Hot-Switching Test of Non-Contact Type MEMS Switch

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Abstract — **This paper presents the performance and power handling properties of a capacitive MEMS switch. The switch is a completely non-contact-type switch built with several capacitors that contain air gaps, and free from contact failures that frequently occur in contact-type switches. The switch was designed for 24 GHz automotive radar applications, and the average RF performance of the fabricated switches includes insertion loss of 0.5 dB and isolation of 20 dB at 24 GHz. The lifetime, power-handling properties, and linearity are examined in a hot-switching mode. After 10^9 continuous cycles in a hot-switching mode with 18 mW RF input power, mechanical failures or RF performance degradation were not detected. Power handling capacity of 0.9 W under hot-switching condition was achieved.**

Index Terms **— lifetime, linearity, power handling, RF MEMS, switch.**

I. INTRODUCTION

Microelectromechanical systems (MEMS) switches for radio frequency (RF) applications are of interest because of their potential for low-loss, low-power consumption, and lack of intermodulation distortion. It has been demonstrated that superior RF characteristics can be achieved, compared to field effect transistor (FET) based switches and diode based switches [1]. A large amount of research effort has focused on the fabrication and the implementation of MEMS switches for various applications and specifications, such as reconfigurable array antennas [2] or phase shifters [3]-[4].

Despite their state-of-the-art performance in insertion loss and isolation over a wide bandwidth, MEMS switches have two major problems, namely, low lifetime and poor power handling. A few efforts are reported to improve lifetime and power handling of MEMS switches. Researches at Rockwell reported a hot-switching small signal (1 mA) lifetime of tens of million cycles [5]. Researches at Raytheon reported a lifetime in excess of 1 billion cycles for a capacitive switch [6]. Researches at MIT reported a 1.5 W of power handling capacity [7]. Researches at Radent MEMS presented a hot-switching lifetime of about 10^7 cycles [8].

For high reliabilities and power handling capacities, we proposed a fully non-contact-type MEMS switch. The proposed switch is built with a variable capacitor structure, which contain small air gaps, instead of the direct or indirect contact pads. This paper presents the lifetime, power handling, and linearity of the novel proposed MEMS capacitive switch.

The proposed switch was designed for 24 GHz automotive radar applications. Millimeter-wave radar technology has already been implemented for various functions on automobiles as a component of the Intelligent Transportation System (ITS). Although millimeter-wave radar has advantages over optical or ultrasonical sensors, during day or night, and in most weather conditions, it cannot avoid the high cost resulting from the complicated structures. The MEMS switches could be employed to reduce the cost of the radar front-end because of their excellent RF properties and potential low-cost manufacturability [9].

II. DESIGN AND FABRICATION

The proposed switch is a laterally driven capacitive shunt switch operated by the change of the capacitance between the signal line and ground lines. The scanning electron microscopy (SEM) photograph of the fabricated switch is presented in Fig. 1. The switch consists of a coplanar waveguide (CPW) line and variable capacitors and actuators. Electrostatic comb drive actuators are used for moving the variable capacitor parts in the lateral direction. The stoppers are used to limit the movement of the actuators, to prevent the contact of variable capacitor metals.

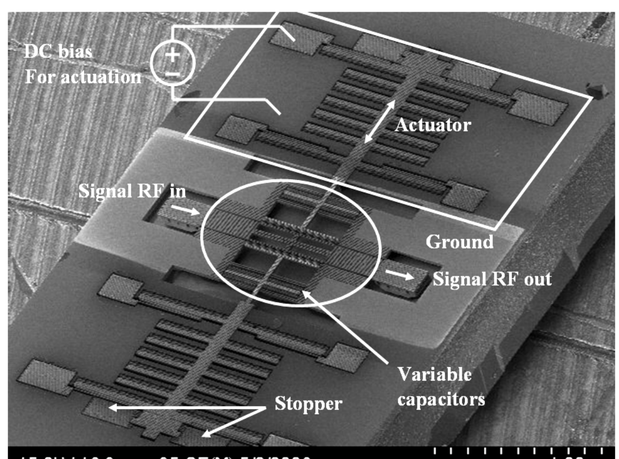

Fig. 1. The SEM photographs of the fabricated switch.

Figure 2 contains the schematic diagram of the MEMS switch except the actuator regions and presents the on/off mechanism of the MEMS switch. The dark grey regions

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indicate fixed structures, and the bright grey regions indicate movable structures. Without applying a direct current (DC) bias across the actuators, the bright grey regions do not move resulting in the on state of the switch. With a DC bias voltage over 25 V, the bright grey regions move close to the signal line resulting in the off state of the switch. The air gaps between the movable parts and the stationary parts of capacitors are 27 ㎛ in the on state, and 2 ㎛ in the off state. Thus, the actuator stroke is 25 ㎛ with a 25 V DC applied voltage.

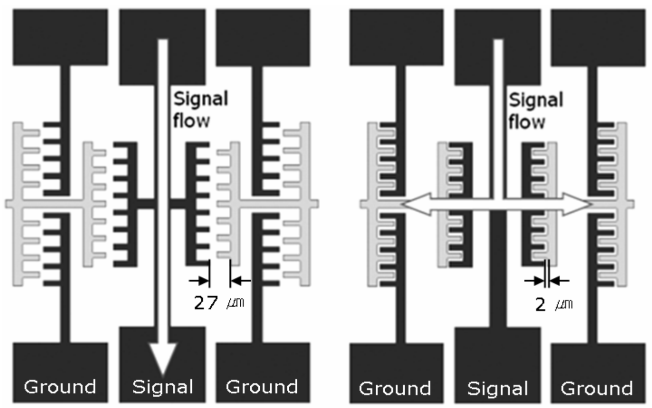

Fig. 2. On/off mechanism of the non-contact-type MEMS switch of on state (a) and off state (b).

The reliabilities and power handling capacities of contact-type switches are limited by contact failures, RF latching, and RF self-actuation phenomena. The RF latching is a situation by which the applied RF power provides enough force on the movable part to hold the switch, when it should have released (i.e. when DC bias is removed). The RF self-actuation is a situation in which the high RF power actually creates enough potential to pull the movable part into the actuated position without applying a DC bias across the switch [6].

The proposed switch is designed to be safe from contact failures, RF latching, and RF self-actuation phenomena. Since the switch is a non-contact type, the problems of contact switches such as the welding and the stiction phenomena do not occur. The on state air gap between movable parts and fixed parts are much wider than those of other contact-type switches. Also movable parts and fixed parts do not touch each other, even in the off state. Therefore, the input RF power levels inducing RF latching and RF self-actuation of the proposed switch are much higher than those of other contact-type switches.

The combs and bar structures of the variable capacitors are modeled with inductors and capacitors. According to the physical dimension of the combs and bar structures the values of the inductors and the capacitors are adjusted. By adjusting the values of the inductors and the capacitors, the switch can be optimized for any frequency. In this study, the switch of which target frequency was 24 GHz was used. The detailed design theory and values of inductors and capacitors were discussed in our earlier design paper [10].

For the switch fabrication, the selective silicon-on-insulator implant (SSOI) process was used to realize the large and precise lateral motion of the actuators. The SSOI process was also discussed in our earlier paper [11].

III. Lifetime Test Results

The RF characteristics of the fabricated non-contact-type switch are measured using an HP 8510XF vector network analyzer. The averaging insertion loss and isolation of the fabricated MEMS switches are approximately 0.5 dB and about 20 dB at 24 GHz, respectively. The RF characteristics of one of the best switches are shown in Fig. 3. The insertion loss and isolation at 24 GHz are 0.29 dB and 30.1 dB, respectively.

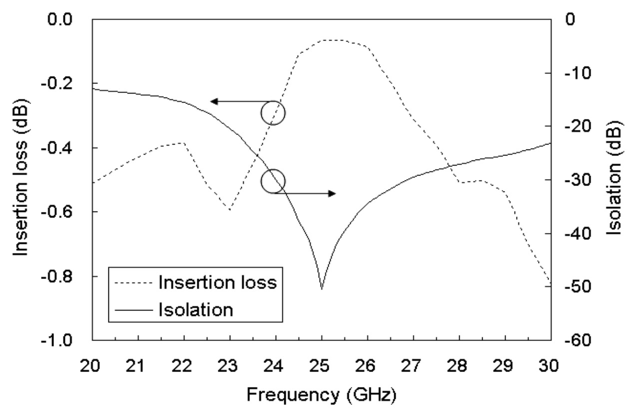

Fig. 3. Insertion loss and isolation of the fabricated switch

The lifetime and the switching speed of MEMS switch was measured using the measurement setup as shown in Fig. 4. As a switch actuation signal, a square wave with a frequency ranged from 50 Hz to 2 kHz and a voltage magnitude of 28 V was supplied by Agilent 33120A function generator and TREK model 603 power amplifier. A RF signal of 24 GHz continuous RF power from a millimeter-wave monolithic integrated circuit (MMIC) chip power amplifier was applied to the switch. The modulated RF envelop that resulted from switch actuation was measured by Agilent 54624A oscilloscope.

The data collected from the lifetime and switching time test set-up are presented in Fig 5. This switch was cycled at 50 Hz with a switching voltage of 28 V. The input signal was a continuous wave having a frequency of 24 GHz and a power of 18 mW that was maximum power available in this setup. The detected envelope of output signal is the upper trace, which is modulated by the control signal shown in the lower trace. In the on state about 8 ㎳ was taken for the MEMS oscillation to vanish, but the first peak appeared within 300 ㎲ from the drop of the control voltage. For the transition from the on state to the off state, about 200 ㎲ was taken. The switch could be operated at maximum control signal frequency of 2 kHz. Even after 10^9 continuous cycles in a hot-switching mode with 18 mW RF input power, the switch was still functional without any mechanical failure.

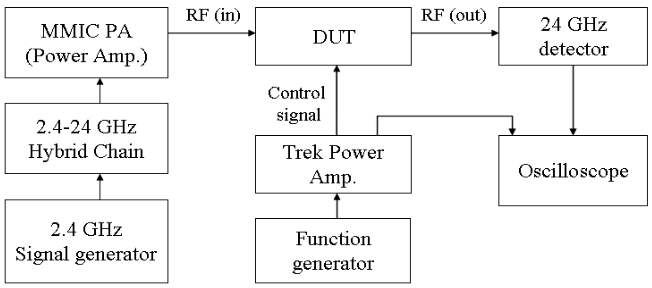

Fig. 4. Experimental setup for lifetime and switching time testing

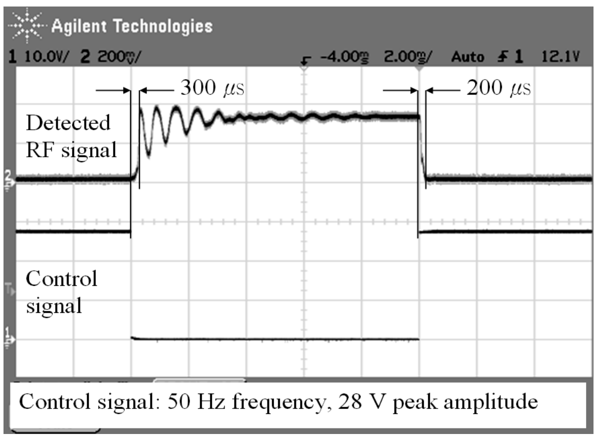

Fig. 5. Switching data from the MEMS switch.

IV. POWER HANDLING AND LINEARITY TEST RESULTS

The measurement setup for power handling and linearity test is presented in Fig. 6. The 24 GHz microwave signal was produced by Agilent E8257D signal generator and amplified by Microwave Power L1826-36 power amplifier. The amplified signal passed through a 16 dB coupler, where the coupled port was connected to a 20 dB attenuator. The 20 dB attenuator was connected to one channel of the Agilent E4417A power meter. The signal was delivered to the switch after passing through a circulator. The output of the switch was delivered to another channel of the Agilent E4417A power meter after passing through a 20 dB attenuator. For the switch actuation, a DC voltage source was used.

Hot-switching mode power handling capacity and linearity properties were measured simultaneously. The on state measurement was performed by applying input RF power and calculating the insertion loss from the measured output RF power. The off state measurement was performed by actuating the switch with a DC voltage of 28 V without reducing input RF power. Then the isolation was calculated from the corresponding measured output power.

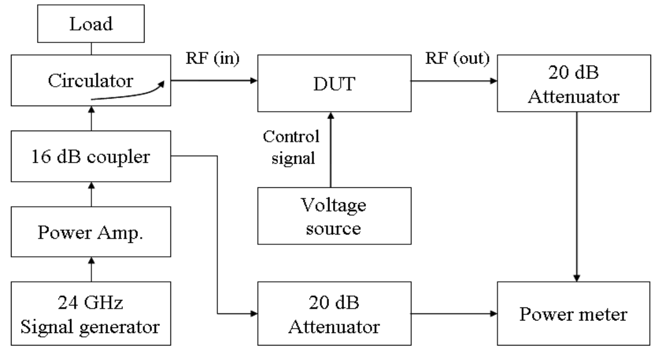

Fig. 6. Experimental setup for power handling and linearity test

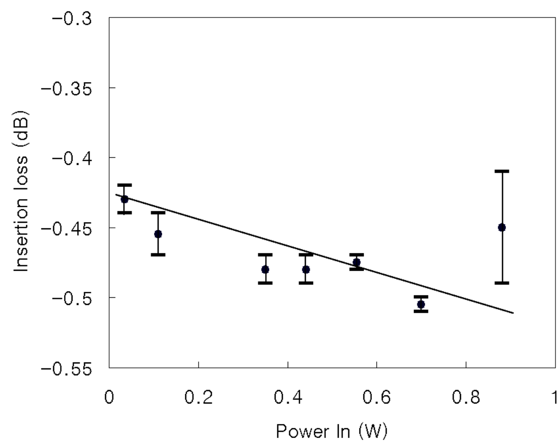

Fig. 7. Measured insertion loss versus input power at 24 GHz

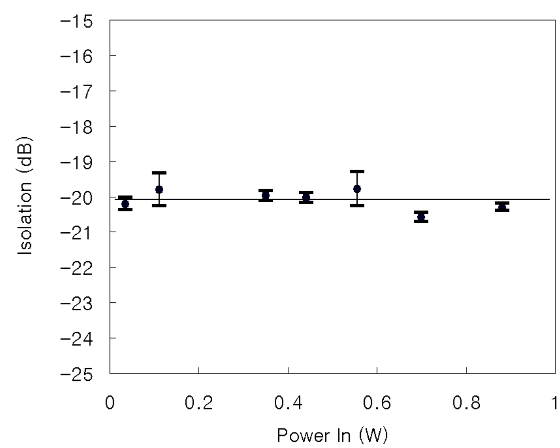

Fig. 8. Measured isolation versus input power at 24 GHz

The measured RF characteristics of the switch at different power levels are summarized in Fig. 7 and Fig. 8. Small nonlinearity in the on state was observed. The insertion loss was slightly increased as increasing input RF power. The isolation was constant up to 0.9 W of the input RF power. It can be seen that the switch could withstand over 0.9 W of 24 GHz RF power with no abrupt degradation.

The RF latching or the RF self-actuation was not detected up to 0.9 W of the input RF power. The RF power over 0.9 W was not available in this experimental setup. Therefore, additional test was performed using a DC bias instead of a RF signal in order to infer the power level where latching or self-actuation occurs. A DC bias was applied between the signal line and ground using another voltage source, and the motion of the switch was observed using a microscope. The latching and the self-actuation were observed at the applied voltage of 27 V and 34 V, respectively. The root mean square (RMS) potentials of 27 V and 34 V can be obtained by 29 W and 46 W of RF power, respectively.

The lifetime and power handling capacity of the presented MEMS switch is compared to previous research results as shown in Fig. 9. The picture contains only hot-switching mode experiments. Although many RF MEMS switches shows impressive results in insertion loss and isolation, lifetime and power handling limit some of the applications and implementations of MEMS switches. The enhancement of lifetime and power handling is essential to making RF MEMS switches attractive for broad applications.

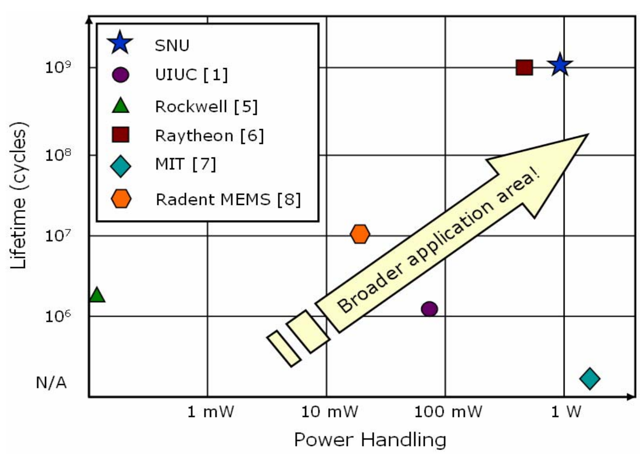

Fig. 9. Hot-switching lifetime and power handling capacity comparison of MEMS switches from published reports [1], [5]-[8]

VI. Conclusions

We have presented the lifetime and the power handling properties of non-contact-type RF MEMS switch. After 10^9 continuous cycles in a hot-switching mode with 18 mW RF input power, the switch was still functional without any mechanical failure. The switch could withstand over 0.9 W of 24 GHz RF power under hot-switching condition with high linearity. By latching or self-actuation test, it could be inferred that RF latching or RF self-actuation would not be detected in an RF power below 29 W. These hot-switching properties are comparable results to those of other most matured MEMS switches, and this is the first study of reliabilities of non-contact-type, laterally driven RF MEMS switches.

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