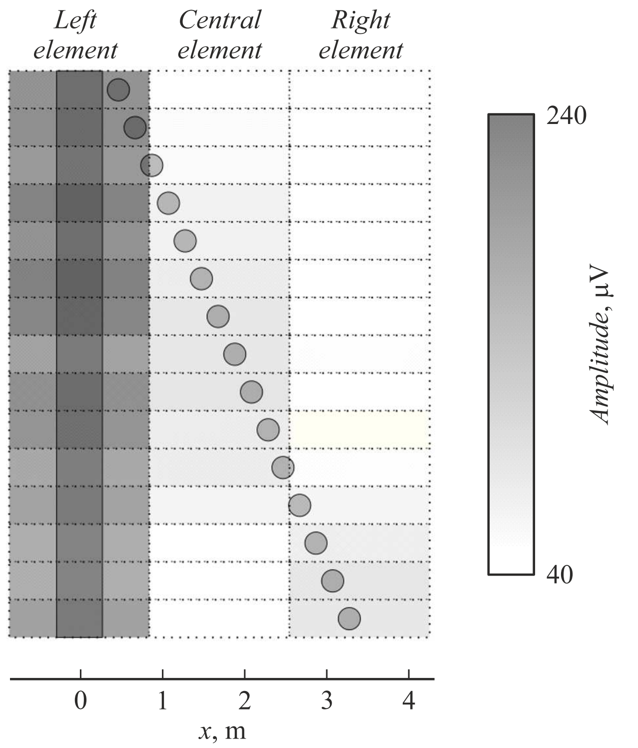

Figure 3. Amplitude of the difference-frequency signal at the array receiver elements versus the spherical reflector position x. The shaded rectangular represents the pole, dark circles represent the reflector in different positions. Dashed lines conditionally subdivide the space region into sections corresponding to each of three array pixels.

The experiment configuration was as follows. The radio imaging system was installed in front of an open window at the second floor of the building. The only reflecting object visible to the radio imaging system was a pole 0.6 m in diameter. The distance between the system objective and pole was 44 m. The receiving array was located in the lens focal plane so that the maximum amplitude of the difference-frequency signal was reached at the left receiving element. Other receiving elements were free of the useful signal. Then, a reflector in the form of a spherical segment 60 cm in curvature radius and 30 cm in base diameter was attached to the pole with a thin lumber. The initial distance between the pole center and reflector center was $x = 50$ cm (the first row in Fig. 3). At each measurement step, the reflector was displaced away from the pole by $\Delta x = 20$ cm, and amplitude spectra of difference-frequency signals at each receiving element were measured (Fig. 3). The final distance was $x = 330$ cm (the last row in Fig. 3). The experimental results showed that the pole and moving reflector become distinguishable at $x > 270$ cm. To make this value comparable with results of the experiment performed inside the room, it has to be decreased by 30 cm. This is because the side areas of the pole also participate in the signal reflection, therefore, in this case the real distance between the objects was the distance between their boundaries but not centers. Thus, the minimal angle at which the pole and reflector are distinguishable from each other was $\theta = 3.2^\circ$ that is in good agreement with the value obtained in the experiment at a short distance.

Thus, in this work a new approach to creating millimeter-wave radio imaging systems was proposed and experimentally demonstrated. Due to using the heterodyne-type signal reception, it is possible to essentially improve the array receiver sensitivity and, hence, to increase the distance range of the radio imaging system by more than an order of magnitude. This allows us to assume the possibility of creating millimeter-wave radio imaging systems with the operating distance of up to several hundreds of meters.

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Conflict of interests

The authors declare that they have no conflict of interests.

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