Power Handling and Linearity of MEM Capacitive Series Switches

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Abstract— **This paper presents the power handling and linearity of a capacitive series MEMS switch. The switching time as a function of incident RF power is also discussed. The MIT Lincoln Laboratory series capacitive MEMS switch handled nearly 10 Watts of RF power under cold switching conditions and up to 1.7 Watts of RF power under hot switching conditions. The power handling is a function of the pull-down voltage of the switch and the frequency of the RF signal.**

I. Introduction

Micro-mechanical series and shunt switches have shown some very impressive results (insertion loss and isolation) from 0.1 to 100 GHz [1], [2], and have been employed in low-loss phase shifters at 10 GHz, 35 GHz and 40-100 GHz. Reliability, switching speed, packaging, and power handling limit some of the applications and implementations of MEMS switches. This paper addresses the power handling, linearity, and switching speed of MEMS series capacitive switches developed at MIT Lincoln Laboratory [1].

The MEMS switches, made from a curling tri-layer membrane, are illustrated in Fig. 1 and thoroughly described in [1]. The switches are actuated by applying an electrostatic bias between the tri-layer membrane and the two pull down electrodes. The up-state capacitance is around 8 fF. When the switch is actuated to the down-state, a metal/insulator/insulator/metal region (100 μm × 50 μm) with a total dielectric thickness of 150 nm forms a down-state capacitance of around 1.2 pF.

Power handling and linearity were measured in four separate experiments at 5 and 10 GHz. The devices are highly linear in the up and down-state with respect to power. However, we have observed several behaviors, such as a frequency dependance to the power handling and power dependance for the maximum down-state capacitance, that require a closer examination of the micro-electro-mechanical system.

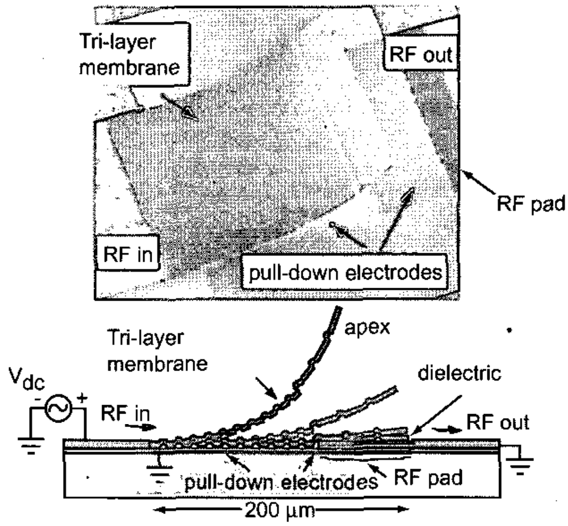

Fig. 1. SEM image of the MEMS series capacitive switch and illustration of the biasing and actuation.

II. Power Handling and Linearity

The power handling and linearity of the MEMS series capacitive switches were measured in four separate experiments at 5 and 10 GHz.

A. Experimental Setup

The experimental setup is shown in Fig. 2. The microwave signal is produced by an HP 8350B signal generator, passes through a step attenuator and is amplified by a TWT amplifier. The amplified signal passes through a circulator and then through a 20 dB coupler, where the coupled port is connected to an HP437B power meter. The signal is delivered to the DUT after passing through a bias-tee and a microwave coplanar probe. The output of the DUT is connected to a coplanar probe, another bias-tee, and another HP437B power meter.

The input and output power delivered to the probe tips are calibrated by measuring the insertion loss of the 20 dB coupler and the insertion loss from input of the input bias-tee to the output of the output bias-tee, when the DUT is replaced by a "short" on wafer standard. The insertion loss and isolation reported in this section include the loss of probe contact resistance and the on wafer transmission lines (800 μm each) leading up to the MEMS switch (typically 0.4-0.8 dB from 5 to 10 GHz respectively). The probe pads are 0.8 μm thick aluminum, which produced a non-repeatable probe resistance, therefore the switch capacitance could not be precisely calculated from the insertion loss values.

B. Linearity

The linearity of the MEMS switch was measured in the up-state and the down-state. The up-state measurement was performed by applying input power and calculating the isolation from the measured output power. The down-state linearity was measured by actuating the switch with a DC pull-down voltage (V_p), and then lowering the voltage to a hold voltage (V_h), chosen to be 3-5 Volts above the DC release voltage (V_r). Then increasing input power was applied to the input and the isolation was calculated from the corresponding measured output power. The results for a typical switch (R5C10W2A) are shown in Fig. 3. The insertion loss and isolation are constant up to 7W. Very small nonlinearity in the up-state is observed at 5 GHz and in the down-state at 10 GHz for high power levels. The RF and mechanical performance of the MEMS switches was not permanently altered by the high power levels.

C. Power Handling

The power handling of the MEMS switches was measured in two similar experiments. In the first experiment, the switch was actuated and held with pull and hold voltages as described in section II-B. An input RF power was applied, then the hold voltage was reduced until the switch released or the applied bias voltage was zero. The results for a typical switch (R5C10W2A) are shown in Fig. 4. The power at which the switch no longer releases is called the "hot switching limit". The hot switching limit for all the tested devices (~14) was between 1 W and 1.7 W.

The second experiment involved actuating the switch with DC bias as before, and then applying an RF power and turning off the DC bias. The results for a typical switch (R5C10W2A) are shown in Fig. 5. Again, the switches fully released for power levels below the hot switching limit and did not fully release above the limit. A plot of the insertion loss with a 10 V bias in addition to the RF power is also shown in Fig. 5. It is interesting to note that even for very high input power levels, the down-state capacitance (120-280 fF and 100-140 fF for 5 and 10 GHz respectively) as extracted from insertion loss values, is significantly smaller than the down-state capacitance (1-1.2 pF) under DC bias conditions. An attempt to explain these results is given in section V.

The results above are typical of all of the devices measured. It is important to note the nearly 3 dB increase in the hot switching power limit from 5 to 10 GHz. A plot of the hot switching power limit or "power handling" versus pull down voltage of the switch is shown in Fig. 6. Several switches supported hot switching over 1.5 W. Switches with higher pull down voltages had higher power handling levels. An increase in the pull down voltage corresponds to an increase in the stored mechanical energy and therefor a greater restoring force to counteract the attractive force of the RF signal.

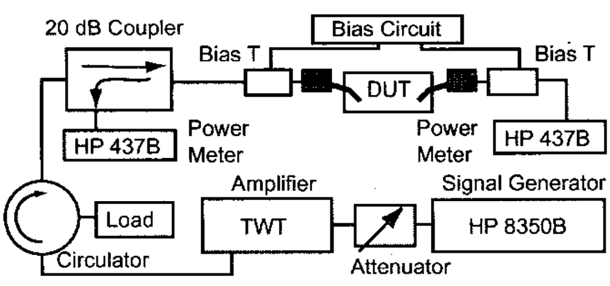

Fig. 2. Experimental setup for power handling and linearity measurements.

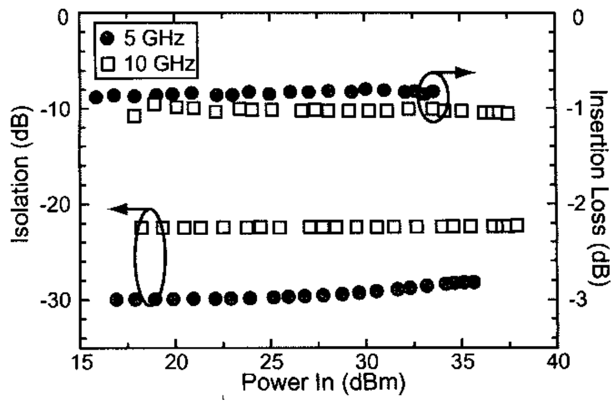

Fig. 3. Measured down-state insertion loss and up-state isolation versus input power at 5 and 10 GHz. Insertion loss includes the loss of 1600 μm of transmission line (0.4-0.8 dB).

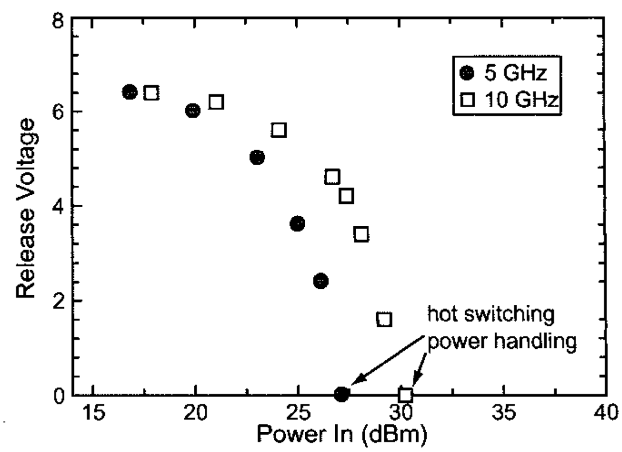

Fig. 4. DC release voltage versus input power at 5 and 10 GHz for a switch tested under hot switching conditions.

III. Switching Time versus Power

The switching time was measured using a stroboscopic technique where a high intensity, short duration LED light source is triggered (from the 5 kHz bipolar biasing waveform) to flash after a given delay. A slow motion video was created by sweeping the delay. The "apex time" is the length of time from return to zero of the bias voltage to the recoil apex of the switch. This time is much longer than the 10-20 μs that it takes for the isolation to become greater than 20 dB. A plot of the apex time versus input power is shown in Fig. 7. The apex time slowly increased with input power until the switch did not release before the next switch cycle began. Slow motion

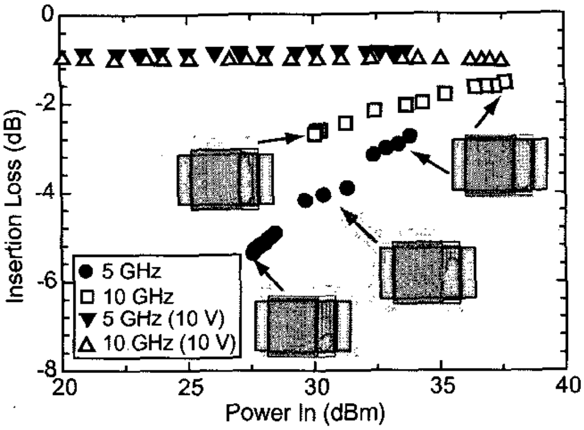

Fig. 5. Measured insertion loss versus input power at 5 and 10 GHz for a switch tested under hot switching conditions. Insertion loss with a 10 V bias in addition to the RF power is shown for comparison. Illustrations of switches represent approximate pulled-down area as recorded from visual inspection.

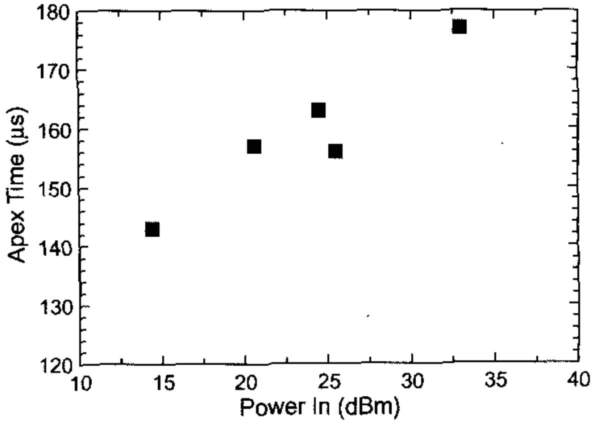

Fig. 7. Apex time versus input RF power level at 10 GHz for a typical switch (R5C10W2AB). The apex time is the length of time from zero bias voltage to the recoil apex of the switch and is much longer than the 10-20 μs that it takes for greater than 20 dB isolation.

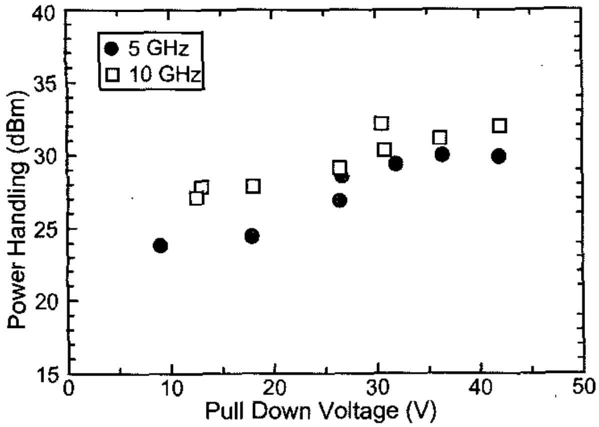

Fig. 6. Hot switching power handling versus DC pull down voltage for all the measured switches.

video showed, for powers near the hot switching limit, the switch hanging in a partially released state until the next cycle commenced.

IV. Discussion of Results

The hot and cold switching power handling levels demonstrated above are the highest RF power levels reported to date for a MEMS device. The upper limit of the cold switching power handling and linearity is most likely well above 7 W and was limited in the above experiments by the output power of the travelling wave tube amplifier. The high power handling levels makes the implementation of these switches in high power T/R switches and matching networks much more attractive.

The experiments above were performed with a 50 Ω system. RF MEMS implemented in a tunable filter, matching network or other resonant microwave circuit may be presented with impedances that differ from significantly from 50 Ω. This will change the RF currents and voltages in the device (especially in the down-state) and may change the power handling and linearity of the switch. This important area is the subject of future research in our group.

V. Theoretical Considerations

The electro-mechanical system under consideration consists, in its simplest form, of a MEMS switch attached to one end of a gap in the middle of an RF transmission line, acting as a series capacitor. The only sources of stimulus are an incident RF signal and the low frequency bias waveform. In order to model the behavior of the system, the mechanical, electrical and magnetic forces must be calculated.

The force due to the displaced switch is given by the negative of the derivative of the mechanical energy stored in the switch, with respect to the direction of motion. The electrostatic force on the switch is similarly given by the negative of the derivative of the energy stored in the capacitor, with respect to the direction of motion. The force due to the capacitor is then given by:

$$F_C = -\frac{dU_C}{dz} = -\frac{1}{2}\frac{d(CV^2)}{dz} \tag{1}$$

where C is the capacitance and V is the voltage across the capacitor. For a parallel plate capacitor the force is given by:

$$F_C = \frac{1}{2}\frac{\epsilon_o A V^2}{(z + t_d/\epsilon_r)^2} \tag{2}$$

where z is the air gap of the capacitor, t_d and ϵ_r are the dielectric thickness and relative dielectric constant, respectively.

At high frequencies, the circuit surrounding the device must be taken into account. The voltage V across a series capacitor in a transmission line is a function of the capacitance C for a series capacitor across the gap of the transmission line.

With the assumption of lumped capacitance, the voltage can be derived using simple circuit analysis and transmission line theory [3]:

$$V = \frac{2V_1^+ Z_s}{2Z_o + Z_s} \cos(\omega t). \quad (3)$$

where V_1^+ is the amplitude of the incident voltage wave, ω is the angular frequency of the incident voltage wave, Z_o is the characteristic impedance of the transmission line, and Z_s is the equivalent RF impedance of the switch ($Z_s = \frac{1}{j\omega C}$). A small resistance and inductance can also be included, but have little effect on the general result for $R < 5\ \Omega$ and $L < 100$ pH. The voltage across the switch can be related to the average incident power wave amplitude by:

$$V_c = \frac{2\sqrt{2Z_o P_{in}}}{\sqrt{1 + 4\omega^2 C^2 Z_o^2}} \cos(\omega t + \phi_\delta). \quad (4)$$

where $\phi_\delta = \arctan(-\omega C Z_o)$ is the phase difference across the capacitor.

When the MEMS switch capacitance is small or at low frequencies ($\omega^2 C^2 Z_o^2 \ll 1$), the switch looks like an open circuit and the voltage across the switch is approximately $2\times$ the incident voltage amplitude. When the switch capacitance is much larger and at high frequencies ($\omega^2 C^2 Z_o^2 \gg 1$), the switch looks like a short circuit (and a -90^o phase shift), greatly reducing the voltage across the switch.

Assuming partial validity of (2) for time varying electromagnetic fields on a parallel plate capacitor, if (4) is inserted into (2), we get:

$$F_C = \frac{2\epsilon_o A Z_o P_{in}}{(1 + 4\omega^2 C^2 Z_o^2)(z + t_d/\epsilon_r)^2} [1 + cos(2(\omega t + \phi_\delta))] \quad (5)$$

Note two facts: 1) the force has static and time varying components. If the MEMS switch mechanical resonant frequency is much lower than the frequency of the input power, the switch will not respond to the time varying component of the force and it may be neglected. 2) The force is a function of the frequency of the incident power, the capacitance of the switch, and the impedance of the transmission line. The frequency dependance of the voltage across the switch provides insight to the observed frequency dependance of the power handling, but cannot fully explain the results of section II-C.

For an overlap (distributed) series capacitance, the voltage and current in the overlap region is not constant and the lumped element approximation is not valid if you need to determine the RF current and charge distribution on each conductor of the overlap region. A full wave analysis of the series switch was performed using Momentum from Agilent EEsof [4]. The results showed that the current on the top conductor goes from a maximum to zero at the trailing edge and the current on the bottom conductor goes from zero to a maximum, travelling from the beginning to the end of the overlap region. As well, the electric field density between the plates is not constant over the entire overlap region. This observation, coupled with the flexible membrane nature of our switch may account for the partial down-state capacitance seen in Fig. 5. It is clear that a more rigorous approach is necessary.

Several methods exist to calculate the electromagnetic forces at RF frequencies. The Virtual Work Method used in the derivation of (1) has been used by Malinin, et al. [5]. Osterberg et al. proposed the use of singularity functions and Coulomb's law [6]. Jackson et al. have used the integral of the Maxwell stress tensor over a closed surface [7] to calculate the electromagnetic force. All of these methods require a knowledge of the charge distribution, electric and magnetic fields for a given geometry. An iteratively-coupled nonlinear thermo-electromagnetic-mechanical model, may be necessary to accurately model the RF power handling [8], and we are actively pursuing this area of research.

VI. Conclusions

The series MEMS capacitive switches developed at MIT Lincoln Laboratory had good linearity at 5 and 10 GHz in the up- and down-states. They handled nearly 10 W of RF power in cold switching mode. Several switches were able to handle over 1.5 W of RF power at 10 GHz in a hot switching mode, the highest reported result to date. The experimental results show that special attention must be paid to the effect that RF power has on the release voltage and switching speed of MEMS capacitive switches.

Certain experimental results, such as a partial down-state capacitance and the frequency dependance to the power handling, highlight areas of future research necessary for full understanding the the observations.

Acknowledgment

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