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TOP-DOWN DESIGN OF INTEGRATED TRANSCEIVER: PECULIARITY AND TEACHING METHOD USING EDA ADVANCED DESIGN SYSTEM (ADS)

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Requirements for the degree of integration, cost, power consumption of transceivers are constantly increasing. In this regard, at present, transceivers are built based on integrated circuits. For the successful development of an integrated transceivers, it is necessary to use the principles of top-down design and end-to-end design, implemented in EDA. The article examines the features and methods of teaching students to develop integrated transceivers in accordance with the principle of the top-down design. The proposed teaching methodology allows students to learn how to use system and circuit modeling tools using EDA Advanced Design System (ADS) produced by Keysight as an example and to study a design flow that includes the following stages: system-level design, block-level design, schematic-level design and layout level design.

Keywords: receiver, transceiver, top-down design, EDA, ADS.

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НИСХОДЯЩЕЕ ПРОЕКТИРОВАНИЕ ИНТЕГРАЛЬНЫХ ПРИЁМНЫХ И ПЕРЕДАЮЩИХ УСТРОЙСТВ: ОСОБЕННОСТИ И МЕТОДИКА ПРЕПОДАВАНИЯ С ИСПОЛЬЗОВАНИЕМ САПР ADVANCED DESIGN SYSTEM (ADS)

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Требования к степени интеграции, стоимости, энергопотреблению приёмно-передающих устройств постоянно возрастают. В связи с этим в настоящее время приёмные и передающие устройства строятся на основе интегральных схем. Для успешной разработки интегрального приёмно-передающего устройства необходимо при проектировании использовать принципы нисходящего проектирования (top-down design) и сквозного проектирования, реализованные в системах автоматизированного проектирования радиоэлектронных устройств. В статье рассмотрены особенности и методика обучения студентов разработке интегральных приёмных и передающих устройств в соответствии с принципом нисходящего проектирования. Предложенная методика обучения позволяет студентам научиться использовать средства системного и схемотехнического моделирования на примере системы автоматизированного проектирования Advanced Design System (ADS) компании Keysight и освоить маршрут проектирования, включающий следующие этапы: проектирование на уровне системы, проектирование на уровне структурной схемы, проектирование на уровне принципиальной схемы и проектирование на уровне компоновки кристалла.

Ключевые слова: приёмник, передатчик, нисходящее проектирование, САПР, ADS.

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Introduction

Modern digital communication systems are built using complex signal processing algorithms, and the complexity of systems increases as new modulation schemes, multiple access protocols and communication standards are introduced [1–5]. Requirements for the integration degree, cost, power consumption and time to market for a transceiver are constantly increasing. In this regard, at present, transceivers are built using integrated circuits (IC). Integrated circuit includes not only functional units and transceiver blocks, but in some cases, transceivers are fully implemented in the form of an integrated circuit.

For the successful development of an integrated transceiver, it is necessary to use modern design principles and tools. This need arises from the fact that the transceivers of any modern digital communication system represent a set of software and hardware, which are developed in close connection with each other [6–11]. Thus, the transceiver consists of a digital part and an analog part. The digital part performs digital signal processing using algorithms specified at the software or hardware level. The analog part implements analog signal processing, including the processing at high frequencies. For example, the requirements for the schematic and parameters of the transceiver blocks of the analog and high-frequency parts follow from the specification and the design features of the whole system. At the same time, in contrast to the design using discrete elements, the cost of an error in the IC transceiver design is high due to the impossibility of adjustments after the manufacture of the IC chip without redesigning and manufacturing the IC. In this regard, at present, the design of transceivers is carried out on the basis of the principle of top-down design [12] and the principle of end-to-end design flow implemented in electronic design automation (EDA), for example, Advanced Design System (ADS) from Keysight Technologies.

The principle of top-down design implies design with sequential simplification of the task by dividing it into several separate subtasks. Initially, the system is described at a high level, and then gradually divided into separate parts with more detailed description until the granularity is sufficient to implement the system at the level of schematic and IC layout, or until the granularity is sufficient for coding. Three levels of design are distinguished: design at the system level, design at the block diagram level, and design at the schematic diagram level. Each design level uses its own methods of modeling the system or device. A fourth design level – design at the chip layout level can be added to these three.

The end-to-end design flow implies the organization of teamwork on a project in a single development environment that supports various design and simulation tools with the transfer of the results of one design stage to the next. At the same time, changes made at any stage should be reflected in all parts of the project at once.

The developers of digital communication systems, transceivers and their individual parts for the successful solution of his task must have not only knowledge sufficient to solve a specific problem, but also an understanding of the entire design route of the transceiver and the place of the task they are solving specifically among other tasks solved by their colleagues.

In this regard, it seems expedient to train engineers and specialists in the field of design of transceivers on the basis of teaching methods involving the principles of top-down and end-to-end design flow. This will not only create a holistic view of the students about the subject, but also teach them the principles of a modern approach to designing receivers and transmitters.

Peculiarity of integrated transceiver design

The signal processing of digital communication systems is realized using digital or analog signal processing based on hardware and software. The hardware can include the following main components responsible for the signal processing steps:

– digital signal processor (DSP);
– digital signal processing circuits;
– analog-to-digital and digital-to-analog converter;
– analog part of the transceiver;
– high-frequency part of the transceiver.

Various stages of signal processing can be implemented both in the digital and in the analog domain. For example, consider the implementation of a superheterodyne receiver in Fig. 1. The receiver front-end in Fig. 1 consists of band-select filter (BSF), the low-noise amplifier (LNA), mixer (Mixer 1), image-reject filter (IRF) and intermediate-frequency amplifier (IFA). The signal spectrum is first transferred to the intermediate frequency fIF by means of the mixer (Mixer 1), and then, by means of I/Q demodulator, the passband signal is demodulated.

The signal is demodulated in the analog domain using a quadrature demodulator based on two mixers, Mixer 2 and Mixer 3, and low-pass filters (LPF) (Fig. 1 a). Then the signal is amplified by baseband amplifier (BBA) and the analog-to-digital conversion is carried out by means of a digital-to-analog converter (ADC) and further signal processing is realized in the digital domain (DSP). In the second case (Fig. 1 b), signal demodulation is carried out using I/Q demodulator implemented in the digital domain and located after the analog-to-digital converter (ADC). It consists of the two multipliers and the FIR digital filters. Such a receiver is often called a Low-IF Receiver, or Digital IF Receiver.

At present, due to the rapid development of microelectronics, several trends are observed in the design of transceivers. Firstly, the development of integrated technologies, especially CMOS technology,

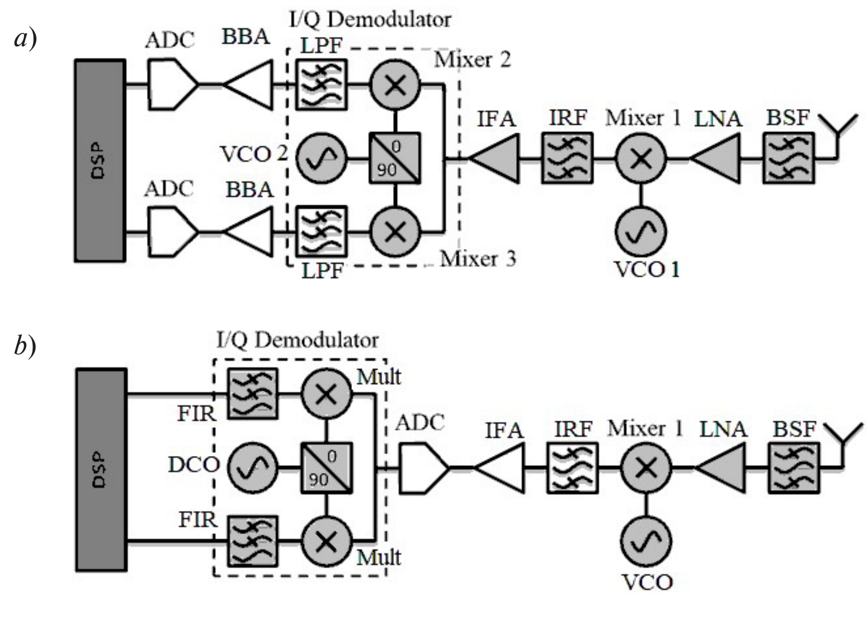

Fig. 1. Block diagram of the receiver with implementation of the demodulator in the analog domain (*a*), in the digital domain (*b*)

has made it possible to implement the system-on-a-chip (SoC) concept, when both digital, analog and high-frequency parts of the transceiver are integrated on a single chip. Thus, there is a trend towards combining different parts of the receiver on a single integrated circuit chip. Secondly, an increase in the clock frequency of digital circuits made it possible to implement digital signal processing at those frequencies at which previously processing was carried out only in the analog domain. Thirdly, the development of microwave microelectronics has made it possible to use new frequency ranges for data transmission, which were not previously used in consumer electronics. For example, in the frequency range up to 10 GHz, digital signal processing methods have become possible, and in the frequency range up to 100 GHz, personal local networks operate. Fourthly, sophisticated digital modulation schemes are now being used to increase the data rate through the performance of digital circuits.

The complexity of the structure of the transceivers makes it necessary to use special approaches, software tools and design routes in their development.

Top-down design and software tools

Top-down design refers to design that progressively simplifies a task by breaking it down into several distinct subtasks. At the beginning of the design, the basic requirements for a digital telecommunications system are formulated, for example, the probability of erroneous reception, frequency band, modulation type, etc. At this point, the structure of the telecommunications system as a whole and the implementation features are still unknown. For example, it is not known what part of signal processing will be implemented in the form of hardware, and what – in the form of software, it is not known what parameters low-noise amplifier should have, etc.

Therefore, initially the system is described at a high level, followed by step-by-step division into separate components with a more detailed description. This process continues until the granularity is enough to implement the system at the level of circuit schematic and integrated circuit layout, or until the granularity is sufficient for coding. This approach allows you to split the task into separate subtasks, the solution of which will ultimately comply with the expected result at the beginning of the system design.

Therefore, for example, a block diagram of the linear path of the receiver can be represented as a set of typical functional units – amplifiers, frequency converters, automatic gain control (AGC) devices, etc. Each typical unit can be represented by connecting several operational links – amplifier stage, frequency filter, etc.

Four levels of design are distinguished depending on the level of detail of the task [12]:

– System Level,
– Block Level,
– Circuit/Transistor Level,
– Layout Level.

Fig. 2 illustrates a flow chart of the top-down design and bottom-up verification process. At the design stage at the system level, based on the existing specification, the structure of the telecommunication system is developed, which makes it possible to implement the given specification. In this case, the description of the components of the system is carried out with a high level of abstraction, i.e. without considering the implementation features. For example, a transmitting-receiving device includes a low-noise amplifier, which at the design stage at the system level can be described by the mathematical operation of multiplying a signal by a constant.

After the structure of the system is defined, the design moves to the block diagram level. At this stage, the system is divided into an analog part and a digital part. The digital part consists of the digital signal processing algorithms that will be implemented at the hardware level and at the software level.

Further, the analog and digital parts of the system are also divided into component parts, sub-blocks. The description of the constituent parts is carried out already at the functional level, considering the implementation features. For example, a low-noise amplifier at this design level will be described by

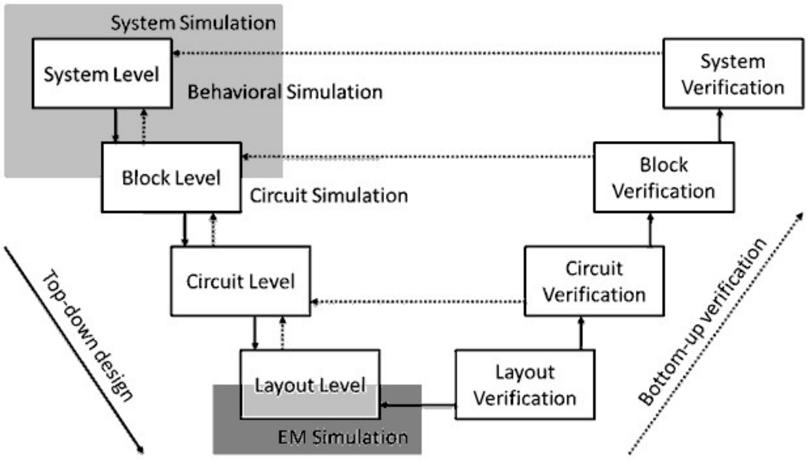

Fig. 2. Top-down design flow chart

a functional model that considers harmonic distortion and amplifier noise. However, the behavioral model will only describe the behavior of the amplifier and will not consider its implementation at the circuit level.

After the structure of the system and the parameters of the system blocks have been determined, design begins at the level of circuit schematic. Analog circuits are described as a netlist of IC elements, and digital circuits are described as a netlist of logical elements. For example, as a result of designing an integrated low-noise amplifier, the circuit schematic of the amplifier and the parameters of the circuit elements, the geometric dimensions of transistors, resistors, capacitors, etc. will be determined.

After the circuit schematics are developed, the design phase begins at the level of the chip layout. At this stage, the integrated circuit is represented by a set of polygons that characterize the layered structure of the integrated circuit. For example, as a result of designing an integrated low-noise amplifier, the arrangement of the circuit elements will be determined, and the conductors connecting the circuit elements will be drawn.

At any stage of the design, it may turn out that the requirements for the parameters of the device being developed cannot be met. In this case, it is necessary to return to a higher level of design and formulate realizable requirements.

The development of transceivers at the modern level involves computer-aided design using simulation of both individual blocks of the system and the entire system. Computer-aided design is made possible by simulating the characteristics of a device or system being developed. Since each design level assumes its own level of abstraction when describing the device being developed, the modeling principles should be different. There are several types of modeling tools:

– system modeling simulator;
– mixed-mode signal simulator;
– circuit simulator;
– electromagnetic simulator and extraction of parasitic parameters of the crystal layout.

System modeling tools are typically used for system-level modeling. This is based on methods of digital signal processing at the software level. These modeling tools differ, as a rule, in a large set of libraries with models of communication channels of transceivers and models of their sub-blocks, functional units and operational links.

Mixed-mode signal simulator are based on an approach that simulates the operation of complex digital circuits and digital signal processing implemented at the hardware level.

Circuit simulator is used to simulate circuits at the transistor level, which allows you to obtain the most accurate characteristics of the device in development. But due to the complexity of the mathematical apparatus, the application of this approach to large circuits is limited.

Electromagnetic simulator and parasitic extraction tools enable the simulation of high frequency passive devices and IC interconnects.

However, the scope of the modeling tool can cover not one, but several levels of design due to the expansion of their functionality. For example, mixed-mode signal simulators can be used for system-level simulations, but the simulations are less convenient. The number of libraries with models of communication channels, transceivers and their components in digital-analog modeling environments is very limited today.

It is advisable to carry out all stages of IC development in one software environment, which makes it possible to implement the principle of end-to-end design. It implies organizing work on a project, transferring the results of one design stage to the next and reflecting changes in all parts of the project. Therefore, software developers strive to cover all stages of development in one software environment.

Historically, Advanced Design System (ADS) produced by Keysight EEsof EDA and AWR Design Environment produced by AWR Corporation are dedicated to MMIC and RF IC design, so the focus has been on frequency domain circuit simulation and electromagnetic analysis. To model the whole system, system simulation tools are used with functional models of analog devices and the launch of circuit simulation when using system modeling.

The Virtuoso Design Environment produced by Cadence Design Systems and Tanner produced by Mentor Graphics were originally focused on the development of digital, mixed signal, and analog ICs using silicon-based technology. The main modeling tools here are mixed-mode signal simulation and circuit analysis of ICs in the time domain. To analyze the parasitic effects of the IC layout, the method of extracting parasitic parameters is used, which allows taking into account the influence of the parasitic effects of the IC layout in circuits with a large number of active elements at relatively low frequencies. For system-level design, mixed-mode modeling tools with a limited set of libraries are available.

With the development of integrated electronic technologies and the integration of all elements of transceiver on a single chip, it becomes necessary to use a wider set of modeling tools, which forces developers to create software that can interact with competitors' products. For example, Keysight Technologies releases the Goldengate software product, which integrates into the Virtuoso design environment from Cadence Design Systems and provides a development environment in which all functions are implemented.

After the layout of the chip has been developed, it is necessary that the system will meet the requirements. For this, bottom-up verification is used (Fig. 2). As part of the bottom-up verification, during a simulation, the parameters of the developed device are determined, and then the obtained parameters are used at the next higher stage of verification. For example, after electromagnetic analysis and during a simulation at the level of the circuit schematic of the low noise amplifier, the decoupling parameter between the output and the input can be determined. This parameter can be substituted into the functional model of the amplifier at the block level simulation. If the obtained result does not meet the specification, it is necessary to repeat the design.

Teaching method in compliance with the top-down design methodology

At Peter the Great St. Petersburg Polytechnic University (SPbPU), within the framework of the international educational master's degree programs "Microelectronics of Telecommunication Systems", students are trained in the transceiver design in accordance with the principle of the top-down design. In a number of courses, students study the principles of transceiver design methods for digital communication systems. Students begin to study the principles of constructing transceiver at the system level, then come to the block level. After that, the construction of blocks of transceivers at the transistor level is studied.

The training begins with an examination of the principles of constructing modulators and demodulators, block diagrams of receivers and transmitters. During the training, students have the opportunity to explore signal processing at various stages and carry out simulations using system simulation tools. So, when studying the design principles of transceivers at the system level, students study the principles of pulse code modulation and passband modulation and detection, block diagrams of modulators and demodulators, block diagrams of linear paths of transceivers, and have the ability to simulate their work using EDA Advanced Design System. At this stage, the functioning of both digital and analog and high-frequency parts of the transceiver is considered. Therefore, for example, in Fig. 3 shows a block diagram of the transceiver with NRZ pulse modulation, taken from a student's laboratory work, and an eye diagram of the

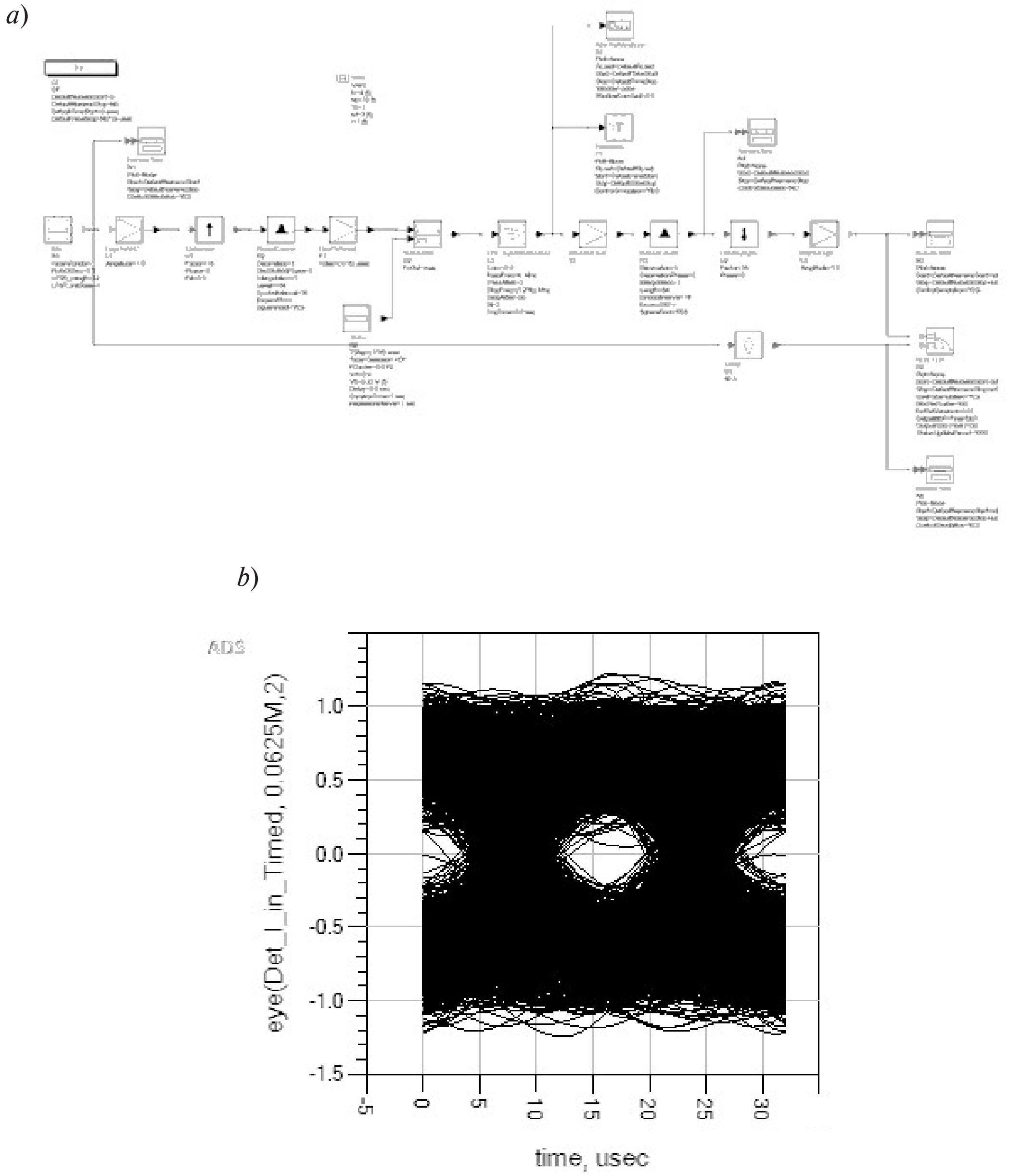

Fig. 3. Block diagram (*a*) and eye diagram (*b*) of a communication system with NRZ pulse modulation

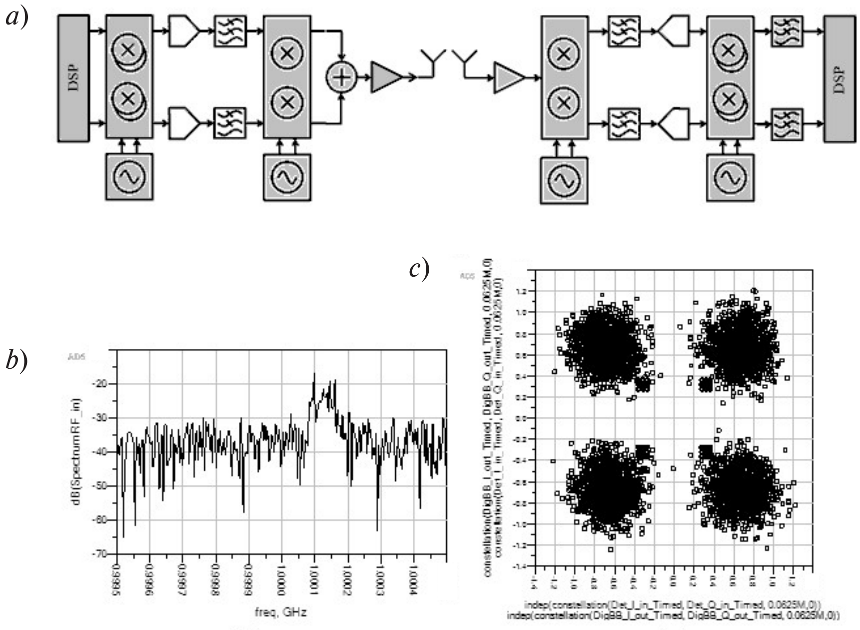

Fig. 4. Block diagram (*a*), spectrum of the signal at the input of the receiver (*b*) and the signal constellation (*c*) of the communication system with 4-QAM passband modulation

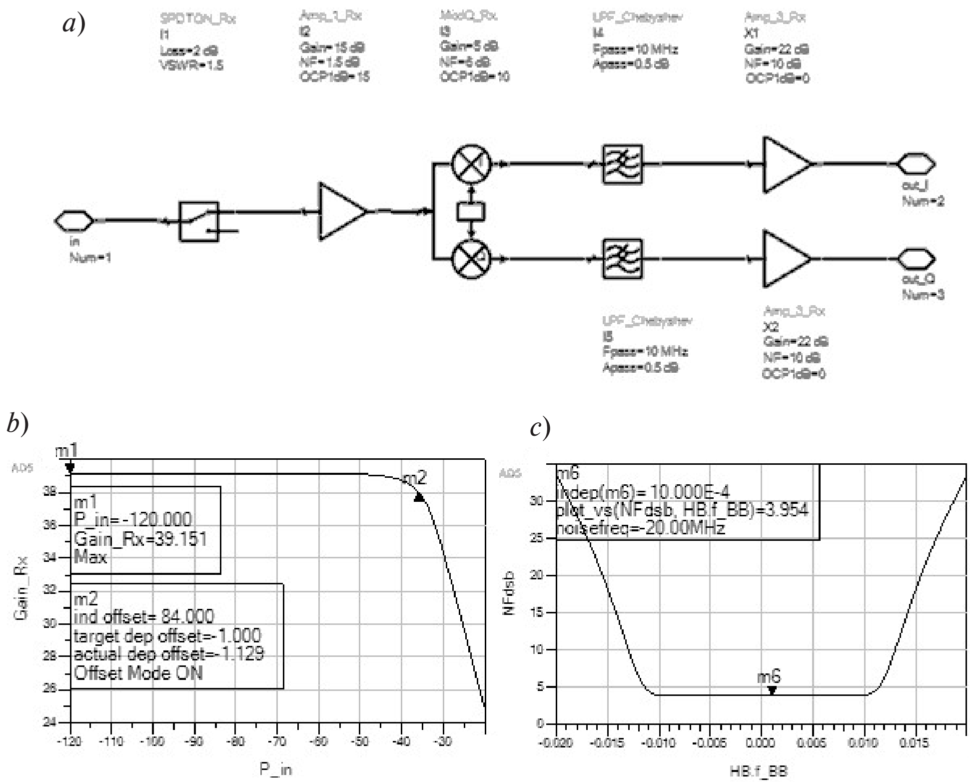

Fig. 5. Block diagram of the receiver (*a*), gain (*b*) and noise figure (*c*) of the receiver

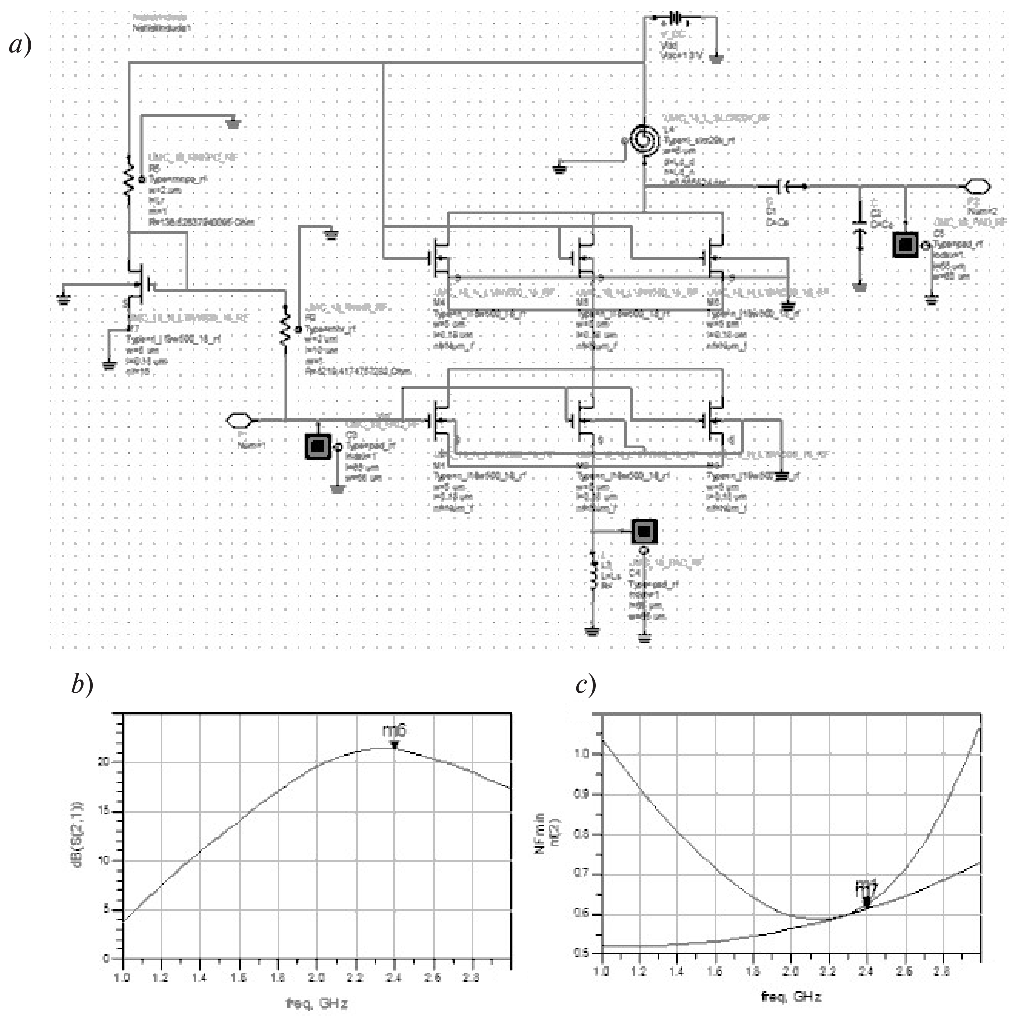

Fig. 6. Schematic diagram of a low-noise amplifier (*a*) and simulation results, gain (*b*) and noise figure (*c*)

signal at the input of the receiver. A block diagram of the transceiver with 4-QAM pulse modulation and the results of modeling the signal spectrum at the receiver input and the signal constellation at the detector input is shown in Fig. 4. In the course of laboratory work, students have the opportunity to investigate signals at various nodes of the circuit and obtain the dependence of the bit error probability on the noise power in the communication channel.

After studying system-level design, students move on to design at the block level. At this stage, students study electrical functional models and parameters of physically realizable units of transceivers, which take into account their noise and nonlinear properties. Students study the influence of the physically realizable block parameters on the characteristics of the entire system. So, for example, Fig. 5 shows a block diagram of the receiving device taken from a student's laboratory work, during the simulation of which the student is introduced to such parameters as the noise figure, the 1 dB compression point.

Moving on to the circuit level, students start the implementation of the main units (amplifiers, mixers, reference oscillators) at the transistor level using PDK of manufacturing integrated circuits. So, for example, one of the student's tasks is to design a low-noise amplifier and simulate its main parameters (Fig. 6) using circuit simulation.

Such an approach in teaching students allows not only to create a holistic view of the subject and basic principles of functioning of transceivers, but also to introduce them to both the top-down design method and the design environment itself.

Conclusion

At the current stage of development of digital communication systems, transmitting and receiving devices are a combination of hardware and software. In their development, it is necessary to use the principles of top-down design and modern design tools. An engineer participating in the development of a transceiver must not only be able to solve his highly specialized task, but also understand the principles of the operation of the system as a whole in order to successfully interact with colleagues within the framework of a large project. In this regard, the use of the methodology for teaching students in accordance with the principles of the top-down design seems appropriate, since this allows not only to introduce the principles of design but also to use development tools. Advanced Design System produced by Keysight Technologies is a good choice of a software tool to study the transceiver top-down design. The EDA ADS provides an opportunity to cover whole design stages from system level design to layout level design and includes system, circuit and electromagnetic simulator to the digital signal processing algorithms, behavioral and circuit modeling. Thus, the students could study the end to end design, that gives them perceptual unit of such a complicated topic as the top-down design of transmitter and receiver.

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