Structural implementation of a beamforming module for active phased array antennas

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Abstract. The paper presents the results of research to determine the requirements for the construction of subarray elements of active electronically scanned array (AESA), as well as the results of their practical implementation. A radio engineering concept for constructing an AESA has been proposed, and the design of the AESA elements has been selected and justified. The results obtained are of great importance for the development of modern microelectronics technologies in the field of providing a high-speed radio communication channel with aircraft.

1 Introduction

Modern radio-electronic devices cannot be imagined without transmitting and receiving devices - antennas or antenna systems. At the current level and speed of technology development, the creation and effective operation of radio-electronic devices requires the use of multi-band systems such as active phased array antennas. To ensure expansion of the capabilities of active phased array antennas, an important task is the development of the element base.

Let us consider what an AESA is to understand the essence of the proposed concept for constructing an antenna array. AESA are structurally combined groups of multi-channel antenna array modules [1,2], each of which consists of a radiating element and an active device - a transmitting module. In addition, the circuit diagram includes a power distribution device, a signal conversion path, a signal generation and processing device, and a control device. On the one hand, the transmitting module is connected to the AESA, and on the other, through the power distribution device to the generator part of the signal conversion path.

The design of the AESA is of great importance, since increasing the functionality of transmitting devices directly affects the resolution, range and ability to view space.

AESA modules are distributed according to functionality:

- formation of the microwave level and power required according to the specified parameters;
- control and regulation of microwave signals, allowing you to set the amplitude, phase, depth in relation to stability over time;
- control of beam switching time according to specified parameters.

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To reduce high-frequency losses, the amplifier module must be located next to the emitter, which will eliminate the introduction of a high-frequency feeder path at a high-power level. Thus, the amplifier module will be the active part of the module.

The requirements for the stability of the amplitude and phase characteristics of the AESA are extremely important. They can be achieved using elements with high stability, using automatic phase and amplification circuits in each module, or specialized design solutions.

The design of the antenna array should be developed taking into account the following requirements:

the dimensions of the array in the plane of the antenna panel opening are determined by the geometry of the emitters and should not increase (to ensure the assembly of the combat array);

- the height of the sublattice is strictly limited and must be minimal (mass minimization);
- when designing the structure, the issue of dose loads (cases of electronic components) must be taken into account;
- the number and size of subgrid attachment points must satisfy the maximum permissible loads.

To improve the characteristics of the receiving and transmitting capabilities of the AESA, it is necessary to determine the optimal design of the antenna array.

2 Radio engineering concept for constructing an AESA

It should be noted that the possibilities for reducing the size of AESA reception and transmission channels are limited [3-7] by the current level of technology for manufacturing the element base, as well as a certain location of effective heat-removing cooling devices.

In the proposed concept, the emitter for the AESA subarray is proposed to be developed considering the following requirements:

- minimal losses due to mismatch of emitters when scanning over a wide sector;
- possibility of working on right or left circular polarization;
- possibility of heat release;
- minimum weight.

The input impedance of the emitters installed as part of the AESA depends on the scanning angle of its directional pattern. Based on the previously described concept and this property, the circuit of the matching device of the emitter with the transceiver board should be developed considering the peculiarities of matching the emitters.

The required matching of emitters is achieved in two ways:

1. Matching elements can be in the internal circuit of the antenna array.
2. Through a change in the emitter itself or the entire radiating structure (coordination of the “external space”).

For impedance matching, transformers are used, implemented on four-terminal circuits with lumped and distributed elements.

It is possible to create electrically tunable transformers that will ensure impedance matching throughout the entire scanning sector of the pattern due to change. If the parameters change occurs discretely, then the coordination can occur in separate angular directions.

Improving the matching between the channels of individual emitters can also be based on compensation of signals induced at their inputs due to the presence of spatial mutual coupling that arises between them as part of the array. Formed through mutual connections, in fact, multi-pole matching devices can provide almost perfect matching, but their implementation turns out to be very difficult.

To prevent microwave signal distortion when designing a printed circuit board, the following aspects deserve special attention:

- electromagnetic wave reflections (return losses);
- crosstalk;
- noise on power buses (filtered);
- skin effect;
- dielectric losses.

In the developed concept, a coplanar waveguide is used as a microwave transmission line, which makes it possible to achieve better isolation between channels, reduce the level of power emitted by the transmission line, and reduce the influence of the housing on the characteristic impedance of the line. Coplanar waveguide is often used on printed circuit boards as an alternative to microstrip, compared to which it has a number of advantages:

- The level of radiation losses is significantly reduced. The electric field strength lines are closed in the same layer in which the strip is laid, thanks to the adjacent earth polygons.
- Higher level of inter-channel isolation. The land polygons located below and on both sides of the strip act as screens.
- By using the same substrate, you can achieve a smaller central stripe. This feature is very useful in connection with the use of radioelements in compact packages intended for surface mounting.
- Less influence of conductive shield located near the transmission line.

The appearance of the coplanar waveguide is shown in Figure 1a. The main difference between a coplanar waveguide and a coplanar line shown in Figure 1b is the presence of a reference ground polygon under the central strip.

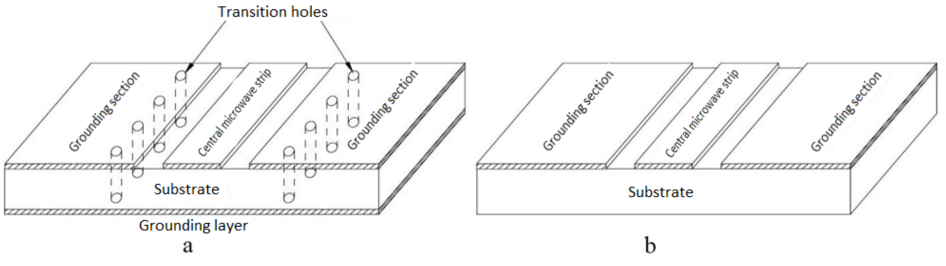

Fig. 1. Appearance of coplanar transmission line.

In this concept, transmitting modules are not separated into independent functional units and are structurally implemented on a single printed circuit board. The microwave board is a rigid-flex structure and has a complex structure. The transmitter channels are implemented on one of the outer layers, and the emitting aperture is on the other. The outer layers are responsible for transmitting microwave energy, so Rogers 4000 material, which has stable characteristics, was chosen as the dielectric of the rigid part of the printed circuit board.

The internal core of the printed circuit board, implemented on FR material, contains power and control circuits. The flexible part of the printed circuit board ensures the delivery of power and control signals from the central unit to the monolithic microwave integrated circuit system and is implemented on the internal layers of the printed circuit board using polyamide films, which tend to easily change their original shape, including after applying a conductive pattern.

Reducing the size and weight of the structure can be achieved through the use of flexible dielectric materials in the manufacture of printed circuit boards. In addition, this increases a number of other characteristics: electrical, heat transfer, reliability. To remove thermal energy from the active components of the AESA transmitting and receiving path, the internal shielding copper layers are made thicker.

As a result of the implementation of the concept to achieve the described characteristics, the authors developed and implemented an AESA design based on microwave boards, which is presented below.

3 Results and discussion

In our AESA design, we will dwell in more detail on the technologies used on the microwave board of the beamforming module.

The crystals are installed in special grooves on a printed circuit board (PCB), which is shown in Figure 2. The grooves ensure optimal matching of the microcircuit with the input and output paths and are technologically performed by milling the PCB to a depth of one/several layers. In the case under study, it is assumed that the microwave part of the transmitting modules will be installed in the slots together with the heat removal system [8-10].

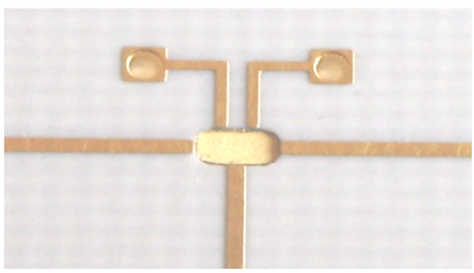

Fig. 2. Blind slots for mounting a monolithic integrated circuit.

To control the quality of the obtained parameters of individual functional units of the path, transmission line outputs from the internal layers are provided, which is shown in Figure 3.

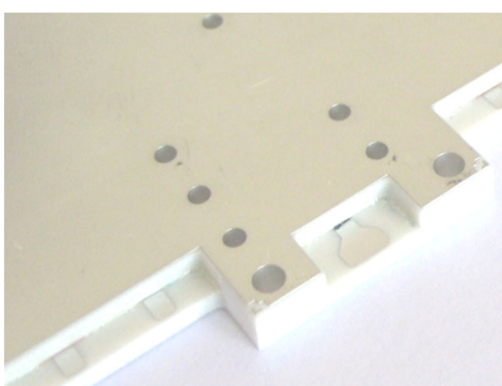

Fig. 3. Coplanar type transmission line output from inner layer.

To ensure signal integrity, sealing and heat dissipation, the printed circuit board of the beamforming module, which is responsible for direct radiation of the electromagnetic wave, is made with end metallization. The appearance of an example of metallization is shown in Figure 4.

Fig. 4. An example of metallization of the end of a hybrid printed circuit board.

When assembling an AESA, it is important how the crystals are attached to the base of the PCB. To choose a fastening method, it is necessary to start from the type of material of the connecting adhesive layer. This layer plays an important role, as it is responsible for heat removal, as well as good matching of the temperature coefficients of expansion of the connected elements in a wide range of operating temperatures (-45÷80°C). In addition, with the right choice, you can increase resistance to dynamic impacts (acceleration up to 150g), vibrations and shocks. At the same time, high-quality operation of microcircuits is possible if the connecting layer conducts electricity. The difference in the temperature coefficients of expansion of the crystal and the base when the temperature drops upward or downward causes internal stresses in them (tension or compression). The degree of stress depends on the ratio of temperature expansion coefficients. This voltage has the highest values on the contact surfaces of the connecting layer.

The most accurate and productive method of applying adhesive with paste properties to a monolithic integrated circuit is gridography. This method allows for precise dosage, which affects the high reproducibility of the geometric dimensions of the compound. During the bonding process, most adhesives can vary widely in temperature and time, but curing time decreases rapidly as temperatures increase. The cold curing mode is implemented at room temperature but requires a long exposure. It is for this reason that to speed up the gluing process, it is performed with heating 60...200°C, depending on the chosen manufacturer. Adhesives that release active components when heated during use of the antenna array should not be used when mounting crystals.

To protect the microwave monolithic integrated circuit power inputs from voltage ripples, filter capacitors with a capacity of 0.01 μF and 100 pF are installed. During the design, the distances recommended by the manufacturer from the inputs and outputs of the monolithic integrated circuit to the transmission line were observed - 0.1 mm, and from the power terminals - 0.3 mm. Electrical connections between the MIC, transmission lines and power supply filter elements are made by contact welding of thin gold wire.

4 Conclusion

The level of performance and reliability of manufactured equipment, in particular AESA, directly depends on the selected materials and element base, correct construction and compliance with technological processes. When designing the arrangement of elements on the monolithic integrated circuit, their fixation and the use of certain materials, it is important to consider a number of aspects:

- expected service life and operability;
- technical conditions under which it is planned to use the equipment;
- environmental conditions during storage and operation
- speed, voltage and other requirements.

The presented article proposes a design concept for an AESA with an emphasis on the use of a coplanar waveguide for the transmission line and a method for constructing a microwave board of a beamforming module, which will improve the matching between the channels of individual emitters.

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