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Environmental Monitoring Using Smart Millimeter Wave Antennas

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Abstract: The principles of construction of smart antennas for small-sized radio systems in the millimeter wave band on the basis of open radiating structures are considered. It includes active semiconductor elements that provide generation, emission into space and reception of signals scattered from objects in a single device. The presented materials are of interest for developers of small-scale radar facilities of millimeter range, for example radars for preventing collisions of vehicles, as well as communication systems.

Keywords: radar, millimeter wave band, small-sized radio system, open radiating structures, detection.

I. INTRODUCTION

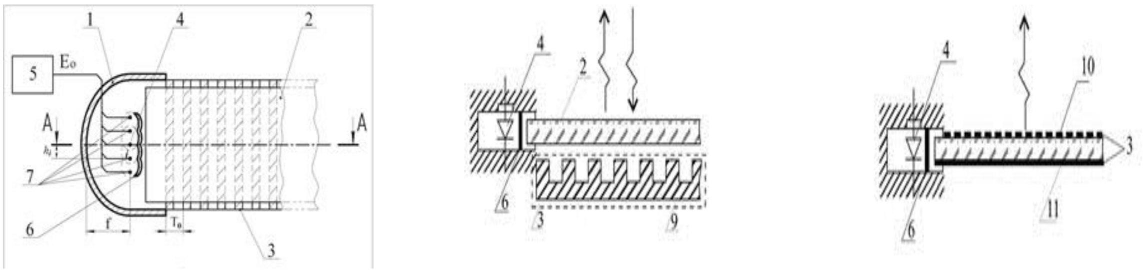
Currently, optical and infrared devices are most widely used for solving surveillance (reconnaissance) and targeting problems. With their help, it is possible to obtain excellent characteristics for measuring angular coordinates. However, they have serious disadvantages in determining range. In addition, their effectiveness is significantly reduced at night and in poor weather conditions (haze, fog, rain, snow, sandstorms, etc.). Using radio waves to solve the problem of environmental monitoring allows us to solve this problem. However, to obtain approximately the same accuracy in measuring angular coordinates as in the optical and IR wavelength ranges with antenna sizes acceptable for on-board systems, it is necessary to use short wavelengths, for example millimeter wavelengths, which are now used in short-range radar systems at ranges when the attenuation of radio waves in this range under bad weather conditions it still has an acceptable value. When creating on-board short- and ultra-short-range millimeter-wave radar systems, problems arise related to the need to minimize the dimensions and weight of devices. This led, in due time, to the emergence of autodyne-type transceiver systems, which have the simplest design [1-3]. The operating principle of these devices is based on the autodyne effect, which consists of changes in the oscillator parameters under the influence of its own radiation reflected from the location object or information radiation from a third-party source. The self-oscillator in these devices simultaneously performs the functions of a radio transmitter and receiver. The simplicity of the design of autodynes ensures their low cost, small dimensions and weight of transceiver modules, which has led to their widespread use in non-contact object indicators, speed and distance meters [1-2], and non-destructive testing sensors [3].

A further development was the creation of smart (intelligent) antennas [4-7], which in a single module combine generation and reception devices, and also provide radiation into space and reception of signals. Such devices are called active antennas. This paper examines the construction of intelligent or smart antennas for small-sized short-range radar systems.

II. OPEN RADIATING SYSTEM

Such devices are implemented in the form of an open radiating system. They are intended for use in microwave technology, namely, in transceiver devices based on open resonant emitting systems such as diffraction gratings with semiconductor diodes and can find application in mobile communication systems, radar, radio vision, etc. It contains - Fig. 1a the first reflector 1, which is made in the form of a segment of a parabolic cylinder with a rectangular opening.

A planar dielectric waveguide 2 is introduced into it. A periodic structure 3 is placed near its wide face. A semiconductor generator diode (Gunn) 4 is located on the focal axis of the parabolic cylinder and is connected to the supply voltage source. It performs the function of generating an electromagnetic wave, which, propagating along a planar waveguide, powers a periodic structure in the form of diffraction or strip gratings, through which it is emitted into space. Those. The periodic structure performs the function of converting a surface wave in a planar waveguide into a spatial one, which is radiated into space. In addition, it ensures the transformation of the received spatial wave from volumetric to surface, which is supplied through a planar waveguide to mixing diodes -7. They are located in the focal plane at certain distances from the generator diode. Each of them is connected to the corresponding output of the bias voltage source and the input of the Doppler frequency amplifier.



a) b) c)

Fig.1. General view of the smart antenna: a-top view; b - smart antenna side view with a periodic system in the form of a diffraction reflective grating -9; c - smart antenna with a periodic system in the form of a ribbon array -10 with a metal screen -11; 1 - parabolic reflector, 2 - planar waveguide, 3 - periodic structure, 4 - generator diode, 5 - bias voltage source, 6 - second reflector, 7 - mixing diodes

The power source of the generator diode can modulate its power supply to form the required type of radiation (pulsed, continuous, frequency modulated). The displacement of the mixing diodes relative to the focal axis of the parabolic cylinder leads to the fact that the beam is focused on them, which is deflected relative to the axis of the slow-wave system by an angle $\psi_i \approx \frac{h_i}{F_0}$, which is determined by the geometric displacement of the i-th diode relative to the focal axis h_i and the focal length F_0. In this case, the projection of the period T_0 of the diffraction grating onto the direction of wave propagation in the i diode $T_i = T_0 / \cos(\psi_i)$ will determine the angle of deflection of the beam by the diffraction grating relative to its normal [8-10].

The beam deflection angle for the *i*-th diode will be determined:

$$\theta_{i\,m} = ar\cos\left(n' - \frac{\lambda}{T_0}\cos\left(\frac{h_i}{F_0}\right)\right), \qquad (1)$$

where n' is the refractive index of the planar waveguide material.

In the millimeter wave range, polystyrene or fluoroplastic is usually used for its production. Having small losses.

The second reflector - 6 relative to the diodes is located on the side opposite to the first. In this case, the diodes are located on the focal axes of the second reflector. It can be made in the form of segments of elliptical cylinders - Fig. 1a, or segments of elliptical cylinders, each of which consists of metal rods 6 - Fig. 1b, c (the depth of immersion of which can vary). This makes it possible to adjust the connection between the generator and mixing diodes, i.e., the level of the reference heterodyne signal necessary for superheterodyne reception. The first focal axes of each of the segments of the second reflector coincide with the location of the generator first diode, and the second focal axis of each of the segments coincides with the location of the corresponding mixing diode. The periodic structure can be made in the form of a reflective diffraction grating 9 - Fig. 1 b, or in the form of a strip grating 10 - Fig. 1c, located on the wide edge of a planar dielectric waveguide, the opposite edge of which lies on the metal substrate -11. In this case, for the manufacture of a tape slow-down system and a planar dielectric waveguide, double-sided fluoroplastic foil can be used.

By choosing the law for changing the depth of the slits of the reflective grating or changing the distance between it and the planar waveguide, the field distribution on the radiating aperture can be controlled. To fully utilize the aperture, it is necessary to achieve uniform field distribution across it. To do this, the distance between the first elements of the slow-wave system and the planar waveguide must be greater, decreasing as we move towards more distant slits. Thus compensating for the increase in coupling, the decrease due to the radiation of the slits into the space of the level propagating along the planar waveguide of the field. Since the field of a surface wave when contained by a diffraction grating decreases exponentially. Then, to equalize the feeding of the slits, the change in the distance between the planar waveguide and the radiating slits should be approximately the same. For strip gratings, the field distribution at the emitting aperture can be adjusted by changing the width of the emitting slits.

III. SMART SYSTEM RANGE

For diffraction gratings that convert a surface wave into a volume wave, difficulties will arise when implementing long antenna arrays. Since in this case it will be quite difficult to achieve a uniform field distribution over the aperture. At the same time, antennas with a length of up to 250λ [11] have actually been implemented for airfield surveillance radars, i.e. on a wave of 8mm, about 2m long and 0.2m wide, i.e. 25λ. At the same time, their radiation pattern width in azimuth was about $\Delta\theta$=5mrad, and the elevation angle was about $\Delta\beta$=50mrad. When using such antennas, the error in determining the azimuthal bearing can be about 0.05 mrad, i.e. approximately 5cm for every kilometer of distance. In terms of elevation, the error will be approximately 10 times higher. The antenna gain without taking into account losses in the planar waveguide will be determined as

$$G = \frac{4\pi}{\Delta\theta\Delta\beta} \tag{1}$$

and will be about 47dB.

We will assume that the radar receiver bandwidth is consistent with the spectrum width of the signal reflected from the object. In the millimeter range, the width of the housing line of reflections from airborne objects does not exceed ΔF = 10Hz. The noise level referred to the antenna input is:

$$P_N = kT\Delta FN \tag{2}$$

where $k \approx 1.38*10^{-23}$ W/Hz×deg is Boltzmann's constant, T is the absolute noise temperature in degrees Kelvin, N is the noise factor of the receiving device referred to the input, ΔF is the bandwidth of the receiving device.

Under normal conditions T =20+273≈300° K for calculations you can take $kT \approx 4\times10^{-21}$ W/Hz. which corresponds to dB -204dB/W Hz. At 10Hz bandwidth this would be -194dB/W. The given noise figures for 8 mm range mixing diodes are about 10 dB. Modern powers of solid-state generators at 8mm wavelength are up to 1…10 W. The reduced noise figure of mixing diodes does not exceed 10 dB. Since to detect a non-fluctuating target with a probability of correct detection [13] D = 0.9 and a false alarm $F = 10^{-3}$ in Gaussian noise, the required signal-to-noise ratio μ is approximately 13 dB, the minimum detectable threshold signal will be approximately -171 dB/ W. The signal-to-noise ratio μ at the input for monostatic systems can be written from the radar equation [12, 13]:

$$\mu = \frac{\Pi}{R^4} F_{TrT}^2 F_{Tr}^2\ \sigma_T \tag{3}$$

where R is the range to the observation object with RCS σ_T, F_{TrT}^2, F_{Tr}^2 are the signal attenuation factors on the path between the transmitter– Tr/receiver– R and the target– T. For monostatic radars they are the same when detecting, for example, air targets at high altitudes approximately equal to 1. . Π -potential of the system, determined by the power of the transmitter P_{Tr}, the noise level of the receiverP_N, the characteristics of the antenna system and the wavelength of the radar radiation λ [12, 13]:

$$\Pi = \frac{P_{Tr} G_{Tr} G_r \lambda^2}{P_N (4\pi)^3} \tag{4}$$

Monostatic systems use one antenna for transmitting G_{Tr} and receiving G_r. Therefore $G_{Tr} = G_r$.

Relation (4) allows us to estimate the requirements for the radar potential depending on the required target detection range μ=13 dB or the range at which the accuracy of measuring its bearing is ensured at approximately 1/100 of the radiation pattern width μ=40 dB, and the realized radar potential can be calculate using (3). Estimates show that even when using antennas with apertures of 0.5 m×0.2 m and generators with an average radiation power of about 0.1 W, it is possible to detect and estimate the angular coordinates of objects with an RCS of more than 0.1 m^2 at ranges of several kilometers.

IV. CONCLUSION

The proposed smart antenna allows the formation of multi-lobe radiation patterns when emitting and receiving signals by using the resonant properties of diffraction gratings loaded on active semiconductor elements (Gunn generator diodes and mixing diodes with a Schottky barrier). This makes it possible to implement in one structure the generation, emission into space and reception of reflected secondary fields, which significantly reduces the dimensions, weight and cost of the device and allows its use in short-range on-board radio systems. Such systems will make it possible to implement environmental monitoring at distances of several kilometers. The proposed smart antennas can be used not only in the construction of on-board radar systems, but also in duplex communication systems.

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