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RADIO MEASUREMENTS

MEASUREMENT OF DC AND AC RESPONSE CURVES OF A BIPOLAR TRANSISTOR AS A FUNCTION OF FREQUENCY

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We discuss improving the reliability of measured DC and AC response curves for a bipolar transistor as a function of frequency using the mass-produced 2T937 transistor (Russia) as an example. We describe preparations for measurement and the actual measurements in considerable detail. We provide experimental response curves for the 2T937 transistor. A special test (measurement) board was developed to prevent the measured response curves from being affected in any way by the transistor mount or interface hardware (power buses, soldering leads, matching devices, adapters, etc.). A bare transistor chip was used to eliminate any effect of the transistor package on the results and improve the size and weight specifications of devices using the 2T937 transistor. The transistor chip can be directly mounted to a test board whose topology is used to connect the transistor chip to the device. The microstripline board is designed to enable measurements to be performed in the microwave frequency band using a probe station with standard calibration .

Keywords: *bipolar transistor, bare transistor chip, test (measurement) board, DC and AC response curves, extremely-high-frequency range.*

Various sub-fields within the RF industry (radar, radio navigation, telecommunications systems, and computer systems) are now undergoing rapid development as radio equipment operating frequencies continue their march upward into the microwave and UHF regions and modern semiconductor integrated-circuit technology enters commercial production. This makes the measurement accuracy requirements for the parameters of individual components and assemblies more severe.

Measurement reliability and accuracy [1, 2] are extremely important for microwave devices, since most development work for radio equipment is performed using computer-aided design (CAD) packages. However, CAD is limited by a lack of active-device libraries: The standard libraries do not include Russian transistors or most mass-produced foreign transistors [3]. The lack of models for specific transistors in CAD libraries (specifically, Microwave Office) effectively prevents the use of such models for designing RF devices.

Apin, Balabolin, and Hvalin [4, 5] produced a computer model of the 2T937 transistor based on the experimental DC and AC response curves as a function of frequency. The proposed modeling approach enables inclusion of a variety of important effects on real transistors in high-power-signal transmission mode: model parameters as a function of base dimensions; current gain and base impedance as a function of collector current; and junction capacitance as a function of applied voltage. When developing computerized transistor models, optimization of the experimental characteristics will ensure that the model DC and AC response curves as a function of frequency are similar to the actual response curves [6–8]. The measurement accuracy for the response curve and the modeling accuracy for discrete-components/assemblies (high-power bipolar transistors)

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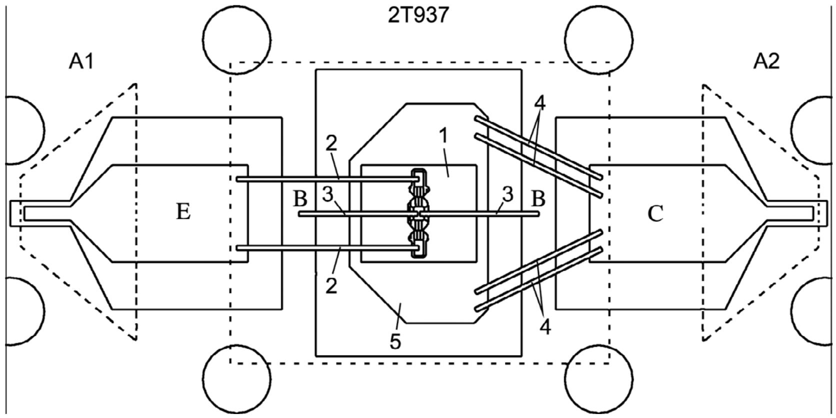

Fig. 1. Test board with transistor chip mounted: A1, A2–adapters to coplanar transmission lines; 2T937 – section of board containing transistor chip and contact pads; B, C, E–contact pads for base, collector, and emitter, respectively; *1*) transistor chip; *2–4*) soldering wires for emitter, base, and collector, respectively; *5*) mounting pad for transistor chip.

also determines the repeatability of the parameters used to describe the individual assemblies, as well as the reliability and stability of the system as a whole.

Test board. Determining the response curves of the transistors as a function of frequency (the elements of the wave scattering matrix, also known as the *S* matrix) requires the use of an interface between the transistor leads and standard measurement assemblies and devices. This interface generally includes transistor mounting hardware and two or more adapters (impedance matching devices) to connect to the portion of the measurement circuit required. In order to measure the RF parameters, the transistor must be matched to this interface. The error in measuring the parameters of the transistor itself may be quite large under certain matching conditions, especially in at microwave frequencies [9–11]. NPP Almaz has developed a test (measurement) board to reduce the measurement errors in the AC response curves as a function of frequency due to mismatch between the interface and the transistor input/output. When designing broad-band amplifiers (covering more than one octave), the structural elements of the transistor package (electrical capacitance and inductance of leads, contact pads, soldering leads, etc.) will inevitably have an adverse effect on the response curves and make it more difficult to match the input and output of the amplifier stages over the full range of operating frequencies. In order to prevent the standard transistor package from affecting the measured response curves, the Russian-manufactured 2T937 transistor was mounted directly to the test board in bare-chip form.

Prior test boards [10] have generally been used for measuring the scattering parameters of four-port networks; in certain cases, however, a six-port connection is required to measure the scattering-matrix elements of microwave transistors. Some more complex test boards [11] actually have two microstrip lines with equivalent wave impedances and gaps for connection of transistors; the functional capability is poor, since these boards can only be used to measure the parameters of transistors as four-port networks. The basic test board requirements are determined by the specific applications of the transistors and the need to connect the transistors to the measurement probes for a vector network analyzer (VNA). Modern vector network analyzers are widely used to measure the parameters of microwave devices; we used a PNA-X analyzer (Agilent, USA) for this study.

In summary, the test board is required in order to prevent the standard transistor package from affecting the measured response curves or the resultant accuracy of the computer model. The test board should permit direct mounting of the transistor chip and include the portion of the topology (Fig. 1, 2T937 – section of the board containing the transistor chip and contact pads) directly used to connect the transistor to the device being developed. At this point in development of the CAD design project, all required connectors and corresponding sections of the board topology are connected to an equivalent circuit to prevent additional topology-related transistor modeling error.

The board should also enable the chip contact pads to be connected to the PNA-X vector network analyzer; this means that we must develop two identical adapters A1 and A2 (see Fig. 1) consisting of segments of coplanar transmission lines with smoothly varying geometric dimensions.

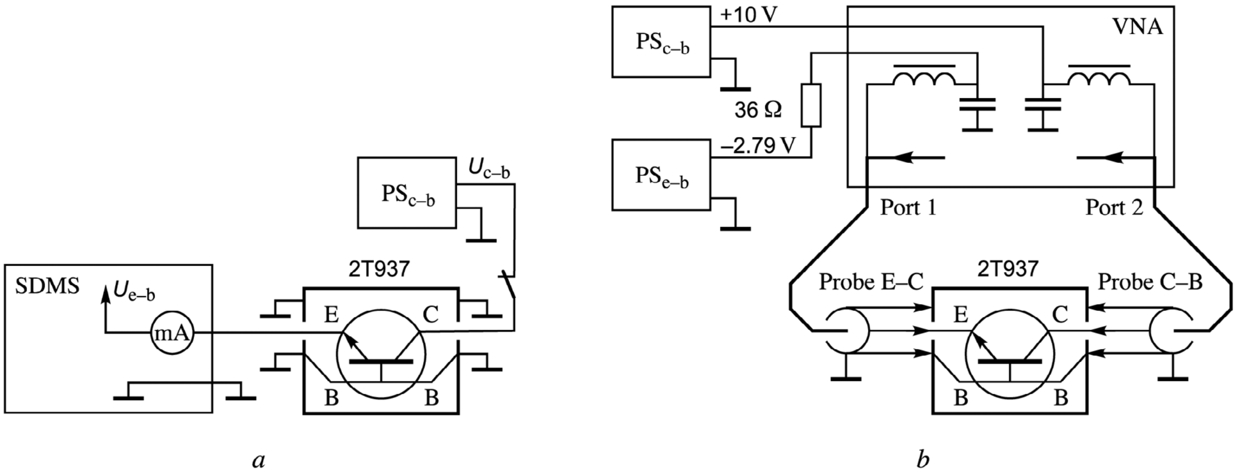

Fig. 2. Diagrams for measurement of DC (*a*) and AC (*b*) response curves of a 2T937 transistor as a function of frequency SDMS–semiconductor device measurement system; PS_{c-b}, PS_{e-b}–power supplies for the collector–base voltage U_{c-b} and emitter–base voltage U_{e-b}; VNA–vector network analyzer with three-contact emitter–base (E–B probe) and collector–base (C–B probe) probes connected to Port 1 and Port 2, respectively; all other notation identical to Fig. 1.

The modeling of the test-board components in the CAD environment took these requirements into account. The high end of the operating frequency range is at 5.5 GHz. The board was fabricated on a 1-mm-thick polycore base using microstripline conductors 7.5 μm thick. Since the adapter specifications are based on the segments of coplanar transmission lines and are most critical for microwave measurements, the adapters were optimized [3] and complied with the following specifications over the entire range of operating frequencies: maximum direct losses 0.015 dB; maximum input and output voltage standing wave ratio (VSWR) 1.05.

The test board supports operation of the transistor chip over the entire range of operating frequencies for typical values of the input power, power supply voltage, and bias voltage. These typical values were selected somewhat arbitrarily so that the transistor could also be tested under non-optimal operating conditions. We were therefore able to study nonlinear operating modes in high-power microwave transistors, which supports development of a nonlinear transistor model and the ability to use this model as a basis for designing transistors that have optimum power and electrical response curves.

The test board (see Fig. 1) contains coplanar emitter E and collector C lines to solder the emitter and collector jumpers (leads) to, respectively. The collector C occupies the entire bottom portion of the chip. Transistor chip *1* is glued to pad *5* using EChE-S conductive cement. The corners of the pad are cut off to reduce the parasitic capacitance to ground. The minimum possible pad dimensions are determined by available transistor chip mounting capabilities, and the collector jumpers (leads) are soldered in place with gold wire. All jumpers have diameter 20 μm. The transistor base B is symmetrically soldered to a grounded surface using two jumpers *3*. Adapters A1 and A2 are used for switching between the measurement probes and the transistor contact pads.

Measurement of DC and AC response curves of a 2T937 transistor as a function of frequency. Figure 2 shows the circuit for measuring the DC and AC response curves of the transistor as a function of frequency. The PNA-X VNA was calibrated in the standard manner using the calibration plate included with the probe station. The transistor was powered from an emitter–base and collector–base power supply (PS_{e-b} and PS_{c-b}, respectively) or from power fed via Ports 1 and 2 on the PNA-X analyzer. The PNA-X also has built-in LC filters with inductance $L = 100$ nH and capacitance $C = 2700$ pF.

The measurement error in the transistor parameters has a substantial impact on the model results. This measurement error is reduced by designing the test board so that it is as similar as possible to the operational design of the input and output microwave circuits in amplifier boards using the 2T937 transistor [5].

Parasitic oscillations occur in the transistor when the connections to the power supply circuits are poor or in when there is fairly strong field-mediated interference between input and output. The corresponding segments of the microstripline conductors actually act as radiating antennas, and the microstripline conductor at the input of the chip acts as a receiving antenna. Sections of microstripline conductor become efficient antennas when their length approaches a quarter wavelength. This may occur when using sections of microstripline conductor to connect the probes, or when using temporary soldered lines to connect the chip.

In order to suppress parasitic oscillations in the transistor, the chip is surrounded by a miniature metal shielding enclosure filled with a microwave-absorbent material. The indium-foil shield covered the transistor chip and was tightly pressed against a grounded surface on the board. Two rectangular pieces of microwave-absorbent material are placed on the top and bottom ends of the chip. The required gap between the indium shield and the transistor-chip topology is maintained by the thickness of the microwave absorber.

Shielding the transistor chip eliminates the roll-off in the DC current-response curves at voltages sufficiently high to excite oscillations. A diagram showing the DC input and output response curves is shown in Fig. 2*a*. The collector–base voltage U_{c-b} and emitter–base voltage U_{e-b} are determined, respectively, by power supply PS_{c-b} and the semiconductor device measurement system (SDMS), which also measures the resultant current. Two groups of DC input (base current I_b and emitter current I_e) and output (collector current) response curves were obtained as follows. The input response curve (base current as a function of emitter–base voltage U_{e-b}) was recorded with no resistor in the emitter circuit. The base current was limited to 5 mA by the SDMS. The collector was operating under no-load (NL) conditions.

A second group of input response curves (emitter current I_e as a function of emitter–base voltage U_{e-b}) was obtained for two values of the collector–base voltage U_{c-b} = 5 V and 10 V. During the measurements, the SDMS was operated in a mode that limited the emitter current to 200 mA.

The DC output response curves show the collector current I_c as a function of the voltage U_{c-b}. When measuring the static output response curves (see diagram in Fig. 2*a*), a 36-ohm resistor was inserted in the transistor emitter circuit to hold the base current at a certain value. The collector current was limited to 50 mA by the SDMS. The value I_c = 50 mA occurred at a power-source voltage U_{ps} = –2.79 V. Since $I_b \leq 1$ mA, $I_c \approx I_e$. Apin, Balabolin, and Khvalin described the simulation results for the 2T937 transistor obtained from the input (I_e) and output (I_c) DC response curves in terms of the Gummel–Poon model [4, 5]. The current I_e was brought to saturation using hardware, and we did not use our model to reproduce this mode.

The complete transistor model must also reproduce the AC response curve as a function of frequency (the so-called *S* parameters) in addition to the DC response curve. The traditional approach for constructing a model transistor calls disentangling the unknown *S* parameters of the transistor from the *S* parameters of the test board [10] as a first step. In this case, one first develops a model for the combined system – transistor on test board – and then determine the parameters for the transistor.

One common technique for measuring the *S* parameters of transistors in the near-field mode consists of the following: the incident and reflected voltage waves from the test board (which includes the transistor itself and a mount for the transistor) are separated from one another, and the ratios of the incident and reflected waves are measured as the phase differences between the incident waves are varied over a range of 0–360° [12, 13]. Twelve-pole reflectometers are then used to measure the complex reflection coefficients (CRCs) at the input and output of the aforementioned device for two values of the phase difference between incident waves [13]. The transistor is then removed from the test board, and the CRCs are measured at the inputs of the coax-stripline junctions in the transistor mount. The transistor mount is then removed from the circuit, and the complex reflection coefficients are measured at the outputs of the 12-pole reflectometer, along with the voltage ratio of the incident waves from the oscillator. The resulting systems of equations are then solved for the unknown *S* parameters of the transistor [13].

A diagram of the AC measurements as a function of frequency is shown in Fig. 2*b*. The connection between the input and output of the test board and the PNA-X vector network analyzer was implemented using three-contact probes with contacts separated by 150 μm. Eight AC response curves were measured over the 0.5–5.5 GHz interval, providing the amplitude and phase response curves for the scattering-matrix parameters S_{11}, S_{12}, S_{21}, and S_{22}. Figure 3 shows a sample amplitude-response curve for the transistor gain $S_{21}(f)$.

The measured DC and AC response curves for the 2T937 transistor used to determine the parameters of the Hummel–Poon bipolar transistor model still require optimization. The actual problem of using six DC response curves and eight AC response curves to determine the 60 parameters of the Hummel–Poon model is a complex, multi-criterion, multi-parameter problem to be discussed separately [3], and will not be addressed in this paper. Approaches for similar optimization of the response curves for bipolar transistors are provided in, e.g., [3, 7, 8]. Khvalin [3] and Samoldanov, Ignat'ev, Lyashenko, et al.

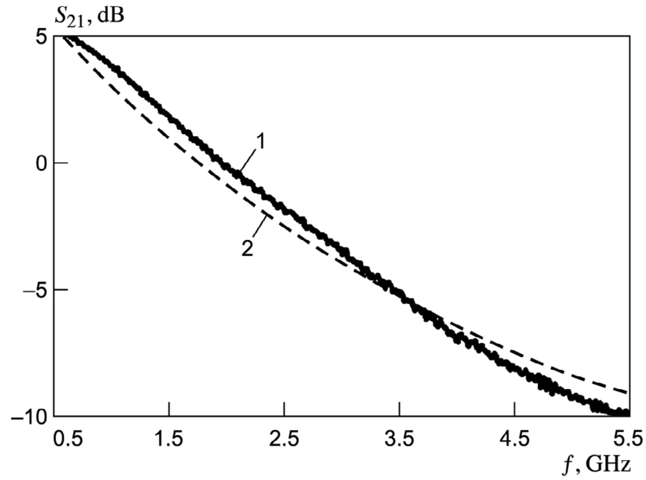

Fig. 3. Measured (*1*) and calculated (*2*) amplitude frequency response curves (calculated using model [4, 5]) for the transfer coefficient S_{21} of the 2T957 transistor.

[8] published computer models of the BFR90 bipolar transistor based on its experimental response curves. The relative errors in the models for the amplitude frequency response and the phase frequency response of this transistor were on the order of 10 and 9%, respectively.

Optimization of the Hummel–Poon model based on the experimentally obtained DC and AC response curves of the 2T937 transistor as a function of frequency was discussed in [4, 5], where the results obtained from calculation of the basic response curves for the 2T937 transistor using our computer model (compatible with the common CAD software Microwave Office) were compared against the measured values for the response curves. The model results were consistent with the experimental data obtained, and the model error for the DC and AC response curves as a function of frequency for the 2T937 transistor were of order 10% [4, 5].

Conclusion. The test board developed for this paper can be used to eliminate all effects due to power buses, soldering leads, matching devices, adapters, and other accessories on the measured response curves for the transistor, and will improve the reliability of the measured transistor parameters. In order to eliminate any effect the transistor package might have had on the measured results, a bare 2T937 transistor chip was used. The transistor chip was directly mounted to the test board, whose topology was used to connect the transistor chip to the device. The proposed approach for measurement of basic transistor properties and developing computer models of the active devices based on these measurements is also applicable to other microwave devices [14–18].

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