UNIVERSITY OF CALIFORNIA,
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High Power Direct-Contact RF Laminate Microswitch

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Electrical Engineering and Computer Science

by

Sung Jun Kim

Dissertation Committee:
Professor G. P. Li, Chair
Assistant Professor Mark Bachman
Professor H. Kumar Wickramasinghe

2014

DEDICATION

To my best supporter father, mother and brother

It would not be possible without your support

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I would never have been able to finish my dissertation without the guidance of my committee members, supported from friends and my family. Family, they are my biggest supporter. They are patient, always wait for me and always being my side. I sincerely appreciate to my advisor, Professor G.P. Li, for guiding, training, patience and advices me. I would like to thank Professor Mark Bachman, co-advisor, for advices in many years.

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ABSTRACT OF THE DISSERTATION

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By

Sung Jun Kim

Doctor of Electrical Engineering and Computer Science

University of California, Irvine, 2014

Professor G. P. Li, Chair
Assistant Professor Mark Bachman, Co-Chair

Silicon based Microelectromechanical systems (MEMS) technology has produced radio-frequency (RF) micro switches for the past two decades and exhibit low loss, high linearity and low power consumption compared with conventional solid state switch. However, it has been challenged beyond 10 watts since its limited power handling capability.

We have introduced Laminate technology to overcome limited power handling capability in conventional RF MEMS switch. It made possible large actuation stroke, strong force to actuate movable part, more robust conductor lines and less lossy substrate. The microswitch reported here is how to design high power RF laminate switch, addressing design trade-off; how mechanical, RF performance and switching performance are correlated and how power handling capability changes by design.

The main device failure mechanisms in high power application are self-actuation due to high incident power and high temperature in device. We have guided how to minimize self-actuation problem and reduce heat source which cause increasing device temperature. Latching system, switch stays switched state without having operation signal, is also a part of this switch. In hence power consumption is zero when switch is switched.

The switch showed low contact resistance, 0.3 Ω and decent RF performance, -0.35 dB insertion loss and -18 dB isolation at 9 GHz for low power testing. This switch showed successfully switching at high power testing, 15 Watts at 1.9 GHz and it is expected successful switching higher power 25 Watts at 1.9 GHz by simulation and calculation. Current high power testing was done at 15 Watts, 1.9 GHz due to limited lab equipment.

Section I – Overview and Fundamentals

This section contains a general overview of RF MEMS switch (Chapter 1).

CHAPTER 1: Introduction

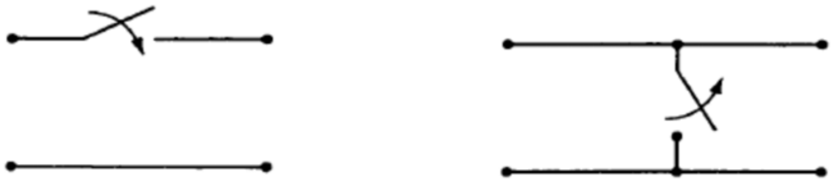
1.1. RF MEMS switch

Micro Electro-Mechanical System (MEMS) is miniaturized mechanical and electro-mechanical elements. RF MEMS switch is particularly designed MEMS device as radio-frequency (RF) switch for RF applications such as phase shifter, diversity antennas, resonators, line switches, attenuators, isolators and tuning circuits and use mechanical movement to achieve an open or short circuit.

Since RF MEMS switch was introduced at early 1991 from Larson *et al* at the Hughes Research Labs [1], it has been studied actively in various research labs, universities and companies, and showed excellent RF and mechanical performances, low insertion loss and high isolation overall DC to mm wave frequency and a few billion times switching cycling time [2][3][4][5][6][7][8].

1.2. Series and Shunt RF MEMS switch

RF MEMS switch has two types, series and shunt switch, Fig. 1. Series type RF MEMS switch is that disconnecting and connecting incoming signal. When it is OFF, the circuit is open circuit, incident RF signal is reflected, and when it is ON, incident signal pass though RF MEMS switch. Shunt type RF MEMS switch is that guiding RF signal to ground when it is ON. When incident signal though switch at ON-state at series type switch, and there is no additional component on signal line for shunt type switch. Series type switch is good for lower frequency (DC ~ 30 GHz) since RF MEMS switch gives additional losses with signal line loss and shunt type switch is good for higher frequency (15 ~ 100 GHz).

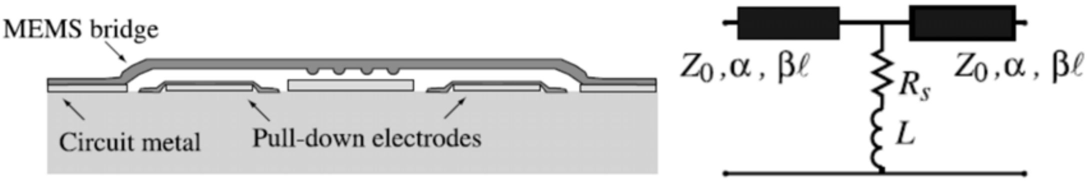


a) b)

Fig. 1. MEMS switch a) Series, b) Shunt

1.3. DC and Capacitive RF MEMS switch

RF MEMS switch can be categorized by two, Direct Contact (DC) switch and capacitive switch, and both of different type switches can be used as series and shunt switches depends on applications. Fig. 2 and Fig. 3 shows illustration and RF lumped circuit model of DC MEMS shunt and series switch. When it is OFF state, it has small capacitor (typically < 100 fF), C_s shown at Fig. 3, since there is parallel plate capacitor with air gap between movable part and signal line. The capacitive MEMS switch is shown at Fig. 4. Dielectric material such as silicon nitride is deposited to signal line to make large capacitance at ON state. When it is OFF state, it has also capacitance, much smaller than ON state capacitor. Therefore it can be a variable capacitor having two different values. This can be used to any applications requiring high ratio of two capacitors.



a) b)

Fig. 2. Shunt DC MEMS switch a) Cross section, b) Equivalent circuit [9]

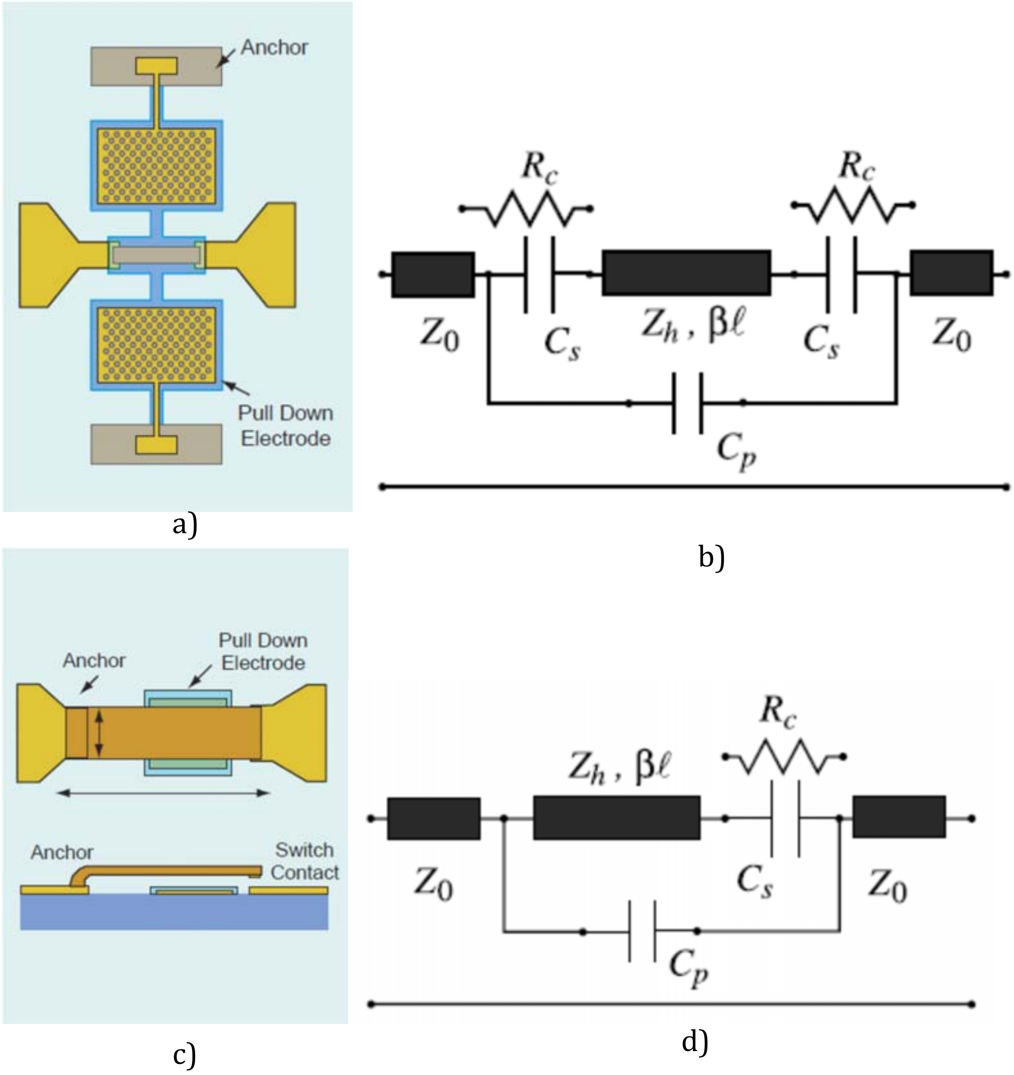


Fig. 3. Series DC MEMS switch a) Two electrodes, b) Equivalent circuit, c) Inline series switch, d) Equivalent circuit [10]

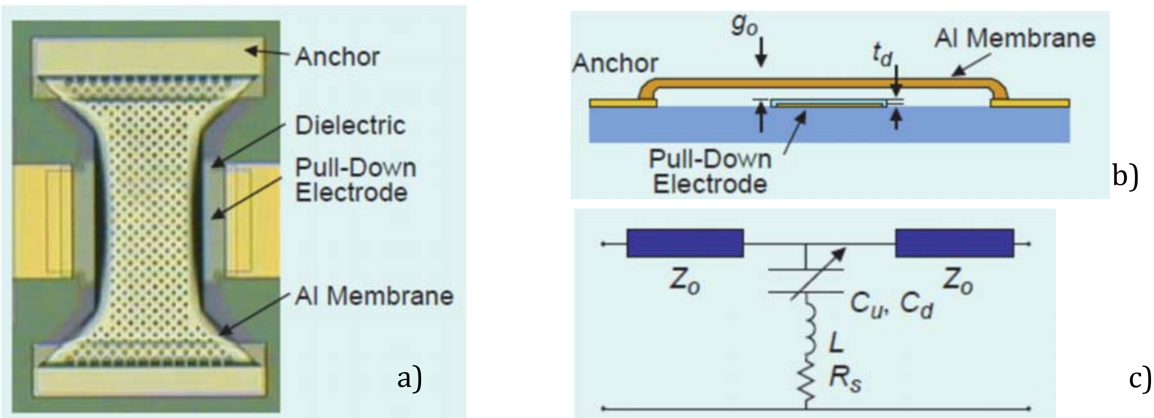


Fig. 4. Capacitive MEMS switch a) and b) Top and Side view, c) Equivalent circuit [10]

1.4. Actuation type

The common movable part design is thin membrane with fixed at the end of membrane with anchor and thick metal with fixed at one of ends of the metal with anchor in RF MEMS switches. There are usually three actuation types, electrostatically, thermally and magnetically shown at Fig. 5, to move this movable part.

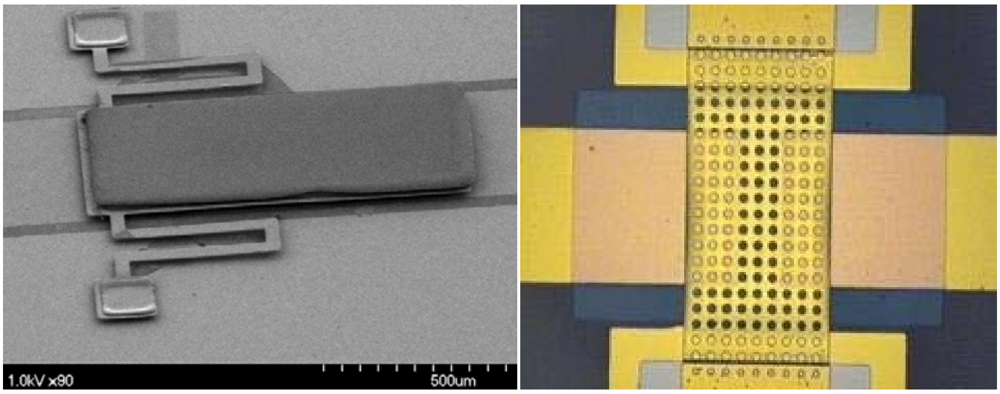


Fig. 5. a) Magnetically actuation, b) Electrostatically actuation

1.5. Silicon MEMS switches and its limitations

Despite of excellent RF performance of RF MEMS switches, very low insertion loss (-0.1dB loss through millimeter wave frequency), very high isolation (only a few femto-F capacitance at OFF state) and very high cut-off frequency, it has been showed limitations. The well-known its limitations are packaging and power handling.

RF MEMS switch has movable part and 3D structures. In hence the packaging has to protect this switch from outside impact. Many RF MEMS switch require hermetic packages since sensitivity of humidity. In conventional hermetic packaging process in MEMS, it requires post cleaning process to MEMS circuits after release them from wafer. Scribing procedure introduces contaminations to MEMS design, so it requires additional cleaning process. In these reasons the packaging cost is high.

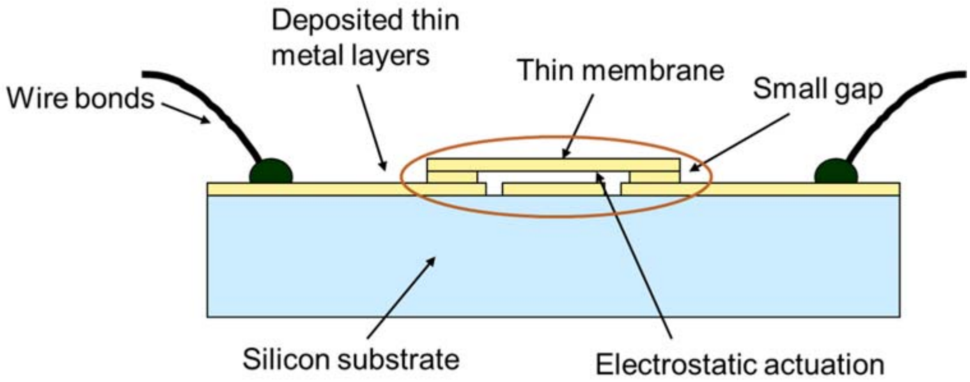


Fig. 6. Conventional Silicon based RF MEMS switch structure

Most of common RF MEMS switch can handle only a few mW with high reliability and has been reported ~10 W handling power from researchers. The reasons are that usually narrow conductors are used, fabrication difficulty for handling high power affordable design, wire bonding has to be avoided during packaging, actuation methods may need to be re-considered shown at Fig. 6.

1.6. Technological challenges in high power RF MEMS switches

RF MEMS switch technology has been researched for the past two decades and exhibit low loss, high linearity and low power consumption compared with conventional solid state switch. However, the largest bottleneck for high power application is its limited power handling capability. Many of switches are sensitive to temperature. More fundamentally, as a lossy substrate at radio frequency, silicon switches generate a significant amount of heat, and its distribution is not uniform and it can cause mechanical design distortion. Eventually it causes structural failure and degradation at high power.

Manufacturing of traditional silicon MEMS is planar thin film processes, gap between signal lines and moving components is typically narrow. One of the power handling limitations come from this narrow gap and across voltage the device, and as a result self-actuation at high power level. Other limitation of using RF MEMS switch as high power application is 'stiction' which is movable element is stick to signal line in the down state position. It is usually occurred electrostatic force due to across voltage in device is stronger than movable part release force. Contact resistance between movable part and signal line is also one of the keys limiting handling power capability and RF performance. If contact resistance is too large, it becomes heat source and destroy switch.

1.7. Structure of this dissertation

Chapter 2 presents a laminate technology in MEMS technology. MEMS technology has been proved providing excellent performance in RF, and laminate technology also has been developed to approach MEMS area. In this chapter how laminate technology can be adapted to MEMS.

Design parameters of high power RF laminate MEMS switch and how these parameters are co-related, mechanically (switching speed, power handling capability) and RF performance, is introduced in Chapter 3. This switch has 3D structure and movable part is in it. In hence when design parameter is changed, mechanical performance is changed and RF performance is also changed. Chapter 4 shows each switch part and assembly and Chapter 5 shows the switch measurement result in low power and high power. Chapter 6 shows which part will fail at harsh condition.

Section II – High power RF Laminate MEMS Switch

This section contains a high power RF LMEMS switch.

CHAPTER 2: Laminate technology

2.1. Introduction

Silicon based Microelectromechanical systems (MEMS) technology has produced radio-frequency (RF) micro switches for the past two decades and exhibit low loss, high linearity and low power consumption compared with conventional solid state switch [1]. However, its power handling capability beyond 10 watts has always been a challenge [11][12]. Many of switches are sensitive to temperature. More fundamentally, as a lossy substrate at radio frequency, silicon switches generate a significant amount of heat, and its distribution is not uniform and it can cause mechanical design distortion. Eventually it causes structural failure and degradation at high power [13][14][15][16][17].

The gap between membrane and signal line is narrow because of planar thin film processes and it has high chance to have self-actuation at switch OFF state. The signal conductor line thickness is also very thin (a few micron). Therefore it is hard to carry high current in typical high power application. The silicon substrate is lossy material and has low thermal conductivity. This material characteristic is not favor to in high power application. The common switch actuation method is electrostatic actuation. It is hard to generate strong force and requires high operation voltage (> 20 V) which is huge compare to voltage level (5 V) in industry. When the actuation force is not enough strong, it can have 'stiction' problem which is movable element is stick to signal line in the down state position. It is usually occurred across voltage in device is higher than movable part release voltage [1]. These addressed problems need to be solved for high power applications and laminate technology can be good approach to solve them.

2.2. Laminate Technology

In current time PCB industries have developed highly sophisticated tooling needed to do high precision manufacturing. They have developed micron size manufacturing and this ability can make possible for building MEMS devices. Resonance Lab in University of California, Irvine has been developed this Laminate technology manufacturing methods for MEMS devices [18][19][20][21][22]. This approach has various advantages, large material selection, various substrate type, easy integration even though between very different materials, easy packaging.

2.3. Proposed Laminate MEMS technology for high power application and its challenge in meeting high power RF application

Power handling capability is important in this switch. Wide and thick conductor is needed to carry high current, and good thermal conductivity and low loss tangent in substrate is also desire. Silicon has been used in RF MEMS applications in many years. However silicon is lossy material and the generated loss becomes heat source. Microstrip line is well known as good for high power (about 100 W to 200 W) applications [23].

The limitation of power handling comes from conductor and dielectric loss of device. When high power comes to microstrip line, conductor and dielectric loss become heat source and increase temperature of devise, and it can cause break down of devise. Conductor loss is dominant loss in silicon substrate and the loss can effect to device performance depends on conductivity of silicon. If the conductivity is higher than 0.015 S/m, the loss itself without considering device design is higher than device using FR-4 substrate. On the other hands dielectric loss is dominant in FR-4 substrate device at high frequency or higher conductor loss than dielectric loss when device is small or at low frequency in low loss tangent substrate such as RO4350. Dielectric loss is dominant at high frequency in PCB Fig. 8. shows loss comparison silicon substrate with varies having conductivity, FR-4 substrate and RO4350 substrate. The design is microstrip line simulated by HFSS [24]. All consductor width is 1.651 mm and substrate height is 1.65 mm (silicon), 0.82 mm (FR-4), 0.742 mm (RO4350) to match with 50 Ω. By using PCB substrate, FR-4, RO4350, relatively thin substrate with wide conductor can be achieved for transmission line circuit. Additionally laminate technology has more advantage for choosing varies materials and building complex 3D structure which is strong advantage to against high temperature and high power RF switch.

The proposed basic structure of high power RF (Radio Frequency) laminate microswitch is shown at Fig. 7. It is consisted with PCB (FR-4), signal line layer (FR-4), spacer (FR-4), spring (Polyimide) with magnet and top coil layer (FR-4) and these are glued together using conductive epoxy.

As frequency and incident power are higher, skin depth decrease, then it causes increasing the current density inside of conductor and dielectric loss is also getting higher. In hence the temperature in device is also increasing and device can be damaged by it; magnet can be de-magnetized, conductive epoxy holding signal line layer can be melt, spacer and top coil layer, polyimide spring and PCB can be damaged.

These materials temperature limitation can be power handling limitation of the microswitch. Knowing increasing temperature depends on incident power and operating frequency is important to avoid device failure. Fig. 9. is done by ANSYS workbench simulation at steady state temperature condition linked with ANSYS HFSS to convert device temperature profile from HFSS loss information. The ANSYS workbench simulation has been calibrated with using IR camera, FLIR A300. The ambient temperature was set to 25 ºC at simulation condition. The microstrip line conductor width is 1.643 mm and 0.1778 mm height of RF signal layer is on the PCB, FR-4 and RO4350. In this simulation FR-4 has 4.4 dielectric constant and 0.02 loss tangent, and Ro4350 has 3.66 dielectric constant and 0.004 loss tangent.

The de-magnetized temperature is 275 ºC, and recommended maximum operating temperature of FR-4 and RO4350 are 125 ºC and 150 ºC and device showed failure at around this temperature. The melting temperature of polyimide and conductive epoxy is 232 ºC and 250 ºC. Device better not exceed this temperature without considering other device failure mechanism.

The simulation result showed that if FR-4 has been used for PCB, the expected capable handling power is 14 W at 4 GHz. On this other hands when RO4350 which has lower tangent loss, dielectric constant and higher thermal conductivity has been used, the handling power at 4 GHz is higher than 50 W, Fig. 9. In this simulation FR-4 maximum operating temperature limits power handling of device in temperature point of view. However the maximum operating temperature is at steady state condition, so if the device exposed to higher then the temperature for short time, it doesn't be a failure reason.

If microstrip line width is mm size and high frequency, dielectric loss is dominant. RO4350 has lower loss tangent than FR-4, so the temperature rising is much less than FR-4 at high power. Moreover it has lower dielectric constant than FR-4, the substrate thinner and thermal conductivity of RO4350 (0.69W/m/°K) is higher than FR-4 (0.294W/m/°K). If RO4350 is used for PCB, the expected usage range of device is at up to 50 W at 10 GHz.

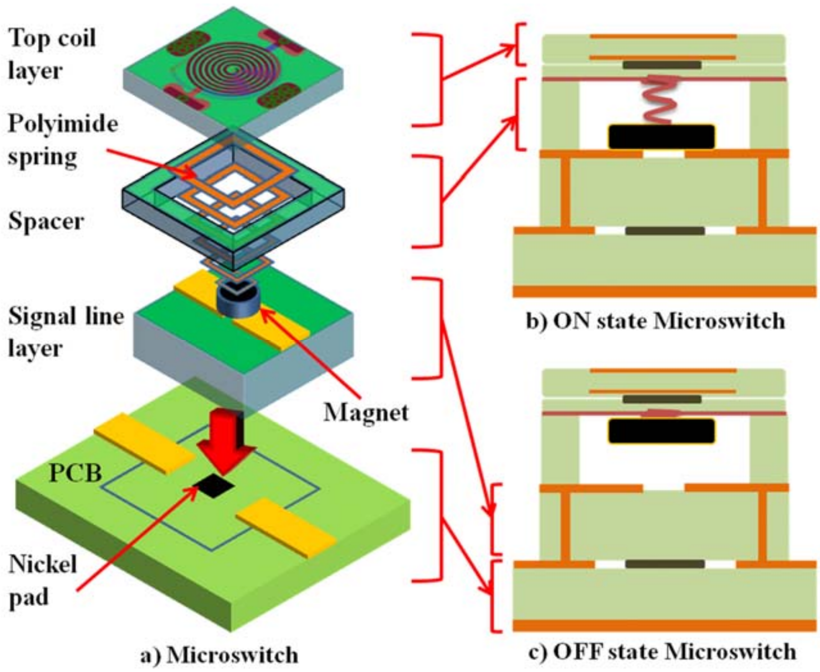
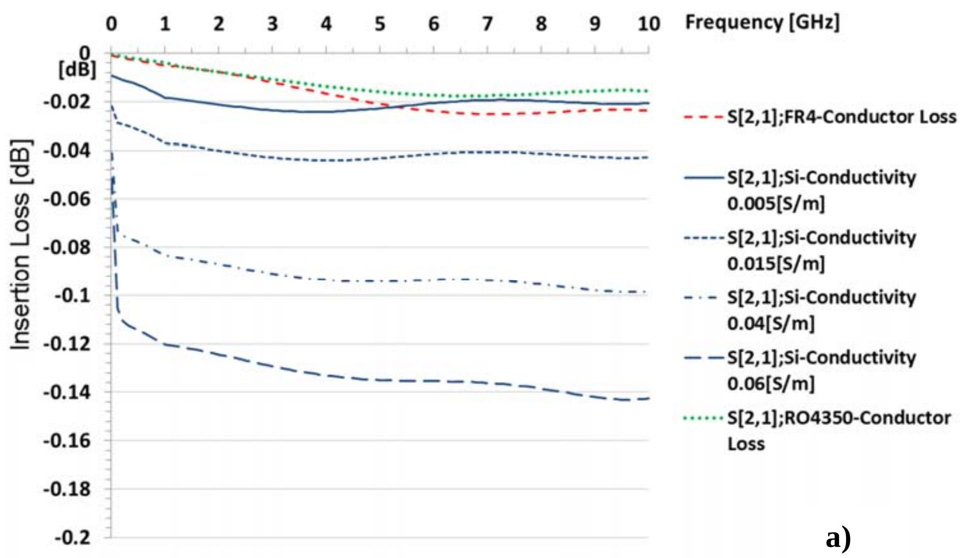


Fig. 7 a) Overview of direct contact high power RF microswitch, b) Side view of 'ON' state laminate microswitch, c) Side view of 'OFF' state laminate microswitch



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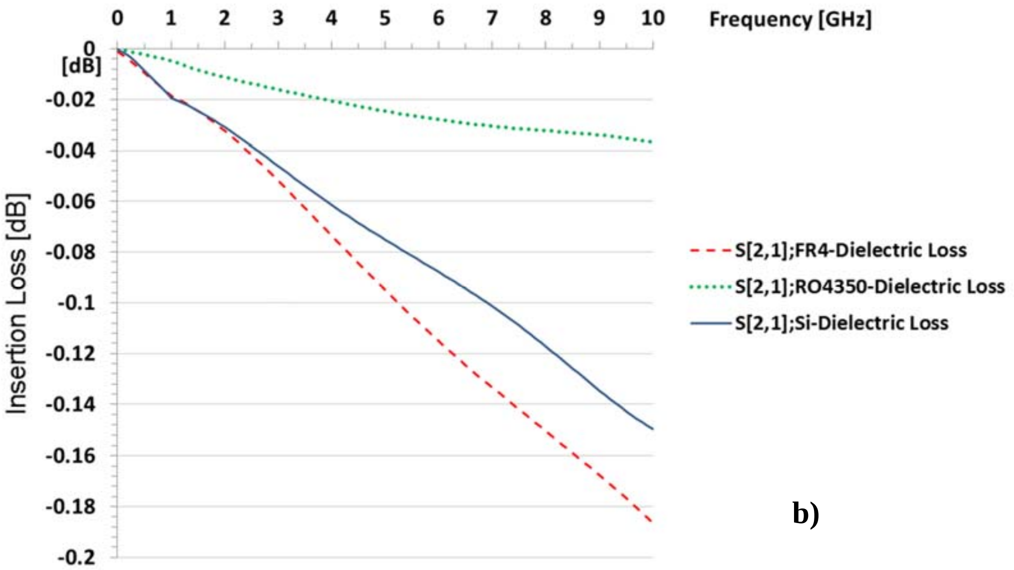


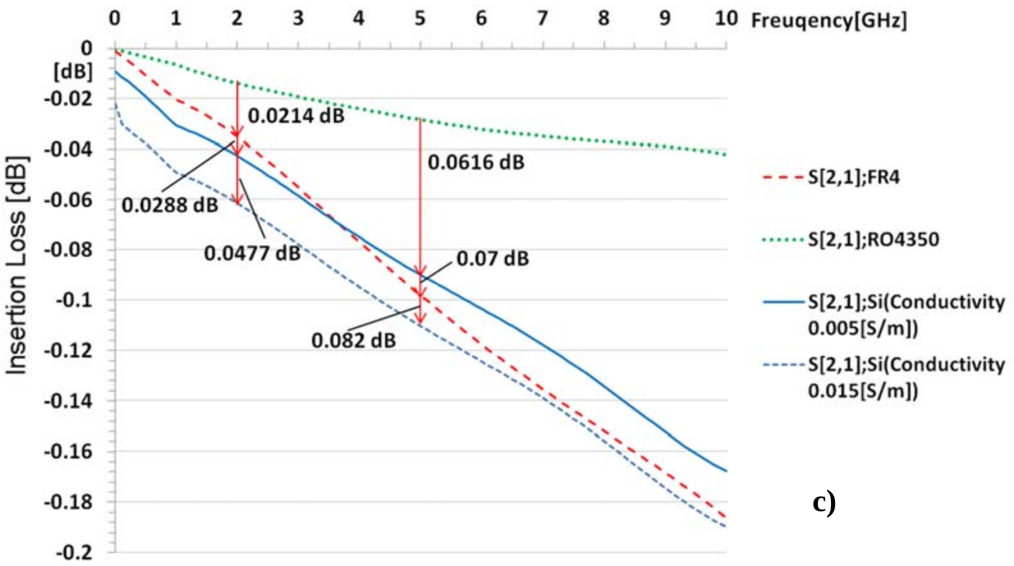


Fig. 8 a) Microstrip line conductor loss HFSS simulation, b) Microstrip line dielectric loss HFSS simulation, c) Microstrip line loss HFSS simulation, FR-4, RO4350 and Silicon substrates

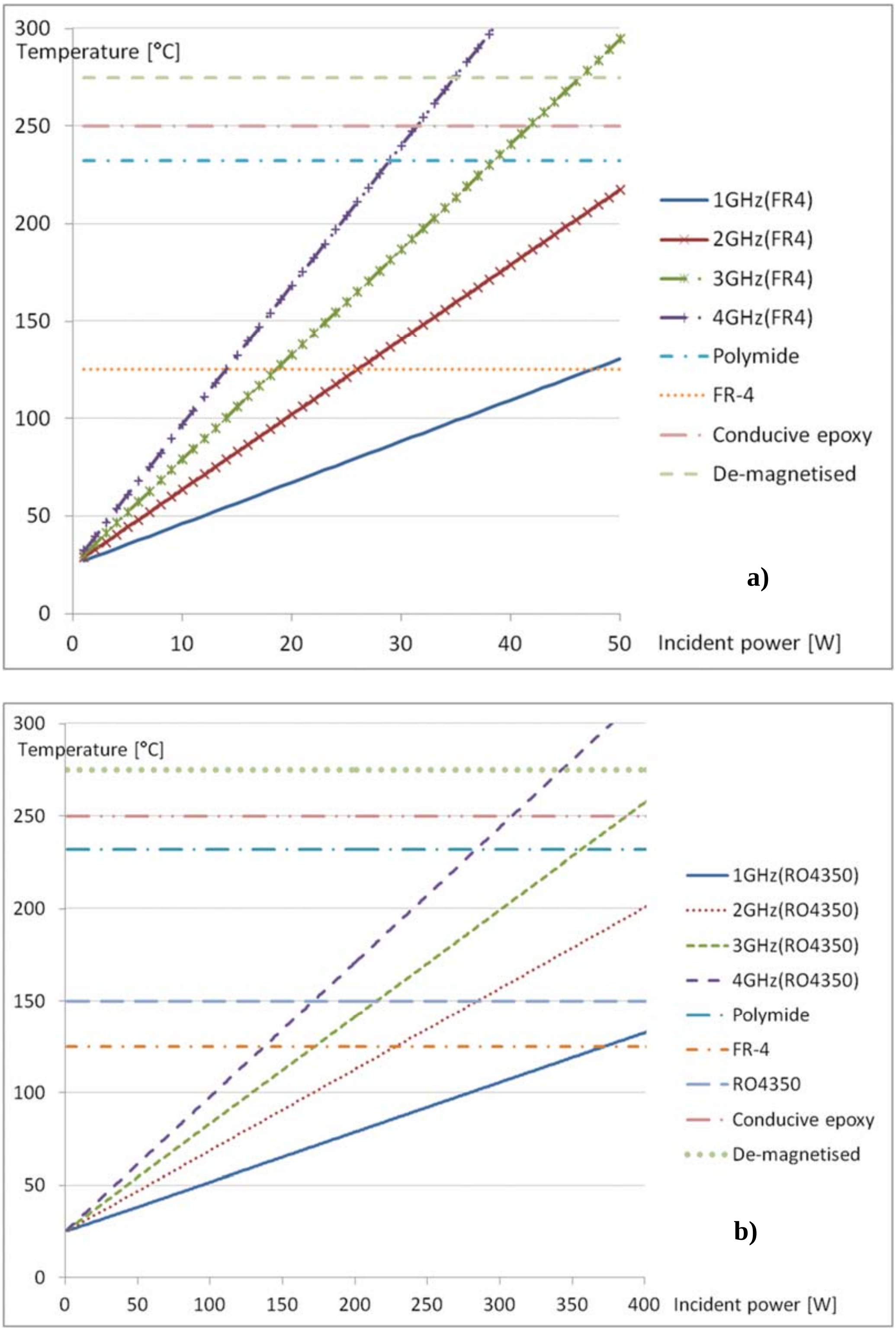


Fig. 9 Changed temperature ANSYS simulation with incident power at various frequencies in microstrip line, a) FR-4 substrate, b) RO4350 substrate

CHAPTER 3: High power RF Laminate Microswitch; Design

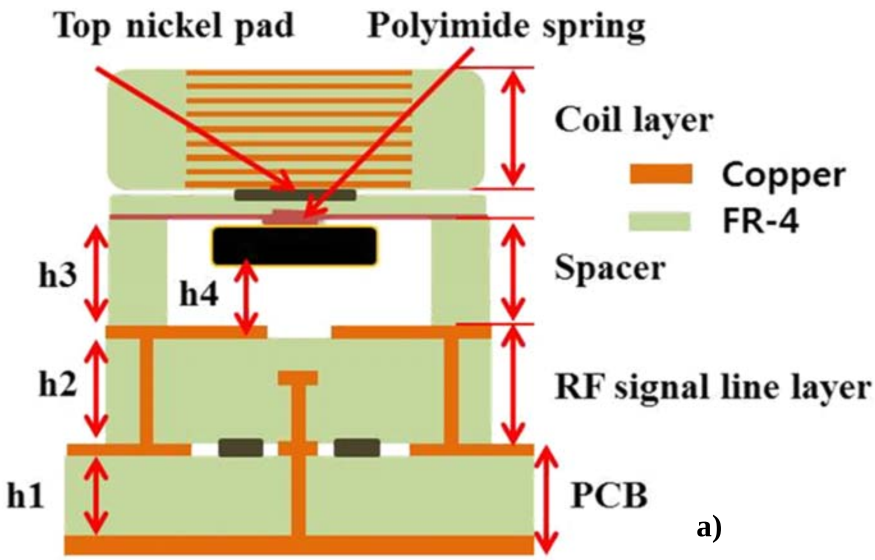
3.1. Design Parameters

The high power RF LMEMS switch design is shown at Fig. 10. It is consisted with PCB, signal line layer glued nickel pad under the layer, spacer for securing large actuation stroke area, a polyimide spring attached with permanence magnet and multi-layer coil to generate strong electromagnetic actuation force. Signal lines are connected to PCB through via holes. Magnet controls switch 'ON' and 'OFF' state by placing and connecting signal lines. The magnet is actuated by EM force generated by top coil layer. This switch is RF and high power switch so all of design consideration should be considered with both perspective sides, mechanical, RF performance and switching. Wide conductor, having good thermal conductivity and low loss substrate, enough spacer height to avoid self actuation at high power condition, multilayer coil to generate enough strong electromagnetic force to move magnet up and down position (switch 'OFF' and 'ON' state) are desired for high power RF switch. This switch is 3D structure and many parts are correlated for functionally working as RF performance, switching and handling high power at the same time. In this reason there are many design consideration, contact resistance between magnet and signal line, spacer height which relates isolation, dynamic speed (ON state to OFF state, OFF state to ON state), pull-in voltage at off-state, generated electromagnetic force to overcome against the force with holding voltage at on-state, multilayer coil and gap distance at signal line.

Fig. 10, c) is top view of RF signal layer. 'w' is related with carrying current ability, insertion loss, isolation and pull-in voltage at OFF state because the capacitance at OFF state changes with 'w'. 's' is related with contact resistance with magnet, isolation and insertion loss of switch, pull-in voltage at OFF state and holding down force at ON state since the capacitance is changed depends on ‘s’, separation, if magnet diameter is fixed.

Fig. 10 a) and b) is side view of high power RF LMEMS microswitch design. The switch get incoming signal from PCB, so ‘h1’ is decided to have 50 Ω microstrip line at PCB. ‘h2’ is related with RF performance and ON state latching force between magnet and bottom nickel pad. ‘h3’ is related with required de-latching force at ON to OFF and OFF to ON, isolation of switch. In these reasons design parameters are correlated.

This LMEMS switch acts as RF switch after the assembled component (Coil layer + Spacer + RF signal layer) on the PCB. The ‘h1’ at PCB is not fixed as certain height and the microstrip line width is also varies with ‘h1’. The GND of ‘RF signal line layer’ is the PCB GND and substrate height of ‘RF signal line layer’ is ‘h1’+’h2’. In this reason the ‘RF signal line layer’ is highly dependent to PCB and its RF characteristic changes with ‘h1’.



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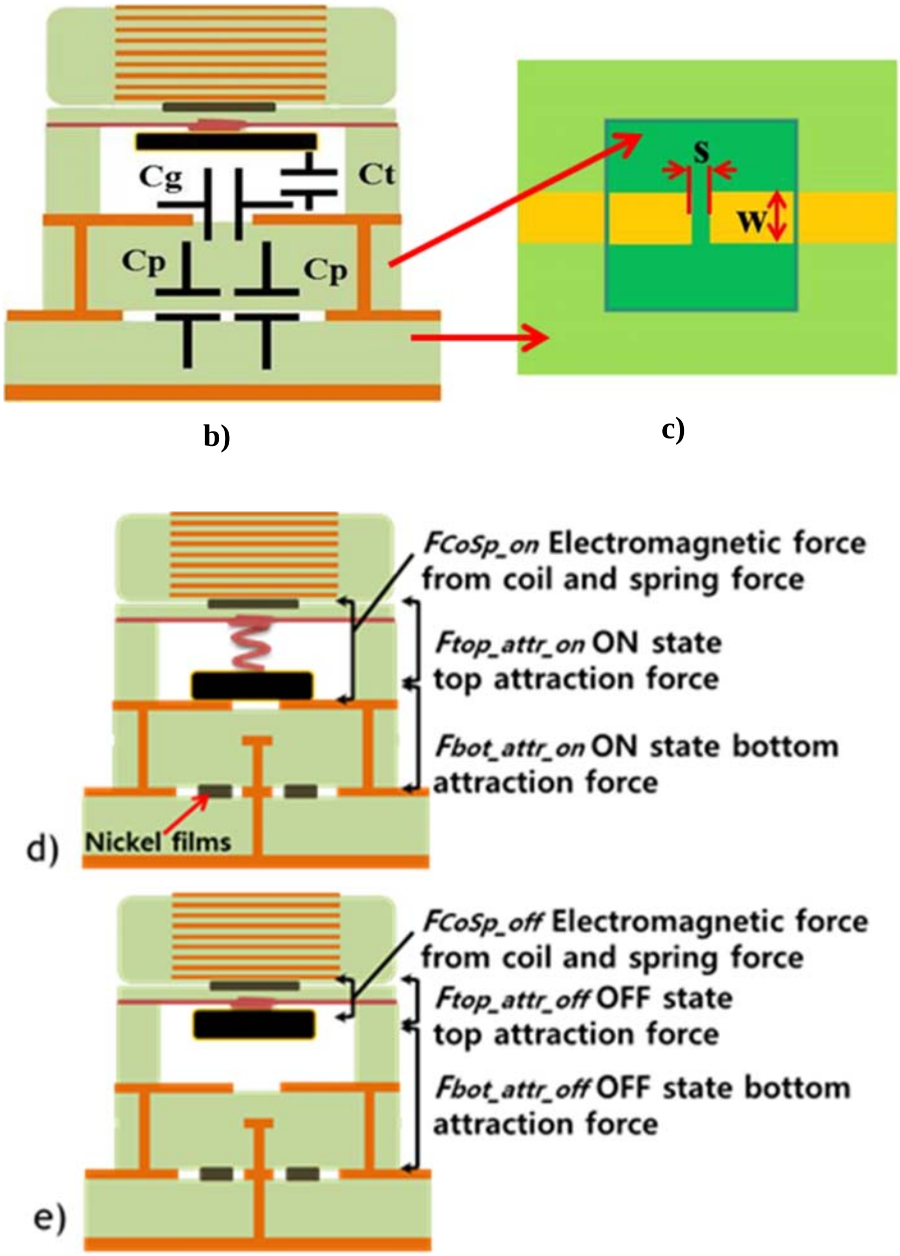


Fig. 10 Microswitch design parameters a) Switch 'open' state side view, b) Parasitic capacitors at end of signal lines in direct contact LMEMS switch(GND line is omitted to describe parasitic capacitors), c) Top view of RF signal line layer on PCB, d) and e) a cross sectional view of the RF switch at ON and OFF state respectively

3.2. Carrying current capability in conductor line; Top coil, Signal line

The top coil is total 6 layers and 5 V, 900 mA current guided to coil to generate EM force. The each layer of coil has 6 turns and 0.1016 mm conductor width. The generated force was measured with varies distance from coil [26]. The 0.1016 mm copper width is narrow for 900 mA at steady state time condition, but only short period pulse signal is needed to actuate the switch since this switch type is latched type switch which doesn't need any power source at latched state, 'ON' or 'OFF'. If carrying current time is 0.5 s, the fusing current of 0.1016 mm width and 1 oz thickness copper is 1.465 A [27].

One of the limitations for handling high RF power in this switch is electromagnetic force from coil has to be stronger than holding force. High current needs to be guided to the top coil to get stronger force from coil. The conductor width of coil is 0.1016 mm and it is narrow for carrying high current. However this switch is latched type switch using permanent magnet and top and bottom nickel pads to hold magnet up ('OFF' state) and down ('ON' state). When switch is ON or OFF state, it doesn't need control signal. It means if coil can handle high current only for a few seconds, switching dynamic time, conductor width can be narrow. Eq (1) [27] is known as fusing current and calculated graph is shown at Fig. 11. I is fusing current, A is conductor area ([mil^2]) and t is second (time). The assumption of this calculation is the conductor thickness is 1 oz and a straight line on FR-4.

$$I = \frac{0.188 \times A}{t^{0.5}} \qquad (1)$$

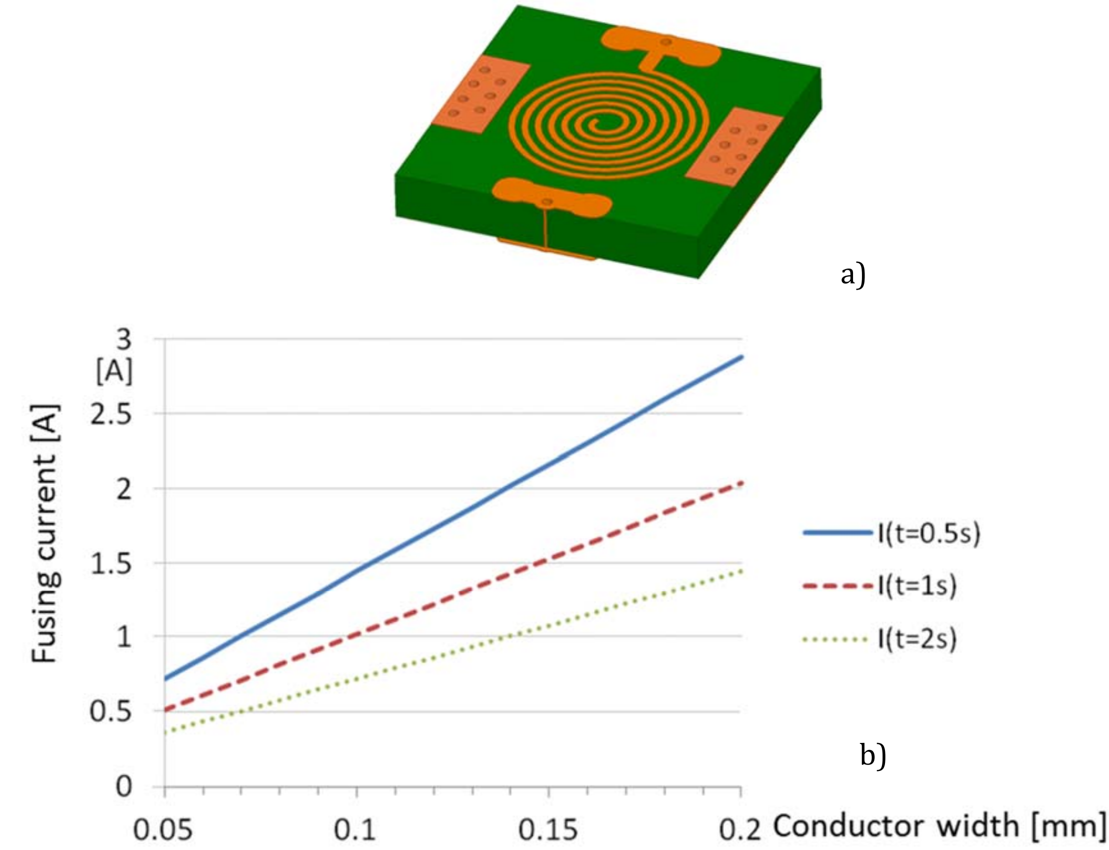


Fig. 11 a) Top coil, b) Fusing current in conductor line

Carrying high current ability is important in high power device. Large conductor area can carry high current and wide conductor is more important than conductor thickness since this switch works at high frequency. Fig. 12 is shown calculated recommended conductor width depends on current and frequency using Eq. (2). The calculation was done based on IPC (Interconnecting and Packaging Electronic Circuits)-D-27, Design Standard for Flexible Single-and Double-Sided Printed Boards [28]. I is recommended maximum carrying current, ΔT is temperature increasing and A is conductor area ([mil^2]).

$$I = 0.065 \times \Delta T^{0.43} \times A^{0.68} \quad (2)$$

This calculated recommended conductor width for current carrying ability is at steady state and FR-4 condition and this calculated number varies depends on temperature increasing, ΔT. In this calculation conductor width is better at least 1.5 mm for steady state time condition and 0.6 A with 5 GHz, shown at Fig. 12 a). However, if time is considered as short time, higher current can be carried at same conductor area, Fig. 12 b)

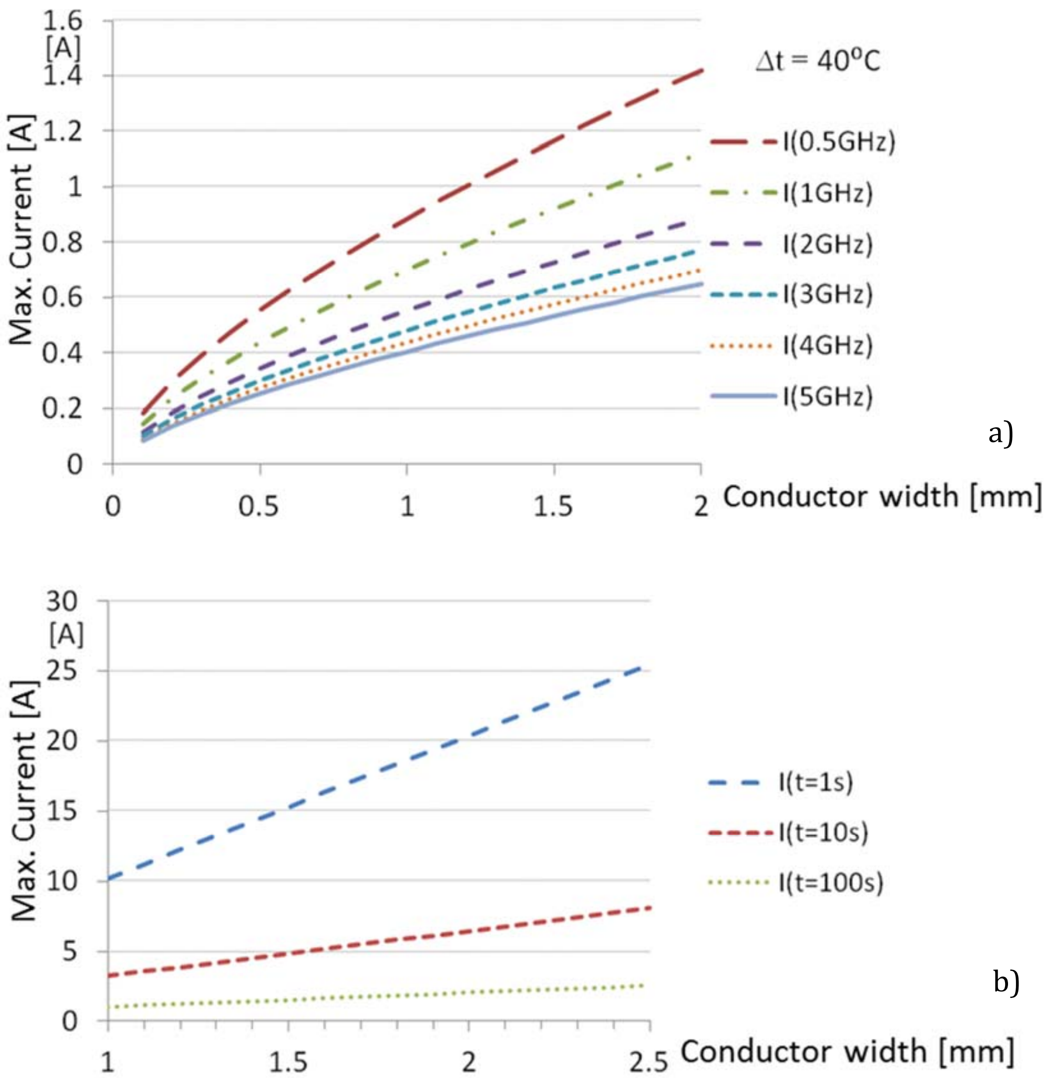


Fig. 12 a) Maximum carrying current at conductor line on PCB, b) Fusing current at conductor line

3.3. Design consideration for RF performance

One of the key design considerations to achieve good RF performance is to minimize parasitic effects in the 3D configuration. Parasitic circuit elements degrading RF performance exist, shown in Fig. 13 a). Magnet, spring and nickel pad under RF signal line layer have been removed in Fig. 10 a) and b) to descript parasitic elements in microswitch in this figure, Fig. 13, a). The open gap at the signal line and the distance between signal line layer and top coil layer are attributed to parasitic capacitors C_g, C_p and C_t. C_g and C_p are determined by the distance between two signal traces and to the ground plane. C_t is capacitor between signal lines and the top coil. This Pi network degrades the isolation of this switch significantly. If S_{12} as calculated in Eq. (3) is small, high isolation can be achieved. Since Z_1 is $1/(jwC_p)$, Z_2 is $1/(jwC_g)$ and Z_0 is 50 ohm, smaller C_g and larger C_p is preferred for higher isolation [23].

C_p can be adjustable by changing the substrate height, *h2*. *h1* is fixed for 50 ohm incident signal lines. If *h2* is small, the isolation of the switch is improved, but it requires strong EM force from top coil to de-latch magnet at the switch 'ON' to 'OFF' state. To have both proper de-latching force and high isolation we have introduced an additional thin ground line inside of RF signal layer to guide fringing capacitor to bottom ground plane, as depicted in Fig. 10 a). Simulation results performed by HFSS indicated that the isolation without narrow ground line is -20 dB at 4.14 GHz, and is improved to –20 dB at 6.88 GHz with the line. The insertion losses of the signal line layer without and with ground line is -0.3 dB at 5.3 GHz and at 8.4 GHz respectively. The insertion loss at 10 GHz is -0.92 dB and -0.39 dB for without and with ground line respectively. The ground line reduced fringing capacitor significantly and thus improved RF performance, and moreover it made the switch design less dependent on PCB.

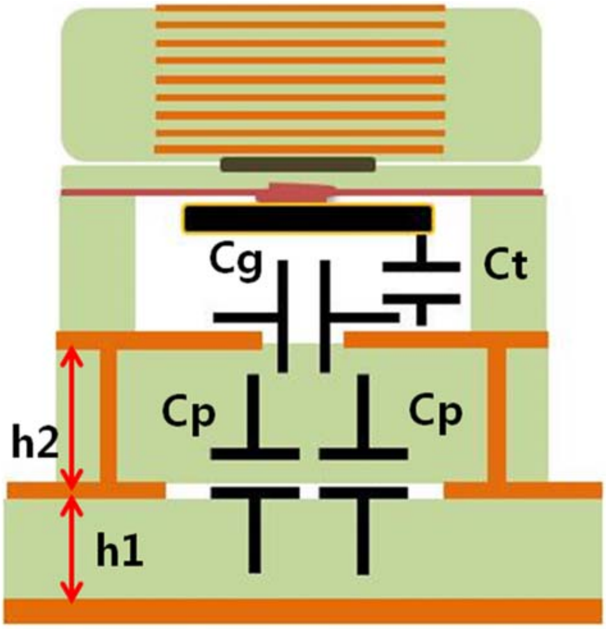
$$\boldsymbol{S12} = \frac{2Z_{12}Z_0}{\Delta Z} \tag{3}$$

$$\boldsymbol{Z_{12}} = \boldsymbol{Z_{21}} = \frac{C_g}{jwC_p(2C_g+C_p)}, \boldsymbol{Z_{11}} = \boldsymbol{Z_{22}} = \frac{C_p+C_g}{jwC_p(2C_g+C_p)} \tag{4}$$

$$\Delta \mathbf{Z} = (\boldsymbol{Z_{11}} + \boldsymbol{Z_0})(\boldsymbol{Z_{22}} + \boldsymbol{Z_0}) - \boldsymbol{Z_{12}}\boldsymbol{Z_{21}} \tag{5}$$

Isolation of the switch is also influenced by spacer height, h3, shown in Fig. 10 a) and b), in the switch. Since the diameter of the magnet is large enough to cover almost all the signal line area, a parasitic plate capacitor between the signal line and top 'OFF' state magnet contributes to C_t, in Fig. 13 a). The spacer height was carefully designed for a trade-off between having proper actuation force without hot switching at high input power and achieving good isolation.

Other advantage of using this GND line is making the device as less dependent on PCB substrate height. In this paper the 1.643 mm conductor width, 1.016 mm (FR-4) and 0.762 mm (RO4350) substrate height has been used for simulation and measurement. However the microstrip line width and substrate height can be changed depends on applications. If there is no GND line at signal layer, the signal line layer use GND plane of PCB, in hence the substrate height becomes to h1 + h2 at signal line layer. However if there is GND line in the layer, it minimize the substrate height changing effects.



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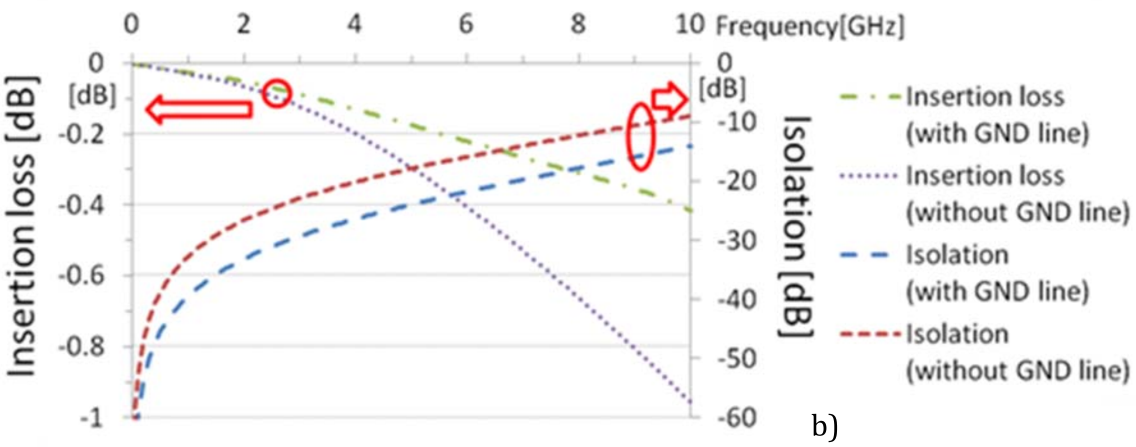


b)

Fig. 13 a) Parasitic capacitors at end of signal lines in direct contact LMEMS switch, b) HFSS simulation result in GND line (with GND line vs. without GND line)

3.4. Contact resistance between magnet and signal line

This high power RF LMEMS switch is direct contact type switch and contact resistance exists at ‘ON’ state. This existing resistance increase signal loss and becomes heat source. It can degrade contact surface and cause high contact resistance (>20 Ω) when the microswitch is failed. The contact resistance was measured at cold switching case during 0.5 million times 'ON' and 'OFF' switching cycling. The used current was 120 mA and the on state contact resistance showed 0.3 ~ 0.8 Ω over during 0.5 million times cycling. The resistance showed starting 0.3 Ω at the beginning. However the contact surface has been damaged little by little during switching cycling, and it increased the contact resistance [26].

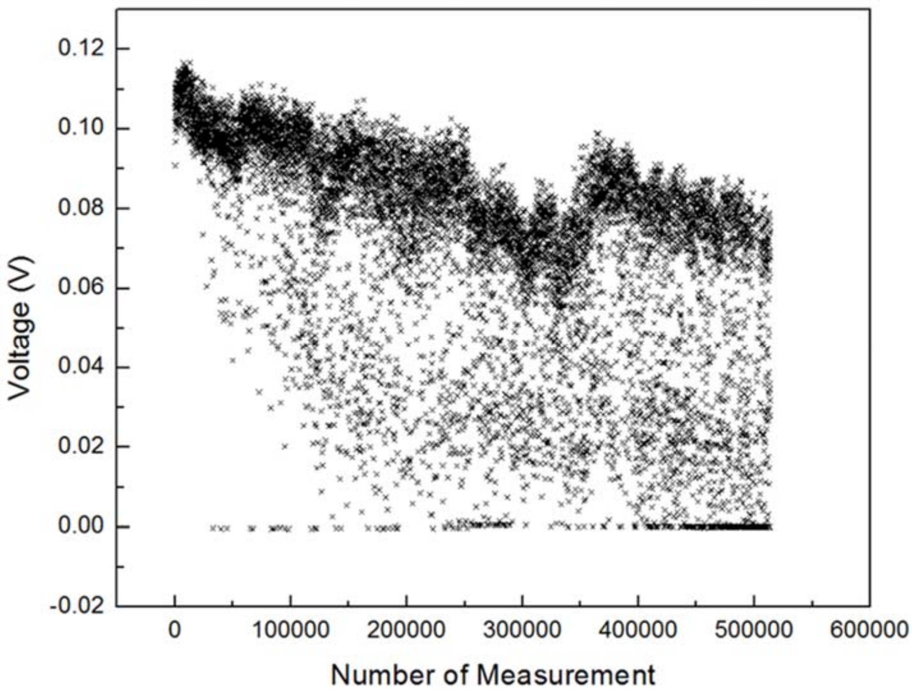
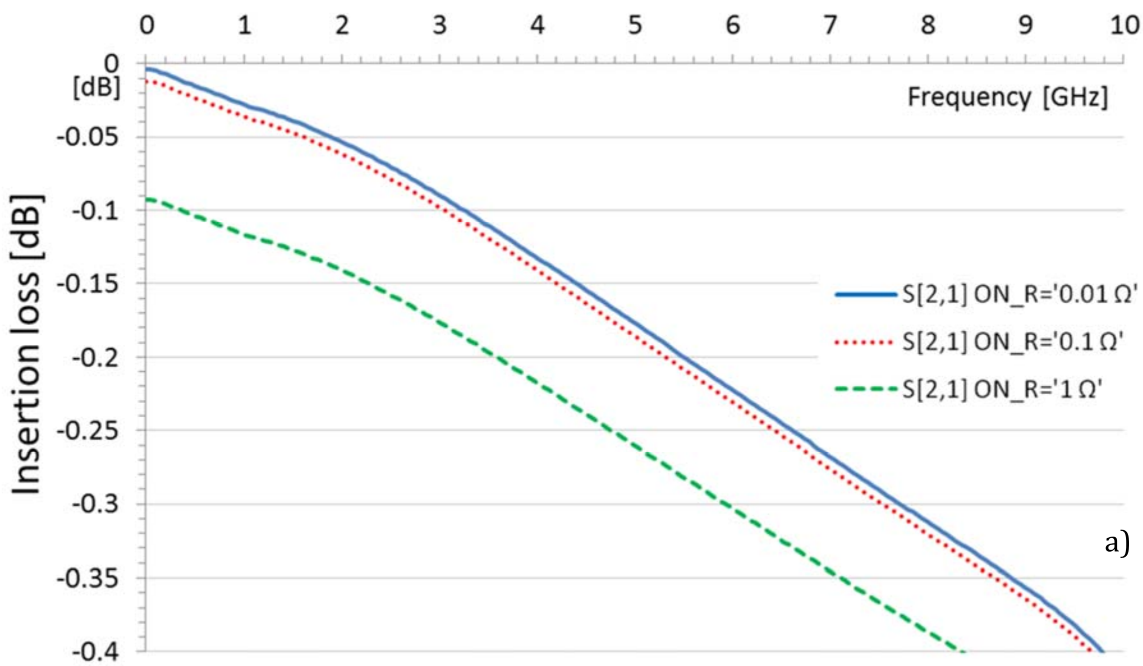
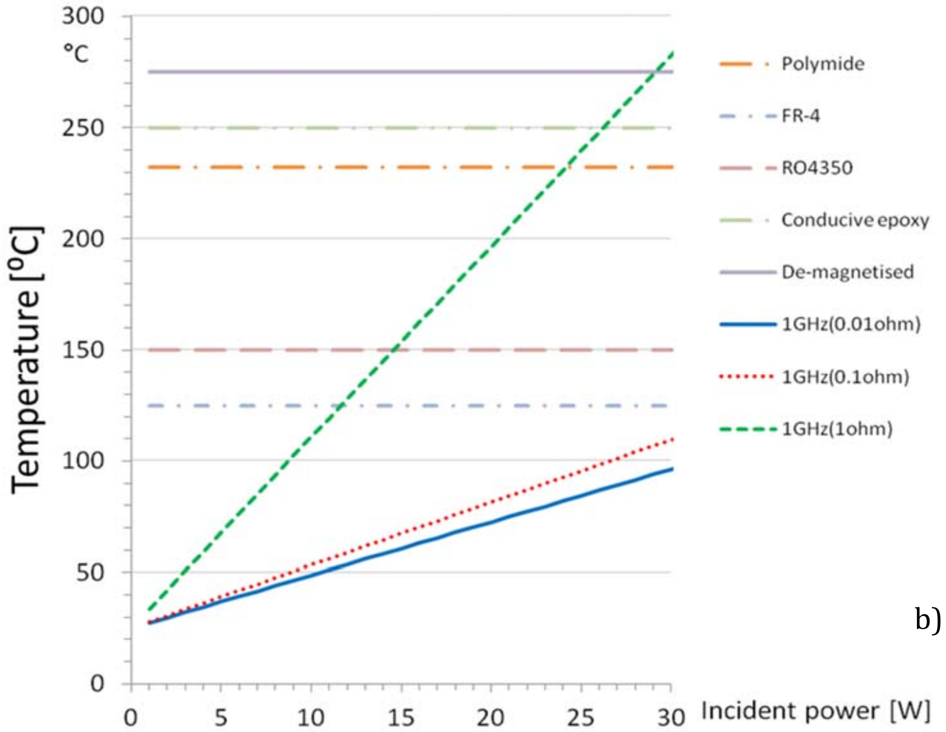


Fig. 14 Contact resistance between magnet and signal line during switching [26]

The contact resistance is one of the major main signal loss reasons, and this loss generates heating in device, then it limits handling power in device. , shown at Fig. 15 and Fig. 16. The simulated model is shown at Fig. 10 a). Fig. 15 a) is simulated loss in the case of using FR-4 as PCB and Fig. 16 a) is the loss when substrate is RO4350. Fig. 15 a) and Fig. 16 a) are done by HFSS simulation with Fig. 10 a). Fig. 15 b), c) and Fig. 16 b), c) are shown converted temperature at 1 GHz and 5 GHz from loss and done by ANSYS workbench. When RO4350 is used for PCB, the switch showed lower loss and lower temperature rising at given frequency due to lower tangent loss, higher thermal conductivity and able to be thinner than FR-4. In this simulation showed this RF high power LMEMS switch can handle 7 ~ 11 W with FR-4 at PCB and 14.5 ~ 46 W with RO4350 at PCB at 5 GHz assuming contact resistance is between 0.01 Ω to 1 Ω. The lowest limitation because of temperate comes from FR-4 (125 °C) and RO4350 (150 °C) and these limits power handling capability. These temperatures are recommended maximum operating temperature, and it doesn't mean the device will be broken at this temperature. Additionally the switch 'ON' state duration time is short (> 2s), so the microswitch can work at higher temperature than 125 °C (FR-4) and 150 °C (RO4350).



a)



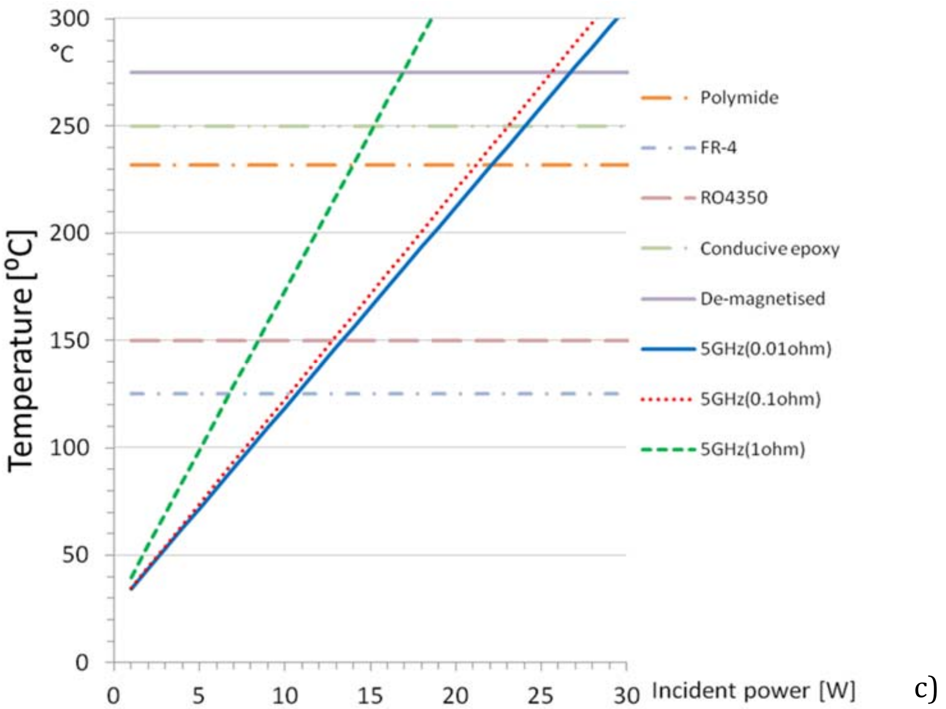
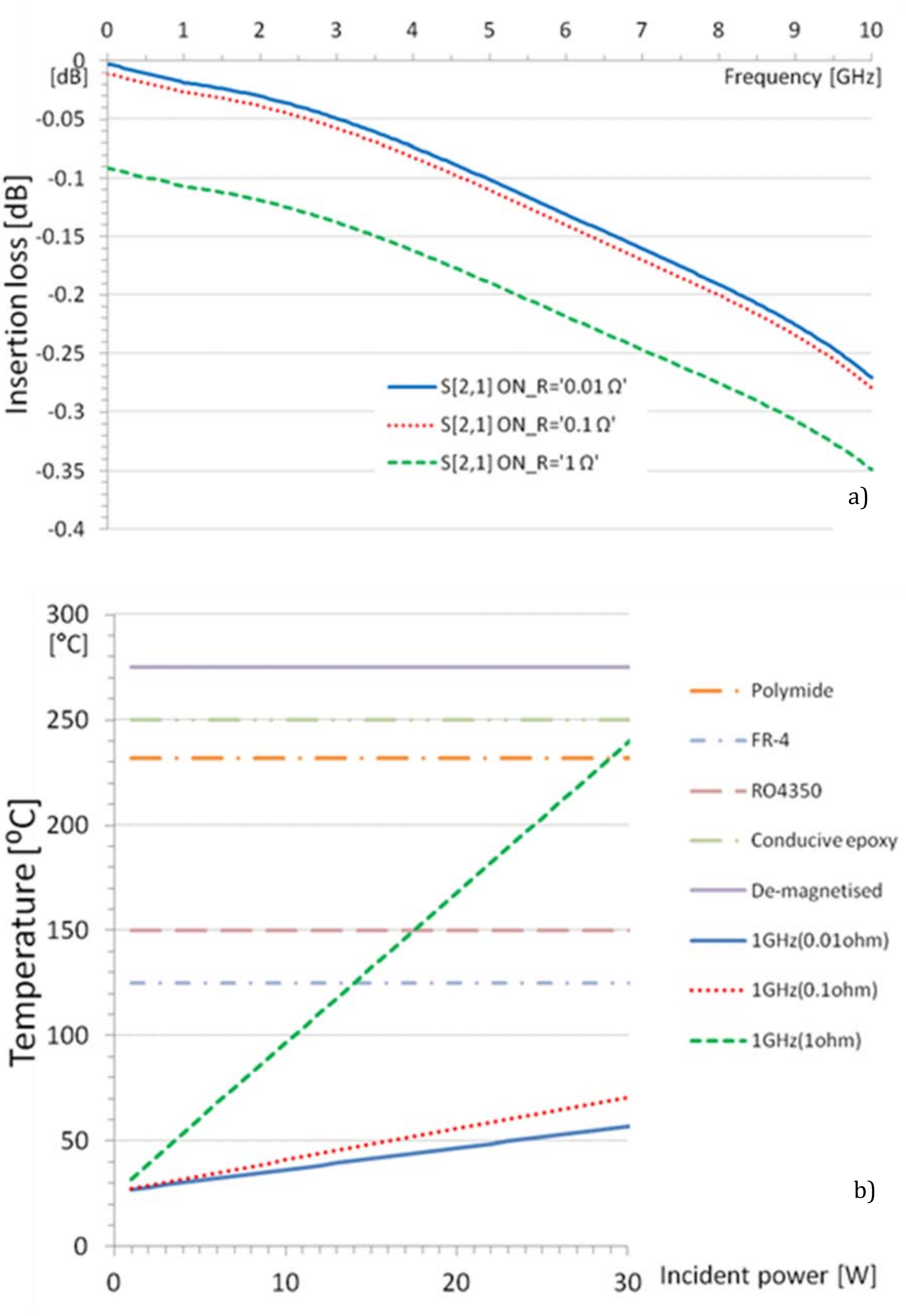


Fig. 15 a) Simulated insertion loss changes due to contact resistance with FR-4 substrate, b) Temperature changes on RF LMEMS switch due to contact resistance at 1 GHz and c) 5 GHz



Insertion loss [dB]
Frequency [GHz]
[dB]
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
0 1 2 3 4 5 6 7 8 9 10
S[2,1] ON_R='0.01 Ω'
S[2,1] ON_R='0.1 Ω'
S[2,1] ON_R='1 Ω'
a)
Temperature [ºC]
[°C]
300
250
200
150
100
50
0
0 10 20 30
Incident power [W]
Polymide
FR-4
RO4350
Conducive epoxy
De-magnetised
1GHz(0.01ohm)
1GHz(0.1ohm)
1GHz(1ohm)
b)

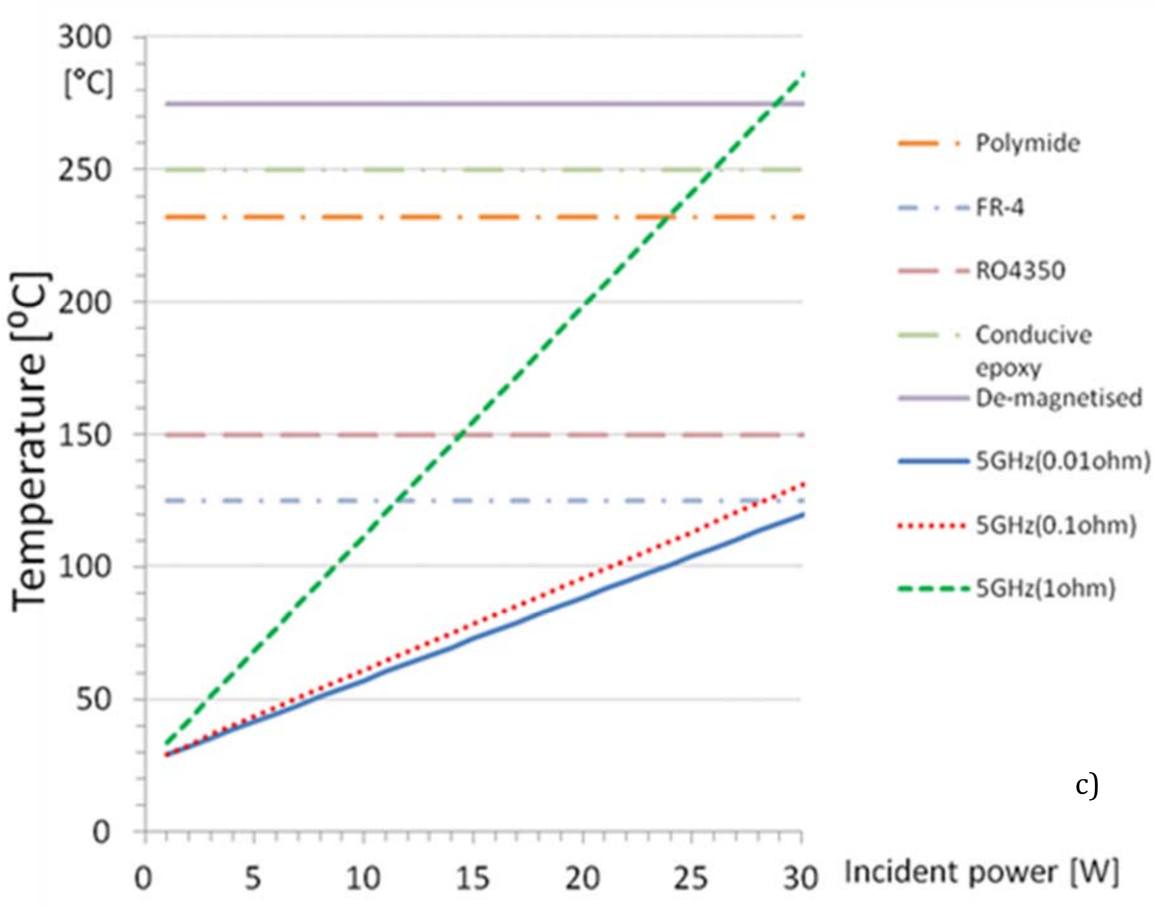
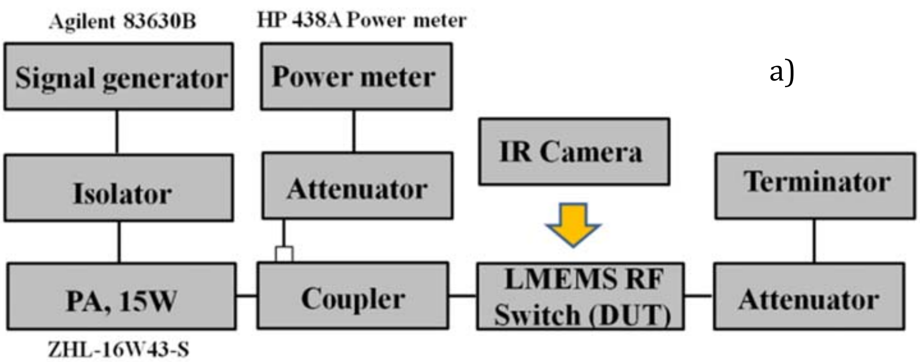
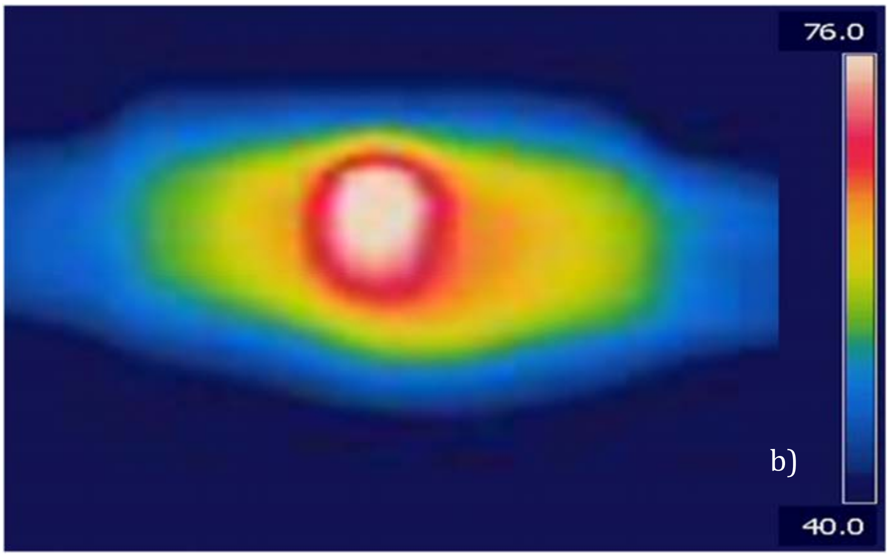


Fig. 16 a) Simulated insertion loss changes due to contact resistance with RO4350 substrate, b) Temperature changes on RF LMEMS switch due to contact resistance at 1 GHz and c) 5 GHz

Fig. 17 a) shows temperature observation setup. FLIR A300, infrared camera, was used to determine temperature profile. The bare copper emissivity is very low, 0.10, so a matte black paint to have high emissivity was coated to metal part of switch. The purpose of this measurement is to know where the peak temperature is with incident high RF power. However fully assembled switch is pre-packaged and top coil layer is covered all over signal line including contact area with movable magnet. This signal line can't be observed at fully assembled state. During the measurement top coil was removed to see signal line and the magnet was placed on the signal to make ON state. The ambient temperature was 22.75°C and the RO4350 has been used for PCB substrate. The peak temperature was observed at contact area between magnet and signal line due to contact resistance, and raising temperature was changed by it. The highest temperature was 76 °C with 0.5 Ω contact resistance and 132 °C with 1 Ω contact resistance, Fig. 17 b). The incident power is 15 W at 1 GHz.



a)



b)

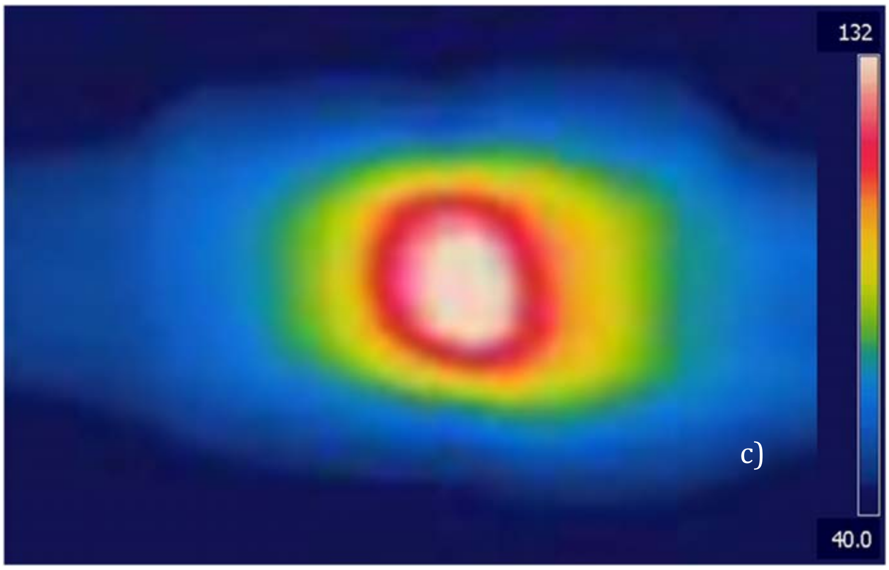


Fig. 17 a) Temperature measurement setup at 2 GHz, 15 W, b) Thermal image with 0.5 Ω and c) 1 Ω contact resistances at 2 GHz, 15 W

3.5. Spacer height; Power handling capability, RF performance

3.5.1. Power handling capability;

Self-actuation at switch OFF state

One of the common problems in MEMS switch at high power application is self actuation, thus large actuation stroke is needed to avoid it. However if the actuation stroke space is too large, electromagnetic force at signal line from top coil is too weak to de-latch 'ON' state magnet. The attraction force between nickel pad under signal line substrate and magnet is strong enough to hold 'ON' state against force from top coil. Moreover parallel plate capacitor exists between top planar coil and signal line since the coil covered large area on the top, and spacer size decides parallel plates distance. This capacitor affects isolation of the switch. If the capacitance is larger, the isolation is getting degraded. Dynamic switching speed is also related with top coil and spacer because of changed EM force from top coil layer and magnet traveling distance, 'ON' to 'OFF' or 'OFF' to 'ON'.

In this prototype switch, the distance, Fig. 10 b), h4, between signal line and magnet are 0.3354 mm and 0.6488 mm. The attraction force between nickel pad under top coil and permanent magnet is 3.1 mN at 'OFF' state, Fig. 10 b). The calculated electrostatic force due to device across voltage, pulling in 'OFF' state magnet to signal line, is μN at 50 W. This force is significantly lower than 'Off state Nickel-Magnet' attraction force (3.1 mN), so self-actuation won't be observed at high power, 50W.

This switch is series switch with small capacitance at OFF state. The voltage across switch is derived at Eq. (6)

$$|V_{sw}| = |V_2 - V_1| = \frac{2|V^+|}{\sqrt{1+4w^2C^2Z_o^2}} \quad (6)$$

In OFF state *C* is very small since the gap distance between signal line and magnet is almost 1 mm, smaller than 60 fF, so *4wcZ* can be negligible. In hence *Vser* is 2V+.

$$F_{e\_p} = \frac{1}{2}\frac{dC_{pp}}{dg}V^2 = -\frac{\varepsilon_o A V^2}{2g_p^2} = -\frac{C_{pp_p}V^2}{2g_p}$$

(7)

$$C_{pp\_p} = \frac{\varepsilon_o A}{g_p}$$

If electro static force from incoming voltage is stronger than $F_{Ni\_Mag\_Up}$, the switch will have unwanted experience, self actuation.

$$\frac{C_{pp\_p} V^2}{8 g_p} > F_{Ni\_Mag\_Up}$$

(8)

The Fig 18 is calculated pull-in force depends on gap distance between signal line and magnet and incident power. The capacitance, C_{pp}, is simulated by ANSYS Q3D. The upper nickel pad and magnet attraction force is strong enough to maintain OFF state from incident power.

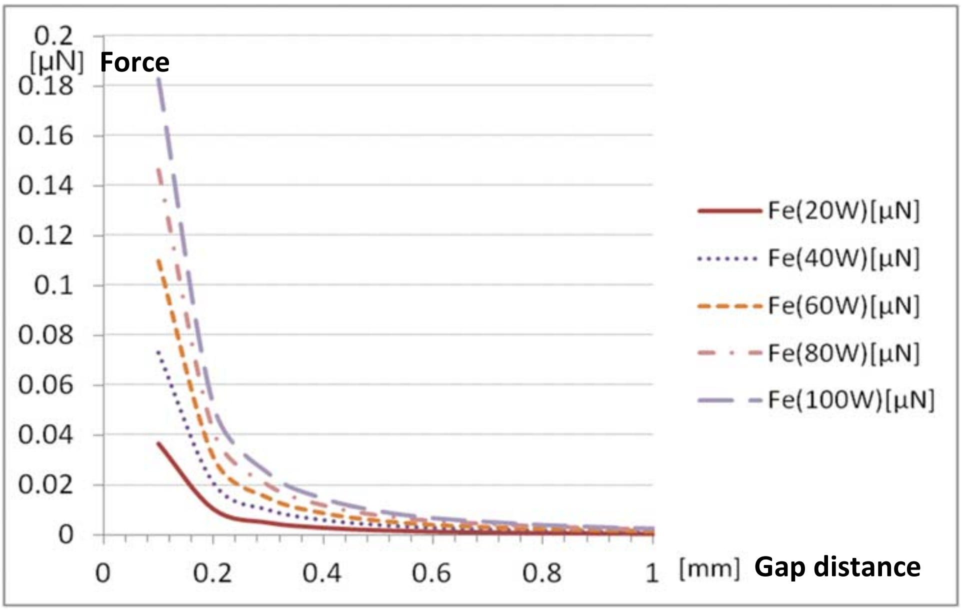


Fig. 18 Pull-in force depends on incident power and gap distance, h4 at Fig. 10 b)

3.5.2. Power handling capability;

Self-actuation when switch is opening

When this switch is ON state to OFF state, there is also attraction force between nickel pad under RF signal layer and ON state magnet. Typically the copper surface roughness of PCB is about 1.6um and the magnet has as well. When the magnet is getting off, holding force with small gap is holding the magnet. The holding fore is stronger as the gap is smaller, stronger incident power and frequency is higher. Stronger electromagnetic force than holding force needs to be generated from top coil. The electromagnetic force at signal line is stranger as the top coil is closer to signal line and with higher current through coil conductor.

The top planar coil is total 6 layers and 5V, 900 mA current guided to coil to generate electromagnetic force. The each layer of planar coil has 6 turns and 0.1016 mm conductor width. The generated force was measured with varies distance from coil which is shown Fig. 19.

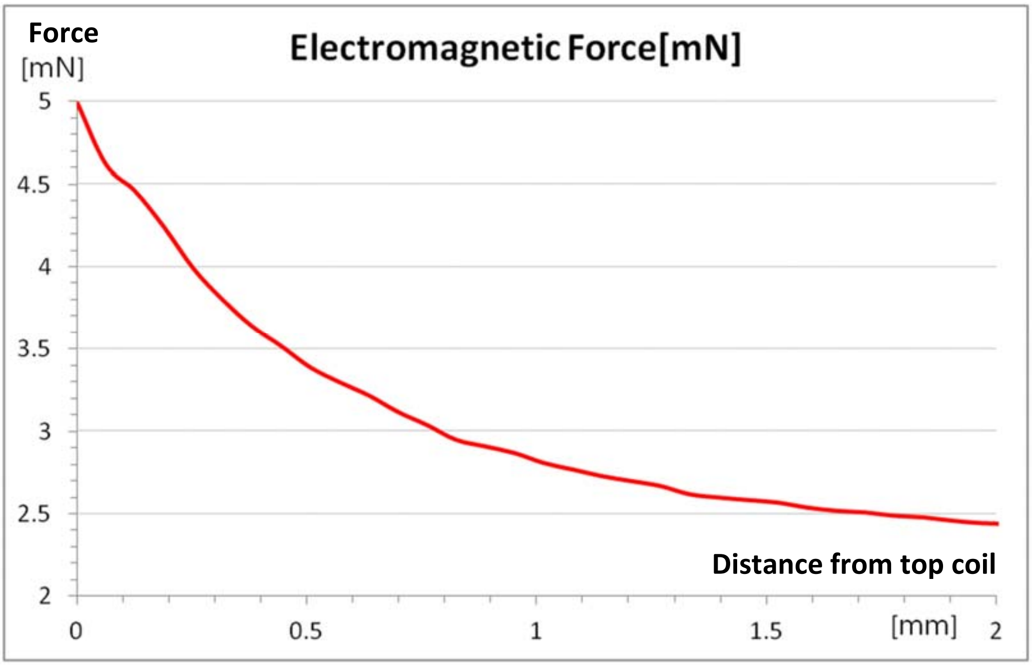


Fig. 19 Electromagnetic force at distance from top coil [26]

If magnet surface roughness is too high, even though it is placed at signal lines to make 'ON' state, actually signal doesn't go through magnet. Fine polished surface on magnet and coating is desired to have low contact resistance. After 1 um polishing contact area of magnet, magnet was re-polished to 0.3um and coated with silver to have low resistance and reliable at high power condition. Even though fine polishing is desirable for low contact resistance, it has trade-off with holding force at on-state. There is small air gap layer between copper signal line and magnet [1] because of surface roughness at 'ON' state. Therefore electrostatic force from incoming voltage exists. If the surface smoothness is fine, it will have very small air gap layer, and it will have strong holding force. Therefore top coil needs be able to generate stronger EM force than the holding force due to incident power at 'ON' state. In this case switch will be 'ON' state while it is supposed to be 'OFF' state, and it can cause damage to contact area of signal line and magnet while it carries high current for too long time.

When this switch is 'ON' state to 'OFF' state, there is also attraction force between nickel pad under RF signal layer and ON state magnet. The holding fore is stronger as the gap is smaller, stronger incident power and frequency is higher. Stronger EM force than holding down force needs to be generated from top coil. The EM force at magnet is stronger as the top coil is closer to 'ON' state magnet and with higher current through coil conductor.

The top coil is total 6 layers and 5 V, 900 mA current guided to coil to generate EM force. The each layer of coil has 6 turns and 0.1016 mm conductor width. The generated force was measured with varies distance from coil [26]. The 0.1016 mm copper width is narrow for 900 mA at steady state time condition, but only short period pulse signal is needed to actuate the switch since this switch type is latched type switch which doesn't need any power source at latched state, 'ON' or 'OFF'. If carrying current time is 0.5 s, the fusing current of 0.1016 mm width and 1 oz thickness copper is 1.465 A [27].

The ON state switch lumped model is 50 Ω microstrip line, contact resistor and variable capacitor, Fig. 20. The variable capacitor is depends on surface roughness of conductor and magnet. The capacitance when it is 'ON' state is not negligible not like 'OFF' state switch since the gap, signal line and magnet, is very narrow. If the capacitance is larger, the holding force is stronger. The voltage across of variable capacitor is shown at Eq.

(13) [25].

$$V_{sw} = V_1 - V_2 \quad (7)$$

$$Z_{in} = \frac{1}{jwC} + Z_o \quad (8)$$

$$\Gamma = \frac{1}{1+j2wCZ_o} \quad (9)$$

$$V_1 = V_1^+(1+\Gamma) \quad (10)$$

$$V_2 = \frac{V_1 Z_o}{Z_{in}} \quad (11)$$

$$|V_{sw}| = |V_2 - V_1| = \frac{2|V^+|}{\sqrt{1+4w^2C^2Z_o^2}} \quad (12)$$

$$F_{e\_h} = -\frac{C_{pp\_h}V^2}{2g_h} \quad (13)$$

$$F_{e\_h} = \frac{1}{8}\frac{C_{pp\_h}}{g_h}V_s^2(1+4w^2C_{pp\_h}^2Z_o^2) \quad (14)$$

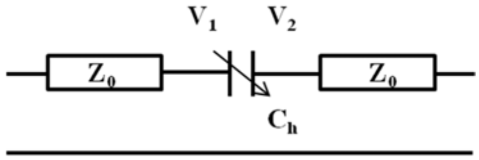


Fig. 20 ‘ON’ state microswitch lumped model

Hold down force can be calculated using Eq. (14) combined by Eq. (12) and electrostatic force equation, Eq. (13). C_{pp_h} is simulated by ANSYS Q3D, and calculated holding force comparing with electromagnetic force from top coil depends on varies distance from top coil. g_h is air layer height between magnet and signal line, and 1μm is used for calculation for the microswitch. If PCB conductor line and magnet are fine surface polished smoothness and g_h has very narrow, the holding force is too strong at high power and high frequency, so top coil need to be able to generate stronger force. The known copper roughness on PCB is about 1.6 um and magnet is post polished to 0.3 um and silver is coated as post processing for low contact resistance and having high resistance to arcing.

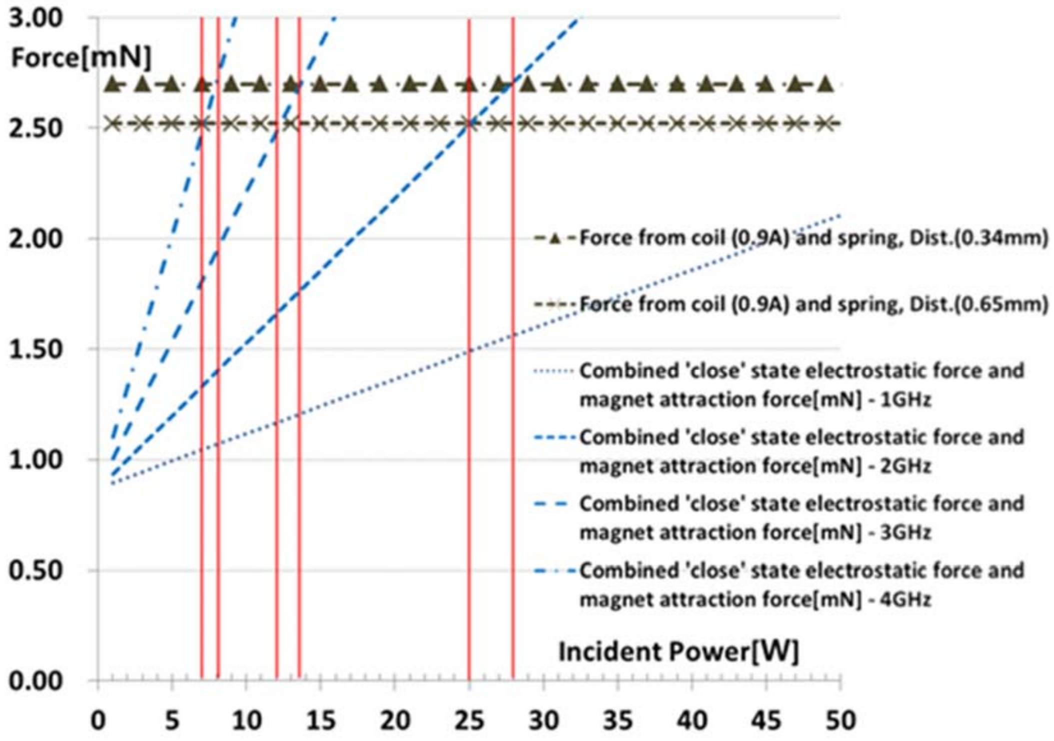


Fig. 21 Calculated holding down force from incident power at different frequency and electromagnetic force at 'ON' state magnet from top coil with two different spacer heights

Fig. 21 shows holding down force due to incoming power and EM force from top coil with varies spacer height. If spacer height is changed, signal line to magnet distance is also changed. In hence the EM force from top coil at signal line is also changed, and in the result, this EM force can be one of the power handling limitation parameters in the microswitch. If the holding force at certain incident RF power is stronger than the force from top coil at 'ON' state, the latched 'ON' state magnet is not de-latched for 'OFF' state.

When g_h at Eq. (14) is 1 um, the calculated holding force in the microswitchs is 2.51mN at 25W at 2 GHz. From this graph, Fig. 21, we can expect this microswitch can handle 25.1W and 27.8W when spacer height, at 'h4' in Fig. 10 b) is 0.3354 mm and 0.6488mm at 2 GHz.

3.5.3. RF performance; Isolation

When spacer height is getting shorter, the distance between magnet and top coil is getting shorter. In the result the force from coil is getting stronger to against holding force from incident RF power. It means the handling maximum power of the switch is getting higher as spacer height is getting shorter. However it has trade-off with isolation at 'OFF' state since the 'OFF' state capacitance is getting higher as spacer height is getting shorter.

Fig. 22 is showing the trade-off, changing isolation of 'OFF' state switch and electromagnetic force from coil at 'ON' state. X-axis is distance between top coil and 'ON' state magnet. When the distance is short, the force from top coil is strong, but isolation is very low. The changed electromagnetic force at 'ON' state magnet can indicate maximum power handling of the switch. Figure is showing after converting the changed force to maximum handling power. X-axis is distance between top coil and 'ON' state magnet.

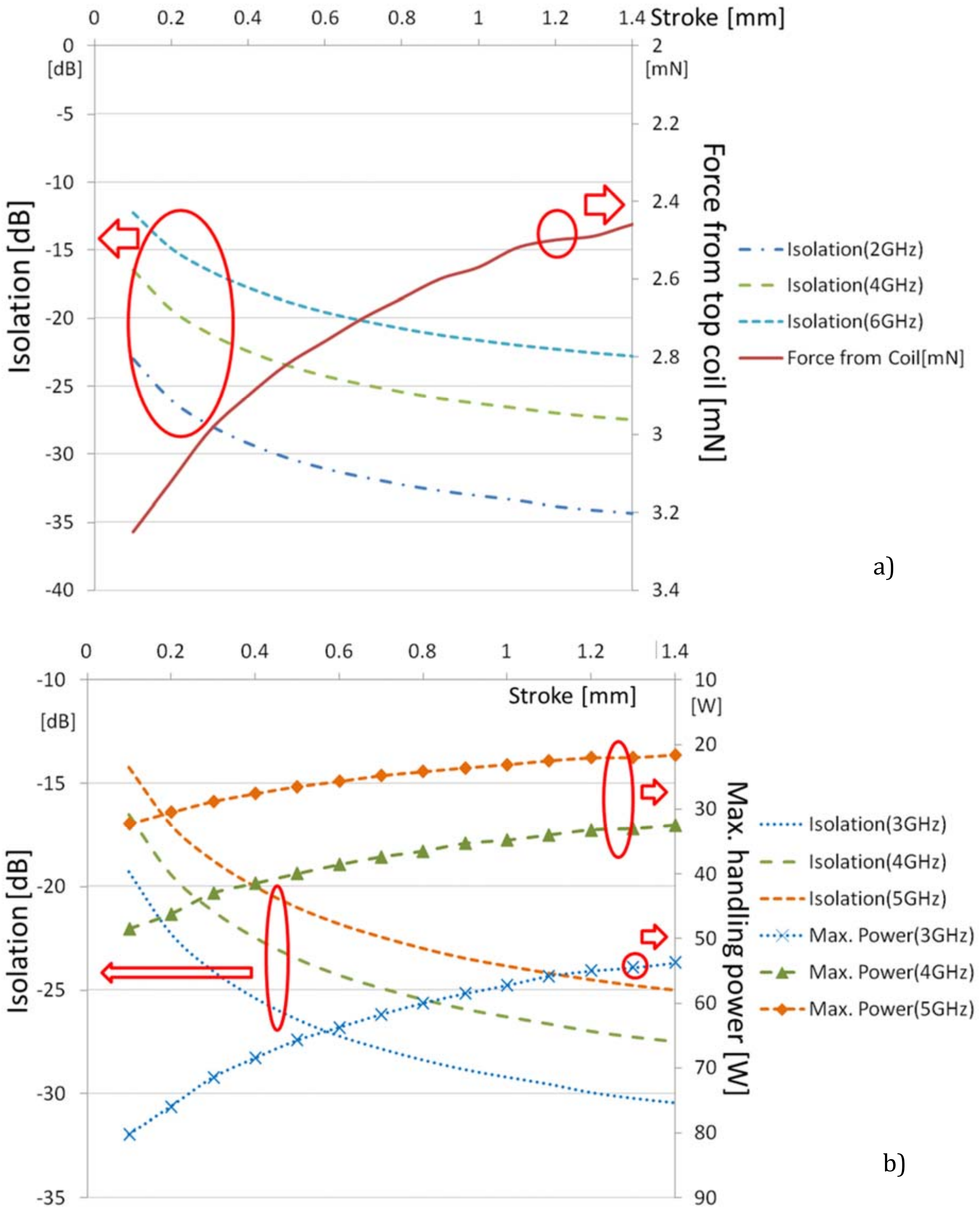
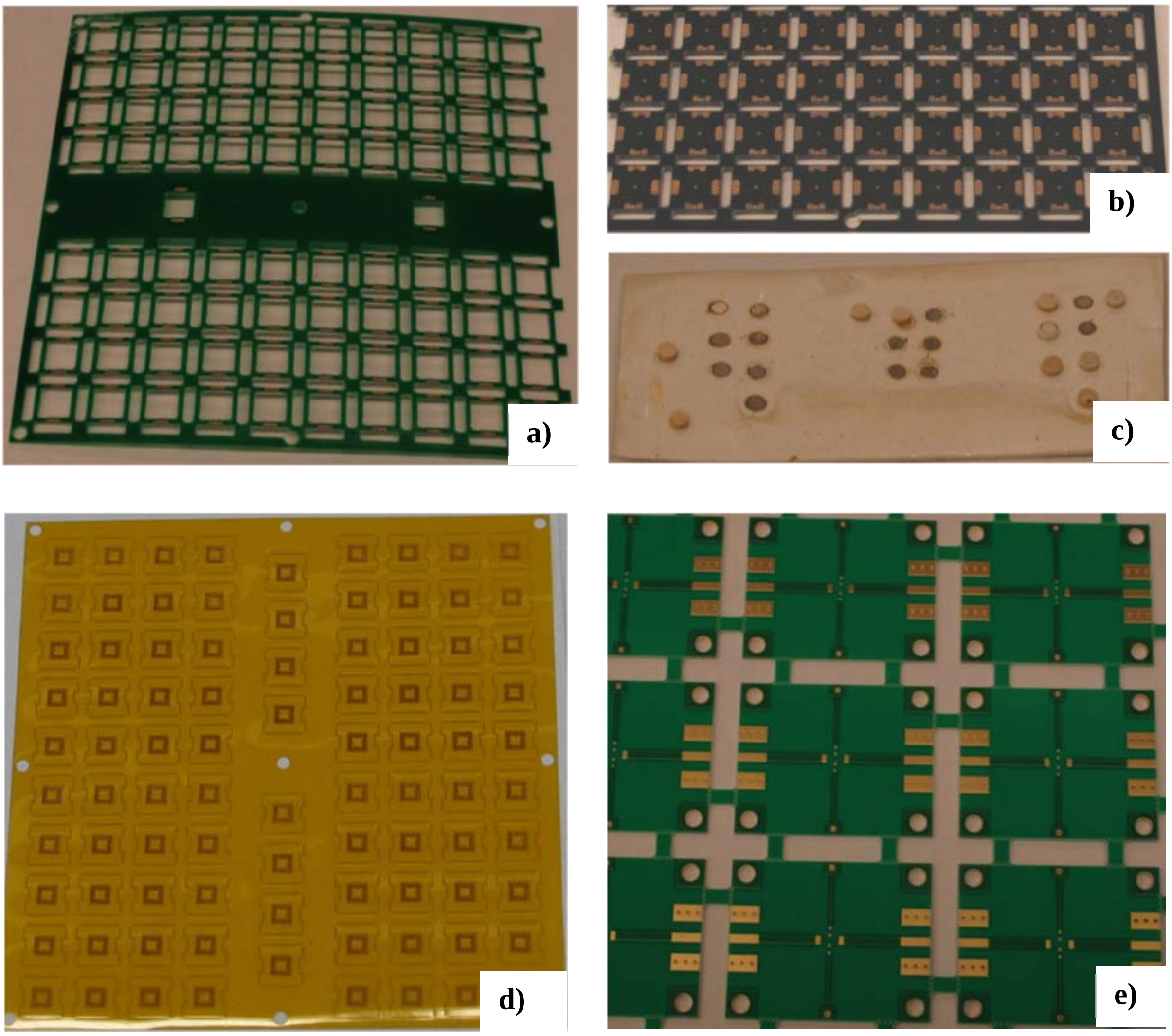


Fig. 22 HFSS simulated isolation and a) changed electromagnetic force, b) calculated maximum handling power changes due to spacer height

CHAPTER 4: Microswitch assembly

4.1. High power RF laminate microswitch parts assembly

Most of high power LMEMS switch parts are panel type. This type parts allows assembling multiple devices at the same time. Top coil, spacer, signal line layers and PCB are made as panel shown at Fig. 23, then these are stacked each other using conductive epoxy. Fig. 24 is shown individual each parts.



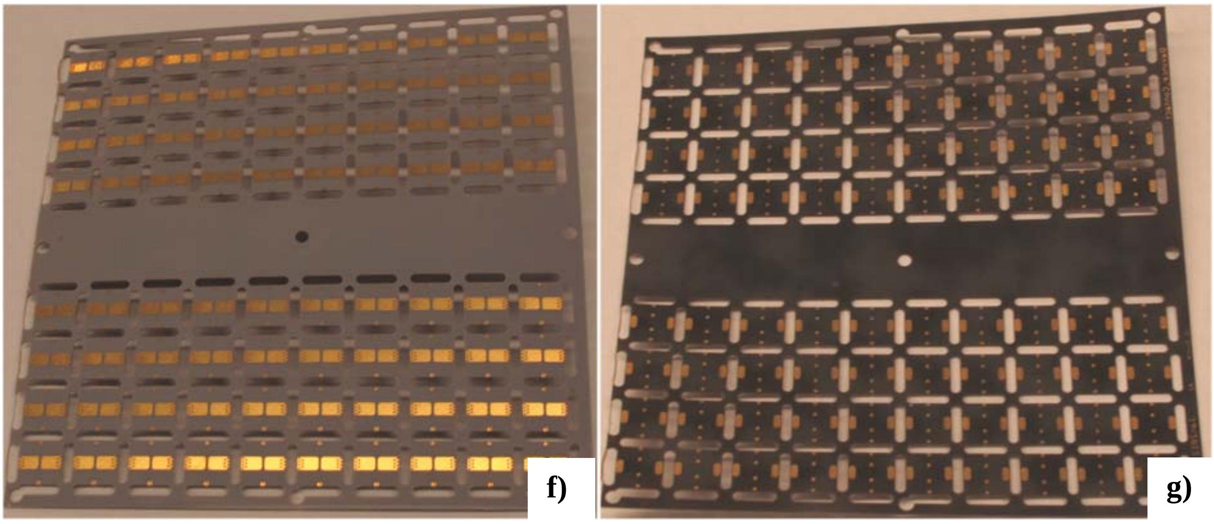
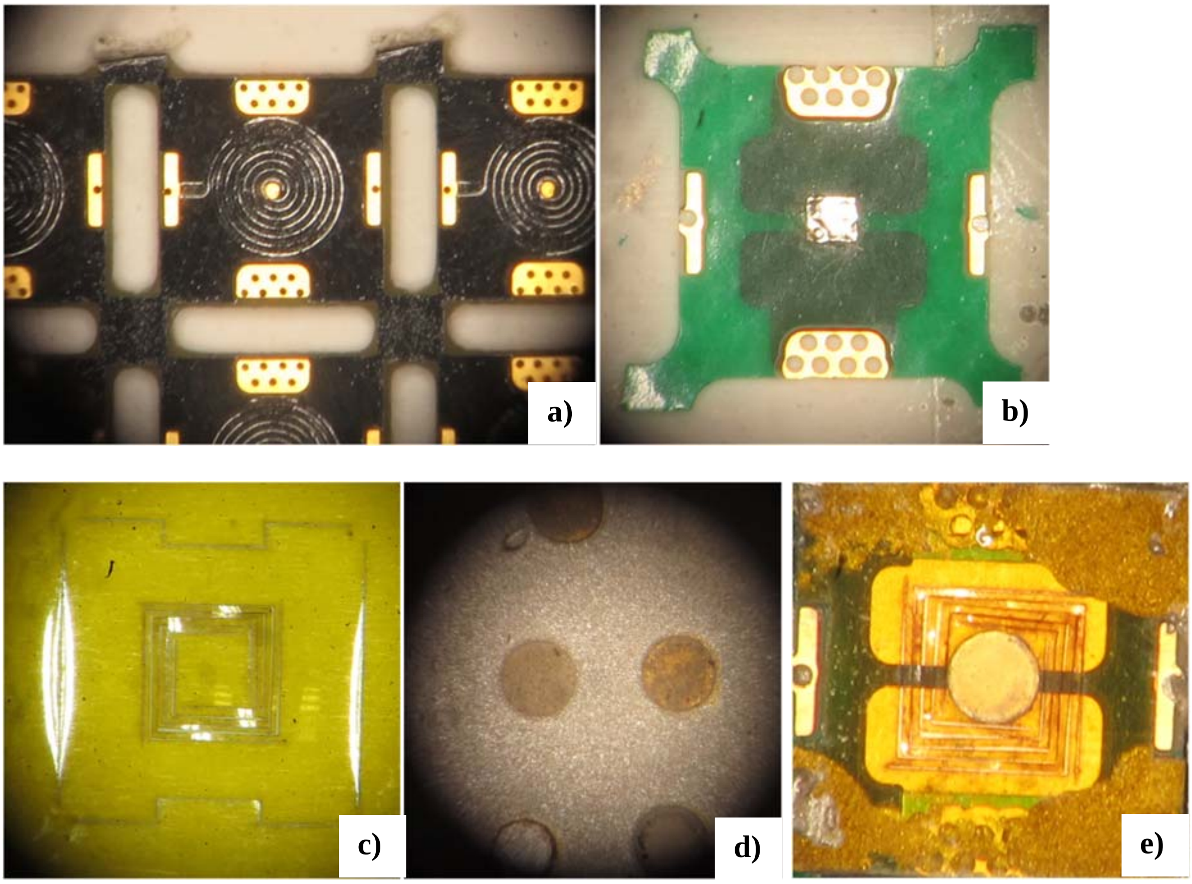


Fig. 23 High power LMEMS switch panel parts, a) Spacer, b) Top coil layer, c) Silver coated magnet, d) Polyimide spring, e) PCB, f) 1. Signal line layer top view, g) 2. Bottom view



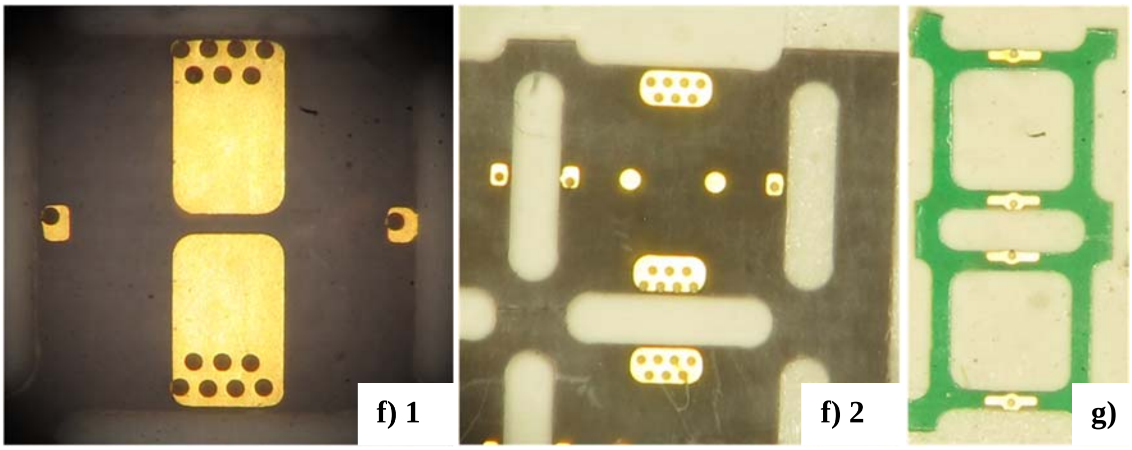


Fig. 24 High power LMEMS switch individual parts, a) Top coil layer, b) Nickel pad and holder layer, c) Polyimide spring, d) Silver coated magnet, e) Magnet glued with polyimide spring on nickel pad holder, f) 1. Signal line layer top view, 2. Bottom view, g) Spacer

CHAPTER 5: High power RF Laminate Microswitch Measurement

5.1. Measurement equipment

This dissertation focuses on a high power RF laminate microswitch. The commonly used measurement equipment is vector network analyzer for small signal measurement. The common MEMS switch size is um size, but out switch size is mm size, so SMA connectors were used for connecting VNA with DUT instead of using probes.

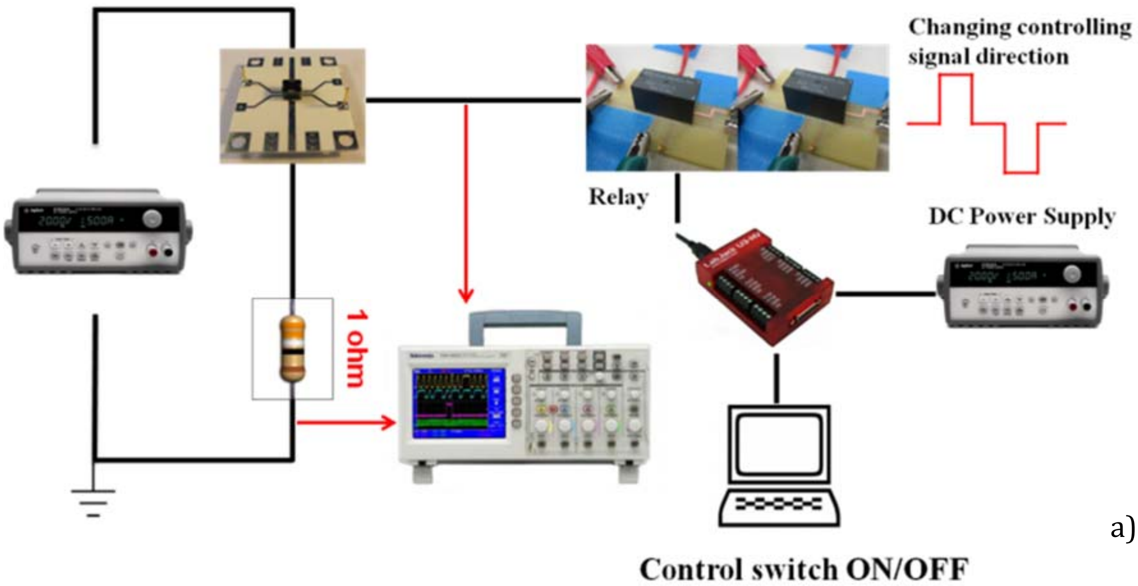
Additionally high speed oscilloscope is also needed to measure large signal since dealing with high power to the microswitch.

5.2. Dynamic response

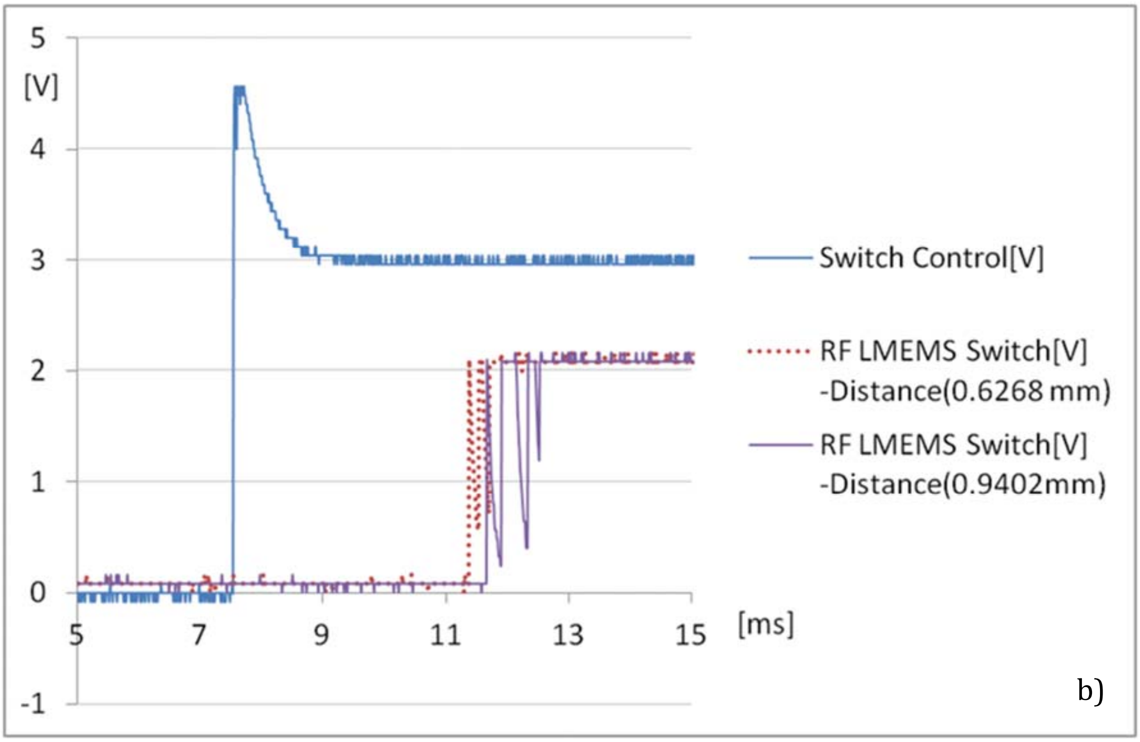
The dynamic speed of switch is also related the distance, Fig. 10 a) 'h3' or b) 'h4'. When spacer height is short, the EM force at 'ON' state magnet is stronger than when spacer height is long. Moreover the magnet traveling distance is also shorter than when it is long height. Fig. 25 b) and c) is shown the measured dynamic response depends on spacer height.

The switch actuation is controlled by top coil, forward and backward signal, 5V 900 mA, to coil. The control signal direction is controlled by using two relays to have three state signals, forward signal, backward signal and no signal. The measurement setup is shown at Fig. 25 a). This switch is latched system, and when it is ON or OFF state, it doesn't need control signal. Moreover the coil needs higher current than it can carry at steady state condition, so if the high current control signal is guided to the coil for long time, the coil will be damaged and microswitch failure reason.

When short height spacer (signal line to magnet is 0.6268 mm at 'OFF' state) is used for the distance, the 'OFF' to 'ON' time after applied 'ON' control signal is 4.17 ms. There is also settling time to be fully latched 'ON' state since the movable magnet can be tilted when it touched to signal line. The settling time is 0.33 ms. When long height spacers (signal line to magnet is 0.6268 mm at 'OFF' state) are used, the 'OFF' to 'ON' time is 5.02 ms, and the settling time is 0.86 ms. It needs traveling time from top latched place to be 'ON' state. However the traveling time is barely needed at 'ON' to 'OFF' state time. When short spacer used, the 'ON' to 'OFF' time is 0.431 ms. When long spacer used, the time is a little longer than long spacer was used, 0.441 ms, shown at Fig. 25.



a)



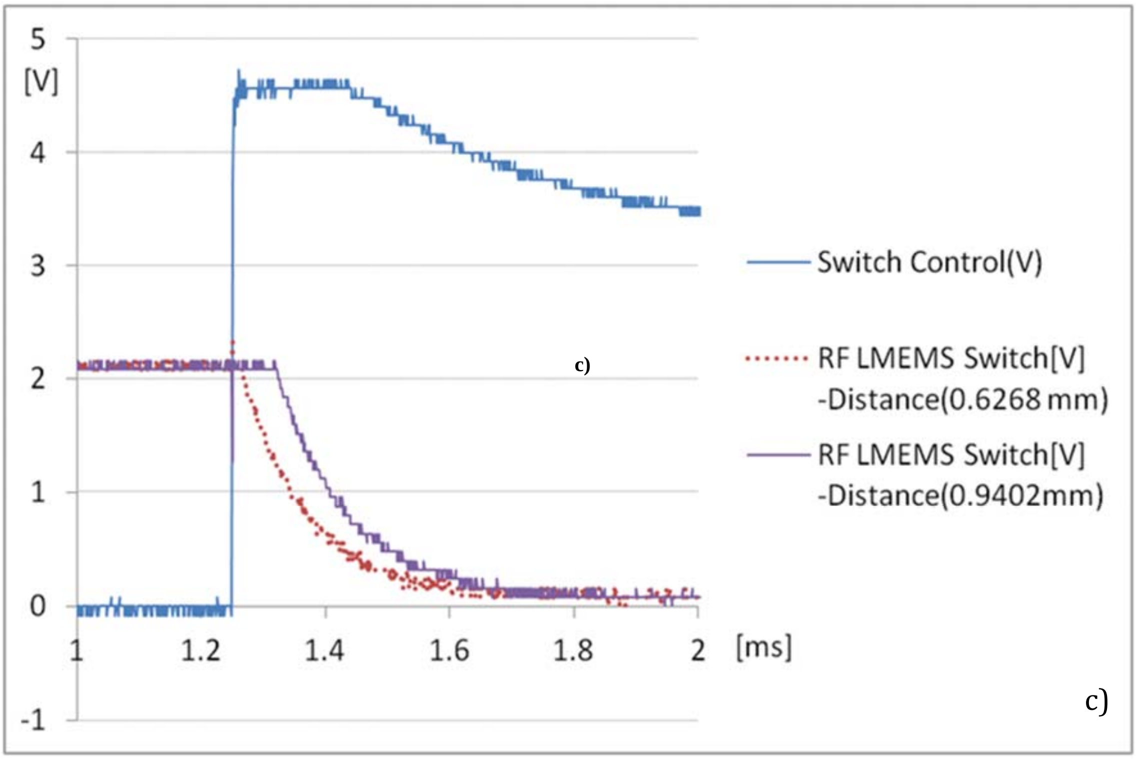
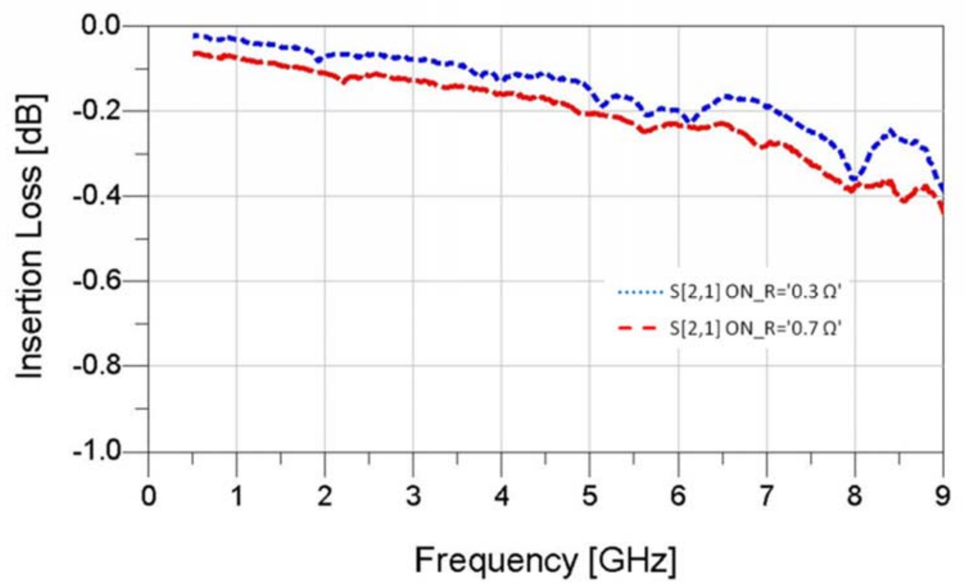


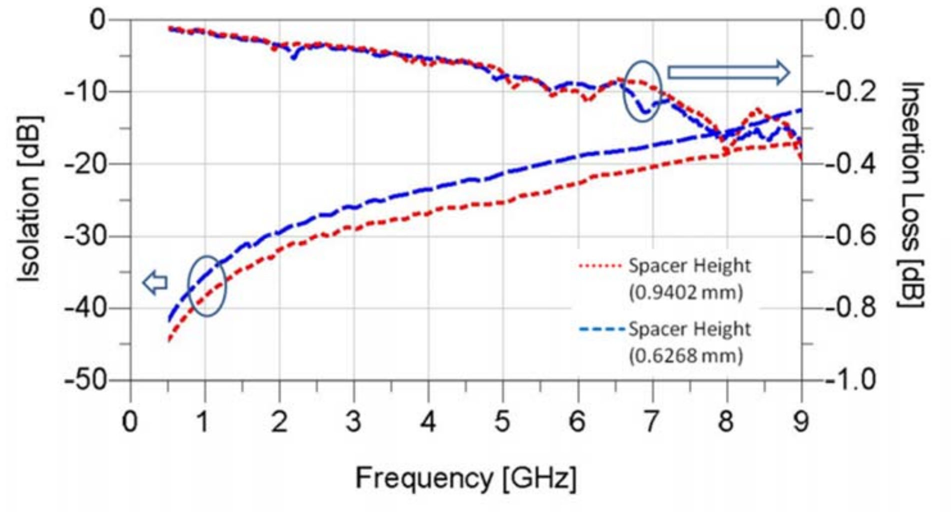
Fig. 25 a) Dynamic high power RF LMEMS microswitch response measurement result, b) ‘OFF’ to ‘ON’ response time measurement, c) ‘ON’ to ‘OFF’ response time measurement

5.3. RF performance

We designed a microstrip line printed circuit board to mount the microswitch, illustrated in Fig. 1. e) to acquire RF performance data. Fig. 26 a) shows insertion loss changes depends on contact resistance, 0.3Ω and 0.7Ω. Fig. 26 b) shows changed s-parameter with two different spacers, 0.6268 mm and 0.9402 mm, used. Insertion loss was merely changed in comparing both cases, but 4.692 dB isolation different at 10 GHz. It is because capacitance exists at 'OFF' state. The simulated capacitances at 'OFF' state are 10.73 fF and 5.959 fF when short and long spacers were used. It is simulated capacitance by Q3D. The measurement was done by VNA, HP8510C. The switch achieved an insertion loss of -0.384 dB and an isolation of -16.804 dB at 9 GHz, shown at Fig. 26 a) and b) 0.9402 mm spacer height.



a)



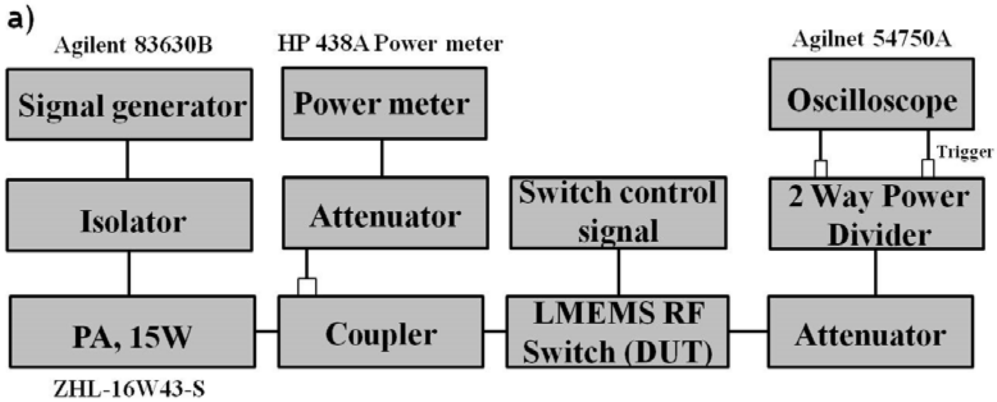
b)

Fig. 26 a) Measured 'ON' state s-parameter having two different contact resistances, b) two different spacer height

5.4. High power testing

We were able to test this switch at high power condition repeatedly. Fig. 27. a) is the measurement set up. Power amplifier, ZHL-16W-43, was used for generating RF power up to 15W, and Oscilloscope, Agilent 54750A was used for measuring RF signal in time domain. Incident power, 41.76 dBm, was guided to LMEMS RF switch. The total attenuation from attenuators, RF cables and a power divider between LMEMS switch to oscilloscope is -55.43 dBm. The device operates successfully at 15W and 1.9 GHz, depicted in Fig. 27. b).

a)



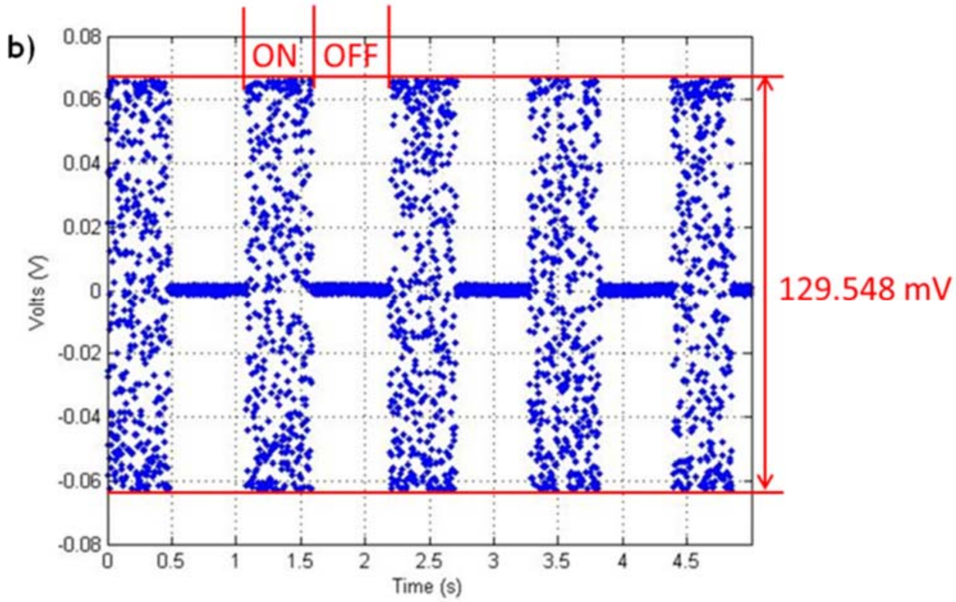


Fig. 27. a) High power measurement setup, b) LMEMS RF switch measurement result with 15 W power injection at 1.9 GHz.

CHAPTER 6: Microswitch Failure

6.1. Top coil

The top coil has 6 layers, 2 layers are laminated on the top and bottom of FR-4 and 4 layers are inside of FR-4. The coil width is 0.1016 mm. 900 mA is guided to the coil to control switch. The coil width is comparably thin for 900 mA, so if the current is incited for long time, > 10 sec, the coil can be burned easily.

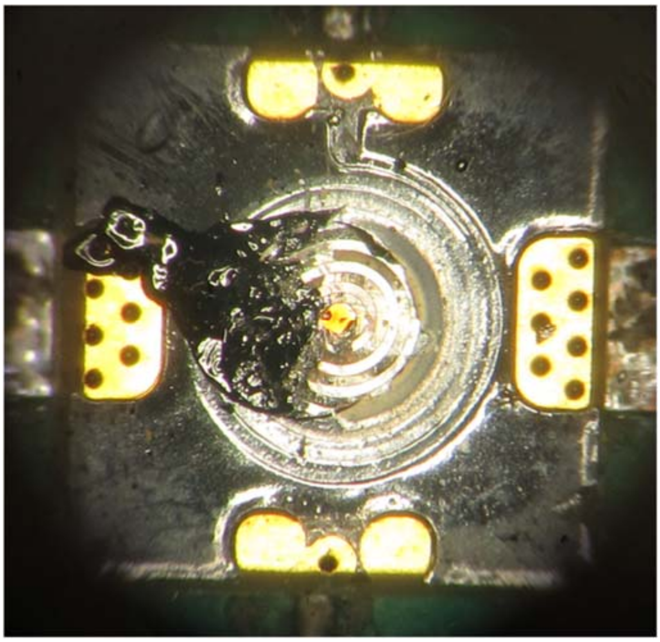


Fig. 28 Failed top coil layer

6.2. Contact area; Magnet and signal line

This switch is direct contact switch, so contact resistance is exists. The DC contact resistance is 0.2~0.3 Ω. This resistance is not critical at low frequency and low power. The contact area is hot spot at ON state. When the incident power is high and the switch is ON state for long time, the increased temperature at hot spot can be enough high to damage 'RF signal layer' is shown damaged 'RF signal layer' due to the hot spot. Even though the damaged layer is OFF state, Fig., this discontinued line showed connection with high resistance (> 60 Ω) since substrate was damaged and internal GND line was connected to disconnected line.

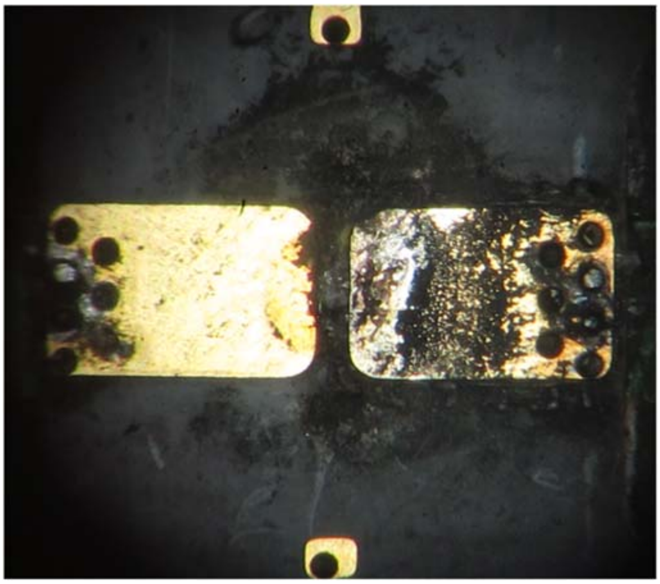


Fig. 29 Failed signal line layer

6.3. Arching

Arching is observed during switching when incident power is high. This arching can damage the surface of signal line and magnet, and it introduces high contact resistance and welding signal line and magnet. These can cause the switch failure.

CHAPTER 7: Conclusion

7.1. Conclusion

In this dissertation we introduced designing high power RF LMEMS switch using laminate technology. We showed how geometric parameters are correlated mechanically, performing in RF and switching performance. Maintaining low contact resistance is important in this switch since this microswitch is direct contact switch type; the contact resistance degrades RF performance and generating heat. The measured contact resistance is 0.3 Ω. The insertion loss showed -0.4 dB at 9 GHz. High power testing at 15 Watts, 1.9 GHz, has been showed at Chapter 5.

Typically power handling capability limits come from self-actuation at 'open' state or latching, sticking to signal line, at 'open' state or destroying device at contact area by increased high temperature, around 150 C^0. Observing self-actuation is not expected since large actuation distance and strong attraction force between magnet and top nickel pad enough to against self-actuation at 'open' state. From the calculation, this switch can handle 25 W at 2 GHz. The measured 15 W condition was because of equipment limitation not limited power handling capability of the microswitch.

7.2. Future work

7.2.1. To improve power handling capability

Typically device failure due to increased temperature, self-actuation from high incident power or arching limits switch power handling capability. We have showed which part is limiting power handling capability in this microswitch at Chapter 3. Self-actuation when switch is opening from switch ON state limits high power handling. If we can achieve stronger force from top coil, this switch can switch at higher power. If the self-actuation problem is solved, the next upcoming potential problem is hot spot, contact area between magnet and signal line, temperature can cause device failure. The main heat source comes from contact resistance and we can reduce the contact resistance by depositing materials to surface or further improve surface roughness. Furthermore, signal line and magnet surface damages after multiple (million times) switching since this switch is direct contact switch. It cause increasing contact resistance and higher heat source. This can be improved by studying materials for depositing on surface as well.

7.2.2. To improve reliability

The switch characteristics changes after multiple (million) times usage. The spring constant can be changed due to multiple time usage and high temperature, the substrate dielectric constant and loss tangent are changed by temperature, contact resistance also changes due to signal line surface damage. We can make feedback system to monitoring the switch characteristics and add compensation system, then the switch performance degradation can be minimized.

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