High-performance inline RF MEMS switch for application in 5G mobile networks

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Abstract. This article presents the results of the design and analysis of a radio-frequency switch made using microelectromechanical systems technology. The device is the capacitive switch with a hybrid type of contact, in which the movable electrode of the structure – the metal membrane is part of the microwave signal line of the coplanar waveguide. The switch design is characterized by a high capacitance ratio and low contact resistance. The zig-zag elastic suspension is used to reduce the value of the pull-down voltage – 2 V and the switching time ~ 7 us. The central resonant frequency of the switch is 3.8 GHz. In this case, in the open state, the value of the insertion loss is not more than -0.2 dB and the isolation value in the close state is not less than -55 dB. The effective frequency range is the S-band, as well as the C-, X- and Ku-band, in which the isolation value is at least -30 dB. The presented inline RF MEMS switch is suitable for use in various types of ground and satellite communications, in particular for devices and systems of 5G mobile networks.

1. Introduction

Microelectromechanical systems (MEMS), with their extremely small size and full integration into the radio-frequency interfaces of various telecommunications devices, have become the most promising technology in the last few decades. There is a growing demand for devices with extremely high performance, low power consumption, and compact dimensions in a variety of satellite, defence and communications systems. To date one of the most promising areas of application of MEMS technology is associated with circuits and devices for ultra-high frequency (UHF) (microwave) and radio-frequency (RF) communication. In recent years, the introduction and dissemination of new wireless communication standards, in particular the fifth generation of mobile radio – 5G, has set new challenges in the development of hardware for transceivers. Key RF subsystems in 5G RF transceivers include antennas, configurable filters, power amplifiers and multiple-input multiple-output (MIMO) antennas. At the same time, it can be noted that in all these 5G RF systems or subsystems, from a hardware point of view, the RF switch is one of the most fundamental and important components that is used to route signals along RF transmission paths with a high degree of efficiency; its RF characteristics, switching time, RF signal power and their reliability can directly affect the corresponding properties and performance of 5G applications. RF MEMS switches can effectively replace the currently used active semiconductor analogies based on PIN diodes and FET transistors at frequencies up to 10 GHz and compete with coaxial switches in the range up to 40 GHz or more.

RF MEMS switches are classified according to the actuation mechanism, the movement of the suspended parts, the type of contact, the type of mechanism used, and the electrical configuration. Today electrostatic RF MEMS switches are the most common among micromechanical switches. This is due to the almost zero power consumption in the switched-on state, the small size of the element,
the compatibility of the device manufacturing process with the technological processes of manufacturing integrated circuits (IC) using silicon technology and technology based on $A^mB^n$ elements, the relative ease of manufacture and the short switching time. Electrostatic RF MEMS switches are divided into two types – cantilever and membrane switches with metal-metal and metal-dielectric-metal contacts, respectively. Resistive RF MEMS switches have some advantages over capacitive RF MEMS switches, as they are characterized by a lower pull-out voltage value and a higher switching speed. On the other hand, capacitive RF MEMS switches are characterized by greater reliability and are subject to fewer failure mechanisms. In addition, for the design of RF MEMS switches of medium and low power, switches with a capacitive contact type have an important advantage—the ability to design switch designs with a low value of the pull-down voltage.

Currently, capacitive RF MEMS switches with metal-dielectric-metal contact are the most common in the technology in RF MEMS devices [1, 2]. The main problem of capacitive RF MEMS switches is the imperfect roughness of the contacting layers, which leads to a decrease in the capacitance ratio. Decrease in the capacitance ratio, in turn, leads to a shift in the resonant frequency from the required one and a decrease in the isolation value in the closed state of the RF MEMS switch.

There are a number of studies that have been conducted to achieve a high value of the capacitance ratio of capacitive RF MEMS switches and a low value of the pull-down voltage. In [3], a design of a capacitive RF MEMS switch using a ceramic dielectric layer with a high permittivity is proposed. In [4], a high capacitance ratio was achieved by using the curved design of the metal membrane of the capacitive RF MEMS switch. Another method used to achieve a high value of the capacitance ratio is to increase the air gap between the metal membrane and the dielectric layer [5, 6]. However, there are some obvious disadvantages of these methods, which are that the charge problem of the dielectric layer becomes more significant the smaller the thickness of the applied dielectric layer and the electromechanical parameters of the switch change when the air gap changes.

Meanwhile, a number of studies have proposed some approaches to obtaining a high value of the capacitance ratio, which consist in the use of dielectric materials with high permittivity [3, 7-9]. However, the value of the capacitance ratio is limited by the minimum thickness of the dielectric layer, the maximum value of the permittivity, and the maximum value of the air gap between the metal membrane switch and the RF transmission line. In this regard, the methods used in [4-6] are not the most suitable.

In this paper we present the developed the design of a high-performance capacitive inline RF MEMS switch, which is characterized by a high capacitance ratio, in which the disadvantages of the methods previously used to increase the capacitance ratio are eliminated. Also, the designed RF MEMS switch should be characterized by good radio-frequency characteristics, a low value of the pull-down voltage and a short switching time. In addition, the developed design of the RF MEMS switch should be characterized by a small form factor for use in RF devices and systems of 5G mobile networks.

2. Design and methodology
The proposed capacitive RF MEMS switch consists of a dielectric substrate with a coplanar waveguide (CPW) located on its surface, areas for the contact pads for applying a constant (DC) pull-down voltage to fixed pull-down electrodes, and a metal membrane built into the CPW signal line (t-line) between the RF input and output ports and is part of it, fixed to the anchor areas by means of zigzag elastic suspensions, as shown in Figure 1 (a)-(d). The choice of materials is made on the basis of the results [10-12].

When a DC pull-down voltage is applied to the fixed pull-down electrodes relative to the metal membrane (positive potential on the fixed pull-down electrodes, negative potential on the metal membrane), an electrostatic force occurs that exceeds the mechanical elastic force, and as a result, the metal membrane sinks to the down position – it is attracted to the fixed pull-down electrodes and the upper metal layer of an additional fixed metal-dielectric-metal (MIM) capacitor, which is formed by this metal layer, a dielectric layer with a high permittivity – high-k ($\text{TiO}_2$) and a metal layer of the
signal line CPW. As a result, the incoming RF signal along the signal line of the CPW is shunted to the ground line CPW. In this RF MEMS switch design, an additional fixed MIM capacitor is connected to a shunt capacitor with metal-air-metal (MAM) plates formed by the upper metal layer of the MIM capacitor, a metal membrane and the air space between them. In the case when the metal membrane is in the down position, the MAM capacitor changes to the resistance in the electrical circuit.

Table 1 shows the geometric dimensions of the main structural elements of the proposed capacitive inline RF MEMS switch: CPW, metal membrane, via holes, anchor regions, contact pads for supplying the DC pull-down voltage, fixed pull-down electrodes, air gap, contact pads, additional fixed MIM capacitor and dielectric layers.

In Figure 2 schematically shows the developed zig-zag elastic suspension with an indication of the geometric dimensions. Each elastic suspension consists of five successively connected elastic suspensions with two-fold symmetry, forming the shape of a meander, as well as one connecting elastic suspension having the shape of an elastic beam.
Table 1. Dimensions of the proposed inline capacitive RF MEMS switch.

| Parameter                                | Dimensions      | Material         |
|------------------------------------------|-----------------|------------------|
| Substrate                                | 900x700x500 um  | Sapphire         |
| CPW - G W G                              | 15x140x6 um     | Copper           |
| Membrane - right/left part               | 60x50x1 um      | Aluminum         |
| Membrane - central part                  | 80x20x1 um      |                  |
| Via holes                                | 4x4x1 um        |                  |
| Anchors                                  | 140x130x8.2 um  | Aluminum         |
| Contact pads                             | 100x100x6 um    | Copper           |
| Fixed pull-down electrode                | 60x60x12 um     | Copper           |
| Air gap, $g_0$                           | 1 um            |                  |
| Dielectric film (MIM) - right/left part  | 200x140x0.2 um  | TiO$_2$ ($\varepsilon_r = 90$) |
| Dielectric film (MIM) - central part     | 150x40x0.2 um   |                  |
| Dielectric film (on fixed pull-down electrode) | 60x60x0.1um | SiO$_2$ ($\varepsilon_r = 4$) |

3. Performance numerical analysis

3.1 Electromechanical modeling
In numerical modeling of continuum mechanics problems, the quality of the calculated finite element grid is an important parameter. The question of grid quality is of critical importance in contact problems, since, on the one hand, small elements reflect the behaviour of the structure with higher accuracy when loads are applied to it, and on the other hand, such problems, due to their nonlinearity, require significant computational resources.

Figure 3 (a) shows the results of the distribution of the potential energy in the movable structure of the inline capacitive RF MEMS switch during electrostatic activation. Figure 3 (b) shows the switching time (closure time) inline capacitive RF MEMS switch.

According to the results of the numerical simulation of the electromechanical model of the developed inline capacitive RF MEMS switch design, it follows that the value of the pull-down voltage is 2 V and the switching time to the down-state of the metal membrane is 6.9 us.

3.2 Electromagnetic modeling
Figure 4 shows the results of numerical simulation of S-parameters (scattering parameters) of the developed inline capacitive RF MEMS switch. Based on the results of the analysis of the scattering
parameters, it follows that the central resonant frequency of the switch is a frequency of 3.8 GHz. In this case, in the open-state, the value of the insertion loss is not more than -0.2 dB and the isolation value in the down-state is not less than -55 dB. The effective frequency range is the S-band, as well as the C-, X- and Ku-band, in which the isolation value is at least -30 dB.

![Figure 4](image1.png)

Figure 4. Simulation of the S-parameters the inline capacitive RF MEMS switch.

Figure 5 shows the results of numerical coupled electromagnetic and thermal calculations of the developed capacitive inline RF MEMS switch design when switching an RF signal with a frequency of 3.8 GHz and a power of 1 W in the open-state. The maximum heating in the developed design of the inline capacitive RF MEMS switch occurs in the contact region – the region of the metal membrane. The metal membrane also acts as a heat sink from the contact area. The maximum heating temperature does not exceed the mark of 115°C.

![Figure 5](image2.png)

Figure 5. Thermal calculations of the developed capacitive inline RF MEMS switch design.

The value of the capacitance ratio of the developed inline capacitive RF MEMS switch is 5930. When using, for example, Si₃N₄ (εᵣ = 7.5), which is the most common material of the dielectric layer of shunt RF MEMS switches, as the material of the dielectric layer, the value of the capacitance ratio will be 545.

The value of the contact resistance in the closed position of the developed inline capacitive RF MEMS switch does not exceed 0.8 Ω.

4. Conclusion
This article presents the results of the design of the capacitive inline RF MEMS switch with a hybrid contact type. The device is the capacitive switch with a hybrid type of contact, in which the movable electrode of the structure – the metal membrane is part of the microwave signal line of the CPW and the shunt connection with the ground line of the CPW is applied directly to the surface of the dielectric
substrate. In addition, the switch design is characterized by a high capacitance ratio, obtained by using an additional fixed MIM capacitor. To reduce the value of the pull-down voltage and increase the speed of the switch the zig-zag elastic suspension is used. According to the results of the finite element analysis, the value of the pull-down voltage is 2 V with a short switching time to the down-state (closure position) – no more than 7 us (switching voltage 5 V). Based on the results of the analysis of the scattering parameters, it follows that the central resonant frequency of the switch is a frequency of 3.8 GHz. In this case, in the open-state, the value of the insertion loss is not more than -0.2 dB and the isolation value in the close-state is not less than -55 dB. The effective frequency range is the S-band, as well as the C-, X- and Ku-band, in which the isolation value is at least -30 dB. The value of the capacitance ratio of the developed inline capacitive RF MEMS switch is 5930 and the value of the contact resistance in the close-state does not exceed 0.8 Ω.

The presented inline RF MEMS switch is suitable for use in various types of ground and satellite communications, in particular for devices and systems of 5G mobile networks.

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