On the design of an Ohmic RF MEMS Switch for reconfigurable microstrip antenna applications

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Abstract: - This paper presents the analysis, design and simulation of a direct contact (dc) RF MEMS switch specified for reconfigurable microstrip array antennas. The proposed switch is indented to be built on PCB via a monolithic technology together with the antenna patches. The proposed switch will be used to allow antenna beamforming in the operating frequency range between 2GHz and 4GHz. This application requires a great number of these switches to be integrated with an array of microstrip patch elements. The proposed switch fulfills the switching characteristics as concerns the five requirements (loss, linearity, voltage/power handling, small size/power consumption, temperature), following a relatively simple design, which ensures reliability, robustness and high fabrication yield.

Key-Words: - Ohmic, resistive, direct contact, switch, RF MEMS, PCB, reconfigurable, microstrip antenna array

1 Introduction

The exponential growth of wireless communications increased the need for more sophisticated system design, to achieve higher integration, power saving and robustness. Great effort is paid in developing high frequency - low scale designs to follow the trends of the market for smaller, technologically more advanced applications. Technological advances in radio-frequency (RF) front-ends, such as reconfigurable antenna arrays, require state-of-the-art system design to allow operation in cognitive wireless networks.

Generally, a reconfigurable antenna should be able to vary the operating frequency, polarization, beamforming, impedance bandwidth and radiation pattern to fulfill the requirements of the application. Nevertheless, the system cost is often determined not from the actual antenna, but from the surrounding technologies that provide reconfigurability [1].

The design diversity of reconfigurable antennas, as far as beamforming is concerned, demands the use of variable-geometry configuration, which should be precisely controlled via high quality switches. This is the approach followed in this work [2, 3, 4].

In the frequency range between 2 and 4 GHz where we intend to work at, there are three kinds of switches that can be used for multiple element reconfigurable microstrip antenna implementations, Pin Diodes, GaAs FETs and RF MEMS **[5].** Summarizing and comparing their characteristics, Table 1, shows that RF MEMS excels to Pin Diodes and GaAs FETs switches as concerns Isolation, Insertion loss, linearity and power consumption. Regarding switching speed, which appears poor in the table below, it is considered more than sufficient for RF control circuit applications.

Table 1. A comparison among different types of RF Switches

Switch Type	Isolation	Insertion Loss	Power Consumption	Switching Speed	Linearity	Cost
Pin Diodes	Good	Good	Poor	Good	Poor	Good
GaAs FETs	Good	Good	Good	Excellent	Poor	Poor
RF MEMS	Excellent	Excellent	Excellent	Poor	Excellent	Poor

The electrostatic RF MEMS switches are divided in two main categories, Capacitive and Ohmic (also referred as resistive or direct contact). Capacitive RF MEMS switches operate on frequencies beyond 4 GHZ due to the low dielectric constants of the insulating layers which are available today. This makes them inappropriate for the frequency range we intend to work at.

On the other hand Ohmic RF MEMS switches operate on frequency range between DC and 60 GHz. Consequently they considered the appropriate type of MEMS Switch for the operating frequency range of our application.

Criteria on the choice of the better type of Ohmic RF MEMS switch for this application is the simplicity, the compatibility with the microstrip lines, the robustness and the long term reliability since the switch has to be able to perform millions/billions of switching cycles [6,7].

Microstrip antenna fabrication techniques use the well-established printed circuit board (PCB) technology. Thus, a microstrip antenna can be small in size and low in profile as well as robust with a smooth surface, suitable for mobile communications. In addition, when used in arrays they provide reconfigurability in terms of operating frequency, bias mode and beamforming.

The design of a reconfigurable antenna using RF MEMS switches could be implemented either based on the hybrid mode, that is using individual RF MEMS switches which should be bond in the PCB as shown in Fig. 1, or the integrated mode, where each switch is fabricated on the same substrate with the antenna patches in a single manufacturing process, as shown in Fig. 2.

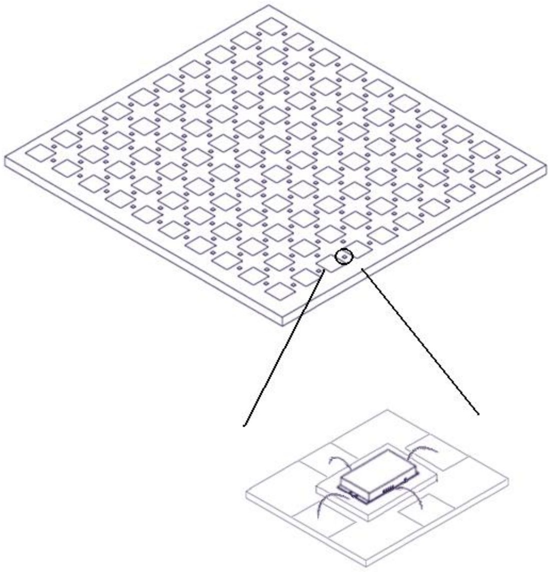

Fig.1 Hybrid configuration of the microstrip array antenna and the expanded view of a packaged RF MEMS Switch

With the current technology, it is possible to fabricate such an antenna using the hybrid method. Nevertheless, that could result in several drawbacks regarding cost and compatibility, especially when designing topologies with significant number of switches.

In general, the cost of a single RF MEMS switch is very low, thanks to the similar to VLSI design and batch processing methodology and tools. Nevertheless, the cost is increased dramatically due to the devise-level hermetic packaging. In addition to that, there are real estate problems due to the relatively great size of the packaging and the large number of the switches which have to be used for the complete antenna configuration.

Another important drawback of the hybrid mode is the impedance mismatching, during the packaging and assembling process. RF MEMS switches require wire bonding in the package introducing impedance mismatch and consequently signal loss. Besides, further signal loss is introduced during the assembling, between the package and the board. Last but not least, additional signal loss is introduced because of the incompatibility between the substrates of the RF MEMS switch (usually high permittivity materials such as Si and GaAs) and the microstrip's antenna element (usually microwave laminate PCB) due to the difference in the electrical properties of their materials [5].

Hence, to maintain an overall good performance in hybrid mode design it is vital to use extra adapting circuitry to reduce the undesirable RF signal reflection.

In monolithic configuration, the RF MEMS switches are built on the PCB substrate, under the same process with the antenna patches. Using the integrated mode we eliminate problems regarding cost, since the fabrication process needs only one packaging procedure for the whole application, real estate problems, due to the small size of the RF MEMS switches without the packaging cells and matching as the switches are parts of the microstrip antenna structure.

The main drawback of this configuration is the yield of the design, since both antenna and RF MEMS switches are built simultaneously. Thus, the manufacturing cost is increased since a single RF MEMS switch failure would result in wasting the whole structure. Some other typical technology obstacles of the integrated mode are the planarization of the high aspect ratio microstrip waveguide Cu layers, the profile and surface roughness and the compatibility requirement of the temperature (250^{o}C) [8, 9,].

This paper presents the design and process considerations of an ohmic RF MEMS Switch, implemented in the integrated mode. The design approach followed in this work was mainly towards the simplicity of the RF MEMS switch and its compatibility with the substrate material properties (mechanical, thermal, chemical, electrical, etc) of the antenna. The new configuration is designed to be fully integrated in the RF system, minimizing the main drawbacks of both the hybrid and integrated design modes. The investigation of the proposed design has been carried out using Coventorware 2008 [10] as well as FEKO 5.4 [11] for the full electromagnetic wave analysis.

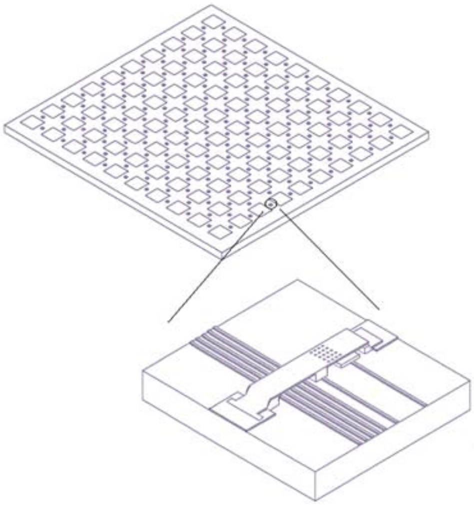

Fig.2 Integrated configuration of the microstrip array antenna and the expanded view of the ohmic RF MEMS Switch

2 Design considerations

The presented ohmic RF MEMS switch is intended to be used to control a microstrip antenna array built on PCB,

The advantage of these types of antennas is the ability to beamforming according to the requirements of any application. The switch investigated here will be used to reconfigure the antenna geometry. Thus, it has to present good performance in certain electrical characteristics, as shown below:

i. Very low insertion loss in the "ON" condition.
ii. Very high isolation in the "OFF" condition.
iii. Good linearity over a wide frequency range.

In addition, the structure of the switch should be as simple as possible, to reduce the possibility of failure during the manufacturing process, maintaining high yield. Moreover, this process should take into account the material characteristics of the antenna, such as:

i. The temperature developed during the fabrication process should not exceed the glass transition temperature (Tg) of the PCB material which is usually in between 125-250°C depending on the PCB type [12].

ii. The chemical, mechanical and electrical characteristics of the material used to form the contact area of the switch should be the appropriate to maximize the reliability of the RF MEMS device.

Due to the fact that the RF MEMS switches will be developed by applying an integrated monolithic process simultaneously with the microstrip antenna array elements, extra consideration should be paid in biasing each switch, since the bias lines will be constructed at the same level. It is important that they should not affect the operation of the antenna, either by creating any type of radiation or by affecting the operation of their adjacent switches.

On the other hand, special effort should be paid in designing a switch with the least possible bias voltage avoiding extra circuitry.

It is also important to investigate on the use of dielectric in the switch structure which prevents from sort-circuit although it may create stiction phenomena.

3 The proposed switch

The proposed ohmic RF MEMS switch is shown in Fig. 3. The design is using two different materials, i.e., copper for the anchors, biasing tracks and the electrode and gold for the posts, contact and cantilever. The most common materials that could be used for the fabrication of the cantilever and contact surface were copper (Cu), aluminum (Al) or gold (Au).

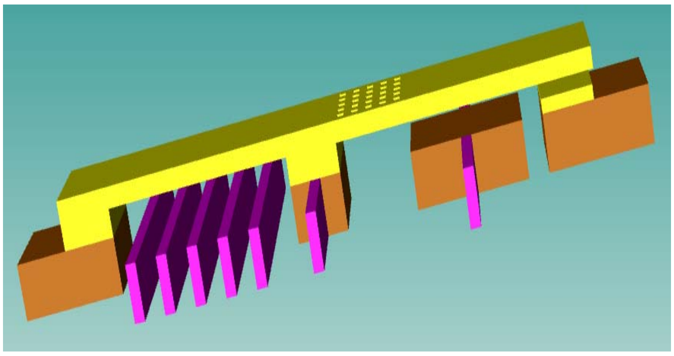

Fig.3 The proposed ohmic RF MEMS Switch

Examining the trade-offs of each one of them, it has been decided that Au was the most appropriate material for the following reasons:

i. The conductivity of Au is better than Al and worse than Cu. Better conductivity implies less skin depth, which is an important parameter for the lossless RF signal transmission via the cantilever. ($0.452 \cdot 10^6$/cmΩ for Au, $0.377 \cdot 10^6$/cmΩ for Al, and $0.596 \cdot 10^6$/cm Ω for Cu).

ii. The young's modulus of Au is similar to that of Al and much smaller than that of Cu. Consequently, the stiffness of the cantilever made by Au will be lower fulfilling the requirement for lower pull down voltages of the cantilever (78GPa for Au, 70GPa for Al, and 110GPa for Cu).

iii. Considering the nearly-hermetic packaging it is inevitable to face contaminations issues in the long term.

Au is the most chemically stable material among the three materials since it does not form oxides or sulfides offering greater longevity. Au-Au ohmic contact switch has been shown that it can reach 10^8 cycles of lifetime [13, 14].

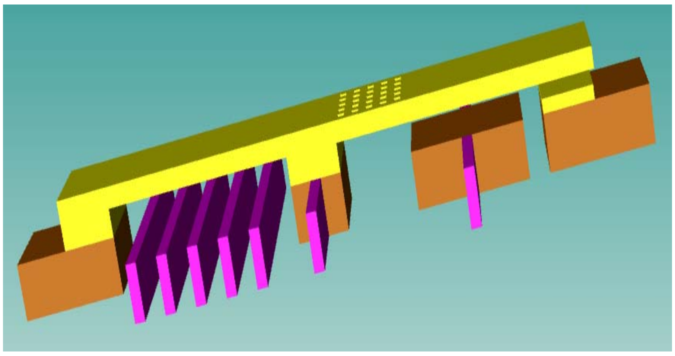

Fig.3 The proposed ohmic RF MEMS Switch

The pull down voltage of the switch must be as low as possible and it depends on the dimensions of the cantilever (length and height), the distance from the electrode and the stiffness of the gold. The stiffness in turns, mainly depends on the shape of the cantilever and the existence of perforation. Holes have been applied to reduce some of the residual stress in the cantilever, reducing the Young's modulus of the RF MEMS structure. The ligament efficiency (μ) is 0.625 and results to a reduction of the Young's modulus of 25% [15]. Perforation will also contribute in the removal of the sacrificial layer and the release of the cantilever.

The width chosen matches that of the signal lines (150um). The thickness of the cantilever affects significantly the magnitude of the pull down voltage [15]. In addition, it depends on the operating frequency range (2-4GHz in our case), since it has been shown that it has to be at least twice the skin depth of the material used to provide low insertion loss [16]. Besides it has been proven that for operating frequencies below 4GHz the skin effect is much less significant than the resistive loss of the signal lines [17]. The thickness of the cantilever made by electroplated gold has been calculated some 3um.

Due to the application, a bridge-type construction has been designed to allow several biasing tracks to pass underneath the switch. The width of those tracks is kept small (20um each), so that they do not attract the beam above them.

Most of the ohmic RF MEMS applications use dielectric layer on top of the electrode, to make sure that the cantilever will not touch the electrode which implies a sort circuit. Nevertheless, adding dielectric involves high temperature processing steps. That is not an important drawback using Silicon substrates. Since this switch is using a PCB substrate, such a high temperature process step is prohibited.

The lack of dielectric, although it demands greater consideration as far as the pull down voltage is concerned, simplifies the fabrication process and prevents from stiction of the bridge due to dielectric charging, a known failure reason of electrostatic actuated RF MEMS switches [18].

Finally, the contact area of the switch had to be kept relatively small to maintain high isolation during the OFF state, in the highest operating frequency. Simultaneously, it should be large enough to provide good conductance in the ON state. Another issue to be concerned is the roughness of the contact area. An acceptable figure for switch contact is about 50 nm, but even then the effective contact area couldn't be more than 6-7%. As a result the actual contact resistance is much higher than the calculated.

4 The proposed fabrication processes

The proposed fabrication processes of the presented design is using the RO5800 of Roger Corporation as a substrate, which is a high performance microwave laminate (e_r=2.2, tanδ=0.0009, copper thickness 9 or 17.5 um (1/4 or 2/4 oz) and dielectric thickness 3.175mm). An important reason for choosing this specific substrate except of the excellent microwave characteristics was the increased rigidity since polishing steps will have to be used during the fabrication process.

A rough description of the proposed monolithic antenna fabrication processes are presented below:

4.1 First fabrication process

1. Mechanical-Chemical Polishing: The roughness of Cu on the top of the laminate is in the range of 0.5-1um, according to the manufacturer. As a result, this area should be first polished down below 70nm, the least acceptable roughness level for a DC RF MEMS Switch. This first step is important in order to obtain a reliable and repeatable contact area, and is demonstrated in Fig.4.

Fig.4 The polishing step

2. Gold posts placement: Gold posts deposition should be carried out in two phases (2u each) using masks and photoresist layers to construct the anchors and the contact area, as shown in Fig.5 and Fig.6 respectively.

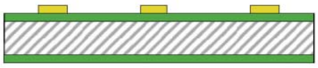

Fig.5 First gold posts deposition

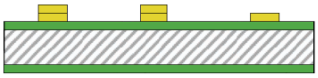

Fig.6 Second gold posts deposition

3. Copper wet etching process: The antenna patches, the anchors, the electrode plates and the bias tracks should be developed in the copper surface. Consequently, a wet etching process is necessary to be followed, as shown in Fig.7.

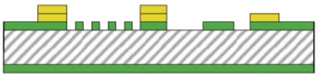

Fig.7 Copper wet etching process

4. Comprehensive Molding Planarization, 1st step: To confront high heights (some 17u of copper and 4u of gold posts), a new method called Comprehensive Molding Planarization have been presented by H. P. Chang et al [19] which includes two steps. First a thick photoresist layer spin coated, which is shown in Fig.8.

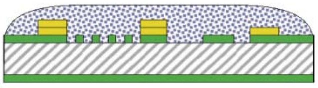

Fig.8 Thick photoresist layer spin coated

5. Comprehensive Molding Planarization, 2nd step: The second step is a molding step to planarize the photoresist in order to make it suitable for the gold membrane deposition to ensure mechanical integrity of the deposited membrane, and is demonstrated in Fig.9.

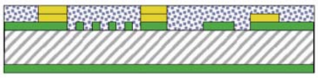

Fig.9 Molding - planarization step

6. Deposition of the cantilever gold membrane: On top of the anchors a gold layer of 3um thickness will form the cantilever of the RF MEMS Switch. This is shown in Fig.10.

7.

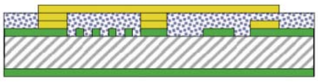

Fig.10 Deposition of the cantilever

8. Cantilever release and perforation: Final step in the fabrication process is the remove of the sacrificial layer, which releases the cantilever. Prior to that, an array of holes defined in the cantilever will be created, which not only will improve the stiffness of the membrane but also will accelerate the removal of the sacrificial layer. [14]. This is shown in Fig.11.

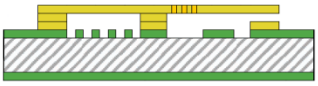

Fig.11 Cantilever release and perforation

4.2 Second fabrication process

An alternative fabrication process confronts the increased copper height and differs only at steps 5 and 6 from the pervious process. As referred by Bahram Ghodsian et al [20], the Comprehensive Molding Planarization process that has been presented above has generally a relatively low yield due to the formation of voids in the photoresist mold during the fabrication process.

The process suggested by the author introduces a new surface planarization in order to create a smooth planar surface with roughness 30–50 nm. This process can be applied with temperatures lower than 220 °C, offers very high fabrication yield and consists of two steps:

5. Surface Planarization step: First, to planarize the surface, a thick polyimide layer is spin coated over the patterned antenna area to a thickness of 22-23 um,

6. Polishing steps: Then a two-step polishing process is applied for planarizing the polyimide material and exposing the top surface for the cantilever deposition.

5 Simulation results

The design and evaluation of the proposed ohmic RF MEMS switch has been carried out using the Coventoreware 2008 and FEKO 5.4 software packages. A 3D view of the new design, produced in the Architect Scene 3D, with the switch in the ON state is shown in Fig. 3. The bridge-shaped part of the switch allows at least 4 biasing tracks to pass through the switch without affecting its operation. The size of the cantilever is such to maintain a good balance among weight, switching time and pull-down voltage. The position and the size of the electrode are chosen so that it will ensure full contact at 28V and it will not attract the cantilever for any voltage-magnitude below 35V. For illustration purposes the z-axes has been magnified ten times. The biasing has been omitted, too.

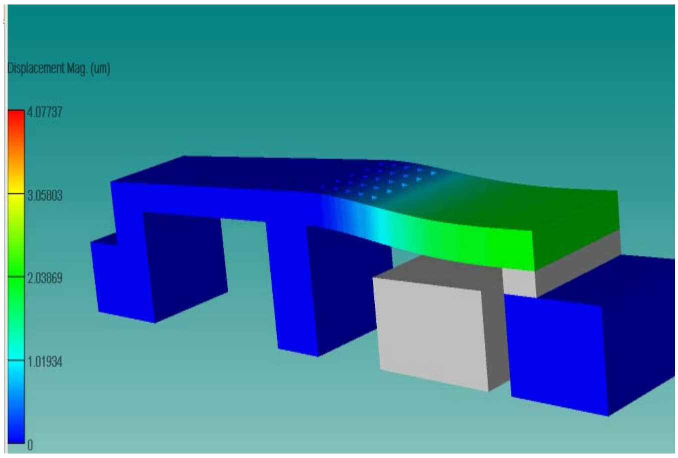

Fig.3 The proposed ohmic RF MEMS switch simulated in Coventor Architect Scene 3D

The electrical and mechanical characteristics of the proposed switch have been obtained via Coventor Cosmoscope. The switching time was some 37us, as shown in Fig. 4.

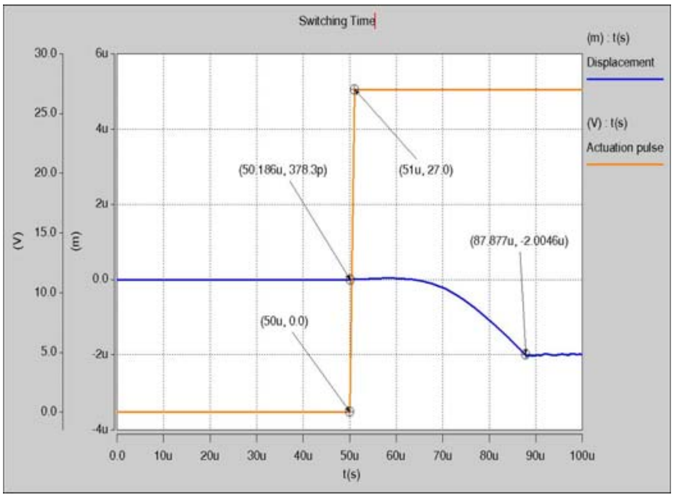

Fig.4 Switching time of the proposed switch obtained via transient analysis

The contact area, the capacitance in the OFF state and the contactance in the ON state are illustrated in Figures 5-8 respectively. The contact area graph indicates a full contact considering the dimensions of the touch (150um × 54um), at about 28V.

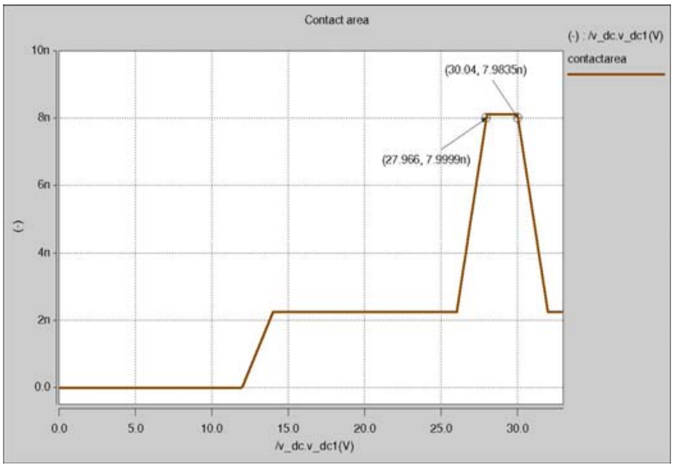

Fig.5 Contact area (nm) of the proposed switch

The switch keeps the capacitance in the range of femptoFarrad in the OFF state, assuring very high isolation.

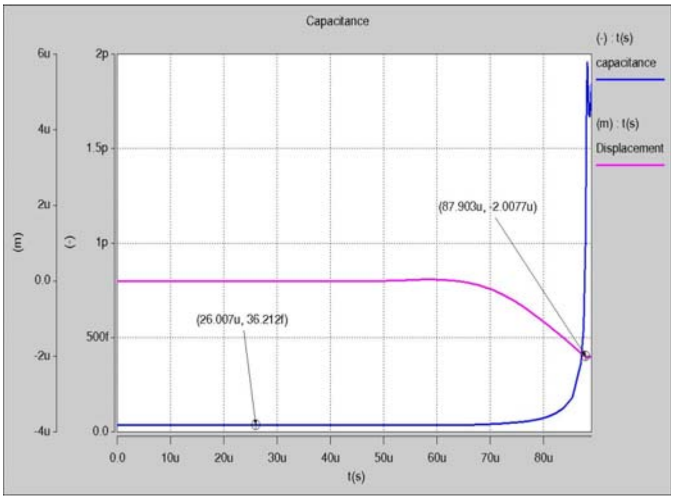

Fig.6 Capacitance (fF) in the OFF state

The switch presents very low resistance in the ON state, some 1.1Ω, at full contact, as shown in Fig.7.

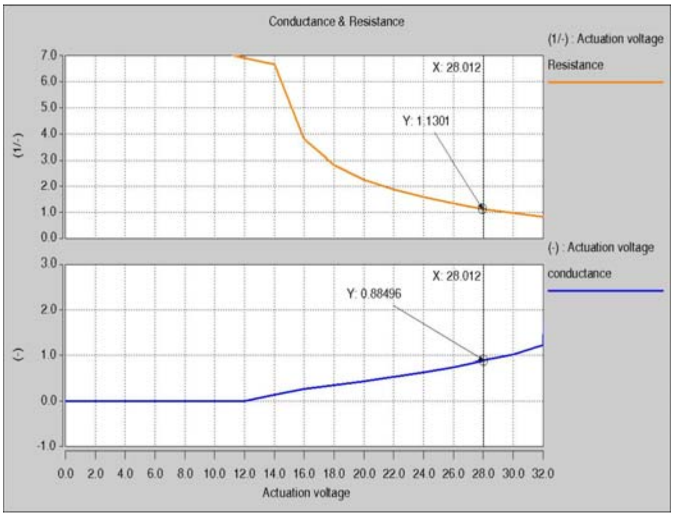

Fig.7 Conductance and Resistance of the proposed MEMS switch

A DC analysis of the novel switch took place to investigate the pull down voltage and the contact force. The results, shown in Fig. 8, indicate a full contact (2um) at 28V. The contact force under the same voltage magnitude is some 10uN.

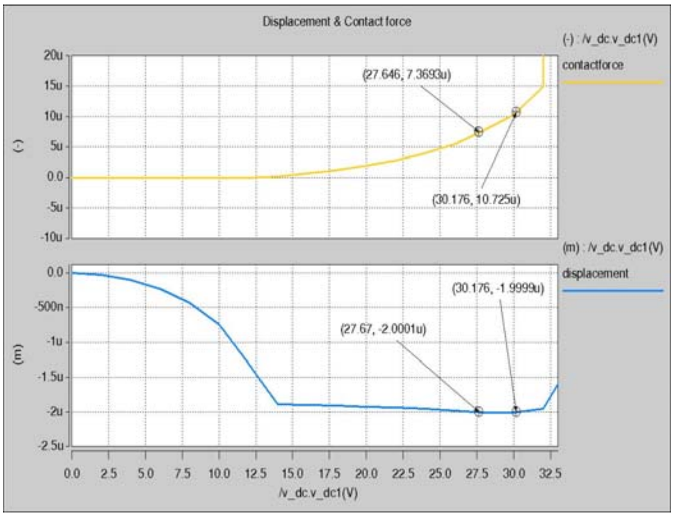

Fig.8 Pull down voltage/Displacement and contact force of the proposed RF MEMS Switch

A full electromagnetic wave analysis has been carried out to further investigate the S-parameters of the switch. Fig. 7 and Fig. 8 present the return loss and the insertion loss of the design in the ON state. The design characteristics and the performance results of the proposed switch are summarized in Table 1.

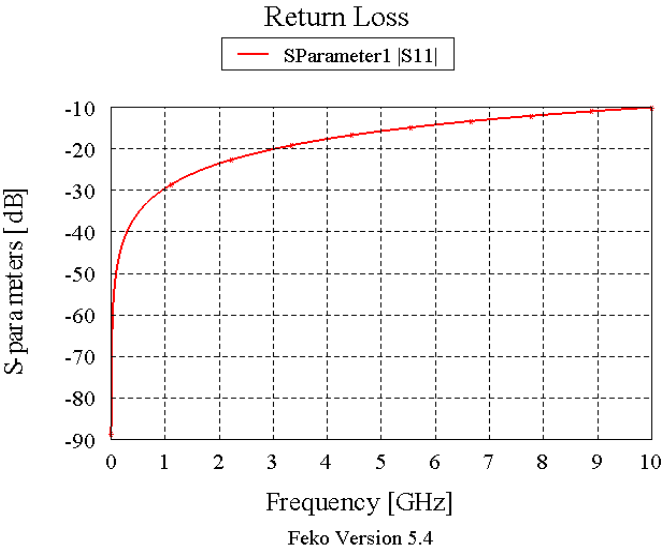

Fig.7. Return loss of the proposed switch in the ON state.

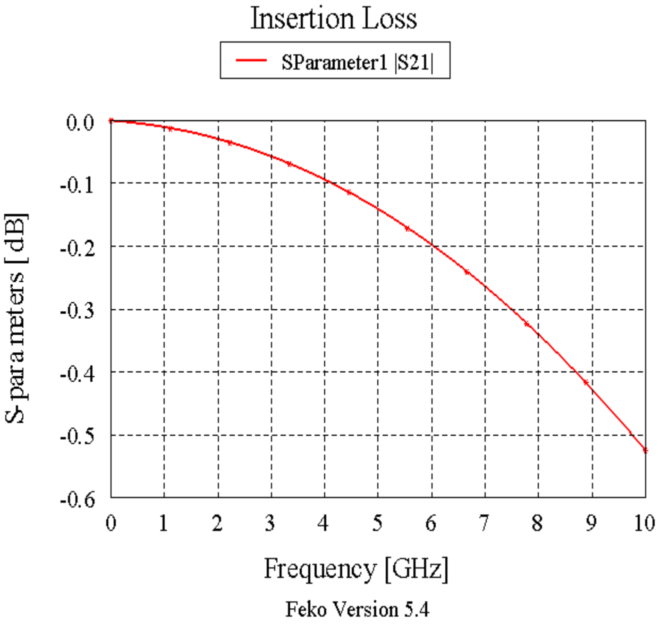

Fig.8. Insertion loss of the proposed switch in the ON state.

As shown, the return loss at 2.4GHz is -22.11dB while at 4GHz is -17.63dB. The insertion loss is also worth mentioned with -0.039dB and -0.094dB at 2.4GHz and 4GHz respectively.

The same parameters investigated in the OFF state of the switch, presenting significant results. The return loss was -0.014dB and -0.042dB at 2.4HGz and 4GHz respectively. The results are illustrated in Fig. 9.

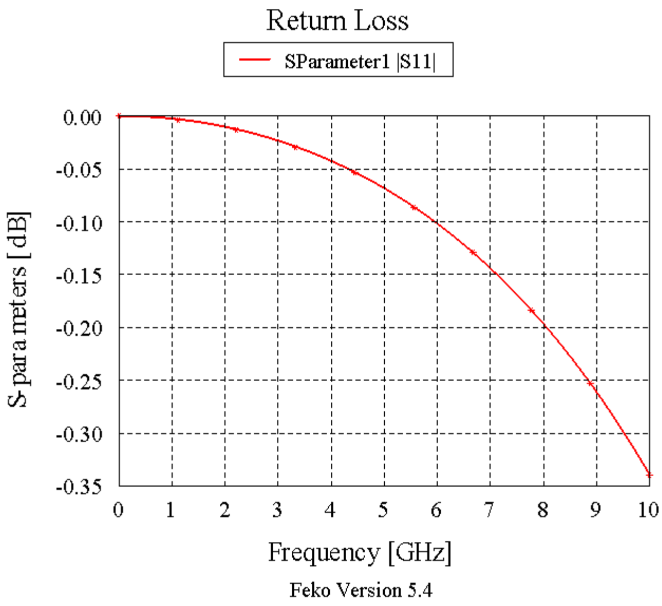

Fig.9. Return loss of the proposed switch in the OFF state.

Finally the isolation of the switch in the OFF state has been investigated and the results are shown in Fig. 10. The analysis results show excellent isolation, which is -24.87dB at 2.4GHz and -20.62dB at 4GHz. Table 1 summarizes the design characteristics and the performance results of the proposed switch.

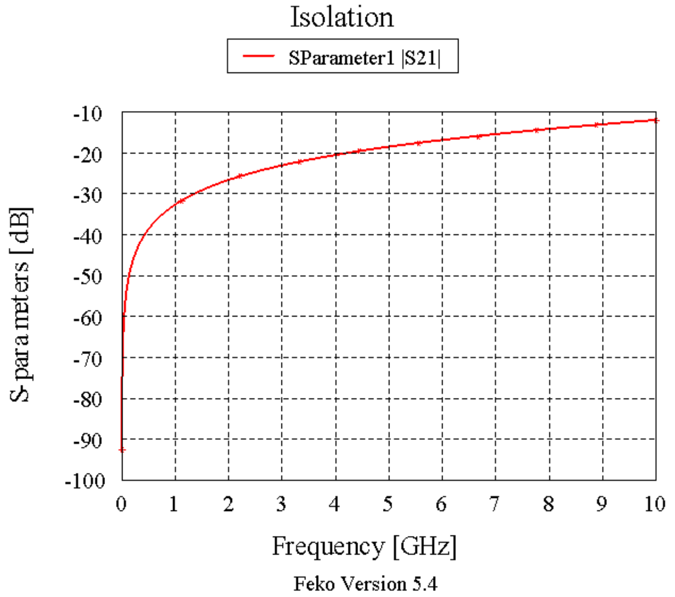

Fig.10. Isolation of the proposed switch in the OFF state.

Table 2. Parameters for the ohmic RF MEMS Switch.

Parameter	**Value**	**Parameter**	**Value**
Length (movable)	440um	Actuation Voltage	27.6V
Width	150um	Switch Time	37uSec
Height	2um	Switch Resistance	1.13Ω
Cantilever Type	Gold	Capacitance (off)	36fF
Thickness	3um	Isolation (4GHz)	-20.62dB
Holes	Yes	Loss (4GHz)	-0.04dB
Conduct Area	150×54um	Conduct Force	10uN

4 Conclusion

A novel ohmic RF MEMS switch built on PCB has been presented. The new design is intended to be used in reconfigurable microstrip antenna arrays. The proposed switch is specified to be developed with an integrated monolithic process simultaneously with the microstrip antenna array elements. The simplicity of the switch assures high fabrication yield keeping the manufacturing cost relatively low. The electric, mechanical and electromagnetic simulation of the design has presented significant results for the insertion loss in the ON state the isolation in the OFF state, the required pull down voltage, the switching time, the conductance and capacitance in the ON and OFF states respectively. All the above make the RF MEMS switch suitable for many antenna applications. This research work is still on-going and the ohmic switch is being further investigated via stochastic optimization programmes such as genetic algorithms and PSO, to achieve lower pull down voltage, smaller cantilever lengths, faster switching time, elimination of the bouncing and settling time phenomena while maintaining significant overall performance.

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