Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Design and simulation of RF MEMS switch for use in the millimetre wavelength range and SPDT RF MEMS switch

To cite this article: I E Lysenko *et al* 2020 *J. Phys.: Conf. Ser.* **1695** 012162

Design and simulation of RF MEMS switch for use in the millimetre wavelength range and SPDT RF MEMS switch

I E Lysenko[1], A V Tkachenko[1,2], O A Ezhova[1] and S I Shafrostova[1]
[1]Southern Federal University, Taganrog 347922, Russia
[2]RF Microsystems, Llc., Taganrog, 347939, Russia

Abstract. This article describes in detail the design of a shunt capacitive RF MEMS switch for Ka-frequency band, as well as the design of a single-pole-double-directional RF MEMS switch made on its basis. An electrostatic and electromagnetic analysis was performed using the MATLAB and ANSYS HFSS software package. The switch uses a 1.52 V actuation voltage and 1.3 μs of switching time to move the membrane from the up state to the down state. The operating frequency range of this switch is between 24-34 GHz with isolation of -53 dB at 29 GHz and reflection loss of -0.25 dB for this frequency range. The design of the switch is made on a GaAs substrate with a thickness of 525 μm with a double-sided insulating layer of silicon oxide with a thickness of 2 μm.

1. Introduction

Microelectromechanical systems (MEMS) is a technological process that is used to design and manufacture the smallest integrated devices or systems that combine mechanical and electrical components. Radiofrequency (RF) MEMS switches could combine the advantages of electromechanical and semiconductor switches. RF MEMS switches provide high RF performance and low power consumption, while having a topological size and cost comparable to semiconductor switches [1-4]. RF MEMS switches are widely used in tele- and radio- communication networks, T/R modules, phase shifters, reconfigurable antennas, tunable and switched filter banks etc. RF MEMS switches can be made in several different configurations depending on: the path of propagation of the RF signal – serial or shunt; activation mechanism – electrostatic, magnetostatic, thermal, piezoelectric; contact type-resistive or capacitive; construction type – cantilever or membrane. Various types of RF MEMS switch designs have been widely studied in serial and shunt electrical configurations for various frequency ranges [5], [6].

In this article, the design of a shunt RF MEMS switch with a capacitive contact type and a single-pole-double-directional (SPDT) RF MEMS switch based on it is carried out. The design of this switch consists of a thin movable metal membrane suspended over the RF transmission line of the coplanar waveguide (CPW) and fixed to the ground lines of the CPW by means of serpentine elastic suspensions on the anchor areas. The substrate is a 525 μm GaAs layer with a two-sided insulating layer of SiO_2 2 μm thick. This configuration of the RF MEMS switch allows you to achieve a low value of the actuation voltage and a small switching time from one state to another, as well as good electromagnetic characteristics, which is confirmed by the conducted electrostatic and electromagnetic modeling.

2. Design and simulation

In this article the researched design of the shunt RF MEMS switch with a capacitive contact type is shown in Figure 1. The developed switch contains a gallium arsenide substrate, the CPW, the movable membrane suspended from the anchor areas using serpentine elastic suspension elements, the fixed pull-down electrode and dielectric layers.

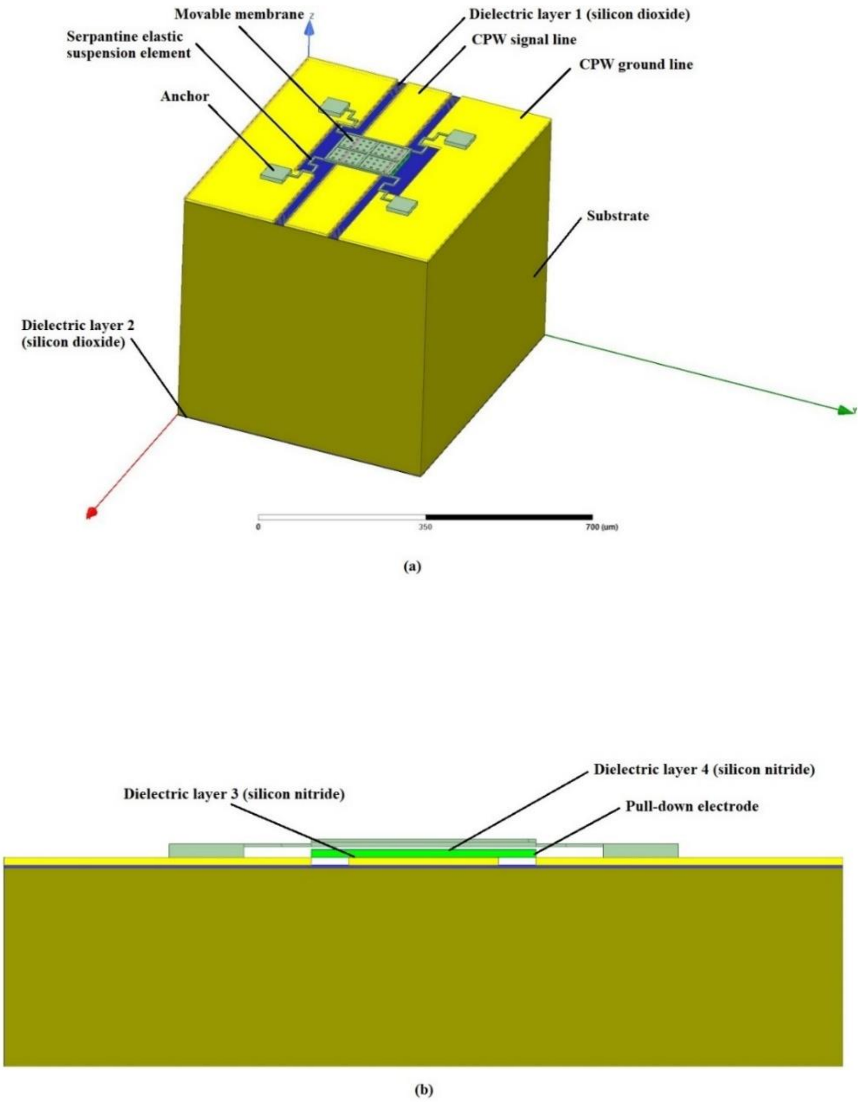

Figure 1. (a) 3D model of the shunt RF MEMS switch with a capacitive contact type; **(b)** Cross section of the design of the switch.

2.1. Electrostatic analysis of switch

The serpentine elastic elements of the switch suspension shown in Figure 1 provide the necessary stiffness coefficient to hold the movable membrane above the RF transmission line of the CPW. Serpentine types of elastic suspensions provide a low coefficient of stiffness compared to other types of elastic suspensions. The stiffness coefficient of a serpentine elastic suspension can be obtained by calculating the stiffness coefficient of each individual segment that are in a series connection. As a rule, the stiffness of each individual segment can be calculated using the Equation (1) [7]:

$$k = Ew\left(\frac{t}{l}\right)^3 \quad (1)$$

where E is the Young's modulus; l, w, and t are the length, width and thickness of each individual segment respectively.

The resulting coefficient of stiffness of serpentine elastic suspensions is equal to $K_{eff} = 4K$. The coefficient of stiffness of the serpentine elastic suspension elements is equal to 0.1563 N/m.

The actuation voltage of the switch can be determined using Equation (2) [8]:

$$V_p = \sqrt{\frac{8K_{eff}\, g_0^3}{27\varepsilon_0 A}} \qquad (2)$$

where K_{eff} is the coefficient of stiffness of elastic suspension elements; g_0 is the value of the air gap between the movable membrane and the RF transmission line of the CPW; A is the overlap area of the movable membrane and the fixed down electrode; ε_0 is the relative permittivity of the air space between the movable membrane and the fixed down electrode.

From Equation (2), the switch activation voltage is equal to 1.5248 V.

The capacitance of the switch in the upstate with a small edging capacitance is determined by Equation (3) [9]:

$$C_{up} = \frac{\varepsilon_0 A}{g_0 + \frac{t_d}{\varepsilon_r}} \qquad (3)$$

where t_d is the thickness of the central dielectric layer; ε_r is the permittivity of the central dielectric layer (silicon nitride); ε_0 is the permittivity of the air space; A is the overlap area.

When an actuation voltage is applied between a movable membrane and a fixed down electrode, this movable membrane bends and shifts towards the fixed down electrode and the capacitance between them increases. The capacitance in the down state of the movable membrane is determined by Equation (4):

$$C_{down} = \frac{\varepsilon_0 \varepsilon_r A}{t_d} \qquad (4)$$

The ratio of capacitance in the down state and capacitance in the up state is often used to determine the performance called figure of merit which must be greater than 50. Figure of merit is defined by Equation (5):

$$C_r = \frac{C_{down}}{C_{up}} = \frac{\frac{\varepsilon_0 \varepsilon_r A}{t_d}}{\frac{\varepsilon_0 A}{g_0 + \frac{t_d}{\varepsilon_r}}} \qquad (5)$$

The capacitance in the up state and down state of the movable membrane is equal to $7.88 \cdot 10^{-14}$ F and $7.43 \cdot 10^{-12}$ F, respectively. Figure of merit equally 94.3.

The switching time from one state to another can be determined using Equation (6) [10]:

$$t_s \approx 3.67 \frac{V_p}{V_s \omega_0} \qquad (6)$$

where ω_0 is the resonant frequency of the switch; V_s is the switching voltage $\left(V_s = 1.2 - 1.4 V_p\right)$.

From here the switching time is equal to 1.3 μs.

The ability of the switch to provide good switching conditions is analyzed by determining the damping coefficient of the elastic suspension elements and the movable membrane, which is determined by Equation (7):

$$b_s = \frac{3}{2\pi}\frac{\mu A^2}{g_0^2} \tag{7}$$

where μ is the air viscosity equal to $1.885\cdot10^{-5}$ Pa.

From Equation (7), the damping coefficient is equal $7.29\cdot10^{-10}$ Pa/m, which indicates very low damping and high switching speed.

2.2. Electromagnetic analysis of switch

Modeling in the up state of the movable membrane is carried out in the frequency range from 0 to 40 GHz using the ANSYS HFSS software package. As can be seen from Figure 2, the reflection loss (S_{11}) is greater than 7 dB in the range from 0 to 30 GHz. Insertion loss (S_{12}) is just over 1 dB for a given frequency range.

When modeling in the down state of the movable membrane, the reflection loss (S_{11}) is not more than 0.25 dB in the frequency range from 0 to 30 GHz. The isolation value (S_{21}) is more than 30 dB for the frequency range from 24 to 34 GHz, while at the frequency of 29 GHz the isolation value is 53 dB. Based on the results of the electromagnetic simulation, we can conclude that this RF MEMS switch is suitable for use in the Ka-frequency range.

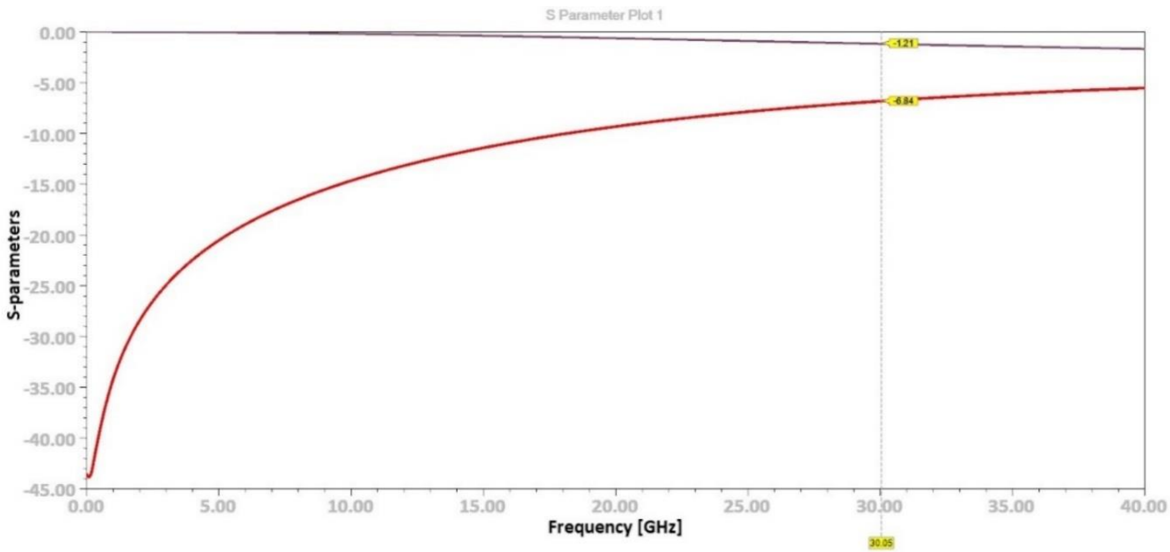

Figure 2. Modeling the S-parameters in the up state of the movable membrane.

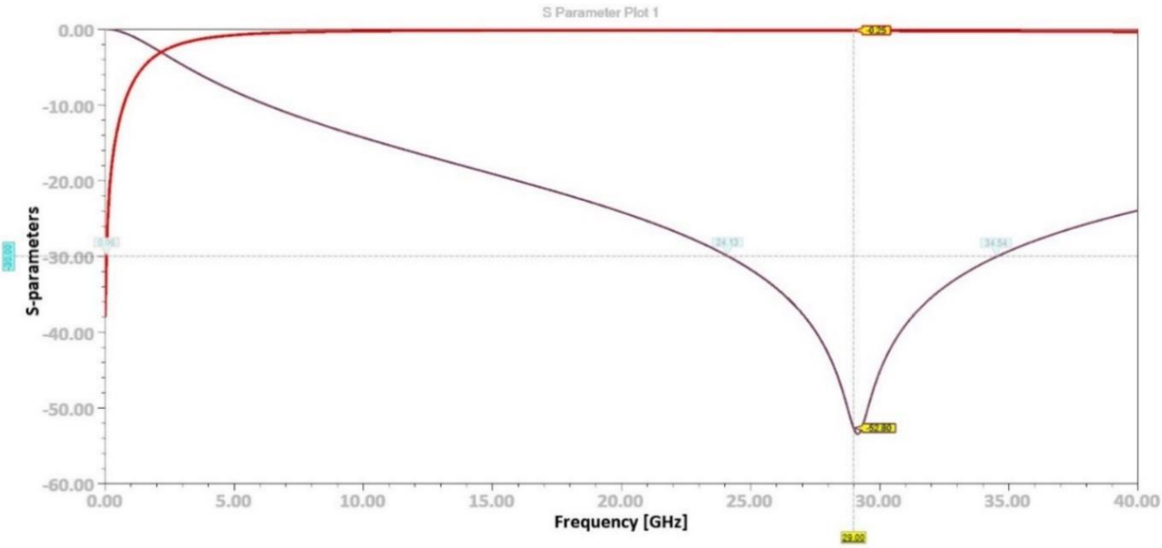

Figure 3. Modeling the S-parameters in the down state of the movable membrane.

3. Single-pole double-throw (SPDT) RF MEMS switch

Single-pole-double-directional (SPDT) is widely used in television and radio communication systems in the microwave and millimeter wavelength ranges [11] in applications such as RF signal routers in transmission and reception systems, switchable linear phase shifters, phased array antennas, and the wide-band tuning networks. Currently, many SPDT switches are implemented using RF MEMS technologies to replace conventional solid-state semiconductor switches. This article presents the SPDT RF MEMS switch for use in the Ka-frequency range.

4. Design and simulation of SPDT RF MEMS switch

The topology of the design of a shunt capacitive RF MEMS switch is shown in Figure 4. When switch 1 is open and switch 2 is closed, the RF signal flows from Input to Output 1 and vice versa. When the SPDT switch is in State 1, the insertion loss is determined by the loss between In and Out 1, and the isolation between ports In and Out 2, and similarly when the SPDT switch is in State 2. Bond wires are used to equalize the potential from the ground plane. The electromagnetic characteristics of the SPDT RF MEMS switch are shown in Figure 5 and Figure 6.

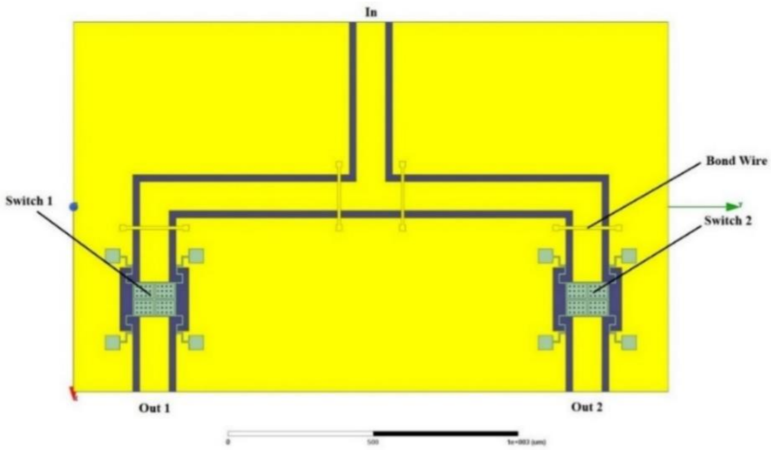

Figure 4. SPDT RF MEMS switch design topology.

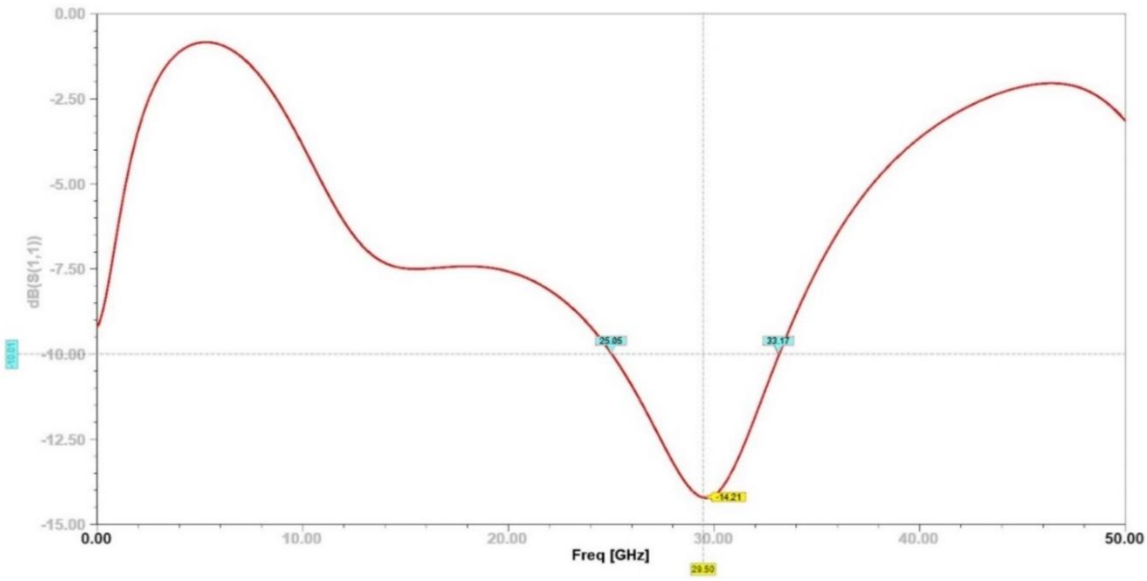

Figure 5. Return loss S_{11} of SPDT RF MEMS switch in State 1.

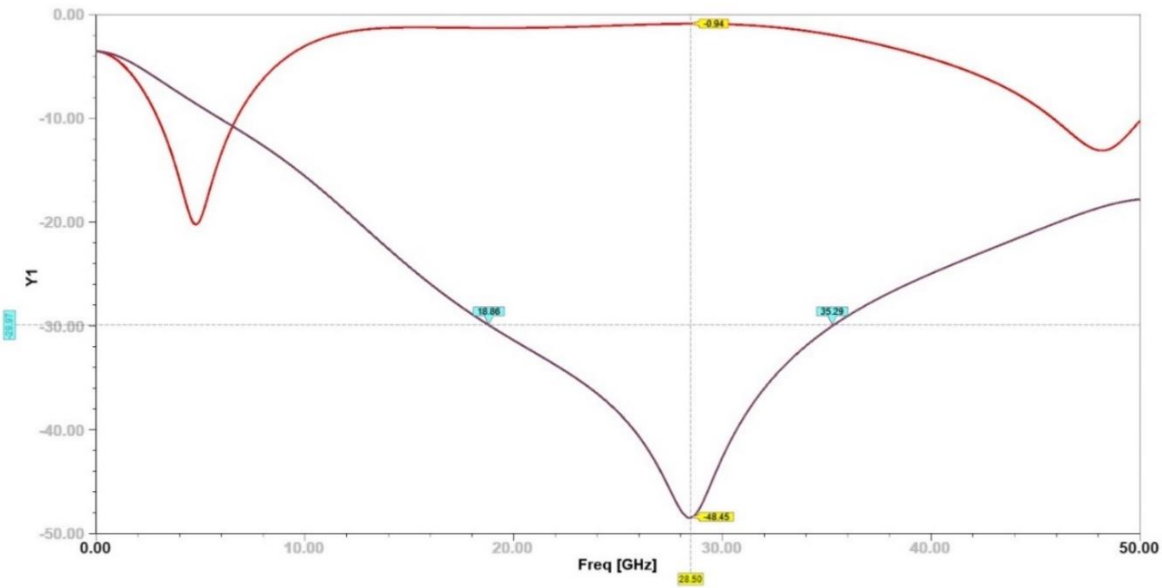

Figure 6. Insertion loss S_{12} and isolation S_{13} of SPDT RF MEMS switch in State 1.

As shown in Figure 5 and Figure 6 in State 1 the reflection loss is greater than 10 dB for the frequency range from 25 to 33 GHz. The insertion loss is less than 1 dB for this frequency range. The isolation between Output 1 and Output 2 is more than 30 dB for the frequency range from 19 to 35 GHz, with the highest isolation value being 48.5 dB at 28.5 GHz. Surface current distribution for a 1W RF signal via SPDT RF MEMS switch in State 1 is shown in Figure 7.

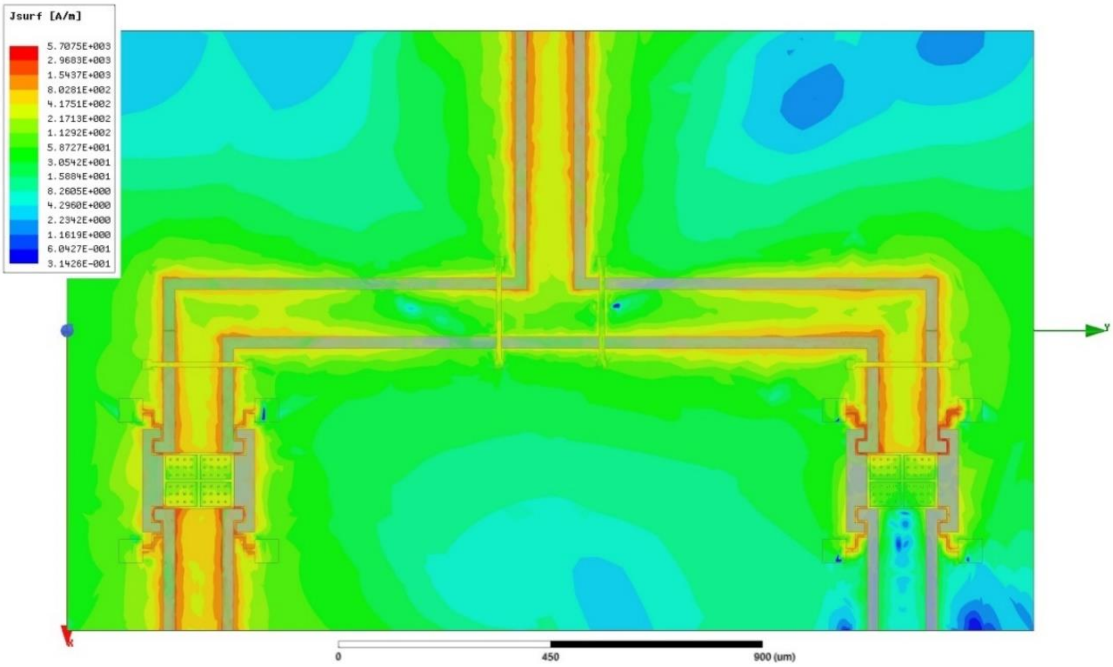

Figure 8. Surface current distribution for a 1 W RF signal via SPDT RF MEMS switch.

5. Conclusion

This article presents the design and simulation of a shunt capacitive RF MEMS switch, as well as SPDT RF MEMS Ka-band switch. The results of electrostatic modeling show the advantages of using serpentine types of elastic suspensions for the design of RF MEMS switch designs, which is expressed in reducing the value of the actuation voltage and switching time. For the presented switch design, the value of the actuation voltage is 1.52 V, and the switching time is 1.3 μs. Based on the results of electromagnetic modeling, it can be concluded that in the down state of the movable membrane, the reflection loss is no more than 0.25 dB in the frequency range from 0 to 30 GHz. The isolation value is more than 30 dB for the frequency range from 24 to 34 GHz, while at 29 GHz the isolation value is 53 dB. The results of electromagnetic simulation of the SPDT RF MEMS switch indicate that the reflection loss is more than 10 dB for the frequency range from 25 to 33 GHz. The insertion loss is less than 1 dB for this frequency range. The isolation between Output 1 and Output 2 is more than 30 dB for the frequency range from 19 to 35 GHz, with the highest isolation value being 48.5 dB at 28.5 GHz. These results show that the proposed SPDT RF MEMS switch is small in size and provides low loss and high isolation when using the presented shunt capacitive RF MEMS switch.

Acknowledgments

The work was supported by the project FENW-2020-0022 to perform scientific research carried out at the expense of the federal budget, in terms of scientific activities on the topic «Development and research of methods and tools for monitoring, diagnostics and forecasting the state of engineering objects based on artificial intelligence».

References

[1] Grant P D, Denhoff M W and Mansour R R 2004 A Comparison between RF MEMS Switches and Semiconductor Switches *ICMEMS'04 Proceed.* pp 515–521
[2] Lysenko I E, Tkachenko A V, Sherova E V, Nikitin A V 2018 Analytical Approach in the Development of RF MEMS Switches *Electronics* **7**(12) pp 1–23
[3] Lysenko I E, Tkachenko A V, Ezhova O A, Konoplev B G, Ryndin E A, Sherova E V 2020 The Mechanical Effects Influencing on the Design of RF MEMS Switches *Electronics* **9**(2) pp 1–26

[4] Lysenko I E, Tkachenko A V, Ezhova O A 2019 Research of the microelectromechanical switch with different materials of metal membrane *Proc. of SPIE* vol **10226** pp 1–12.
[4] Rebeiz G M and Muldavin J B 2001 RF MEMS Switches and Switch Circuits *IEEE Microw. Mag.* **2**(4) pp 59–71
[5] Yao J J 1996 MicroElectromecahnical RF Switch United States Patent *Assignee: Rockwell Int. Corp.* Patent No. **5578976**
[6] Jaspreet M H et al 2014 Methods for the minimization of actuation voltage in MEMS *Int. J. Eng. Res. Appl.* **4**(3) pp 23–27
[7] Guha K, Kumar M, Parmar A and Baishya S 2016 Performance analysis of RF MEMS capacitive switch with non-uniform meandering technique *Microsyst. Tech.* **22**(11) pp 2633–2640
[8] Balaraman D, Bhattacharya S K, Ayazi F and Papapolymerou J 2012 Low-cost low actuation voltage copper RF MEMS switches *IEEE Microw. Theory Tech. Symp.* **2** pp 1225–1228
[9] Lee J, Yang W S, Kang S and Choi C A 2015 Design and parameter extraction based small signal modelling of a novel centre-anchor MEMS series switch *In Proceed. of the 34th European Microw. Conf.* pp 1433–1436
[10] Tang M, Palei W, Goh W L, Agarwal A, Law L C, Liu A Q 2004 A Single-Pole Double Throw (SPDT) Circuit Using Deep Etching Lateral Metal-Contact Switches *IEEE MTT-S Int. Microw. Symp.* pp 581–584