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APPLICATION OF THE RF MEMS TECHNOLOGY IN MODERN WIRELESS SYSTEMS: A POTENTIAL THAT HAS NOT YET BEEN FULLY REALIZED

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Today one of the key triggers of the development of research and development in the field of electronics, radio-frequency components, and systems, system integration and design, as well as information and communication technologies are such data network concepts as the Internet of Things, Internet of Everything, Tactical Internet and the most important among them is 5G – the 5th generation of mobile radio communications. This article presents a vision for the use of devices manufactured using microelectromechanical systems technology, namely passive radio-frequency microelectromechanical devices and systems in synergy with energy-harvesting microelectromechanical devices and systems in such new structural paradigms. The authors present their results on the development, manufacture and research of experimental samples of radio-frequency microelectromechanical switches that can meet the growing need for cutting-edge performance for currently deployed 5G NR FR1 (below 6 GHz) mobile networks or high-performance applications.

Keywords: MEMS, RF MEMS, EH MEMS, microelectromechanical systems, radio-frequency, energy-harvesting, modern wireless systems.

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ПРИМЕНЕНИЕ РЧ МЭМС-ТЕХНОЛОГИИ В СОВРЕМЕННЫХ БЕСПРОВОДНЫХ СИСТЕМАХ: ПОТЕНЦИАЛ, КОТОРЫЙ ЕЩЁ ПОЛНОСТЬЮ НЕ РАСКРЫТ

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На сегодняшний день одним из ключевых драйверов (триггеров) развития научно-исследовательских и опытно-конструкторских разработок в области электроники, радиочастотных компонентов и систем, системной интеграции и проектирования, а также информационно-коммуникационных технологий являются такие концепции сети передачи данных, как Интернет Вещей, Интернет Всего, Тактильный Интернет и наиболее важный среди них – 5G – пятое поколение мобильной радиосвязи. В статье представлено видение использования устройств, изготовленных с применением технологии микроэлектромеханических систем: пассивных радиочастотных микроэлектромеханических устройств и систем в синергии с энергособирающими микроэлектромеханическими устройствами и системами в новых структурных парадигмах. Представлены результаты разработки, изготовления и исследования экспериментальных образцов радиочастотных микроэлектромеханических переключателей, способные удовлетворить растущую потребность в ультрасовременной производительности для развертываемых в настоящее время мобильных сетей 5G NR FR1 (менее 6 ГГц) или высокопроизводительных приложений.

Ключевые слова: МЭМС, РЧ МЭМС, ЭС МЭМС, микроэлектромеханические системы, радиочастотные, энергособирающие, современные беспроводные системы.

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Introduction

In 1835, Joseph Henry invented the first electromechanical device, called a “switch” or “relay”. It consisted of a bulky electromagnet that activated an armature capable of making physical contact between the two electrodes. The clock frequency was limited to tens of hertz.

In 1979, Petersen developed the first micromechanical membrane switches, which were said to fill a niche or fill a gap between conventional silicon transistors with mechanical and electromagnetic relays. This was the starting point that opened the way to microelectromechanical systems (MEMS). The key idea, an original concept at the time, was to combine the capabilities of silicon-based micro-manufacturing with a mechanical relay approach. The proposed MEMS based switch used an electrostatic force applied between a layer of p-doped silicon and a membrane made of a bimetallic material (SiO_2 content and Au) to set in motion a movable suspended structure and establish electrical contact.

In the 1990s, the electrical and microwave community contributed to the emergence of a new class of devices: microrelays capable of processing analog, radio-frequency (RF), and microwave signals.

In 1990, Halg introduced the first integrated microelectromechanical non-volatile memory cell. In 1991, Larson et al. [1] demonstrated the microwave rotary switch of the transmission line. Measurements made up to 45 GHz were already impressed with insertion loss below –0.5 dB and isolation above –35 dB. In 1995, Goldsmith et al. [2] introduced what was to become one of the most well-known membrane configurations for RF microelectromechanical system switches with capacitive contact. Then came the era of RF MEMS [3].

The presented article consists of two parts. The first and main part gives a brief overview of the place of RF MEMS devices in consolidation with the technology of energy-harvesting MEMS devices, and how these technical solutions can contribute to miniaturization, reduce energy consumption, expand possible connections and their efficiency, pursued by the currently developing paradigms of the 5G mobile network, the Internet of Things, the Internet of Everything and the Tactile Internet. The second part of the article presents a brief description of the current research results carried out by this team of authors, the main purpose of which is to develop, manufacture and study experimental samples of single-pole single-throw RF MEMS switches suitable for use in RF transceiver modules of 5G mobile networks in the frequency band NR FR1.

Principles of operation

RF MEMS systems concentrated passive components that implement functions of varying complexity designed to generate and/or redirect one or more RF signals in the circuits and subsystems of wireless transceivers (transmitters/receivers). In RF MEMS, the ability to reconfigure the conditioning function operating on RF signals is always provided by the physical movement and mechanical deformation of the micromembranes, i.e., the fundamental characteristic of sensors and actuators based on MEMS. Given this context, whatever the complexity of the network-controlled air conditioning function in RF MEMS technology is, the main element is the switch (or relay). As with traditional electromechanical relays, RF

MEMS switches are equipped with a metal (or more generally conductive) flexible membrane that, when properly deformed, closes the electrical contact between the input and output ends, allowing the RF signal to pass through the relay and change its state from open to closed. On the other hand, unlike classical devices, RF MEMS switches are highly miniaturized, and the dimensions in the plane can reach several tens of microns, and the thickness (out-of-plane size) is only a few microns (or from 50 μm to 100 μm, also considering the silicon substrate). The most common actuation strategy for controlling the movement of a moving contact, and therefore for controlling the state transition between open and closed, is electrostatic displacement. Voltage (i.e. displacement) is superimposed on the floating part and the fixed actuation electrode, and the force of displacement brings the first electrode into physical contact with the input and output branches, thereby closing them and closing the relay.

However, in addition to the electrostatic force [4, 5], other actuation mechanisms are possible, such as thermoelectric [6], piezoelectric [7] and electromagnetic [8]. In addition, depending on the specific deployment and configuration of the I/O electrodes, the switch can be ohmic or capacitive, as well as serial or shunt, which provides the developer with various degrees of freedom and covers a wide range of performance and performance characteristics.

Essentially, starting with basic reconfigurable elements, i.e. ohmic and capacitive, micro-relays with excellent performance in terms of high isolation, wide frequency range, low insertion loss, pronounced linearity, and almost zero power consumption, proper redundancy, and interconnection enable the implementation of high-performance and widely reconfigurable passive RF MEMS networks [9]. Since then, switching blocks have been successfully demonstrated in the literature, ranging from single-pole double-throws (SPDTs) to more complex single-pole multiple-throws (SPMTs) and switching matrices. Reconfigurable RF power attenuators and splitters/couplers can also be fully implemented in RF MEMS technology, as well as in impedance matching tuners covering a significant portion of the smith-diagram and implementing a large number of different states. In addition, RF MEMS technology has been proven to be a key solution that also allows the implementation of reconfigurable phase shifters and true time delay lines (TDL) for electronic antenna steering and radar systems, as well as in the micro-fabrication of tunable filters for various RF applications.

Market expectations

Among the various concepts outlined by Nguyen in 2001, it is certainly one of the most relevant [10]. Starting with the standard transceiver architecture (transmitter/receiver), the deployment of RF MEMS had to follow two paths. At the first stage, it was assumed that the RF passives in MEMS technology, such as antenna switches, RF/IF (intermediate frequency) filters, LC reservoirs, and resonators, would replace the standard counterparts, increasing the system performance. The second stage of the development of a high-precision RF MEMS device, such as multi-channel selectors with built-in filtering functions and mixer filters, would cause a rethink of the transceiver architecture. The block diagram of RF systems had to be simplified, which would reduce both hardware complexity and power consumption. This transmission topology can provide huge energy savings. In particular, if a high-Q and high-power filter with an insertion loss of less than 1 dB can follow the power amplifier (PA), clearing all spurious outputs, including those resulting from spectrum overgrowth, then more efficient PA designs can be used, despite their non-linearity. For example, a PA previously limited by linearity considerations to 30 % efficiency in modern transmitter architectures may be operational closer to its maximum efficiency, perhaps 50 %. For a typical transmission capacity of 600 mW, this efficiency improvement corresponds to an energy saving of 800 mW. The performance of the transceiver, on the other side, would be expanded by numerous standards and services. Nevertheless, the evolution of the facts went in a completely different direction. Market forecasts published since the early 2000s envisioned hundreds of millions of dollars (US dollars) for RF MEMS in the consumer market segment, which, analysis by analysis, were systematically reduced. These disappointments occurred for two reasons, both internal and external to the technology itself.

At the same time, the first successes in the development of passive RF MEMS components were announced only in the last few years, with a delay of about one decade compared to the market revolution predicted in the early 2000s. This was due to the fact that the rather critical aspects of RF MEMS technology were not fully evaluated at the beginning.

Internal factors were associated with the lack of maturity of RF MEMS in the early years of their discussion, with a particular focus on reliability, packaging, and integration with other (incompatible) technologies. On the other hand, external factors correlated with the surrounding market environment. In fact, mobile apps prior to 3G–3.5 G were not really demanding on high-performance components, such as RF MEMS.

The context of the link began to change with the appearance of 4G-LTE mobile devices (4th generation; Long-Term Evolution). The inclusion of an increasing number of components has caused a gradual trend towards a deterioration in the quality of communication. The antennas no longer functioned under optimal conditions, resulting in lower download speeds, lower voice quality, lower energy efficiency, and more missed calls. The fixed impedance matching between the antenna and the RF front-end (RFFE), classically adopted in previous generations of mobile phones, was no longer the best option. As part of this, for example, for a few years, adaptive RF MEMS impedance tuners have begun to make their way into the consumer segment of the 4G-LTE smartphone market.

Next up is the 5th generation of mobile networks and devices. 5G seems to be the right platform for RF MEMS technology to express its full potential in market applications.

The development scenario of 5G

5G will implement a completely different paradigm compared to 4G, 4G-LTE. Some of the services we use today, such as Wi-Fi internet access and video streaming, will be covered by 5G coverage along with classic features such as voice calls and mobile internet access. It is also important to note that machine-to-machine (M2M) communication data is expected to be transmitted over 5G protocols. Examples of M2M applications are autonomous vehicles, remote surgery, remote manufacturing, and smart cities. In other words, a significant portion of the Internet of Things (IoT), Internet of Everything (IoE) data traffic will depend on 5G networks.

Obviously, the data throughput requirement is going to be huge. Many forecasts call for a 1000-fold increase in 5G transmission capacity over 4G-LTE, providing 10 Gb/s for each individual user. In addition, the data transfer delay will need to be drastically reduced to a millisecond level. To understand the importance of the latter requirement, one can simply wonder how low latency can be critical for applications such as vehicle-to-vehicle (V2V) communication. Finally, more importantly, when using M2M applications, cloud computing, IoT, IoE, and so on, will require a greater symmetry between the downlink and uplink bandwidth of the 5G standard.

How this revolution will become possible at the implementation level is still a hot topic for discussion. Nevertheless, some high-level trends have already begun to show up quite clearly. 5G radio access technologies (RATs) will use three main components to increase the amount of data transmitted [11]:

1. The order of modulation;
2. Aggregated throughput;
3. The order of multiple-input and multiple-output antennas (MIMO).

If the first degree of freedom is a problem mainly at the level of algorithms and electronic design, points 2 and 3 make clear requirements in terms of hardware reconfiguration. In particular, improving aggregated bandwidth means increasing the number of carrier aggregation (CA) components. Translated into the technical characteristics of the equipment, this means that RF transceivers must have high readjusted ability and flexibility in the rapid transition from one frequency band to another. On the other hand, increasing the order of MIMO means having arrays/arrays of integrated antennas (e.g. 4 × 4) small enough for use in smartphones and controlled by high-performance RFFEs with improved switching and filtering characteristics to minimize internal and crosstalk.

From the point of view of mobile infrastructure, another trend towards consolidation is the spread of frequencies across the entire reverse part of the network hierarchy. In this regard, a clear frequency division will characterize 5G networks. The classic macronutrients, covering quite extensive areas, will mostly operate in the range up to 6 GHz. On the other hand, the huge data throughput mentioned above will be achieved by significantly compacting the network. For this purpose, small cells will be deployed that cover very limited spaces, such as a single building or small metropolitan areas (for example, the lobby of a train station or shopping center). Such small cells will allow mass data transmission in the millimeter wave range, that is, significantly higher than 6 GHz. On the other hand, they will require arrays of reconfigurable antennas and RF drivers capable of implementing advanced signal shaping and, in turn, achieving pronounced directivity and effective coverage of the zone.

So, both in terms of mobile phones and infrastructure, 5G will require high frequency flexibility and reconfiguration. RF transceivers must be very flexible in combining multiple components operating at several GHz (below –6 GHz), as well as up to 60–70 GHz (millimeter wave range). In addition, you will need integrated arrays of antennas and RFFE with increased performance, both to increase the order of MIMO, and to solve the problem of signal formation.

It is possible to distinguish these functional characteristics in the specification that must be achieved by passive RF components:

1. Very wideband switches and switching units (such as multi-pole multi-throw MPMT) with low loss (on-off), high isolation (on-off), and very low crosstalk of adjacent channels, operating from 2 to 3 GHz to 60–70 GHz (or more);
2. Reconfigurable filters with pronounced bandwidth suppression and very low bandwidth attenuation;
3. Very wide-band multi-position impedance tuners;
4. Programmable step attenuators with multiple configurations and very flat response in the 60–70 GHz frequency range;
5. Very wide-band multi-position / analog phase shifters;
6. Hybrid devices with mixed phase shift and programmable attenuation – the functionality described in paragraphs 4 and 5 is combined into a unique device;
7. Miniature antennas and arrays of antennas, possibly integrally integrated with one or more of the devices described in the previous paragraphs from 1 to 6.

Given these classes of devices, the RF characteristics they will need to achieve can be summarized as follows:

– Isolation: better than –30/–40 dB for frequencies as high as possible;
– Loss: below –1 dB in the widest possible frequency range;
– Cross-talk: below –50/–60 dB in the widest frequency range;
– Switching time: less than 1 ms, with a few fractions of μs (e.g. 200–300 μs) as a reasonable target;
– Control voltage: within a few volts (for example, 2–5 V).

To summarize, it should be noted that first, the above specifications and limitations can be solved using MEMS technology. In addition, RF MEMS allows you to combine different functionality, which opens up interesting opportunities in terms of reducing hardware complexity. In this regard, it is worth mentioning the possibility of implementing reconfigurable phase shift and programmable attenuation of RF signals using unique passive components, which can also be integrated with an array of antennas in the millimeter wavelength range. Therefore, if RF MEMS components are currently on the path of consolidation in 4G-LTE applications, in the future 5G scenario, they have a significantly large role and large market volumes, both in relation to mobile phones and terrestrial infrastructures.

The synergy of RF and energy-harvesting MEMS

The energy-harvesting (EH) power availability driver deserves a more detailed discussion, as it should be compared to the typical power requirements of IoT nodes.

Simply put, remote sensing nodes (always) consist of three main parts [12]:

1. Sensitive module (sensor, electronic reading interface);
2. Computing unit (Microcontroller unit – MCU);
3. RF transceiver.

Such blocks are the most energy-intensive, and energy consumption, in general terms, increases when moving from point 1 to point 3. The typical power ranges required by the three remote sensing modules are as follows:

1. Sensor assembly 1 μW–1050 μW;
2. Normal operation of the MCU 100 μW–15 mW;
3. RF transceiver: 1520 mW–100 mW or more.

The energy dissipated in the environment can be obtained from four different sources: 1) ambient light; 2) vibration/motion; 3) thermal energy; 4) RF energy. Each of them has different achievable power levels, also depending on the operating conditions (indoor/outdoor, human/industrial environment, etc.).

Currently, research has advanced fueled by the continuous trend of reducing the power consumption of integrated circuits (IC). This paved the way for the use of MEMS technology for EH, using piezoelectric, electromagnetic and electrostatic conversion mechanisms [13].

The fundamental problem resulting from EHs miniaturization is the scaling of the operating frequency, since the resonant frequency of vibrating devices increases with decreasing mass and geometry, while most of the ambient vibration energy is available below a few kHz. There are solutions to solve this problem based on converting the frequency of ambient vibration. For example, complementary magnets can provide a resonant structure with a broadband pulse that also covers the main resonant frequency. The EH in [14] generates power up to 65 μW (RMS) for oscillations up to 12 Hz. Other upconversion approaches use snap and bend induced pulses superimposed on a microtransformer.

Another limitation affecting EHs MEMS is used in a typically narrow frequency band. Vibrational resonance is mechanical resonators that exhibit the greatest vibrations at resonance and filter out most of the spectrum elsewhere. There is extensive literature on strategies and methods for expanding the response to vibrational EH MEMS.

The frequency response of the devices demonstrates a chaotic response (the resonance of the Duffing mode) when the elastic behavior of the vibration-proof masses is nonlinear. This expands the frequency range of the radiation and, in turn, the level of the extracted power. In the literature, hybrid solutions based on piezoelectric and electromagnetic energy converters are discussed, which also differ in frequency conversion up using folded cantilever structures. The tuning of the resonant frequency EH is investigated to maximize the extraction in the widest possible range of operability.

EHs vibration consists of duplicating and changing the main elements of the spring mass. For this purpose, the solution proposed in [15] uses a two-resonant structure to implement an electrostatic EH MEMS of 13×20 mm^2. The entire design has two resonant frequencies, leading the EH to power levels in the range of 1.063 μW (1 g acceleration) in the frequency range of approximately 140 to 190 Hz.

As for the thermoelectric EH, the fundamental principle of converting thermal energy into electricity is the Seebeck effect, which describes the electromotive force that occurs when a thermal gradient is applied to the connection of two different materials. MEMS and film technology contributed to the development of miniature thermoelectric EHs. For example, [16] describes a device containing pairs of thermocouples for converting energy from body temperature (power density 10 μW/cm^2).

RF/electromagnetic EHs is the conversion of energy emitted in the environment (e.g., digital television, 3G, 4G, Wi-Fi) into DC energy. One of the main tasks is to provide ultra-compact devices capable of operating with high efficiency in a wide dynamic range of RF illumination power, as well as in a multi-band and multi-polar environment. Research on hybrid (RF and solar energy) and conformal systems is ongoing. This should be extended by hybridization with heterogeneous EHs (RF–piezoelectric, RF–thermoelectric, etc.) and by coupling EH with wireless power transmission (WPT) technology. Low-power

WPT methods can be used as an alternative way to power cyberphysical systems (CPSS) when little or no energy can be obtained from other sources.

EH MEMS solutions can make a significant contribution to achieving energy autonomy, as well as to miniaturization and integration. it should be borne in mind that EHs are not designed to power remote nodes, since energy storage units are always part of the system. Thus, EH MEMS, especially when working in combination with various sources, can be key elements that ensure battery recharge and virtually infinite service life of a remote IoT, IoE node.

Thus, starting with the EH MEMS technology, the most relevant potential is closely related to the critical factors of miniaturization and integration. A reduction in the size of the EHs implies a reduction in power levels and, in the case of conversion from environmental fluctuations, an increase in the operating frequency band. At first glance, the reduction in the collected capacity looks like a factor that worsens their implementation and application. However, it is necessary to keep in mind two important trends that are followed by technologies that support IoT, IoT, and the Tactile Internet. On the one hand, remote sensing and functional nodes are steadily reducing power requirements due to the rapid development of low- and ultra-low-power (ULP) electronics. As a result, there is a tendency to converge between the power requested by the module, on the one hand, and the power provided by EH MEMS on the other. The second important aspect is miniaturization and integration. In order to ensure the actual spread of IoT, IoE and Tactile Internet, the hardware (HW) being implemented should be characterized by as little form factor as possible. For these purposes, MEMS technology plays a crucial role, since it allows the implementation of small electronic systems that can also be integrated to a certain extent (monolithic) into active electronics, which leads to the creation of chips of a few square millimeters in size, containing a power supply, sensors/actuators, and intelligent control electronics.

Current developments and technologies

At the moment, the author's team has developed, manufactured and studied experimental samples of single-pole single-throw (SPST) RF MEMS switches of two types for use in 5G transceiver modules NR FR1 frequency band. The first type is a capacitive RF MEMS switch with a hybrid contact type with a central resonant frequency of 3.6 GHz. The second type is a capacitive RF MEMS switch with a hybrid type of contact, in which a metal membrane – the movable closing element of the structure is part of the RF transmission line of a coplanar waveguide (CPW) – inline RF MEMS switch. The central resonant frequency is 3.4 GHz.

Fig. 1 shows 3D models of the proposed RF MEMS switches with the designation of structural elements.

A distinctive feature of the presented designs is the absence of the main disadvantages inherent in capacitive RF MEMS switches. Such disadvantages include [17–19]:

– the imperfection of the roughness of the contacting surfaces – the metal movable membrane and the dielectric film applied to the surface of the RF transmission line. This leads to a decrease in the capacitance ratio of this type of RF MEMS switches. A decrease in the capacitance ratio, in turn, leads to a shift in the resonant frequency from the required one and a decrease in the insulation value;

– the charge of the dielectric film under constant bias voltage, which leads to the adhesion of the contacting surfaces – a metal movable membrane and a dielectric layer applied to the surface of the RF transmission line;

– relatively high values of the pull-in voltage (20–40 V) and high values of the switching time (50–80 μs). When solving this drawback, it is necessary to search for the convergence of the electromechanical parameters so that the solution to reduce the value of the pull-in voltage does not lead to an increase in the switching time.

To overcome the described disadvantages, an additional fixed metal–insulator (dielectric film)–metal (MIM) capacitor on the substrate is developed and a switch is used to turn it on or off from the circuit.

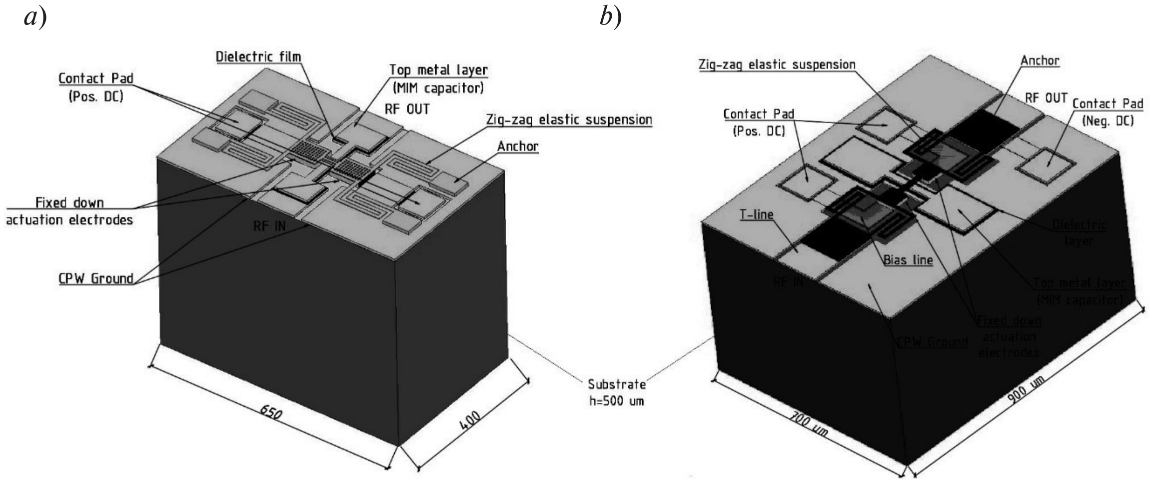

Fig. 1. 3D topology of the RF MEMS switch: *a* — 1st type; *b* — 2nd type

This results in a capacitance ratio that is independent of the roughness of the contacting surfaces and is therefore ideal for dielectrics with high permittivity and roughness. The material of the dielectric film of the additional fixed MIM capacitor is a dielectric material with a high permittivity of high-k dielectrics. Additional fixed MIM capacitor is connected to a shunt capacitor with metal-air-metal (MAM) plates formed by the upper metal film of the MIM capacitor, a metal movable membrane, and an air space between them. The MIM capacitor is connected to the MAM capacitor in series, in the case when the metal movable membrane is in the up-position (open-state). In the case when the metal movable membrane is in the down-position (close-state), the MAM capacitor changes to the resistance in the electrical circuit. At the same time, such disadvantages of these designs as the high geometric dimensions of the metal movable membrane, as well as the high contact resistance introduced by the metal movable membrane in the closed state of the switch, are excluded [20].

The small value of the pull-in voltage and the short switching time is achieved by using four elastic suspensions having a zig-zag shape, a small air gap between the metal movable membrane and the fixed down actuation electrodes, a small thickness of the membrane, as well as the choice of the material of the movable structures using the developed method of material selection in the design of RF MEMS switches [21].

Fig. 2*a* shows an experimental sample of manufactured RF MEMS switches in a specialized microwave package. The method of packaging, in this case, is the package of the separated crystals of RF MEMS switches after all the stages of the process by fixing them in a specialized sealed case for microwave microelectronic devices. This microwave enclosure is designed to work in high-frequency RF signal transmission circuits-flesh up to 50 GHz with matching 50Ω. The input and output of the microwave package are coaxial connectors with a threaded connection, characterized by a minimum amount of loss at the contact points. The contact pads for the supply of a constant control voltage to ensure the electrostatic activation of the RF MEMS switch are thin-film coatings placed on the surface of this microwave package. In addition, one of the advantages of the chosen method of packaging is the possibility of conducting subsequent laboratory tests and measurements of manufactured RF MEMS switches using laboratory equipment, as well as without the use of specialized debugging microwave boards designed to measure the characteristics of RF MEMS switches.

At the same time, in order to package the manufactured samples of RF MEMS switches into the selected microwave package in order to secure them in the housing, it is necessary to develop a transition circuit board (crystal) with separate contact pads made on it for supplying a constant control voltage, as well as a CPW with a break in the place of mounting the switch crystal. Fig. 2*b* shows the manufactured *a*) *b*)

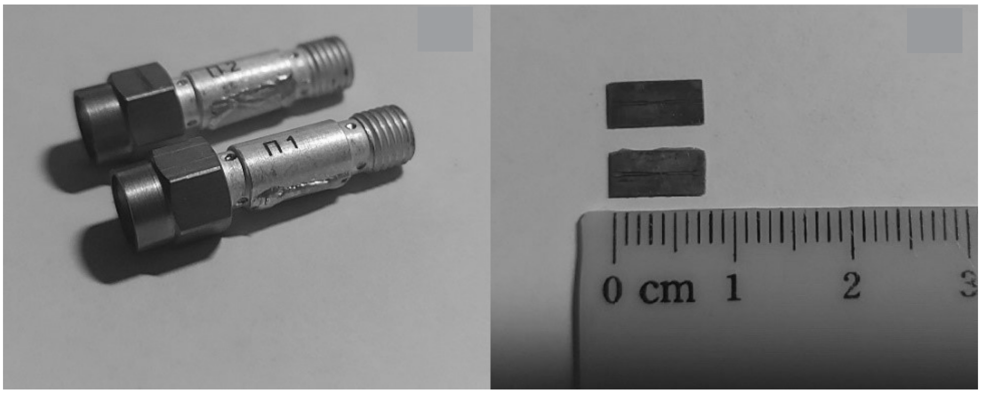

Fig. 2. Manufactured experimental samples of RF MEMS switches:
a – in a specialized microwave package; *b* – experimental sample of manufactured adapter boards

adapter boards. Installation of the RF MEMS switch crystal is carried out by placing it in a pre-centered and etched groove in the adapter board and gluing it with polyimide glue.

The connection of the CPW of the adapter board with the CPW located on the RF MEMS switch crystal is carried out by a gold wire (d = 40 μm) using a micro-welding operation. The connection of the contact pads of the microwave housing-adapter board-crystal RF MEMS switch for the supply of a constant control voltage is also carried out with a gold wire (d = 20 μm) using a micro-welding operation.

Table 1 shows the extended results of laboratory tests of experimental samples of RF MEMS switches.

Table 1

Results of laboratory tests

SPST RF MEMS switch @ 3.6 GHz, S-band		SPST RF MEMS switch @ 3,4 GHz, L, S, C, X-band	
Effective frequency range	S	Effective frequency range	L, S, C, X
Insertion loss (open-state)	–0.07 dB @ 3.6 GHz	Insertion loss (open-state)	–0.18 dB @ 3.4 GHz
Isolation (close-state)	–44.2 dB @ 3.6 GHz	Isolation (close-state)	–55.2 dB @ 3.4 GHz
Contact resistance	Less 1 Ω	Contact resistance	Less 1 Ω
Linearity	High	Linearity	High
Power consumption	Less 1 μW	Power consumption	Less 1 μW
Bias Voltage	3.5 V	Bias Voltage	2 V
Pull-in Voltage	Less 10 V	Pull-in Voltage	Less 10 V
Switching time	~ 10 μs	Switching time	~ 10 μs
Switching power	More 1 W	Switching power	More 1 W
Sensitivity to external mechanical influences	High	Sensitivity to external mechanical influences	High

Fig. 3 shows the experimental results of measuring the electromagnetic parameters (scattering parameters) of the manufactured experimental samples of RF MEMS switches.

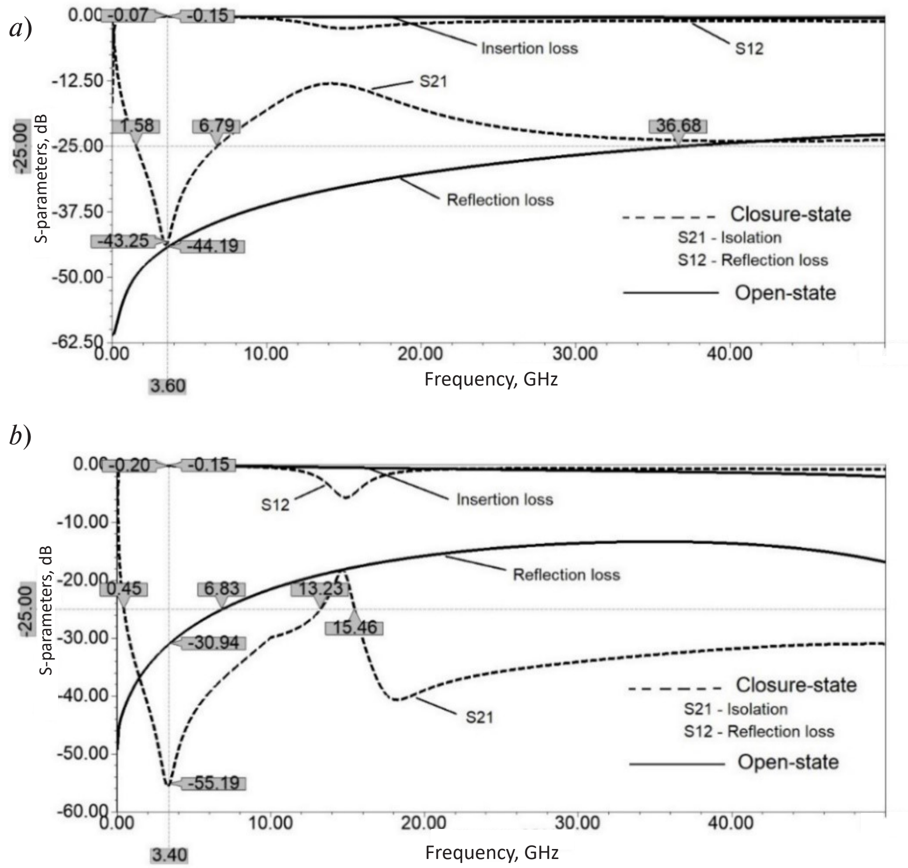

Fig. 3. Results of measuring the electromagnetic parameters
experimental samples of RF MEMS switches: *a* – 1st type; *b* – 2nd type

The obtained high electromagnetic parameters, combined with a low value of the contact resistance in the closed position allow them to be used for efficient operation of 5G mobile network transceivers since these values are less than the typical value of the contact resistance of active semiconductor RF switches based on PIN-diodes and FET-transistors.

The results obtained, namely, the developed manufacturing process and the developed and manufactured experimental samples of RF MEMS switches can be used as a "foundation" for the design of complex RF MEMS networks.

Conclusion

In the first part of this article, we attempted to create a comprehensive vision that currently encompasses the central paradigms of the IoT, IoE, Tactile Internet and 5G, i.e. the 5th generation of mobile communications. This general discussion was based on the use of MEMS technology with specific references to EH MEMS and passives RF MEMS components. First, the IoT was described, highlighting the steadily growing need for the spread of sensory and executive functions, as well as distributed computing power, to provide intelligent capabilities for every object and/or environment of our daily lives (for example, a smart city, smart factory and so on). Then the 5G paradigm was introduced, framing it in the evolution from 1G to the current 4G-LTE. In particular, the high-level characteristics that 5G will need to gain in its evolution, going beyond the existing standards.

The second part of the article provides a brief description the developments of passive RF MEMS components that have already been made by the team of authors. These include the obtained experimental samples of SPST capacitive RF MEMS switches with hybrid contact type for use in 5G NR FR1 mobile network transceivers. Further plans for the development of this work are the development of wafer-level packaging solutions at the plate level with the technology of through silicon vias (TSV) for the redistribution of the electrical signal from passive devices in the package – RF MEMS to the outside world. As well as the development of RF MEMS switches to a different frequency range 5G – NR FR2 in one or more directions (SPnT).

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