Inline Capacitive and DC-Contact MEMS Shunt Switches

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***Abstract*—This paper presents inline capacitive MEMS shunt switches suitable for X/K-band and Ka/V-Band applications. The inline switch allows for a low- or high-inductance connection to the ground plane without changing the mechanical characteristics of the MEMS bridge. Excellent isolation and loss are achieved with this design, and the performance is very similar to the standard capacitive MEMS shunt switch. Also, a new metal-to-metal contact MEMS shunt switch is presented. A novel pull-down electrode is used which applies the electrostatic force at the same location as the metal-to-metal contact area. A contact resistance of 0.15–0.35 Ω is repeatable, and results in an isolation of −40 dB at 0.1–3 GHz. The measured isolation is still better than −20 dB at 40 GHz. The application areas are in high-isolation/low-loss switches for telecommunication and radar systems.**

***Index Terms*—Micromachining, microwaves, mm-waves, phased arrays, radars, RF MEMs, switches, telecommunications.**

I. Introduction

MICROELECTROMECHANICAL (MEMS) series and shunt switches have been successfully demonstrated from 1–100 GHz for low loss switching and phase shifter applications [1]–[5]. The series metal-to-metal contact (dc-contact) switch has an off-state capacitance of 2–8 fF, which results in high isolation up to 20–40 GHz. The loss of the series switch is determined by the contact resistance, and for a contact resistance of 1–2 Ω, the loss is 0.1–0.2 dB. Another design is the capacitive switch which has been mostly used in the shunt topology at 10–110 GHz [6], [1]. The capacitive MEMS switch has an up-state capacitance of 30–100 fF and a capacitance ratio of 40–80, resulting in a down-state capacitance of 1.4–3.5 pF, and excellent isolation at 10 GHz and above. The capacitive shunt switch is typically built with the anchors attached to the coplanar waveguide (CPW) ground plane (or a microstrip $\lambda/4$ stub). Muldavin *et al.* have shown that the capacitive switch can be well fitted using a CLR model and results in very low-loss operation and high-isolation up to 100 GHz and above [2], [6].

This paper details a novel version of the shunt switch topology. The switch can be designed to result in a capacitive contact or in a dc-contact with the use of one additional metal layer. The dc-contact shunt switch results in a very low contact resistance due to the use of a novel pull-down electrode, and therefore in excellent isolation at 0.1–5 GHz.

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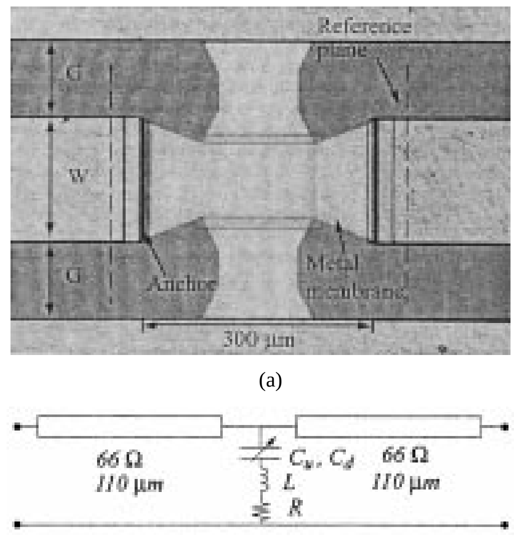

Fig. 1. Photomicrograph of a (a) X/K-band inline shunt capacitive switch and (b) equivalent model.

II. Inline Capacitive Switch Design and Measurements

The inline capacitive switch is shown in Fig. 1. The MEMS bridge is defined in the CPW center conductor, and is suspended over a 4000 Å-thick layer which connect together the two grounds of the CPW line. The idea of an inline air-bridge has been demonstrated before using standard air-bridge technology and is applied here for MEMS switches. A nitride layer is defined over the central portion of the bridge, and forms the capacitive contact between the center conductor and the ground plane once the bridge is pulled down. The advantages of this approach is that it isolates the mechanical characteristics of the MEMS bridge from the electrical connection to the ground. In other words, one can now use a narrow high-inductance or a wide low-inductance connection to the ground plane (in a microstrip or CPW implementation) without changing the mechanical spring constant of the MEMS bridge.

Another advantage of the inline switch in the up-state is the short high-impedance transmission line section due to the height of the bridge. This occurs at the left and right sides of the central bridge portion and help tune out the up-state capacitance. In both the X/K-band and the Ka/V-band switches, the equivalent transmission line impedance is 66 Ω with a length of 100–120 μm. The model shown in Fig. 1(b) is used to accurately fit the up-state return loss of the switch.

Fabrication: The MEMS bridge is fabricated using the standard techniques described before [2]. First, a 4000 Å gold layer is defined which includes the CPW line and ground-to-ground

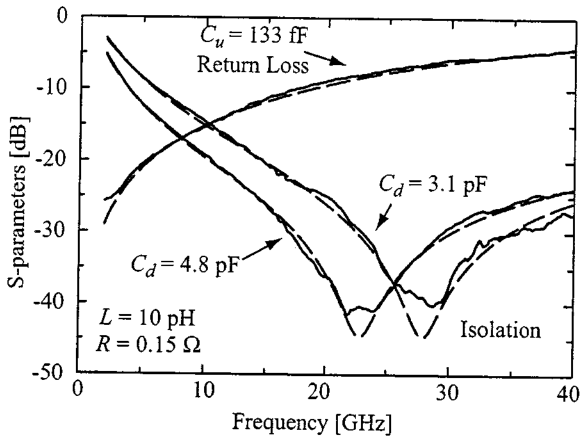

Fig. 2. Measured (solid) and fitted (dashed) S-parameters of a X/K-band inline shunt capacitive MEMS switch.

connection. Next, a 2000 Å-thick nitride layer is deposited using a PECVD process at 250 °C. A 1.5 μm-thick photoresist layer is used as the sacrificial layer, and the MEMS air bridge is fabricated using a Ti/Au sputter deposition with a total thickness of 9000 Å. The CPW line and MEMS bridge anchors are electroplated to a total thickness of 2.5 μm, and the MEMS bridge is released using a critical point drying process. The length of the MEMS bridge is 300 μm and the width depends on the required capacitance. The MEMS switch is biased using an external bias-T circuit between the CPW center conductor and ground.

X/K-Band Switch: The measured S-parameters for an inline X/K-band capacitive switch with a capacitive contact area of 140×100 μm^2 are shown in Fig. 2. The 50 Ω CPW line dimensions are $G/W/G = 96/160/96$ μm on a silicon substrate. The measured line loss is 0.25 dB/cm at 2 GHz and increases to 1.25 dB/cm at 40 GHz. The measured up-state capacitance is 133 fF and agrees well with the electrostatic simulations which predict a parallel-plate capacitance of $C_{pp} = 93$ fF and a fringing capacitance of $C_f = 31$ fF. The measured loss in the up-state position follow the $1 - |S_{11}|^2$ response. Isolation measurements are shown with the bridge fabricated in the down-state position, and with the bridge pulled down using 25 V. The isolation measurements fit well a CLR model with $L = 10$ pH and $R = 0.15$ Ω. The maximum parallel-plate capacitance is 4.8 pF ($C_{\max} = \epsilon_r A/d$), and the achievable pulled-down capacitance is 3.1 pF ($0.65 C_{\max}$). The difference is due to the roughness of the dielectric/bridge layer, and due to slight curling in the bridge preventing a complete conformal contact when the bridge is pulled down. The capacitance ratio is 24 due to the low height of the MEMS bridge. However, as shown in [7], this switch can be used in a tuned T or π-circuit to result in excellent isolation at 10 GHz and above.

The pull-down voltage was 18±2 V, and the applied voltage was set at 25 V. The extracted spring constant is 40±10 N/m using a nominal gap height of 1.5 μm.

Ka/V-Band Switch: The measured S-parameters for a Ka-Band inline switch (Fig. 3) are shown in Fig. 4. The 50 Ω CPW-line dimensions are $G/W/G = 60/100/60$ μm (). There is a 6000 Å-thick oxide layer in the CPW gaps, and

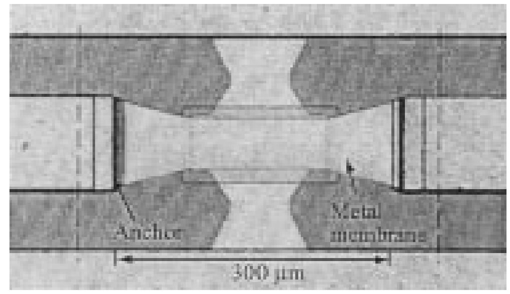

Fig. 3. Photomicrograph of a Ka/V-band inline shunt capacitive switch.

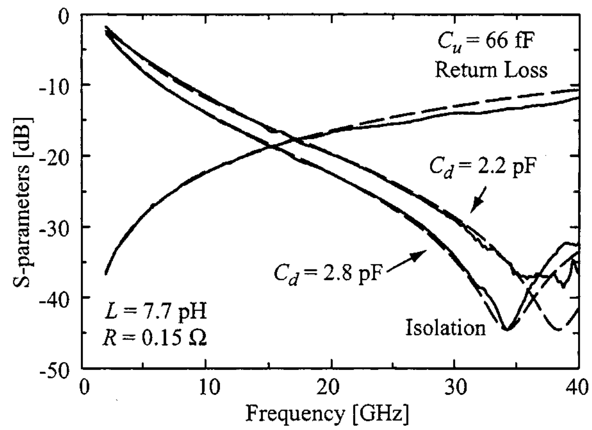

Fig. 4. Measured (solid) and fitted (dashed) S-parameters of a Ka/V-band inline shunt capacitive MEMS switch.

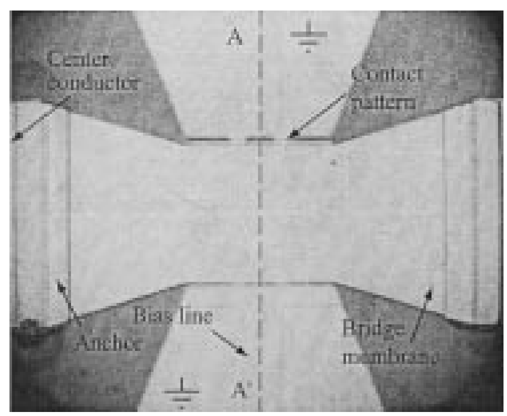

Fig. 5. Photomicrograph of the novel dc-contact inline shunt MEMS switch.

the measured loss is 0.5 dB/cm at 2 GHz and increases to 1.5 dB/cm at 40 GHz. The capacitive contact area is 140 × 60 μm-square and results in a measured up-state capacitance of 67 fF. This agrees with a height of 1.7 μm ($C_{pp} = 48$ fF, $C_f = 18$ fF). The measured down-state performance shows a maximum capacitance of 2.8 pF and a pulled-down capacitance of 2.2 pF ($0.79 C_{\max}$). This means that the MEMS bridge is being pulled down conformally and the reduction in the capacitance is solely due to the roughness of the dielectric. The inductance is reduced to 7.7 pH due to the smaller CPW gap (see [2]). The capacitance ratio is 33, and the Ka/V-band inline switch can be used at 15 GHz to 60 GHz using a T or π-match circuit.

The pull-down voltage was 21±3 V, and the applied voltage was set at 40 V. The extracted spring constant is 24±8 N/m. The

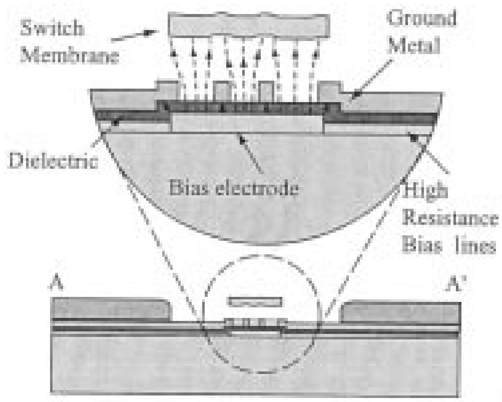

Fig. 6. Illustration of a dc-contact inline shunt MEMS switch. The static electric fields from the bias electrode pull the bridge to the ground contact.

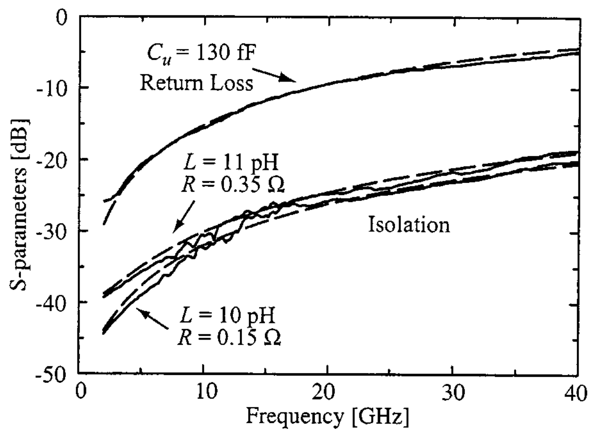

Fig. 7. Measured (solid) and fitted (dashed) S-parameters of an inline shunt dc-contact MEMS switch.

estimated mechanical resonant frequency is 54 kHz, assuming the modal mass is dominated by the central 200 μm portion. The calculated mechanical quality factor (Q) is 0.24, due to the absence of holes, and yields estimated switching times of 9–20 μs for $V_s = 2$ to $1.5V_p$.

III. Novel Metal-to-Metal Contact Inline Shunt Switch

The inline shunt switch can be made to operate at low RF frequencies (dc-10 GHz) using a metal-to-metal contact (Fig. 5). In this case, two metal layers are defined underneath the bridge. The first layer is the pull-down electrode, and is fabricated using a 3000 Å-thick layer of gold (Fig. 6). The pull-down electrode is connected using high-resistivity bias lines to the edge of the ground plane. A 2000 Å-thick nitride layer is used to isolate the bias lines from the CPW ground plane. The nitride layer is also deposited over the pull-down electrode. A 4000 Å-thick Au layer with is deposited on top of the nitride and is connected to the CPW ground using the “bow-tie”-shaped (low inductance) gold pattern. The top metal layer forms the metal-to-metal contact with the MEMS bridge and connects the MEMS bridge to the ground. The MEMS bridge is fabricated as described above using a sacrificial 1.5 μm-thick layer.

The top metal layer has a 10 μm hatch pattern underneath the center of the bridge with openings of 30 μm-square. The openings are essential to allow the static fields from the pull-down electrode to exert a force on the MEMS bridge. This novel electrode design allows for the placement of the pull-down electrode at the center of the bridge, thereby resulting in maximum bridge deflection for a specific applied voltage. The voltage is applied at the bias electrode and the CPW center conductor is connected to the dc ground.

The inline switch is fabricated in a $G/W/G = 96/160/96$ μm CPW line with a center electrode dimensions of 140×100 μm^2. The pull-down voltage is 35 V and the applied voltage is 50 V due to the reduced pull-down area (a result of the metal hatch pattern). The measured up-state capacitance is 130 fF and is the same as the capacitive inline switch described above. The measured contact resistance is very low, around 0.15–0.35 Ω, because the electrostatic force is applied at the same location as the metal-to-metal contact area. This may be one of the advantages of this novel design. The switch results in an isolation of −40 dB at 0.1–3 GHz (Fig. 7). The measured isolation is limited by the inductance to ground and is better than −20 dB at 40 GHz. The isolation at 40 GHz can be improved by 6 dB if a CPW gap of 40–50 μm is used, thereby resulting in an inductance of 5–6 pH.

The metal-to-metal inline switch can be further improved by choosing different metals with higher contact reliability (AuBe, AuTi, Pt, ErPt, …) and by fabricating bumps in the MEMS bridge to contact at specific points with a higher pressure per contact. In our case, the contact resistance of Au/TiAu was repeatable over two months in laboratory experiments with the wafer dried at 80 °C for 20 min and then flushed with nitrogen before testing. No lifetime tests were done in our laboratory.

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