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5 MM WAVELENGTH TRANSCEIVER IN THE MONOLITHIC INTEGRATED GALLIUM ARSENIDE DESIGN

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Abstract

Radar sensors are most widely applied in developing collision prevention systems, security and military systems being exposed to extreme requirements in resistance to the mechanical and ecological effects. Transceiver module is the most important unit in a radar sensor assembly defining its main technical characteristics. The transceiver module importance lies in the fact that its parameters and characteristics determine largely the radar sensors efficiency as a whole (range, resolution, weight and size characteristics). Therefore, requirements to a radar sensors are referred primarily to the transceiver module. Constructing a microwave transceiver module based on the monolithic integrated circuits makes it possible to simplify the module board topology, improve manufacturability, reliability and resistance to the external mechanical effects of the entire radar sensors. Besides, it reduces the radar sensors weight, dimensions and manufacture cost, and provides import substitution of the critical circuitry. The paper describes technology, structure and methods in designing a 5 mm wavelength transceiver in the monolithic integrated gallium arsenide design based on the GaAs pHEMT technology. To separate design and manufacture technology of the diodes and transistors, a multilayer epitaxial structure of gallium arsenide was developed and produced. The paper presents results of simulating the transceiver circuit. It also provides results of the transceiver preliminary testing for resistance to the external factors. Possibility to implement the transceiver in the monolithic integral design using the domestic heterostructures is identified

Keywords

Radar sensor, transceiver module, chirp signal, monolithic integrated circuit, GaAs pHEMT technology

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Introduction. All the radar sensors (RS) transceiver modules (TM) could be divided into two classes based on their operation principle: pulse or continuous.

The TM pulse operation mode is characterized by significant values of the emitted signal power and range of action. However, the so-called “dead” zone appears near a TM in the pulse operation mode, and the distance to a reflection object could be measured with a large error dependent on the emitted pulse duration [1]. One way to eliminate these disadvantages is to reduce the probing signal duration. However, this method is accompanied by significant complication and an increase in the TM circuit cost and, as a result, in the entire RS cost.

To implement a TM capable of operating at the extremely short distances to a reflection object (~ 1 m), the continuous frequency modulated radar technique is the most preferred.

Determining range to the target by the frequency modulation method is based on measuring the transmitter carrier frequency increment during the time of a signal propagation to the target and back. In case of the linear frequency modulation (LFM), the low frequency beat signal extracted in the TM would be directly proportional to the distance to the object [2].

Using the millimeter wavelength range in the TM construction makes it possible to increase significantly resolution in measuring the spatial coordinates, ensure high noise immunity of the radar channel and improve the RS weight and size characteristics [3–5].

In general, TM includes the following main functional components: antenna system (AS) and transceiver, as shown in Fig. 1. The modulating saw tooth voltage U_{contr} is supplied to the voltage controlled oscillator (VCO), which is a part of the transceiver [6]. The amplified microwave signal is sent from the power amplifier (PA) output through the power divider (PD) to the transmitting antenna (A_{tr}). The reflected signal passes to the receiving antenna (A_{rec}) and is transmitted to the frequency converter (FC). Part of power on the second

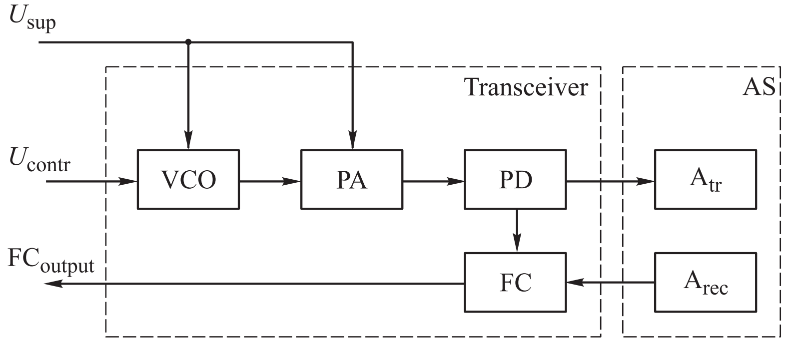


Fig. 1. TM generalized block diagram

PD arm is supplied to the mixer and is used as the reference one (oscillator). As a result of mixing (multiplication) two harmonic oscillations (reflected signal and local oscillator), a beat signal is generated in the transceiver mixer, which instantaneous frequency is equal to the absolute value of difference between instantaneous frequencies of the emitted and received signals. The stabilized voltage U_{sup} supplied from the external converter provides power to the main transceiver units.

Classic approach to constructing a millimeter wavelength TM is based on the waveguide-hybrid technology using the Gunn diode as the element generating the microwave oscillations. This technology advantage is supported by rigorous electrodynamic theory, large number of technical developments, and good radar characteristics of the waveguide products. Disadvantages of this technology include increased weight and size characteristics, high labor capacity in manufacture, and significant energy consumption. Therefore, TM construction establishes a trend of transition to the integrated (microstrip) technology using the unpacked monolithic integrated circuits as the element base.

Microwave TM construction based on the of monolithic integrated circuits (MIC) makes it possible to simplify the module board topology, increase manufacturability, reliability and mechanical strength of the entire RS, reduce its mass, dimensions and manufacture costs, provide import substitution in the critical element base.

Depending on the scope of specific TM functions, as well as to ensure the required characteristics using various technologies, a large number of both TM as a whole and its individual components were developed and created [7–15]. However, using foreign developments in the domestic products is becoming almost impossible under strict sanctions nowadays.

This work objective is to create a monolithic integrated circuit for the millimeter wave transceiver module based on the GaAs pHEMT technology. Development of a highly integrated product would meet the current MIC needs to create a small, highly reliable millimeter wave RS.

Materials and methods in solving the problem of MIC development, simulation results. In 2021–2022, the JSC SPE “Salyut” developed and manufactured prototypes of the MIC millimeter range transceiver (hereinafter — MIC) on request of the NIIIS named after Yu.Ye. Sedakov

MIC includes:

- VCO;
- two-output power amplifier combining the signal divider function;
- frequency converter.

The MIC TM basic electrical schematic diagram is shown in Fig. 2. The VCO is based on the *VT1* transistor, which positive voltage is supplied through a quarter-wave section of the microstrip line (MSL) shorted by the *C3* capacitor and the open quarter-wave loop. Transistor gate offset relative to its source is provided by the *C1*, *R4* auto-offset circuit. Generator frequency is controlled by voltage on the *VD1* and *VD2* varicaps. Lengths of the closed and open loops in the *VT1* transistor source provide the generation mode. Positive frequency control voltage is supplied to the varicaps via the *R1* and *R2* resistive dividers to reduce the frequency tuning slope.

The two-stage PA generates the MIC transmitter output signal and the mixer local oscillator signal of the MIC receiver. PA is built on pairs of the *VT2*, *VT4* and *VT3*, *VT5* transistors in a balanced circuit using the Lange directional couplers on the coupled microstrip lines. A pair of connected microstrip transmission lines is used as the power divider.

The balanced diode mixer is based on a hybrid bridge on the *VD3*, *VD4* Schottky diodes with an external offset to reduce the required power level of the local oscillator signal and increase the temperature stability. The diodes' positive offset voltage is adjustable and stays within (1.2–1.8) V. In practice, it is possible to use 5 V supply voltage from the electrode (+ U_{bias}) via an external chip resistor having the 800 to 1000 Ohms rating.

A directional coupler on two coupled microstrip transmission lines generates the local oscillator signal to the mixer, which width provides necessary matching between the transmitter and the mixer output paths. The gap between them determines the branch power value. The coupler fourth port is connected to the 50 ohms matching resistor, which is shorted to the ground in high frequency by the open quarter-wave loop.

MIC was designed and manufactured on the basis of the GaAs pHEMT basic technological process at the JSC SPE "Salyut" using the T-shaped transistor gate of the 0.07 micron minimum length. Technological process includes manufacture of the normally open field Schottky barrier transistors, thin-film resistors, MPD capacitors, microstrip transmission lines and plated-through grounding holes. At the same time, design and technology of the diodes (in varicap and mixer) and transistors manufacture are separated. For this purpose, the gallium arsenide epitaxial structure consisting of 17 layers was developed and manufactured. A diode layer was formed on the surface top with thickness and concentration of the charge carriers providing alteration in the of Schottky barrier capacity by 3–4 times with the offset voltage changing from zero to 6 V. Then, a contact layer was introduced reducing the diodes' R_s serial parasitic resistance

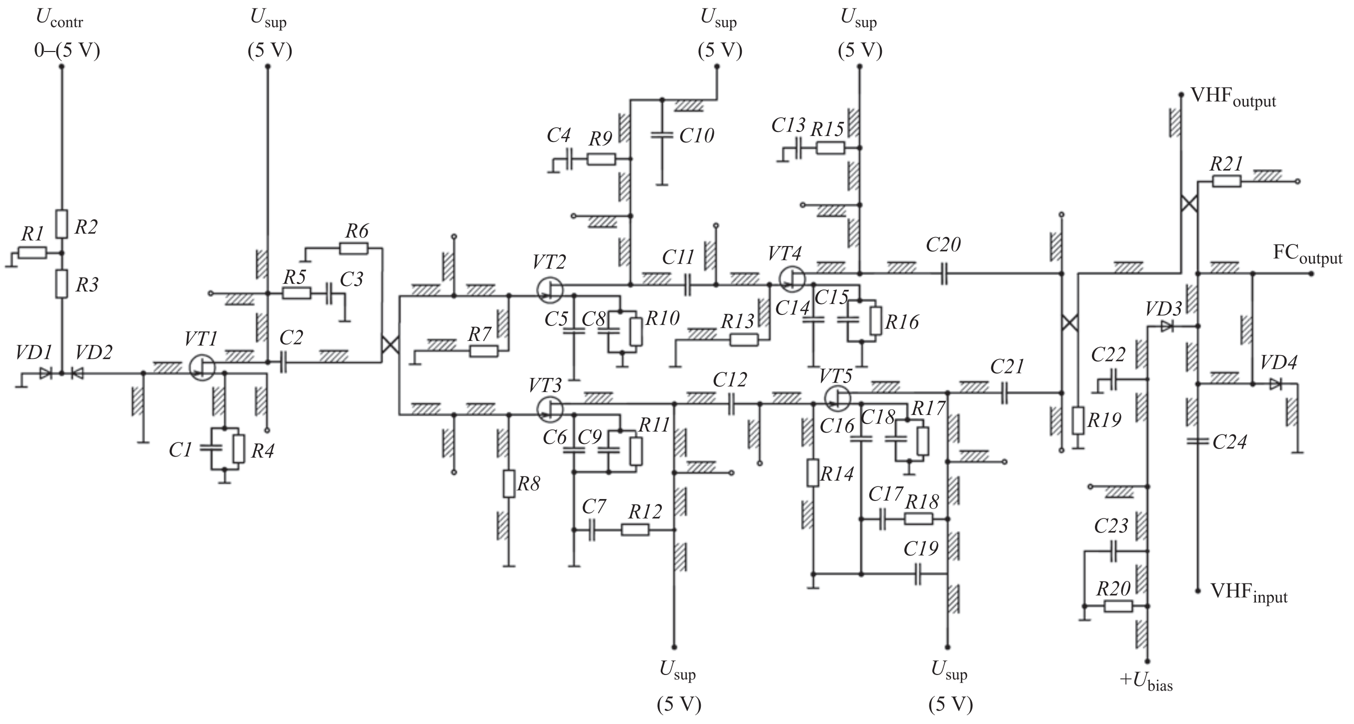


Fig. 2. MIC electrical schematic diagram

by several times compared to the planar diode based on the transistor. The transistor double pHEMT structure is formed below.

MIC chip topology is shown in Fig. 3. The chip overall dimensions are 3.37 × 3.2 × 0.08 mm. Alignment marks, test transistors and the test process cell are also positioned on the MIC chip to control process parameters in the circuit manufacture.

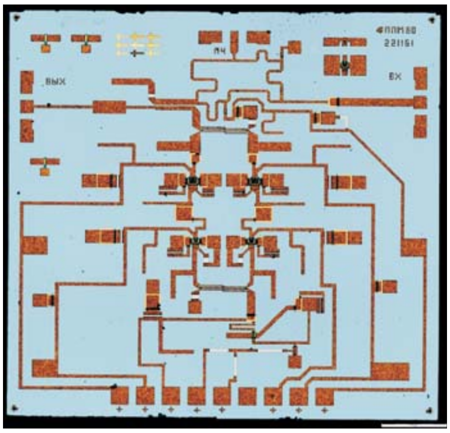
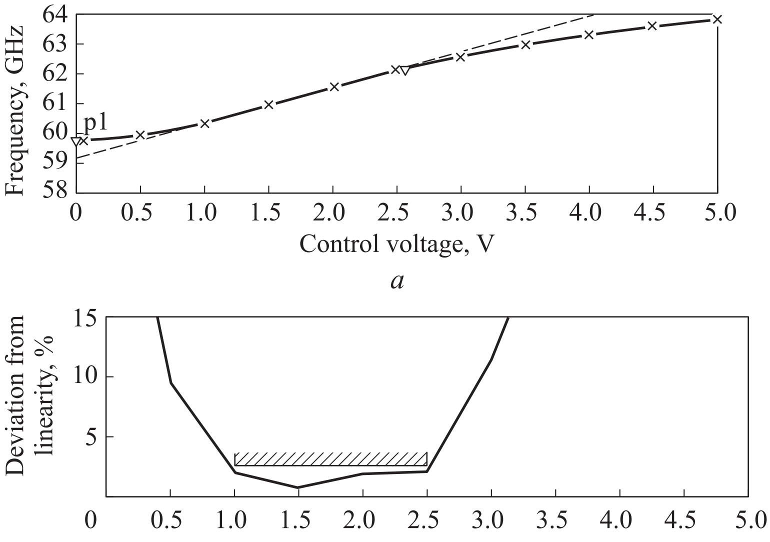


Fig. 3. MIC TM chip topology

MIC circuitry was simulated using the CAD microwave devices at the level of 2.5-D electromagnetic topology analysis to obtain the most correct result.

Simulation was carried out at the 5 V positive supply voltage. MIC TM consumption current was about 200 mA, as a whole.

Figure 4 shows calculated dependencies of the generator output frequency on control voltage (*a*) and frequency control linearity (*b*). When the control voltage raises from 0 to 5 V, the generator frequency changes from 60 to 64 GHz. Within the range of 1.0 to 2.5 V, the frequency-voltage dependence deviation from that of linear is not exceeding 3 % in the frequency adjustment and is at least 1.8 GHz.



a

b

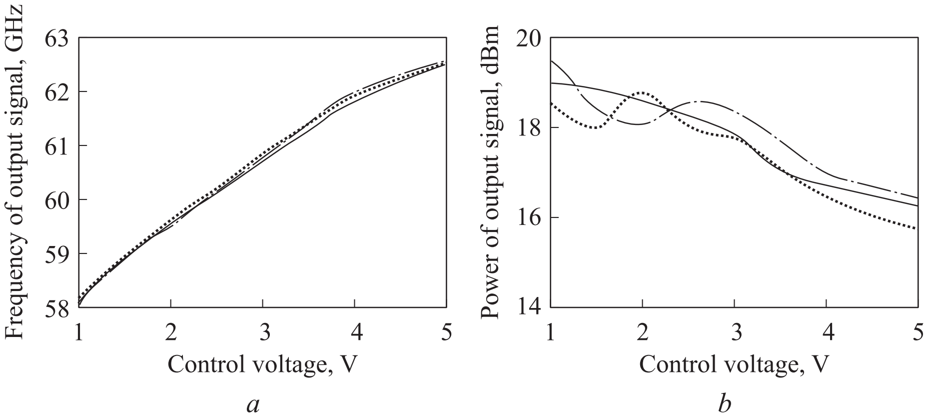
Fig. 4. Generator output frequency (*a*) and frequency control linearity (*b*) design dependencies on the control voltage

The generator design output power in the entire frequency tuning range is in the order of (10–11) dBmW. The output power irregularity is not exceeding 1 dB.

Experimental results. In the next operation step, the MIC chips were manufactured. Manufactured test samples electrical parameters were measured using the microwave probe stations. Under normal conditions, measurements were taken at the manual station. Measurements within the temperature range were carried out at the semi-automatic probe station having the integrated heat and cold chamber and providing microwave measurement of the semiconductor chip parameters within the temperature range of –60 to 200 °C.

The MIC TM electrical parameters were measured at the microwave semi-automatic probe station using a spectrum analyzer to monitor the TM output signal frequency and a power meter to control the output power. The mixer conversion factor was measured using a spectrum analyzer and an external microwave generator. MIC supply voltage varied from 4.75 to 5.25 V. The varicap offset voltage varied from 0 to 5 V.

Figure 5, *a* shows results of measuring the MIC output frequency dependence on the control voltage in sampling 3 good chips. When the control voltage raises from 1.0 to 4.0 V, the frequency changes on average from 58.2 to 62.0 GHz according to a law close to the linear one. Thus, the generator frequency tuning range is at least 3.8 GHz. The MIC output signal frequency measured deviation on the control voltage compared to the design voltage is due to the fact that the generator signal frequency depends not only on the transmission line parameters forming the oscillating circuits, but also directly on the varicaps capacitance, as well as on the field transistor interelectrode capacitances. Magnitude (spread)



a *b*

Fig. 5. MIC output signal frequency (*a*) and output power (*b*) dependence on the control voltage

of these capacitances is determined by both technological spread in the transistor gate length and semiconductor layer parameters in the gate region. Varicap capacity (CV) volt characteristic primarily influences the VCO frequency adjustment linearity. Generator design uses a varicap model built on the experimental CV dependencies measured on the test diode structures, both on different epitaxial semiconductor structures in the same batch and in different places over the wafer area to determine technological spread in the varicap parameters. According to results of the varicaps CV dependencies experimental study, their capacities variation is from 10 to 35 %. At the same time, the simulated process frequency spread in the generator output signal is about 5 GHz or about 8 % with the MIC active component capacity spread of 20–30 %. Experimental MIC output frequency values are within this range.

Figure 5, *b* shows the output power dependence on the varicap control voltage. When the control voltage changes from 1.0 to 4.0 V, the output power varies from 16 to 18.0 dBm. VHF output power drop within the electrical tuning range is on average 2–3 dB.

Fig. 6 shows the module output signal frequency (*a*) and the output power (*b*) dependence on the varicap control voltage at 60 °C.

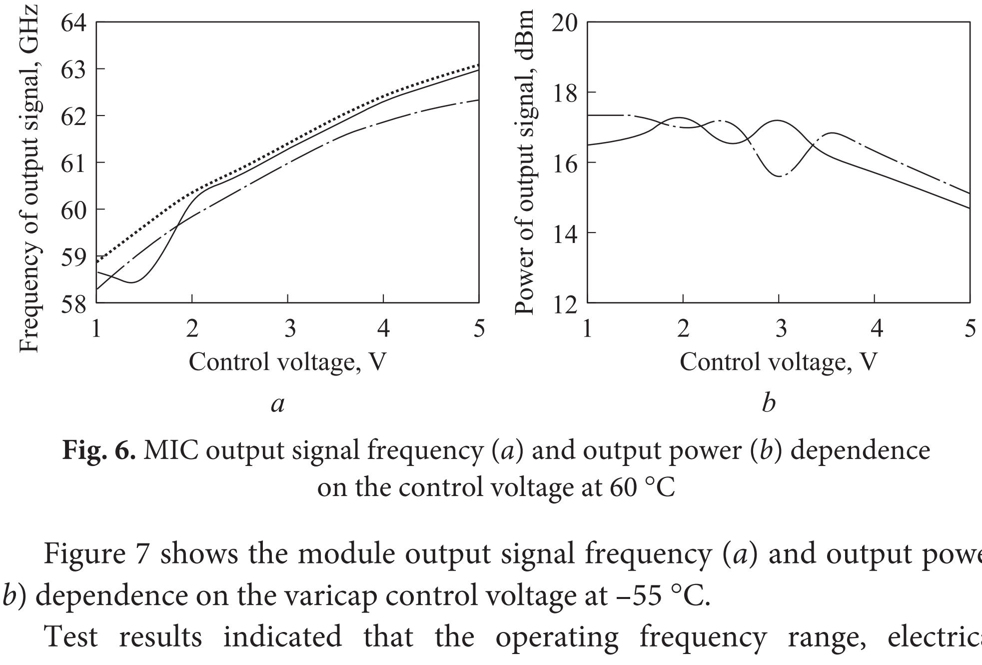


Fig. 6. MIC output signal frequency (*a*) and output power (*b*) dependence on the control voltage at 60 °C

Figure 7 shows the module output signal frequency (*a*) and output power (*b*) dependence on the varicap control voltage at –55 °C.

Test results indicated that the operating frequency range, electrical frequency tuning range, output power unevenness and maximum nonlinearity of the voltage-frequency conversion characteristic VCO MIC TM at the extreme ambient operation temperature was varying within the error limits and the process spread.

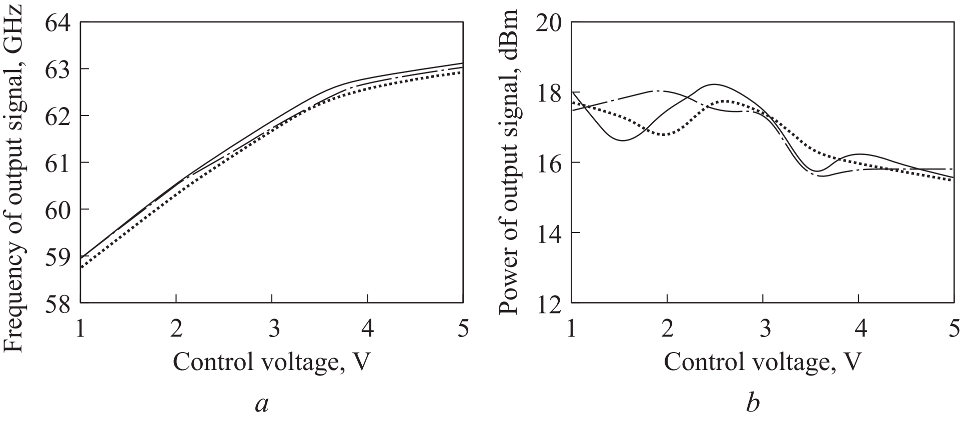


Fig. 7. MIC output signal frequency (*a*) and output power (*b*) dependence on the varicap control voltage at −55 °C

Conclusion. The paper shows possibility to implement a transceiver in the monolithic integrated design according to the basic MIC microwave process with the 70 nm design standards on the gallium arsenide domestic heterostructures.

At the same time, the task of enclosing and sealing the MIC TM remains very urgent. Main options of packaging the millimeter wavelength range MIC include the metal-ceramic LTCC housings [16–19]. There is also a technology involving direct MIC installation into a printed circuit board followed by its housing with the plastic or ceramic cover [20].

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