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RADAR AND COMMUNICATION SYSTEMS: SOME TRENDS OF DEVELOPMENT

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"Looking into the sky, don't forget to look underfoot."
Folk aphorism

Introduction

Progress of modern radio and electronic technologies involves a great number of innovations. Digital methods for signal synthesis and processing have the most significance among the innovations. At the same time, it seems that two specific tendencies, related to radar as well as to communications, may be singled out:

– using of high-frequency ranges (short-centimeter wave band and millimeter-wave band);
– creation of the solid-state active phased-array antennas (APAA).

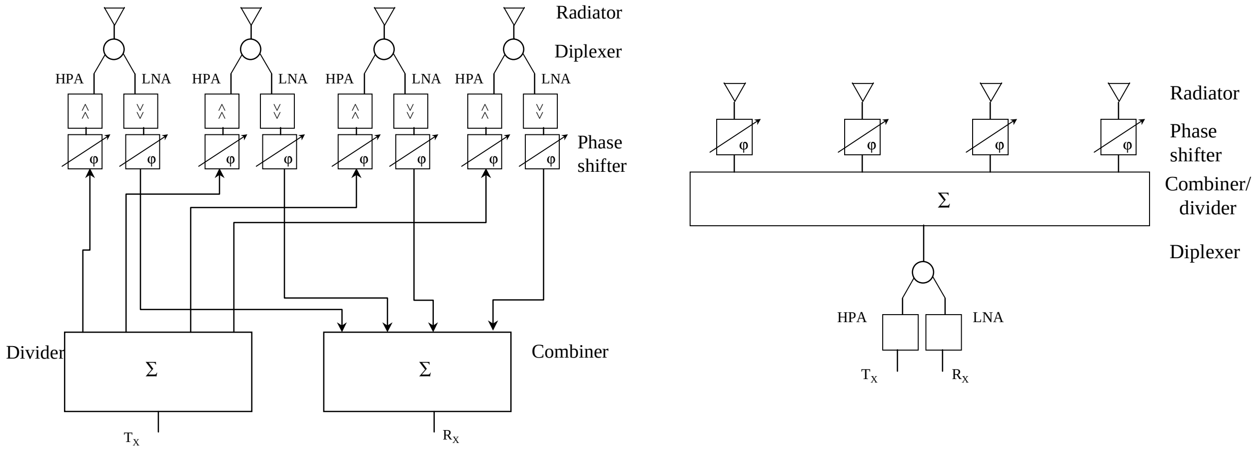
The first of the tendencies has originated from the middle of the twentieth century. It is connected with the striving to increase selectivity and measurement accuracy of radar systems and also to increase a capacity of communication systems. At the same time, it leads to decreasing of overall dimensions, weight, and power consumption of radar and communication systems.

Radars are potentially able to measure a range, two angles, and a Doppler velocity of a target. Resolution and measurement accuracy on each of the coordinates are inversely proportional to the wavelength λ, with all other factors being equal. Therefore, radar selectivity, which is defined as a product of resolutions on each of coordinates, raises as λ^{-3} - λ^{-4}. (Radar selectivity is extremely important characteristic as it determines radar's interference immunity). Target data accuracy, in particular angle measurement accuracy, grows as well. That is especially important for far range targets, because linear errors caused by angle measurement are much larger than range measurement error. On the other hand, if requirements on target data accuracy and on interference immunity are not high, using of higher frequencies allows to reduce antenna overall dimensions, relative bandwidth and radiating pulse width.

The development of PAAs (phased array antennas) has a long history too, but creating of solid-state APAAs became possible only at last three decades due to successes in creating the solid-state microwave elements. Using of solid-state elements allows to raise considerably performances of PAA (reliability, efficiency, serviceability) and flexibility of control, achievable due to convenience of combining PAA and up-to-date special-purpose and general-purpose processors.

Unlike the passive PAA, transmitting and receiving amplifiers of the APAA are located within the antenna and closer to the antenna aperture than phase-controls (Fig. 1a). Amplifiers of passive PAA are located behind the aperture phase-controls (Fig. 1b). Transmitters and receivers of a radar with an active PAA are distributed over the antenna, whereas in radars with passive PAA, aforementioned devices are located outside of antenna.

The considered tendencies conflict with each other , because the cost of APAA rapidly grows as wavelength reduces, so creation of large antennas in the short-centimeter wave band appears to be very expensive, and in the millimeter-wave band it turns to be ruinous. Taking into account economic difficulties in Russia and necessity of maintaining the high level of radio electronic facilities developments, the problem of formulating the economically expedient doctrine of supporting and development of high-end technologies in this area has acquired an important significance.



a) Block- diagram of active PAA b) Block- diagram of passive PAA

Fig.1. Active and passive PAAs

Main Features of Multifunctional Radars and Communication Systems

Let us consider a multifunction radar with a PAA. Let us define as a "multifunctional" such a radar that is capable to carry out at least two functions:

- independent detection of targets within a specified volume of space and preparation of the necessary information for tracking of the detected targets;
- tracking of a specified number of the detected targets.

The requirements to power capabilities of radars operating in these two modes are quite diverse and differently depend on wavelength. It is known that the attainable velocity of surveillance (Ω' rad/s) can be represented as follows [1]:

$$\Omega' = \frac{1}{4\pi R^4} \cdot \frac{P_a S \sigma_{eff}}{q^2 k T_{eff}} \qquad (1)$$

where: R – radar range, m
P_a - average radiated power, W
S – effective antenna area, sq.m
σ_{eff} - radar cross-section (RCS) of the target, sq.m
q^2 - signal-to-noise ratio
k - Boltsman's constant
T_{eff} – effective noise temperature of the receiving system

It is proportional to average radiating power multiplied by receiving antenna area and does not depend on wavelength. Since the cost of producing the power and the cost of creating the antenna grow as wavelength decreases, it is expedient to develop exclusively surveillance radars operating in more long-wave bandwidth, as a rule in meter-wave or decimeter-wave band. Interference immunity and target data accuracy of these radars are lower than aforementioned parameters of radars operating in short-wave bandwidths.

The required energy for single-target tracking depends on the single-pulse radiated energy E, J [1]:

$$R^4 = \frac{1}{4\pi} \cdot \frac{E S \sigma_{eff}}{q^2 \lambda^2 k T_{eff}} \qquad (2)$$

In that case, coverage range depends on wavelength as $\lambda^{-1/2}$, that is it grows with decreasing of wavelength by reason of higher concentration of energy in space. Thus radar coverage range, frequency selectivity and interference immunity increase. Consequently it is desirable to develop target-track radars operating at the short centimeter wave band or even at the long-wave part of millimeter-wave band.

Thus, the ratio of energy consumption per detection and per tracking grows with decreasing of wavelength. In real radar systems, energy consumption per tracking, as a rule, is much less than the consumption per detection in S-band ($\lambda \sim 10$ cm) systems and is incomparably less in X-band ($\lambda \sim 3$ cm) systems, and, in particular, in K*a*-band ($\lambda \sim 0.8$ cm) systems. That is the reason why the 1972 Anti Ballistic Missile(ABM)-Defense Systems Treaty defines that excess of $3{\cdot}10^6$ W·sq.m value of radar average radiated power multiplied by aperture area as an indication of the fact that the radar belongs to the strategic (anti-intercontinental ballistic missile) radar category:

$$P_a S \le 3{\cdot}10^6 \quad \text{W·sq.m} \qquad (3)$$

Let us attempt now to estimate limitations connected with creation of multifunction radars in high frequency bands, using as an example ABM-defense radars and keeping in mind that these estimations are qualitatively valid for other high-power multifunction radars.

Limitations connected with a considerable troposphere attenuation of millimeter and sub-millimeter waves restrict the area of their application in radiolocation and communication. Most favourable area of their application is near-Earth space, where there is no molecular absorption and the influence of ionized clouds is insignificant.

Millimeter waves can be effectively used both in cellular radiocommunication systems as well as in radar systems if a few tens of kilometers coverage range is acceptable (for example, anti-aircraft defense radar systems) or in systems operating at high elevation angles (more than 20 deg, for example, anti-missile defense radars).

Data rate of a communication system depends on the signal-to-noise ratio q at the LNA input which is expressed by the communication link equation [2]:

$$q = \left(P_a S_t\right) \cdot \left(\frac{S_r}{T_{eff}}\right) \cdot \frac{1}{l^2 R^2} \cdot \frac{1}{kB} \qquad (4)$$

where: P_a - average transmitting power,
S_t - transmitting antenna aperture area,
S_r - receiving antenna aperture area,
T_{eff} - effective noise temperature of the receiving system,
R - distance of communication link,
k - Boltsman's constant,
B - bandwidth.

From the equation (4), one can see that system capacity increases at higher frequencies due to concentration of energy radiated by transmitting antenna to space. From the other hand, the value of q is proportional to energetic efficiency P_a S_t of transmitting antenna and S_r / T_{eff} -of receiving antenna.

Comparison of Passive PAA and Active PAA

Along with conditions of radio wave propagation, the main limitation of using higher frequency ranges is the cost of radar. Now the cost of a PAA and of a power amplifier, connected to the PAA or included in its structure, makes up 70-90 % of total radar cost. Basing on our averaged expert estimations, let us make a qualitative assessment of a PAA elements cost realizing radiation of 2 kW average power per one sq.m of passive or active PAA aperture as a function of operational frequency.

As applied to passive PAA, the cost consists dominantly of two components: cost of aperture phase-control elements (aperture phase shifters) and cost of a transmitter. At present, semiconductor and ferrite elements are widely used for phase control in passive PAAs. Costs estimations implemented by leading R&D engineer Dr. Yu. B. Korchemkin for passive PAA elements are presented in Tables 1, 2.

Table 1. The cost of a PAA element using ferrite phase shifters.
Optimistic (pessimistic) estimate

	The cost, USD			
PAA element	λ=10 cm	6 cm	3 cm	1 cm
1. Phase-shifting section (ferrite, waveguide, coil)	100	40	20	15
2. Radiator (two dielectric rods)	60	30	15	5
3. Armature (cradle, body, cover)	40	20	10	5
4. Control circuit, supply, special-purpose calculator	40	20	15	10
5. Mechanical construction	100	60	30	15
TOTAL	340(600)	170(300)	85(150)	50(90)

Table 2. The cost of a PAA element using semiconductor phase shifters
Optimistic (pessimistic) estimate.

	The cost, USD			
PAA element	λ=10 cm	6 cm	3 cm	1 cm
1. Phase-shifting section (p-i-n diodes, plate, tuner)	200	180	170	160
2. Radiator (two planes with stripline radiators)	60	30	15	5
3. Armature (cradle, body, cover)	40	20	10	5
4. Control circuit, supply, special-purpose calculator	30	20	20	20
5. Mechanical construction	80	70	60	50
TOTAL	340(600)	320(500)	275(400)	240(350)

Let us suppose that spacing of radiating element is 0.7λ, that corresponds approximately to 90 degrees sector of electronic beam steering. From (1), the number of array elements $N \sim \lambda^2$. The cost of one square meter of the aperture for that case is shown in Fig.2.

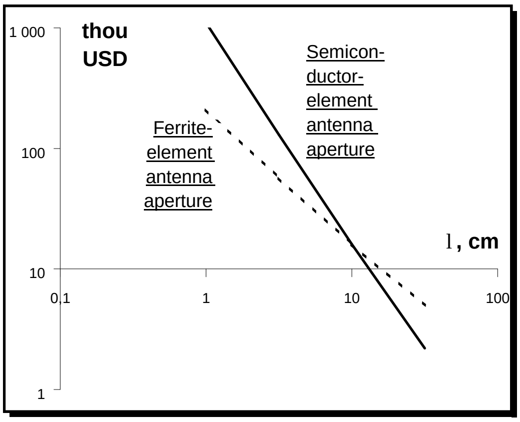


Fig.2. Cost of one sq.m of passive PAA aperture as a function of wavelength

The cost of high power amplifiers for radars with passive PAA using different microwave vacuum tubes can be found from expert evaluation as presented in the Figure 3.

Let us consider now a probable cost of an active PAA aperture. Technologies of semiconductor power amplifiers vary principally within microwave band. As the basic element of the semiconductor APAA module, amplifier determines its cost. For all that, the cost of an active PAA element (module) varies within the aforenamed frequency band slowly, if providing power flux density from an aperture surface unit is constant. As expert estimations indicate, the cost is about USD 1000 - 2000 [3,4] .

With regard to the cost of mechanical construction that roughly is equal to one fourth of module cost, it is possible to estimate the cost of the active PAA (Figure 4). The cost of the passive PAA in combination with the cost of the power amplifier (Figure 3) is shown in the Figure 4 too.

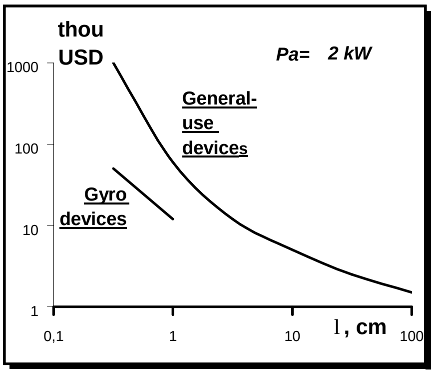


Fig.3 Cost of power amplification by means of different type microwave vacuum devices

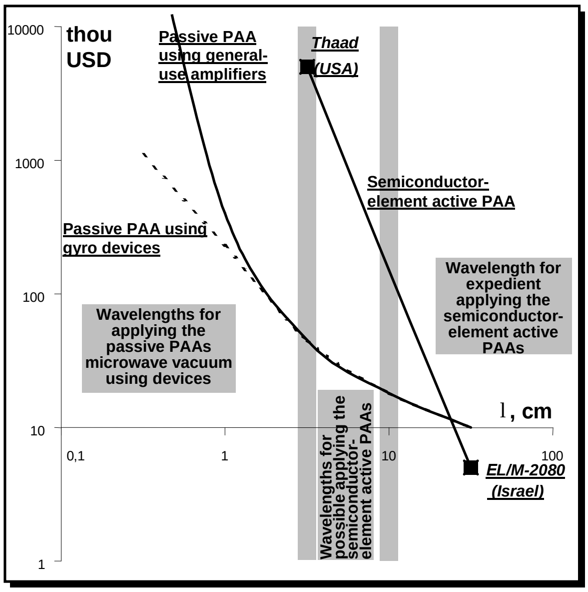


Fig.4. Cost of one sq.m of PAA aperture radiating 2 kW average power as a function of wavelength

It is necessary to mention that cost of any radio system consists of two components: initial cost of development , and cost of maintenance. From our experience, expenses for maintenance of radio-systems with passive PAA exceed expenses for fabrication of the systems. At the same time, our experience of handling with radio systems containing APAA shows that expenses for maintenance are about 10 – 25% of initial expenses for fabrication.

Thereupon, it is appropriate to mention that reliability of radar systems with passive PAA in many respects is defined by a reliability of a vacuum HPA with high-voltage power supply. As a rule a life-time of the HPA is much less than a specified life of the whole radar. For this reason, the HPA is substituted many times during the specified life of the radar.

As for the transmitting APAA, it represents a system of many high-reliability solid state power radiating sources working in parallel. In case of failure of *M* channels of initial number *N*, energetic efficiency of the antenna changes as follows:

$$\frac{(P_a S)_{N-M}}{(P_a S)_N} \approx 1 - \frac{2M}{N} \qquad (5)$$

This means that *10%* failure of modules leads to about *1 dB* degradation of energetic efficiency. Similar relations are valid for receiving APAA.

Maintenance statistics of radio systems with APAA is evidence of high reliability of receiving and transmitting solid state modules. Mean time between failures is about *200 000 hours* for receiving modules and about *100 000 hours* for transmitting modules [3]. Similar data are obtained in our developments. This reliability of modules provides degradation of energetic efficiency of APAA for about *1 dB* during *10 000 hours*. Of course, such performances are achieved in case of optimal construction of antenna with appropriate cooling system, protection from mechanical and environment exposures.

Trustworthy results of research and development the APG-77 radar for F-22 fighter gave evidence of the fact that radars with active and passive PAA have similar cost of development. But the system with a passive PAA exceeded for about 2 times available volume and weight, and had a power consumption which exceeded capability of airborne power supply [5].

At the same time, Figures 2 and 3 allow to propose the expedience of applying the general-use vacuum devices, in particular the gyro devices packaged with permanent magnets, in large and powerful millimeter-wave radars [6].

Examples of PAA of Radar Systems

Let us consider several examples of radars with PAA.

The EL/M-2080 radar recently developed in Israel is an example of the multifunctional L-band radar using the solid-state APAA.

Though there is nearly no information on the characteristics of the radar in publications, some oblique data allow to suppose that antenna area is about 25 sq.m, number of solid-state hybrid modules containing power bipolar transistors is about 600. It is possible to expect that the average power of each module is within 30 to 60 W interval. Hence, $P_a S \cong 4.5 \cdot 10^5$ - 10^6 W sq.m., that is value of $P_a S$ complies with the restriction of the 1972 ABM-defense Systems Treaty. The cost of manufacturing the solid-state modules of the radar is probably about 1,000,000 USD. Several specimens of the radar have been manufactured (Figure 5) [7].

Fig.5. The EL/M-2080 radar

The multifunctional X-band radar of THAAD system (Figure 6) is the other interesting example of APAA with very large quantity of modules.

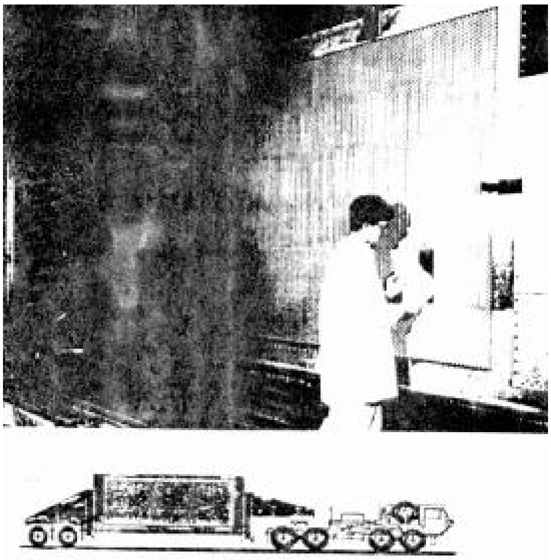


Fig. 6 The «THAAD» radar

The antenna area of the radar is 9.2 sq.m, the number of solid-state modules is 25344, antenna array spacing is 0.6 λ. No information about the module average power is available from publications, however it is possible to suppose that it is between 1 and 10 W. Hence, $P_a S = 2.5 \cdot 10^5$-$2.5 \cdot 10^6$ W sq.m. The cost of a solid-state module is about 1000 USD, that is the overall cost of modules for one APAA is about 25,000,000 USD [8], [9].

Thus, costs of these two radars differ roughly by 1.5 order, though the searching capabilities of the radars are approximately equal to each other. The cost difference of the radars is caused by higher measurement accuracy and interference immunity of the THAAD system.

Whereas there exist no powerful radars with solid-state APAA in millimeter wave band now, the radar “Ruza” (35 GHz) created in 1989 (Fig. 7) by JSC “Radiophyzika” (Moscow) in cooperation with other companies is the most remarkable example of radar with PAA which is passive for transmission and active for reception [10,11]. The array antenna contains 120 large radiators with ferrite phase shifters. Total square of the antenna aperture is about 40 sq.m. The radar uses power amplifier with gyro klystron. Average radiated power is 50 kW, hence, $P_a S \approx 2 \cdot 10^6$ W sq.m. Due to very large spacing of elements, the PAA has conical sector of electronic beam steering of about 1°. The PAA is installed on the positioner which provides mechanical beam steering in the upper hemisphere.

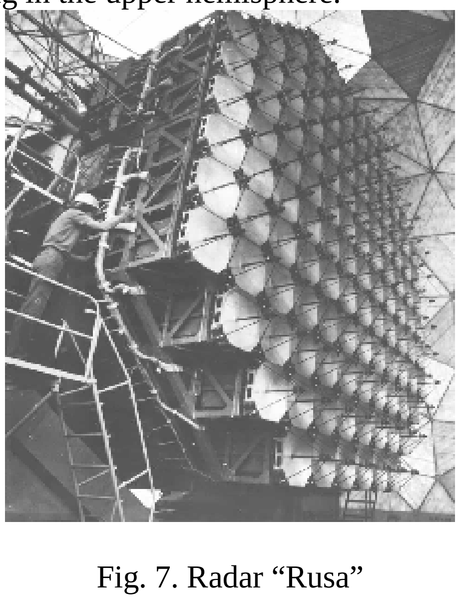


Fig. 7. Radar “Rusa”

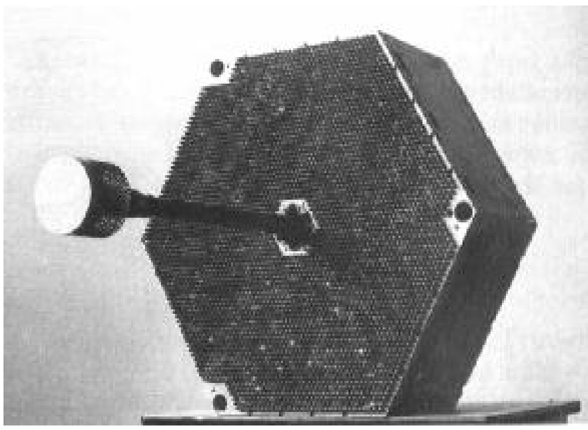


Fig. 8. Reflective PAA of Ka-band

For similar radar with a wide angle of electronical beam steering, the other passive PAA was developed by JSC “Radiophyzika” [12]. This reflective-type PAA developed on basis of ferrite phase shifter is shown in the Fig.8. The PAA contains about 3600 phase shifters arranged over hexagonal grid with spacing 1.1λ. Protruding waveguide-dielectric rod radiators form a flat-topped pattern which suppresses grating lobes. The PAA has a sector of electronic beam steering about ±25°.The array has hexagonal aperture with diameter of its inscribed circle of 0.64 м. Effective illumination of the aperture is provided by a quasioptical exciter. In combination with a commercial klystron on TWT HPA with average output power of 2 kW, the system can provide $P_a S_{eff} \approx 5\times10^2$ W sq.m.

The described array can be used as not only a single antenna but as a subarray of a large “semi-active” PAA of hexagonal structure. For example, assembled of about 10^2 subarrays with HPA, such antenna would have $P_a S_{eff} \approx 3\times10^6$ W sq.m.

APAAs for Communication Systems

As to communications, the trends are partly similar to radar systems and partly different. On the one hand, it is necessary to mark that the trend of using higher frequency bands is very attractive in communications too, because it ensures considerable advantage of system throughput rate and also allows to reduce power consumption, reduce overall dimensions of hardware, and increase a system interference immunity. These advantage seems to be very valuable especially in the case of satellite antennas for communications. On the other hand, communication systems usually operate within the angular coverage which is far less than required coverage of radar systems. Hence, requirements to the radiating power of communication systems are, in general, far easier than that of radars, and very small APAA containing a few hundreds or even a few tens of elements are widely used in this case. Applying of APAA in communication systems is extremely expedient first of all in respect of serviceability, as it allows to reject not enough reliable vacuum high-voltage microwave devices. Also it permits to increase efficiency and flexibility of communication systems.

Very high reliability, possibility to form many beams with independent electronic scanning, broad capability of pattern shaping make APAA very attractive and reasonable technical solution in these systems despite costs of the antenna systems are rather high. Apparently, the APAA replace conventional antennas not only in microwave but in millimeter-wave systems too, first of all, in satellite communication systems.

As far as we know, the first APAA for mobile satellite communications through high elliptic satellite "Molniya" was developed in the Soviet Union in 1970 [13]. The airborne APAA of L-band (800/900 MHz), containing 64 elements providing one electronically steered beam nearly in the upper hemisphere (±80°), is shown in Fig. 9. The transmitting antenna of the system has $P_a S_{eff} \approx 10^2$ W sq.m.

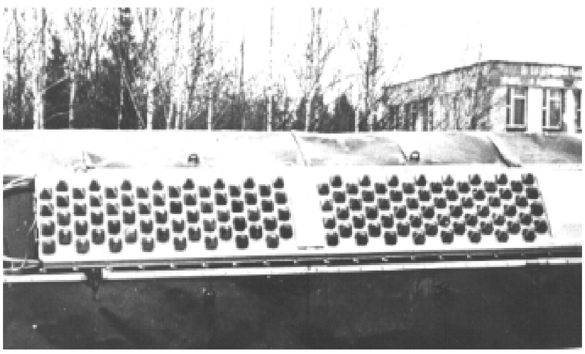


Fig. 9. *L-band* airborne APAA for communication system through the satellite “Molniya"

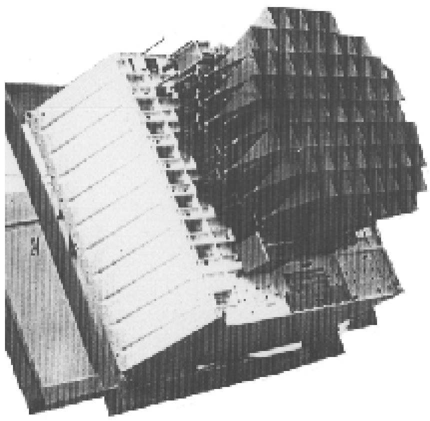


Fig. 10. *Ku-band* APAA of communication satellite “Kupon”

The other APAA developed for geostationary communication satellite “Kupon” [14] (Ku-band) is shown in the Fig. 10. It contains 64 elements. The modules are arranged in nodes of a hexagonal grid with spacing about 3 λ which provides a beam coverage area about ±9° which is enough to cover the Earth from the geostationary orbit. The antenna has 4 independently steered and shaped beams. Maximum $P_a S_{eff}$ of the APAA is about 10 W sq.m

The APAA developed by “Boeing” [15, 16] and used in mobile satellite communication system of millimeter wave band is shown in Fig.11. The APAA consists of 91 element. Hermetic active modules containing monolithic microwave integrated circuits (MMIC) are arranged in nodes of a hexagonal grid with spacing about 0.6λ that provides ±70°-sector of electronical beam steering. Despite each channel contains rather powerful HPA (P_{out} = 0.6 W), the parameter $P_a S_{eff} \approx 10^{-1}$ W sq.m is rather small.

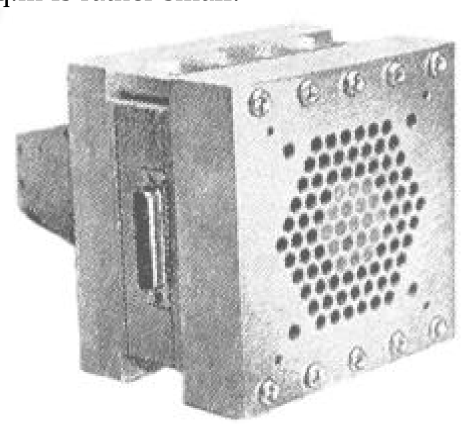
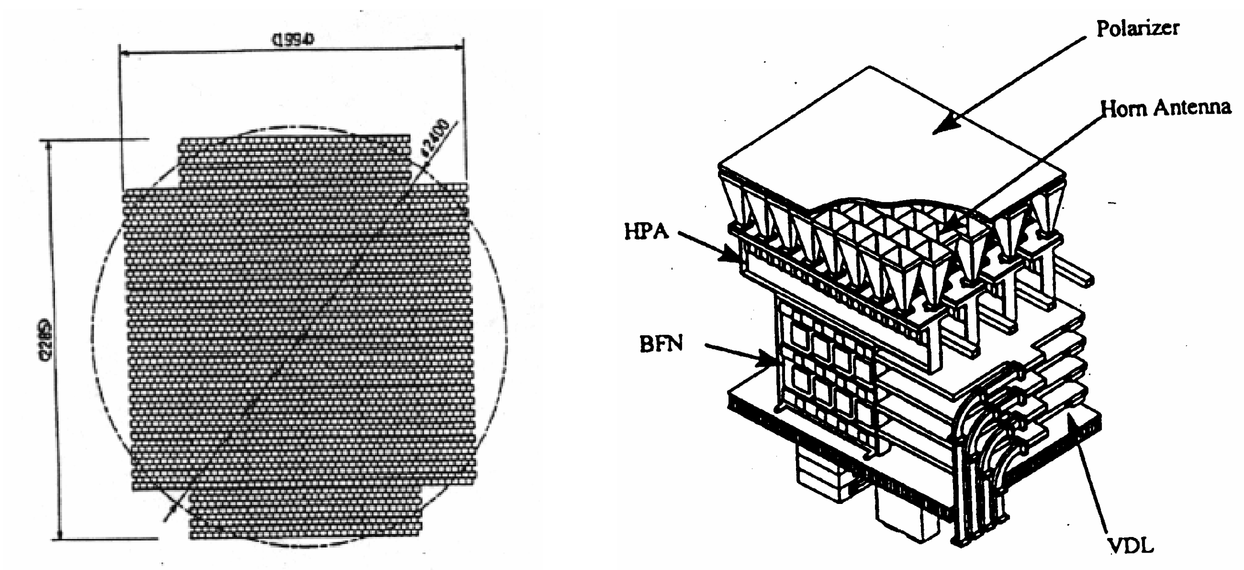


Fig. 11. APAA *(f =44 GHz)* for satellite communications.

The most impressive example of *Ka*-band APAA for experimental high data rate (Gigabit) satellite is under development by CRL and MELCO (Japan) [17]. Both transmitting and receiving APAAs contain about 2800 elements with aperture diameter 2.4 m for transmitting (18 GHz) and 1.6 m for receiving (28 GHz). Output power of the transmitting APAA have to be about 400 W. Noise figure of receiving APAA will be less than 3.5 dB. The array consists of horn radiators spaced at about 2.2 λ that provides ±10°-sector of electronical beam steering. Efficiency of the transmitting APAA $P_a S_{eff} \approx 2 \cdot 10^{3}$ W sq.m is very high for this frequency band. Transmitting (Fig 12) and receiving antenna subarray units containing 64 channels each were already successfully developed and tested [17].



a) Antenna Aperture (44 Subarray Unit)

b) Subarray Unit

Fig.12 Antenna configuration of the transmitting APAA for Gigabit satellite.

Using of APAA containing MMIC is supposed in many advanced *Ka*-band satellite communication systems [9].

Conclusion

In conclusion it is necessary to note that the foregoing consideration shows that achievements in development of effective solid-state amplifiers and especially MMIC have been made possible a creation of APAA at the frequencies up to millimeter waves.

Whereas application of radars and communication systems with APAAs become more and more preferable in various radar and communication systems at the frequencies from *UHF* to *Ka*-band, only systems with small APAA are realistic at millimeter-wave bands now.

As for powerful radar systems, passive PAAs appears to be beyond comparison at *Ka*-band and millimeter-wave bands in the near future.

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