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ELECTROSTATIC SHUNT RF MEMS SWITCH WITH A FLOATING ELECTRODE FOR S-BAND APPLICATIONS: ARCHITECTURE AND MATHEMATICAL MODELING

*I.A. Sizin, A.V. Lukin ,
V.V. Loboda , R.S. Smerdov *

Peter the Great St. Petersburg Polytechnic University,
St. Petersburg, Russian Federation

 vera_loboda@mail.ru

Abstract. This paper presents the design and modeling of an electrostatically actuated capacitive shunt RF MEMS switch with a floating electrode for S-band operation. The proposed architecture incorporates a mechanically fixed, electrically floating metal electrode positioned above the signal line and separated from it by a high- k TiO_2 dielectric layer. This configuration substantially increases the down-state capacitance and improves signal isolation without requiring extremely small interelectrode gaps. The switch is implemented on a coplanar waveguide and uses an aluminum membrane with meander suspensions and perforation to reduce the effective stiffness, actuation voltage, and switching time. The main electromechanical parameters were evaluated analytically and verified by finite element modeling in COMSOL Multiphysics, while the RF performance was analyzed using electromagnetic simulation in ANSYS HFSS. The final design demonstrates a pull-in voltage of 2.7 V, a closing time of 18 μs , a down-state capacitance of 247 pF, and an up-state capacitance of 9.6 fF. In the 2–4 GHz range, the simulated up-state insertion loss is from -0.012 to -0.14 dB, and the down-state isolation is from -43.3 to -89.75 dB. The results show that the floating-electrode architecture provides a high capacitance ratio and significantly enhances the RF performance of the capacitive shunt MEMS switch.

Keywords: RF MEMS switch, shunt architecture, insertion loss, S-parameters, floating electrode, S-band

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РАЗРАБОТКА АРХИТЕКТУРЫ И МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ РЕЖИМОВ РАБОТЫ РАДИОЧАСТОТНОГО МЭМС-ПЕРЕКЛЮЧАТЕЛЯ С ПЛАВАЮЩИМ ЭЛЕКТРОДОМ

И.А. Сизин, А.В. Лукин ,
В.В. Лобода , Р.С. Смердов

Санкт-Петербургский политехнический университет Петра Великого,
Санкт-Петербург, Российская Федерация

vera_loboda@mail.ru

Аннотация. Представлены разработка архитектуры и математическое моделирование электростатического шунтирующего радиочастотного МЭМС-переключателя с плавающим электродом, предназначенного для работы в S-диапазоне. Отличительной особенностью предложенной конструкции является введение неподвижного металлического плавающего электрода, размещенного над сигнальной линией и отделенного от нее слоем high-k диэлектрика TiO_2 , что обеспечивает существенное увеличение емкости в замкнутом состоянии и повышение изоляции. Переключатель реализован на основе копланарного волновода и содержит алюминиевую мембрану с меандровыми подвесами и перфорацией, обеспечивающими снижение эффективной жесткости и рабочего напряжения. Выполнены аналитический расчет основных электромеханических параметров, моделирование переходных процессов в COMSOL Multiphysics и электромагнитное моделирование в ANSYS HFSS. Для разработанной конструкции получены следующие характеристики: напряжение срабатывания 2,7 В, время замыкания 18 нс, емкость в замкнутом и разомкнутом состояниях 247 пФ и 9,6 фФ соответственно. В диапазоне 2–4 ГГц рассчитаны вносимые потери от $-0,012$ до $-0,14$ дБ и изоляция от $-43,3$ до $-89,75$ дБ. Показано, что использование плавающего электрода позволяет существенно увеличить отношение емкостей и обеспечить улучшение радиочастотных характеристик.

Ключевые слова: РЧ МЭМС-переключатель, шунтирующая архитектура, вносимые потери, S-параметры, плавающий электрод, S-диапазон

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Introduction

Modern wireless communication systems, radar systems, satellite platforms, and Internet of Things devices impose increasingly stringent requirements on radio-frequency (RF) switching components operating in the ultrahigh-frequency range. For such devices, low insertion loss in the transmitting state, high isolation in the blocked state, low power consumption, and technological compatibility with integrated fabrication processes are critical. Conventional semiconductor switches, including PIN diodes and field-effect transistors, provide high switching speed and compactness; however, at high frequencies they are characterized by noticeable losses. Against this background, RF MEMS

switches are regarded as a promising class of devices combining low insertion loss, high isolation, high linearity, and low power consumption [1–4].

Electrostatically actuated capacitive shunt RF MEMS switches are of particular interest. This architecture provides efficient shunting of the signal to ground in the down state and makes it possible to achieve high isolation over a wide frequency range at low control power. However, two limitations remain relevant for this class of devices: a relatively high pull-in voltage and the need to increase the capacitance ratio between the up and down states, which directly determines the ultimate radio-frequency performance of the switch. It has been shown in the literature that the pull-in voltage can be reduced by decreasing the effective stiffness of the movable element, using meander suspensions, introducing membrane perforation, and selecting a material with suitable mechanical properties. At the same time, increasing the capacitance ratio requires special design solutions that go beyond the conventional “membrane–dielectric–signal line” configuration [2, 5–8].

In recent years, RF MEMS switch designs aimed simultaneously at low-voltage actuation, while actively investigating improved isolation. Modified geometries of elastic elements, combined contact configurations, and additional capacitive elements have been used for this purpose, making it possible to control the effective capacitance of the structure. However, in many known solutions, improved radio-frequency characteristics are achieved either at the cost of more complex fabrication technology or by reducing the interelectrode gaps. This, in turn, increases the sensitivity of the device to fabrication tolerances, residual mechanical stresses, stiction, and dielectric charging effects [6–11]. Therefore, the search for architecture that provides a substantial increase in the down-state capacitance without using critically small interelectrode gaps remains highly relevant.

One promising approach to this problem is the use of a floating electrode, i.e., an additional fixed metal plate located above the signal line and separated from it by a thin high- k dielectric layer. When the membrane is pulled down, this configuration forms an equivalent system with a substantially higher shunt capacitance than that of a conventional capacitive switch. As a result, high isolation can be achieved while maintaining an acceptable pull-in voltage and technologically feasible structural dimensions. The complete set of electromechanical and electromagnetic characteristics of such an architecture, including the pull-in voltage, switching time, capacitance ratio, and S-parameters, requires comprehensive analytical and numerical investigation [9–11].

The practical significance of developing such switches is associated with the expansion of their application areas in modern wireless and satellite systems, as well as in reconfigurable radio-frequency front ends. For the S-band, this problem is of particular interest because this frequency range is widely used in communication systems, satellite channels, and a number of mass-market radio interfaces. Recent studies, including review papers, emphasize that further progress in RF MEMS devices is associated with the search for designs that combine low actuation voltage, high isolation, technological reproducibility, and stable performance [10–13].

In this paper, an electrostatically actuated capacitive shunt RF MEMS switch with a floating electrode is considered. The switch is implemented on a coplanar waveguide (CPW) and is intended for operation in the S-band. The proposed design includes an aluminum membrane with meander suspensions and perforation, as well as a floating electrode separated from the signal line by a TiO_2 layer. The aim of this work is to perform mathematical modeling of an electrostatically actuated capacitive shunt RF MEMS switch with a floating electrode for the S-band and to evaluate the possibility of achieving competitive electromechanical and radio-frequency characteristics.

Methods

Switch architecture and operating principle

The investigated device is an electrostatically actuated capacitive shunt RF MEMS switch implemented on a sapphire substrate with a CPW. The schematic design is shown in Fig. 1. The shunt configuration

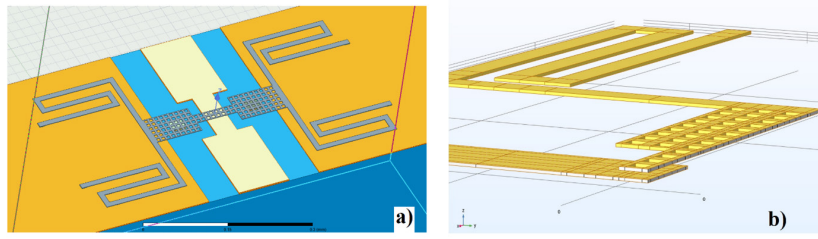


Fig. 1. Proposed design of the electrostatically actuated capacitive shunt RF MEMS switch with a floating electrode: geometrical model (a); top view of the membrane with meander suspensions and perforation (b)

was selected because such structures combine low insertion loss in the signal-transmission state and high isolation in the signal-blocking state [3, 6, 14, 15]. A bridge-type architecture with a movable metal membrane located above the signal line and the actuation electrodes was used as the baseline design.

The key feature of the proposed design is the introduction of a floating electrode, i.e., a fixed metal plate placed above the signal line and separated from it by a thin TiO_2 high- k dielectric layer. This configuration forms a metal–dielectric–metal (MDM) capacitor and substantially increases the equivalent shunt capacitance in the down state compared with a conventional capacitive switch [9, 16]. The movable element is an aluminum membrane with meander suspensions and perforation. The meanders are used to reduce the effective stiffness of the movable system and decrease the pull-in voltage [15, 17, 18], whereas the perforation is introduced for both technological and electromechanical reasons: it facilitates the removal of the sacrificial layer during membrane release, decreases the membrane mass, and affects the dynamic characteristics of the switch [17, 18].

In the up state, the membrane is separated from the floating electrode, and the signal line is not shunted to ground. When a control voltage is applied between the membrane and the lower electrodes, an electrostatic force arises and deflects the membrane toward the signal line. After the pull-in voltage is reached, the membrane comes into contact with the electrode. As a result, the equivalent shunt capacitance sharply increases, and the signal propagating along the line is suppressed. Thus, the structural novelty of the investigated device consists in combining a floating electrode, meander suspensions, and a perforated membrane within a single shunt architecture.

The main design parameters of the RF MEMS switch are given in Table 1. The design dimensions were chosen to provide operation in the 2–4 GHz range, match the CPW to a characteristic impedance of $50\ \Omega$, and maintain technologically feasible interelectrode gaps.

Analytical model

For a preliminary assessment of the switch characteristics, a lumped-parameter model was used. The model relates the geometrical dimensions of the structure, the mechanical properties of the membrane, and the electrostatic actuation force. The total equivalent stiffness of the movable system (K_{full}) was calculated by taking into account the contributions of the central membrane section, the wider membrane sections, the meander suspensions, and the connecting beams [7, 10, 15, 17]:

$$K_{full} = \left(\frac{1}{K_m} + \frac{2}{K_{mb}} + \frac{4}{K_{meand} + K_{beam}} \right)^{-1}, \quad (1)$$

where K_m is the stiffness of the central narrow part of the membrane, K_{mb} is the stiffness of the wider membrane sections, K_{meand} is the stiffness of the meander suspensions, and K_{beam} is the stiffness of the connecting beams between the meanders and the membrane.

The stiffnesses of the meander suspensions and the connecting beams were determined using the following expressions [7, 15, 17]:

Table 1

Main design parameters of the RF MEMS switch

Parameter	Value
Substrate material	Sapphire
Substrate thickness	500 μm
Material of the membrane and suspensions	Al
Material of the conductive layers	Cr–Cu
Dielectric material	TiO ₂
Width of the central CPW conductor, W_s	100 μm
CPW slot width, g_{cpw}	60 μm
Width of the ground planes, W_g	400 μm
Membrane length, L_m	80 μm
Membrane width, W_m	20 μm
Membrane thickness, t	1 μm
Meander length, L_{meand}	150 μm
Meander width, W_{meand}	10 μm
Gap between the membrane and the actuation electrode, g_0	2 μm
Gap between the membrane and the signal line, $g_s \approx g_0 - H_{mdm} - t_d$	1.3 μm
TiO ₂ layer thickness, t_d	100 nm
Floating-electrode thickness, H_{mdm}	0.6 μm
Perforation-window size, $W_{perf} \times L_{perf}$	6 $\times$ 6 μm

$$K_{meand} = \frac{EW_{meand}t^3}{L_{meand}^3N}; \quad (2)$$

$$K_{beam} = \frac{EW_{beam}t^3}{L_{beam}^3}. \quad (3)$$

Here, E is the Young's modulus of the membrane material, t is the membrane thickness, W_{meand} and L_{meand} are the width and length of the meander, W_{beam} and L_{beam} are the width and length of the connecting beam, N is the number of horizontal meander segments.

For the considered asymmetric gap configuration, in which the membrane–actuation-electrode gap differs from the membrane–signal-line gap, the pull-in voltage was calculated as [15, 17]:

$$V_p = \sqrt{\frac{8K_{full}g_0^2(g_0 - g_s)}{27\epsilon_0 A_{eff}}}, \quad (4)$$

where g_0 is the gap between the membrane and the actuation electrode, g_s is the gap between the membrane and the signal line, A_{eff} is the effective overlap area, and ϵ_0 is the electric constant.

The mechanical natural frequency was estimated using the following relation [7, 15, 17]:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{K_{meand}}{M_{mem}}}, \quad (5)$$

where M_{mem} is the membrane mass. The closing and release times were evaluated using [7, 15, 19]

$$T_s = \frac{3.67V_p}{V_s\omega_0}; \quad (6)$$

$$T_r = \frac{\pi}{2\omega_0} = \frac{1}{4f_0}, \quad (7)$$

where V_s is the control voltage and $\omega_0 = 2\pi f_0$.

The up-state capacitance of the switch was determined with allowance for the fringing capacitance [15, 16]:

$$C_{up} = \frac{\epsilon_0 A_{con}}{g_s + t_d/\epsilon_r} + C_f, \quad C_f = 0.35C_{up}^{(0)}, \quad (8)$$

where A_{con} is the interaction area between the membrane and the lower electrode, t_d is the dielectric thickness, and ϵ_r is the relative permittivity of TiO_2 . The down-state capacitance was represented by two parallel contributions: the MDM capacitance of the floating-electrode/ TiO_2 /signal-line stack and the membrane-to-actuation-electrode capacitance [15–17]:

$$C_{down} = \frac{\epsilon_0 \epsilon_r A_{mdm}}{t_d} + \frac{2\epsilon_0 A_{con}}{g_0 - g_s}, \quad (9)$$

where A_{mdm} is the floating-electrode area.

To account for the decrease in the effective membrane area after perforation, the perforation coefficient was introduced as

$$K_{perf} = \frac{A_{perf}}{A}, \quad A_{eff} = A(1 - K_{perf}), \quad (10)$$

where A_{perf} is the total area of the perforation windows, A is the initial membrane area, and A_{eff} is the effective area after perforation.

For a preliminary analytical estimate of the radio-frequency characteristics, a simplified lumped model of the shunt switch was used [5, 20, 21]. The characteristic electrical resonant frequency of the equivalent down-state circuit was determined as

$$f_{c,down} = \frac{1}{2\pi\sqrt{LC_{down}}}, \quad (11)$$

where L is the equivalent inductance of the signal line and C_{down} is the down-state capacitance of the switch. The corresponding angular electrical resonant frequency is

$$\omega_{c,down} = 2\pi f_{c,down}. \quad (12)$$

Unlike the mechanical natural frequency of the membrane, which determines the switching dynamics, f_c characterizes the electrical response of the equivalent radio-frequency circuit.

For the down state, the estimated values of the S_{21} parameter, i.e., the isolation, were then calculated as

$$S_{21}^{down} = -20 \log \left| \frac{2}{2 + j\omega_{c,down} C_{down} Z_0} \right|, \quad (13)$$

where $Z_0 = 50 \Omega$ is the characteristic impedance of the transmission line.

These relations were used for an approximate analytical evaluation of the C_{down} effect on the radio-frequency response of the switch in the down state at the S-band boundaries. The complete frequency dependences of S_{21} and S_{11} (the reflection coefficient) in the range of 2–4 GHz were obtained from electromagnetic simulation in ANSYS HFSS.

Numerical modeling

Numerical analysis was performed in several stages using COMSOL Multiphysics, ANSYS HFSS, and MATLAB Simulink. At the first stage, a simplified model of a rectangular membrane without meanders or perforation was constructed in COMSOL to determine the natural frequencies and mode shapes. At the second stage, meander suspensions were introduced into the model, which made it possible to investigate the effect of reduced equivalent stiffness on membrane deflection, pull-in voltage, and dynamic characteristics. At the third stage, the final design with perforation and a floating electrode was considered; for this design, the static pull-in voltage, time-dependent deflection, and the capacitances in the up and down states were determined. This step-by-step approach made it possible to trace the contribution of each structural element to the final device characteristics.

In the COMSOL electromechanical model, a coupled formulation combining electrostatics and solid mechanics was used. The air gap between the membrane and the lower electrodes was 2 μm ; under the membrane, a TiO_2 layer with a thickness of 100 nm was modeled. A control voltage increasing to 5 V was applied to the lower electrodes. The pull-in voltage was determined from the abrupt nonlinear increase in the membrane deflection, whereas the switching time was defined as the time required for the membrane to reach the contact position with the floating electrode. To calculate the capacitance in the down state, a separate configuration with the established contact between the membrane and the floating electrode was used. This reduced the numerical error associated with mesh deformation at the moment of contact. In parallel, a parameterized computational scheme was developed in MATLAB Simulink. This scheme reproduced analytical relations for stiffness, mass, pull-in voltage, switching time, and capacitance and was used for comparison with the results of finite element modeling (FEM).

Electromagnetic simulation was performed in ANSYS HFSS using a three-dimensional model of the CPW with the integrated switch. Wave ports were assigned with a characteristic impedance of $Z_0 = 50 \Omega$. The metal elements in the model were treated as perfect conductors, and the outer boundaries of the air volume were specified as radiating boundaries, which made it possible to minimize artificial reflections of the electromagnetic field from the boundaries of the computational domain. The S-parameters were calculated in two states: with the membrane in the up position and with the membrane pulled down to the floating electrode. The investigated frequency range was 2–4 GHz. The values obtained in HFSS were used to determine isolation, insertion loss, return loss and were then compared both with the analytical model, as well as with published data for shunt CPW MEMS switches of similar architecture [20–23].

Results and discussion

At the first stage of the numerical study, a simplified model of a rectangular membrane without meanders or perforation was considered. This model was used to estimate the natural frequencies of vibration and the limiting level of pull-in voltage for a high-stiffness movable element. The analysis showed that the first natural frequency of this membrane was 79.6 kHz, whereas the calculated pull-in voltage reached 64.8 V. This result indicates that a simple beam structure without additional elastic elements is unsuitable for low-voltage actuation and requires a reduction in the equivalent stiffness of the movable system. This conclusion is consistent with the general understanding of the influence of elastic-element geometry on the electromechanical characteristics of RF MEMS switches [15, 17, 18].

At the second stage, meander suspensions were introduced into the design, which substantially reduced the pull-in voltage. For the intermediate model without a floating electrode but with meanders, the pull-in voltage was approximately 2.1 V, the down-state capacitance was 6.26 pF, the up-state capacitance was 46.9 fF, and the switching time was about 23 μ s. Therefore, it was confirmed that reducing the stiffness effectively decreases the required control voltage; however, this approach alone does not provide a high capacitance ratio, which is necessary for a substantial isolation increase in the S-band [16–18]. Consequently, an additional design solution was required to increase the shunt capacitance in the down state and improve the radio-frequency characteristics.

The final model included a perforated membrane and a floating electrode. The calculated dependence of membrane deflection on the control voltage is shown in Fig. 2. This dependence demonstrates that at a voltage of approximately 2.7 V, the deflection increases sharply, which corresponds to the loss of stability and the transition of the membrane into the pulled-down state. This result agrees well with the analytical estimate of the pull-in voltage according to equation (4). The small discrepancy between the analytical calculation and the simulation results is caused by the fact that the stiffness of the perforated membrane and the distribution of the electrostatic field are taken into account only approximately in the analytical model, whereas in COMSOL they are described more accurately. Such discrepancies are typical for electrostatically actuated MEMS structures [5, 15].

The time dependence of membrane deflection for the final model is shown in Fig. 3. The obtained dependence indicates that at a control voltage of 5 V, the closing time is approximately 18 μ s. Compared with the intermediate model, the decrease in switching time is primarily associated with the reduction in membrane mass due to perforation. Thus, in the investigated design, perforation has a dual but generally favorable effect: on one hand, it slightly increases the pull-in voltage because of the reduced effective area of electrostatic interaction; on the other hand, it decreases the membrane mass and accelerates the transient process. Therefore, the perforation parameters should be selected as a compromise between mechanical compliance, technological feasibility, and dynamic characteristics.

A comparison between the analytical calculation and the finite element modeling results for the final design is given in Table 2. The differences in the key parameters are small: the pull-in voltage differs by 0.15 V, the down-state capacitance differs by 7 pF, and the switching time differs by less than 1 μ s. This confirms that the analytical model is suitable for the preliminary selection of design parameters. At the same time, the final quantitative assessment of the switch characteristics should be based on numerical modeling.

The capacitance ratio is one of the key parameters of a shunt capacitive RF MEMS switch because it determines the difference between the radio-frequency properties of the two operating states. A small value of C_{up} provides weak shunting of the signal line in the up state and thus contributes to low insertion loss, whereas a large value of C_{down} in the down state leads to efficient signal shunting to ground and enhanced isolation. Therefore, increasing the C_{down}/C_{up} ratio is directly associated with a stronger radio-frequency contrast between the two states of the switch.

For the investigated design, this ratio is approximately $C_{down}/C_{up} \approx 2.57 \times 10^4$, which substantially exceeds the values typical of conventional capacitive RF MEMS switches [6, 7, 16, 23]. This result

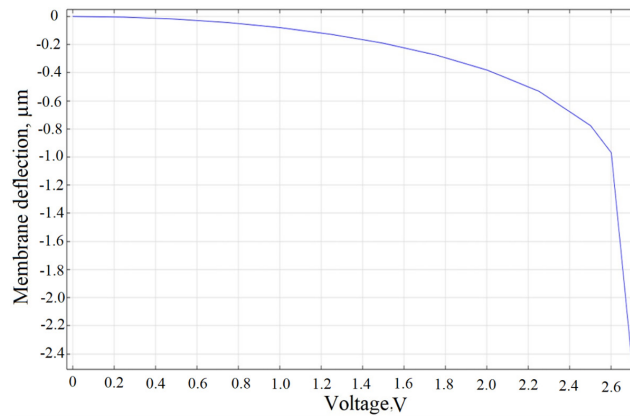


Fig. 2. Dependence of the perforated-membrane deflection on the control voltage for the final model of the RF MEMS switch with a floating electrode

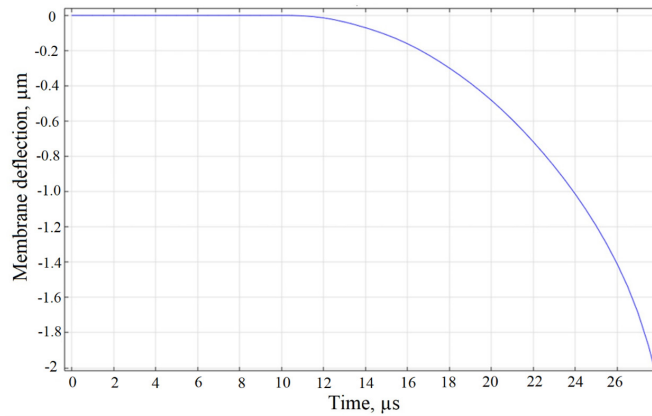


Fig. 3. Time dependence of membrane deflection during RF MEMS switch closing at a control voltage of 5 V

Table 2

Comparison between analytical calculation and finite element modeling results for the final design

Parameter	Analytical calculation	FEM
Pull-in voltage (V)	2.55	2.70
Down-state capacitance, C_{down} (pF)	240	247
Up-state capacitance, C_{up} (fF)	7.2	9.6
Closing time (μ s)	18.6	18

is due to the introduction of the floating electrode and the use of a high-k dielectric, which provide a sharp increase in the down state shunt capacitance while maintaining a low capacitance in the up state. Thus, in the proposed architecture, the floating electrode plays a decisive role in forming the high-isolation properties of the device.

The complete frequency dependences of S_{21} and S_{11} in the down and up states, obtained from electromagnetic simulation in ANSYS HFSS, are shown in Fig. 4. In the down state, which corresponds to the pulled-down membrane, the switch demonstrates high isolation over the entire S-band.

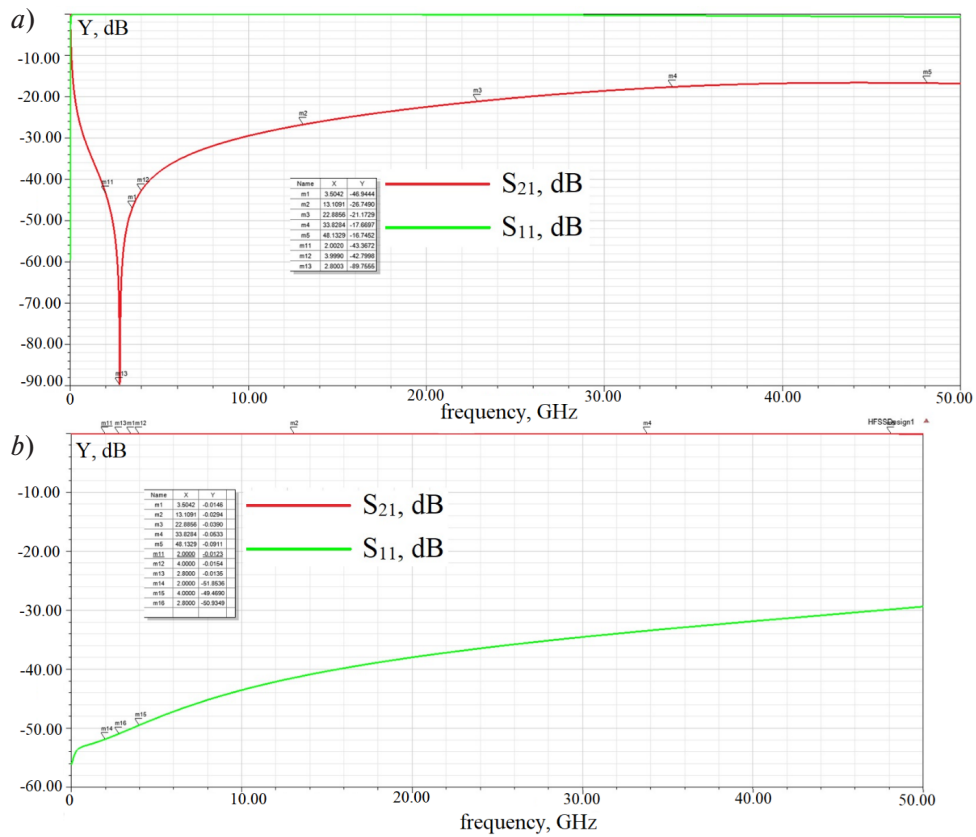


Fig. 4. Frequency dependences of the RF MEMS switch S-parameters in the S-band: down state (a); up state (b)

At 2 GHz, the transmission coefficient S_{21} is -43.3 dB; at 2.8 GHz, a deep minimum of -89.75 dB is reached; and at 4 GHz, S_{21} is -42.8 dB. The pronounced minimum near 2.8 GHz can be interpreted as a manifestation of resonant interaction between the equivalent shunt capacitance and the inductive properties of the transmission line [14, 20]. In the up state, the switch is characterized by low insertion loss: -0.012 dB at 2 GHz, -0.14 dB at 2.8 GHz, and -0.015 dB at 4 GHz. The reflection coefficient S_{11} in the up state is -51.85 , -50.94 , and -49.47 dB at 2, 2.8, and 4 GHz, respectively.

The S-parameter values of the developed model at representative points of the frequency range are summarized in Table 3.

Table 3

S-parameters of the RF MEMS switch in the 2–4 GHz range

Frequency (GHz)	Switch state	S_{21} (dB)	S_{11} (dB)
2.0	down	-43.3	—
2.8	down	-89.75	—
4.0	down	-42.8	—
2.0	up	-0.012	-51.85
2.8	up	-0.14	-50.94
4.0	up	-0.015	-49.47

The obtained results show that the proposed design combines low pull-in voltage values with high radio-frequency performance. From an engineering point of view, this is particularly important because, in conventional shunt switches, improved isolation is often achieved by reducing the gap to the submicron level, which complicates the fabrication process and reduces the reproducibility of the device characteristics. In the present case, a high isolation level is achieved at a gap of 2 μm , that is, under substantially less stringent technological requirements. This provides grounds for considering the proposed architecture to be more robust against parameter variations arising during fabrication.

Conclusion

In this work, an architecture of an electrostatically actuated capacitive shunt RF MEMS switch for S-band operation has been proposed. The distinctive feature of the switch is the use of a floating electrode separated from the signal line by a high k TiO_2 dielectric layer. It has been shown that the combination of a floating electrode, meander suspensions, and a perforated aluminum membrane makes it possible to reduce the pull-in voltage and substantially increase the shunt capacitance in the down state.

Analytical calculation and numerical modeling established that the final design has a pull-in voltage of 2.7 V, a closing time of 18 μs , a down-state capacitance C_{down} of 247 pF, and an up-state capacitance C_{up} of 9.6 fF. The comparison between the analytical model and the finite element modeling results showed good agreement for the main electromechanical parameters, confirming the validity of the selected approach to preliminary design calculation.

Electromagnetic simulation in ANSYS HFSS showed that in the frequency range of 2–4 GHz, the proposed switch provides insertion loss from -0.012 to -0.14 dB and isolation from -43.3 to -89.75 dB. The highest level of signal suppression is achieved near 2.8 GHz, which is associated with the resonant interaction between the equivalent shunt capacitance and the transmission-line parameters. The obtained results indicate that introducing a floating electrode is an effective way to improve isolation without reducing the interelectrode gaps to extremely small values.

Thus, the study confirms that the use of a floating electrode in a capacitive shunt RF MEMS switch is an effective design solution for achieving low-voltage actuation, a high capacitance ratio, and high isolation in the S-band. The developed design can be used in transceiver modules, reconfigurable filters, and other radio-frequency devices for which low power consumption, low signal loss, and high isolation are critical.

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INFORMATION ABOUT AUTHORS / СВЕДЕНИЯ ОБ АВТОРАХ

Ivan A. Sizin

Сизин Иван Андреевич

E-mail: beautyjesus9@gmail.com

Aleksei V. Lukin

Лукин Алексей Вячеславович

E-mail: lukin@compmechlab.com

ORCID: <https://orcid.org/0000-0003-2016-8612>

Vera V. Loboda

Лобода Вера Владимировна

E-mail: vera_loboda@mail.ru

ORCID: <https://orcid.org/0000-0003-3103-7060>

Rostislav S. Smerdov

Смердов Ростислав Сергеевич

E-mail: rostofan@gmail.com

ORCID: <https://orcid.org/0000-0001-8648-5712>

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