Revolutionary Developments in Phased Arrays

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High Gain Antenna Systems for Millimeter Wave Radars with Combined Electronical and Mechanical Beam Steering

A. A. Tolkachev, V. V. Denisenko, A. V. Shishlov, and A. G. Shubov

JSC "RADIOPHYZIKA", 10, Geroev Panfilovtsev St.
P.O. Box 1, Moscow 123363, RUSSIA
E-mail: apex@glas.apc.org

Abstract— Antenna systems for millimeter waves (MMW), considered in this paper, are large plane phased array antennas, installed on two axis angular positioners. This combination provides mechanical scanning in upper hemisphere along with electronical scanning in a given conical scan sector. The modular (subarray) structure is the basis of designing the arrays described. The array architecture and achievable performances are discussed. Key elements developed for Ka-band arrays are presented.

INTRODUCTION

MMW-radars were mainly developed till now for short range coverage systems (10 - 50 km). To detect and to track objects at middle (50 - 200 km) and long (200 - 1000 km and more) range coverage, centimeter- and decimeter-wave radars are usually used. However, it ought to outline that application of MMW-radars for measurements of objects provides more high accuracy, makes it possible to detect objects of smaller sizes, allows to increase ability of their resolution and to determine a structure of complicated objects. Significant improvement in interference immunity of radar also is achieved.

A decrease of antenna size in MMW allows on the one hand to make compact high gain antennas suitable for compact radars, and on the other hand makes it possible to create large antenna systems with top performances hard-to-reach at more low frequencies.

The merits of MMW for the applications, pointed out above, have been demonstrated, for example, by the MMW-radar created by USA at the Kwajalein Atoll [1]. This radar operates in the Ka-band at the wavelength about 8 mm. It has a reflector antenna of 13.7 m in diameter, which gives the gain about 70 dBi.

Being the outstanding example, this radar, however, provides, at best, trajectory measurements of one target only, because the antenna has no quick inertialess beam steering. The angular velocity of beam steering yielded by the mechanical rotation of the antenna is up to 12° per second, which is, naturally, near top value for antennas of such a large size. The possibility of increasing the size of reflector in such systems is also limited, because in this case the mass of construction must be increased abruptly to provide the required high precision of reflector's surface. Detecting and tracking a target by such supernarrow mechanically steered beam proves to be very complicated.

The next problem is transmission of high average- and peak-power signals from high power amplifier (HPA) to antenna. Usually, a complicated quasi-optical beam waveguide or multimode waveguide passed through a pedestal of antenna is needed. Arrangement of MMW HPA directly near a feed of reflector is complicated too. In particular, it is very difficult nowadays to install a HPA with a gyroklystron on the pedestal near reflector.

The problems outlined above also restrict an application of large reflector antennas supplied with small arrays as feeds providing a narrow-angle electronical beam steering (so called hybrid antennas [2]).

Alternatively, the development of advanced technologies for MMW-components, such as compact phase shifters, HPA based on TWT and klystrons, transistor and parametric low noise amplifiers (LNA), as well as the development of other elements, makes it possible nowadays to built MMW radars with large high gain arrays (including active arrays) which have electronical beam steering in a limited area. As large phased arrays, especially in MMW, are very expensive antennas, we think, rather than create the radar with several arrays faced the opposite sides to cover the whole upper hemisphere, the array should be installed on a mechanical positioner, as well as the array must operate both on transmission and on reception.

The main problems of creating the high gain MMW phased arrays for radars are considered in the paper presented.

THE KEY FEATURES OF THE ARRAYS PROPOSED

Main requirements

As the arrays in question are intended for long and middle range radars, the main requirements can be formulated as follows:

- high gain (40 - 70 dBi),
- wide scan sector, up to the upper hemisphere (including limited electronical scanning),
- high radiated power (10^3 - 10^7 W),
- low noise temperature ($< 500^\circ$ K),
- narrow beam ($< 1^\circ$),
- operation at transmission and reception,
- fast electronical beam steering (30 - 100 μs),
- bandwidth up to 1 GHz,
- forming a bundle of scanning beams at reception and capability of widening of beam at transmission.

These requirements can be complied with an array of modular architecture composed of subarrays.

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Modular architecture of the array

The array is constructed of transmitting/receiving modules (TRMs), which really are separately fed and controlled antennas, having the aperture size of 0.4 - 0.6 m. Such unified modules are rather small ones and can be simply manufactured, adjusted and tested at a plant with required accuracy.

Each TRM can be connected to a HPA and a LNA. Therefore, the transmitter and the receiver of radar are distributed over the array and, hence, have the modular structure too.

Receiving branches of TRMs can be connected to a beam forming network (BFN), which forms a bundle of beams.

If a limited angular sector of electronical scanning is acceptable, the array can be constructed of TRMs made in form of reflector antennas. This provides the most simple construction of the array with the best energy efficiency and capability of electronical scanning inside a main lobe of the TRM's pattern. We call such a TRM as TRM of the 1-st type, which has not a beam steering.

If a more wide angular sector of electronical beam steering is needed, the TRM is to be made with scanning beam. Such a TRM should be made as an array itself. This TRM is called here as TRM of the 2-nd type. The number of phase controls in the TRM is defined by a sector of electronical beam steering [3].

All the TRMs, receivers and transmitters are installed on a rigid frame, which provides an acceptable accuracy of their mutual positioning.

Geometry of grid

The TRMs can be arranged in nodes of both rectangular and hexagonal grids, as shown in Fig.1

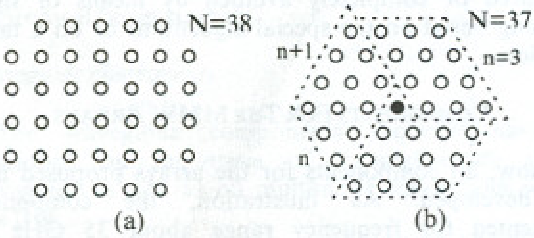

Fig. 1. Structures of rectangular (a) and hexagonal (b) grids.

The former is more convenient for excitation and control of TRMs by rows and columns. Its boundary can be modified in form of a polygon to reduce side lobes.

The latter has advantage of reduced number of elements (for the same scanning area and size of array) and, hence, allows to increase their aperture sizes which are important for arrangement of transmitters, receivers and other equipment. Besides, in this case, the aperture of every TRM can have a form of right hexagon, providing its effective illumination by a quasi-optical feed with an axisymmetrical pattern.

In the case of hexagonal grid with a right hexagon boundary, the number of TRMs in the array is defined by the following expression [4]:

$$N=1+3n(n+1),$$

where n is an integer. For $n = 1, 2, 3, ...$, the N is equal to 7, 19, 37, ..., respectively, which are "hexagonal" numbers. One can see that the array has a central element surrounded by "rings", and n can be interpreted as a number of rings of the array. The number of elements in every ring is equal to $M = 6n$.

On the other hand, the hexagonal grid can be presented as a package of the central element and three arrays in form of identical parallelograms twisted by 120 degrees to each other, as shown in Fig.1(b). Each parallelogram contains $K = n(n+1)$ elements, arranged over n rows and $n+1$ columns. This feature can be used for excitation, control, and monitoring by rows and columns inside these three parts of the array.

Feeding system

Apertures of TRMs are illuminated by quasi-optic feeders. In the 1-st type module, a two-reflector antenna with shaped surfaces providing a uniform illumination of aperture is preferable.

In case of the 2-nd type TRM, the array of reflective type with a quasi-optical exciter is preferable too, because the number of elements in the array of TRM can be up to several thousands, i.e. too much for individual excitation by a waveguide power divider. In array of reflective type, all the phase control elements can be packed closely together because control circuits and cells are arranged behind the array aperture. This gives advantage of more wide electronic beam scanning.

Though the compact packaging of elements in feedthrough-type MMW array is more complicated, our investigations have shown that it can be also realized by using small subarrays inside the TRM.

The TRMs are to be fed coherently from a master oscillator through a power divider. As the size of array equals to many hundreds of wavelengths, a single-mode rectangular waveguide has too high loss and is not effective. Multimode waveguide transmission lines, despite design problems, seems to be more efficient, because they have low loss and are more compact than beam-waveguides.

Return signal received and amplified after TRMs can be delivered to BFN through both waveguides and cables. The latter case is reasonable, if the signal is down-converted after LNAs, to perform a beam-forming at an intermediate frequency. Furthermore, analog-to-digital conversion of the signal can be preferable. In this case, a digital BFN is to be used.

Transmission and reception overlapping

To operate both on transmission and on reception, each TRM should be connected to HPA and LNA through a duplexer. In case of a single linear polarization, a ferrite circulator can be used for this purpose.

If a circular polarization is chosen, the assembly of 90-polarizer in circular waveguide and orthomode transducer (OMT) is more preferable because of low loss, good matching and simple construction.

If dual-polarization operation both on transmission and on reception is required, combinations of the circuits described above can be used.

Combination of electronical and mechanical scanning

The angular area of electronical beam steering depends on the TRM's construction. In case of the 1-st type TRM, the scan sector is defined by the main lobe of TRM. HPBW of the lobe is 55 - 85 angular minutes, which is the scan area.

If the 2-nd type TRM is used, the capability of electron beam scanning depends on element spacing in the array. Really, the ±(30° - 45°) scanning in MMW arrays is achievable.

To provide scanning in the whole upper hemisphere, the array is installed on a pedestal with a two axis angular positioner.

It is very important not to fix precisely, but to measure and to predict accurately an angular position of the array, because this position is needed to calculate phases in array elements for required beam pointing at the moment when the signal can reach a target [5].

The former condition can be provided by two angular sensors of high precision. The latter condition imposes requirement on the mechanical positioner which must rotate the array quietly, without vibrations and jumps. The motors without gearing, so called momentum-motors, are the most suitable for this purpose.

Beam steering and control

Control signals to phase shifters are formed in the beam steering controller (BSC) of array. If the second type TRMs are used, their multielement arrays must be supplied with local BSCs. Control networks can be arranged using the row-column technique.

All the BSCs and other controlled equipment of the antenna system is to be connected to a common bus.

Test and adjustment

To provide phasing of array in case of the second type TRM, original phases of ferrite phase shifters should be measured and taken into account.

To adjust phases of TRMs in the whole array, a source with test equipment installed, for example, on the tower can be used.

Discussion

It should be outlined that all the principles formulated above are well known in individual cases. However, being combined together these principles offer ample scope for progress in MMW large array antennas.

The considered modular array antenna, as compared with an antenna system based on a single large reflector, has the following advantages, which are in fact advantages of arrays compared to reflector antennas:

- electronical beam steering combined with mechanical beam scanning improves capability for detection and tracking of targets;
- capabilities of beam shaping and beam reconfiguration combined with its scanning are provided;
- it is possible to form several separately steered beams both on transmission and on reception;
- a lot of unified elements: TRMs, amplifiers, waveguide components, etc., can be applied in the antenna; this gives possibility to create arrays of various sizes assembled of the unified elements;
- lower requirements to the frame geometry and the array assembly precision can be formulated, due to both its flat form, which is more simple compared to shaped surface of a large reflector, and the capability of electronic phasing of the TRMs;
- HPAs are distributed over the whole aperture of array; this allows to avoid an application of superhigh power transmission lines and to increase the radiated power due to combining of output powers of HPAs on the air;

On the whole, application of phased arrays in MMW as well as in other frequency bands impart high flexibility to radar. This corresponds to the main tendency of development of advanced radars with powerful computer systems.

The following disadvantages of such antenna system also should be mentioned:

- the antenna system has comparatively high cost;
- the construction of antenna has a big mass;
- gain control circuits and phase control circuits should be used in TRMs to compensate amplitude and phase deviations and to equalize illumination of the aperture;
- there are grating lobes in pattern of the array, which exceed essentially an average level of side lobes, if special techniques are not used.

Nevertheless, the architecture of the antenna system proposed provides, probably, the cheapest construction of MMW radar with the specifications described.

The grating lobe level can be reduced by means of decrease of gapes between TRMs as well as by uniform illumination of the TRM apertures. In case of beam steering, the technique of grating lobe suppression can be based on the use of the elements with flat-topped patterns formed due to mutual coupling between them [2,3]. The injurious effects of the grating lobes on radar operation can be reduced or completely avoided by means of signal processing based on the special algorithms or on a target indication.

COMPONENTS FOR THE MMW ARRAYS

By now, all components for the arrays proposed have been developed. As illustration, the components implemented for frequency range about 35 GHz are considered below.

Transmission/reception modules

The reflector antenna with shaped surfaces [6] and dual-mode feed horn for the TRM of the 1-st type with 0.6 m diameter is shown in Fig.2. The gain is about 45 dBi and HPBW about 50 ang. min. The TRM can be employed in rectangular array. The hexagonal analog of the TRM is also available.

The experimental model of the 2-nd type TRM [7] is shown in Fig.3. It is the hexagonal array of reflective type containing about 3600 waveguide-dielectric elements with the spacing about 1.1 of wavelength. The elements form the flat-topped patterns which suppress the grating lobes [3]. The array has the aperture 0.64 m in diameter (inscribed circle) illuminated effectively by the exciter containing horn, shaped subreflector and the perforated metallic radome [8].

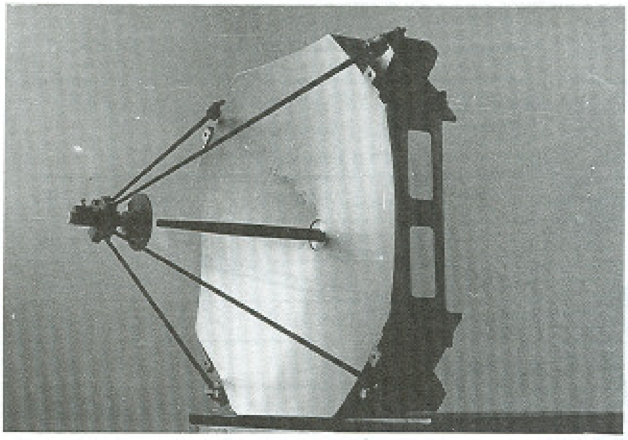

Fig. 2. TRM of the 1-st type: shaped dual reflector antenna

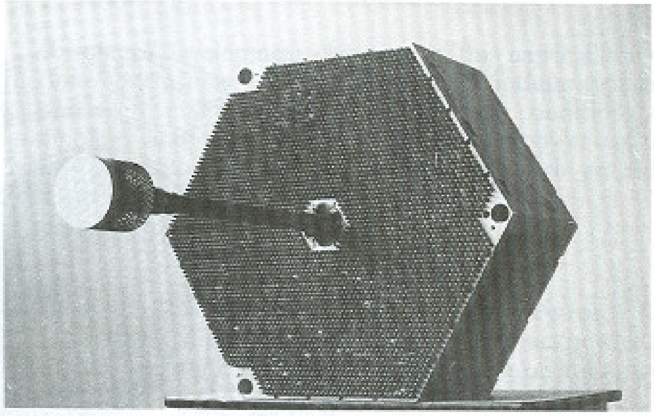

Fig. 3. TRM of the 2-nd type: reflective phased array antenna

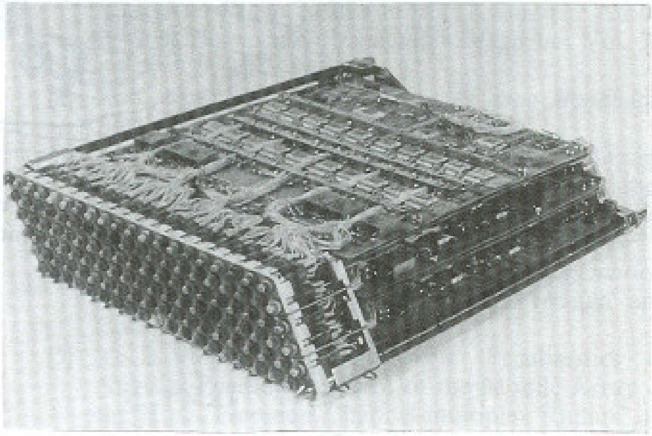

Fig. 4. Subarray containing 120 ferrite phase shifters and control cells arranged over 20 rows and 6 columns

Electronical beam steering is provided by latched ferrite phase shifters of the Faradey type, which are assembled in subarrays combined with the control cells, as shown in Fig. 4, [9]. The subarrays are assembled in the three blocks, as shown in the Fig. 1(b). The blocks contain n = 35 rows and n+1 = 36 columns. All the subarrays are controlled by the local BSC of the TRM. Inside the subarray the elements are controlled in series by rows and in parallel by columns. The cells provide the 3-bit individual phase control of elements. Switching time is about 30 µs.

Being under tests and adjustment now, the TRM is expected to provide electronical beam scanning in the cone ± 25° with HPBW about 0.9° and maximum gain 40-42 dBi. It is capable to operate at RHCP on transmission and at LHCP on reception.

The upgraded subarray based on the modified more thin phase shifters is also under development now for the TRM of 0.44 m. in diameter. Elements of the array have the spacing about 0.86 wavelengths providing ± 40° electronical beam steering.

Waveguide components

The waveguide components required have been developed on the basis of a single-mode standard waveguide as well as on multimode waveguides with low loss [10].

Amplifiers

The travelling wave tubes (TWT) and klystrons for HPAs of various output pulse-power (from 10 to $2\text{x}10^4$ W) with reasonable amplitude and phase stability have been developed. They are compact, rigid and reliable to operate in a rotating array.

Transistor and parametric amplifiers supplied with anti-transmit - receive switches are suitable to be used as LNAs.

Beam-forming network

As mentioned above, the output signals in Rx-branches of array can be translated both at MMW and at intermediate frequency or in a digital form.

The quasi-optic BFN of the Rotman type for Ka-band with 120 inputs and 5 outputs has been developed. The more compact 850 MHz BFN based on microstrip technology has been developed, too. Certainly, a digital BFN in form of FFT-processor can be also implemented.

EXAMPLES OF MODULAR ARRAYS UNDER DEVELOPMENT

Large array of the radar for global space monitoring

The radar is intended to detect, track and catalogue space debris objects (down to 1 cm in size) in the near space at the range coverage up to 1000 km [11].

The aperture aperture is a hexagon with cut off corners as shown in the Fig. 5. The array is protected by the radome about 33 m in diameter. The forming of two polarizations is performed by using of two HPA and two LNA connected to the each TRM. Example of the block-diagram is shown in the Fig.6. Phase controls φ_T provide beam steering on transmission, 1-bit phase shifters φ_P provide polarization switching, controls φ_{R1} and φ_{R2} form the two independent beams at orthogonal polarizations on reception. HPAs on klystrons with output power about 20 kW each supply the total radiated pulse power of about 17 MW, which is at about 3 order more than in radars available. Main parameters of the array for this radar are presented in the Table 1.

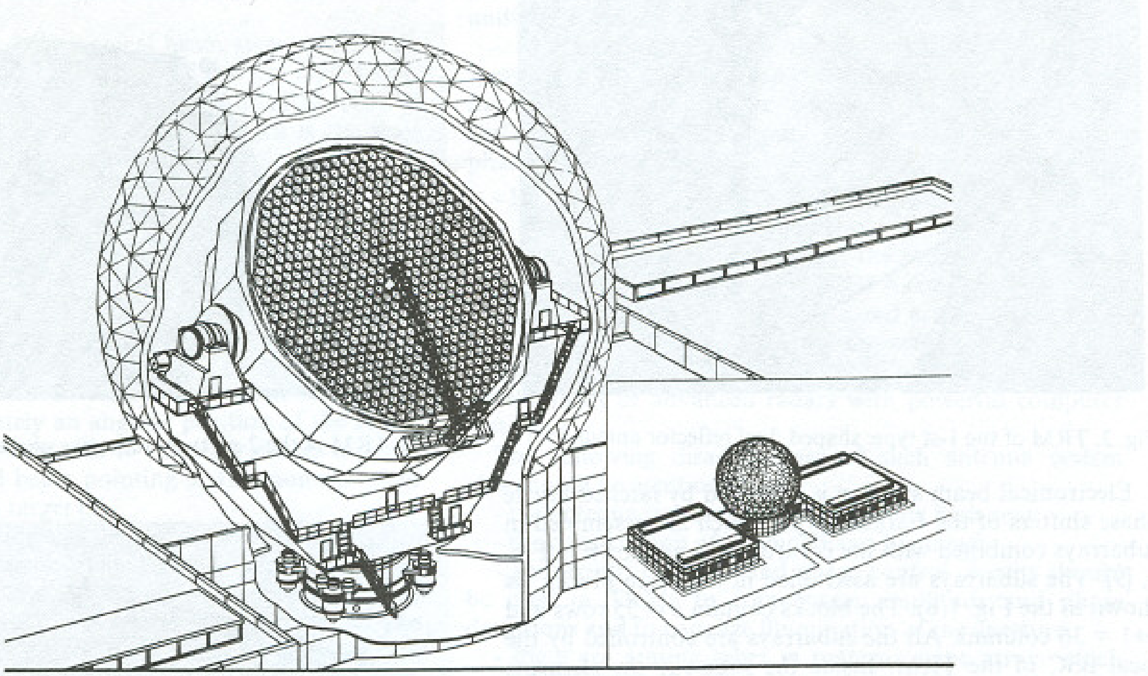

Fig. 5. The general view of the radar for global space monitoring.

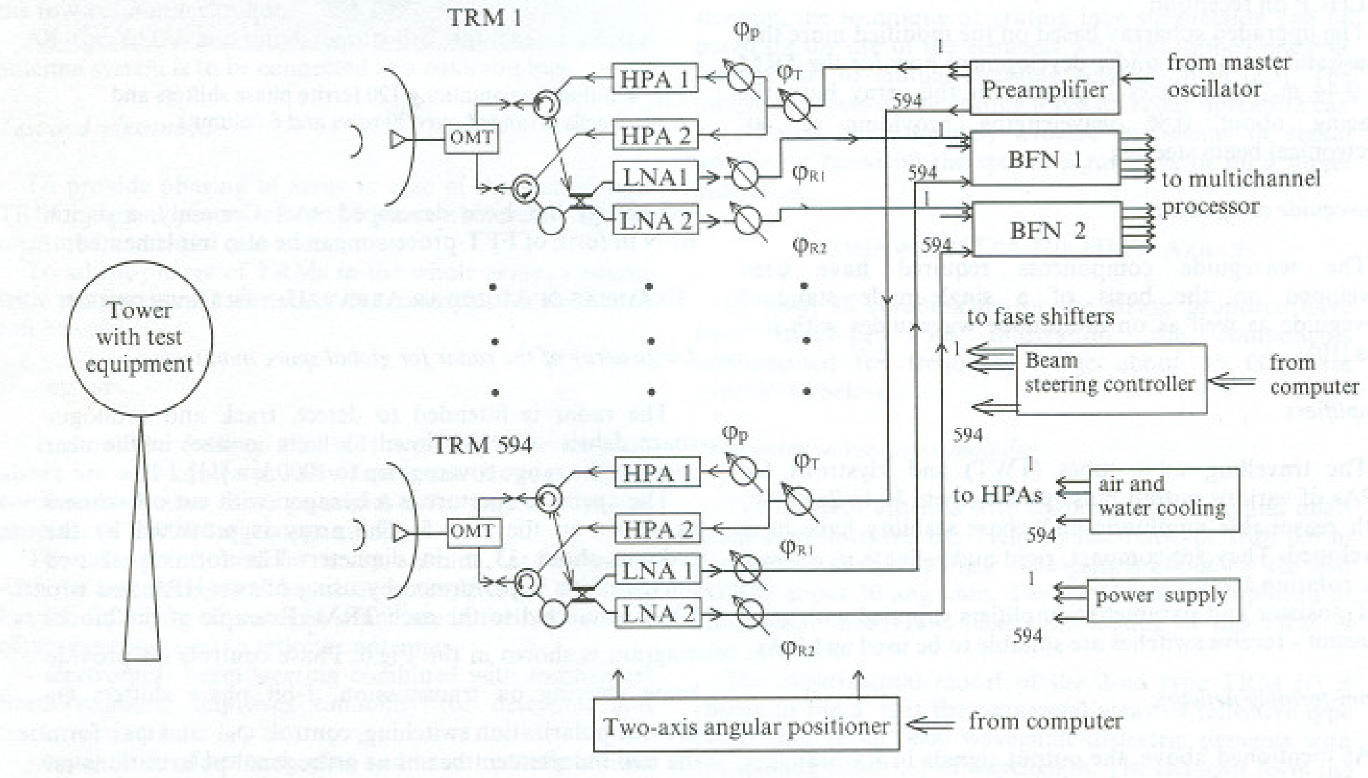

Fig.6. Block-diagram of antenna system for the space-monitoring radar

TABLE I
Prognosticated Parameters of The Phased Array Antennas

Parameters	Array for the global space monitoring radar	Array for the air traffic control radar
TRM size, m	∅0.64 (1st type)	∅0.44 (2nd type)
Number of TRMs	594	7
Aperture size , m	16.9	1.3
Polarization	RHCP&LHCP	RHCP/LHCP
Freq. range, GHz	34.5	34.5
Freq. band, MHz	300	50
HPBW, ang. min.	2	27
Electr. beam steering sector	0.9°	80°
Switching time, μs	30	30
Gain Tx, dBi	72	44.5
Gain Rx, dBi	71.3	44
Output power, W	$1.7 \cdot 10^7$	$1.5 \cdot 10^3$
Inp. noise temp.	< 450°K	< 500°K
Number of Rx-beams	5	5

Array of the radar for air traffic control

Array for the radar intended, for example, for detection and tracking of many aircrafts (including their landing) can be made of the TRMs of the 2-nd type [12]. As an example, parameters of the array composed of small TRMs based on upgraded subarrays are presented in the Table 1. The HPAs of 200 W output power are used in the array. The array contains 7 TRMs. Only one HPA (and LNA) is connected to each TRM as opposed to the array for space monitoring radar.

Other modifications of the MMW arrays

Arrays based on the architecture proposed and the components developed can be implemented in many versions. For instance, arrays containing 7,19,37, etc. TRMs of the 2-nd type can be used in multifunctional radars.

One further possibility is to use for a small radar only one TRM or assembly of several TRMs of the 2-nd type supplied with one common quasi-optical monopulse feed as an antenna in its own right for a short range coverage radar.

The examples considered above were develop for Ka-band, but the same philosophy seems to be applied for more high frequency bands. The most particularly promising is the W-band near 95 GHz.

Conclusion

Results of development presented in this paper allow to definite conclusions that MMW arrays of modular type are attractive in many applications. There are conditions of technology and experience of creating high power radars which allow to develop and manufacture such antenna systems in the coming years.

Acknowledgment

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