Low Actuation Voltage RF MEMS Switches With Signal Frequencies From 0.25GHz to 40GHz

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Abstract

A novel low-voltage radio-frequency micro-electromechanical system (RF MEMS) switch is reported. The device switching voltages are 14-17 volts. When the device is operated in an 'on' state, an insertion loss of less than 0.5 dB with a return loss of –15 dB at 40GHz was measured. When operated in its 'off' state, an isolation of better than 27 dB over the frequency band from 0.25GHz to 40GHz was achieved. The RF MEMS switch equivalent circuit model shows that the 'on' resistance is 0.3 Ω and the 'off' capacitance is 90fF, which results in a figure of merit of 6000GHz.

Introduction

The low insertion loss and high isolation RF characteristics over a wide frequency range make MEMS switches the most attractive devices for reconfigurable antenna and integrated circuit applications (1). Most of RF MEMS switches utilize rotary (2), cantilever (3-4), and membrane structures (5-7). They have demonstrated superior RF characteristics compared to active-device-base solid state switches such as FET and diode switches. These RF MEMS devices, however, require very high actuation voltages (usually 30-50 volts). The high voltage operation is far beyond standard monolithic microwave IC operation, which is around 5 Volts DC biased operation. There is a crucial need for improved apparatus and method which address this drawback of known RF MEMS switches. At the University of Illinois, we proposed a novel RF MEMS switch for low voltage operation (8). The experimental results of the RF MEMS switch show a promising low voltage operation and excellent RF performance over the frequency band from 0.25GHz to 40GHz.

In this paper, we will present the fabrication and measurement results of a "hinged" RF MEMS switch. The results show that the device switching voltages are 14-17 volts. When the device is operated in an 'on' state, an insertion loss of less than 0.5 dB at 40GHz with a return loss of –15 dB at 40GHz was measured. When operated in its 'off' state, an isolation of better than 27 dB over the frequency band from 0.25GHz to 40GHz was achieved. The RF MEMS switch equivalent circuit model shows that the "on" resistance is 0.3 Ω and the "off" capacitance is 90fF, which results in a figure of merit of 6000GHz.

Device Structure

The schematic cross-sectional view of the RF MEMS switch is shown in Fig. 1. The RF signals are guided by a coplanar waveguide (CPW) structure, which is composed of a signal line and ground planes on both sides. A conductive pad is inserted in between the top and bottom electrodes and hangs across the signal line and ground planes of the coplanar waveguide. Brackets are applied to guide the pad as it moves up and down. The top and bottom electrodes facilitate the application of the actuation voltages. The actuation voltage provides an electrostatic force to make the conductive pad move up and down in a single-pole-double-throw configuration. When a voltage is applied on the bottom electrodes, the pad contacts the signal line and ground planes and provides a through path for signals, as shown in Fig. 1(a).

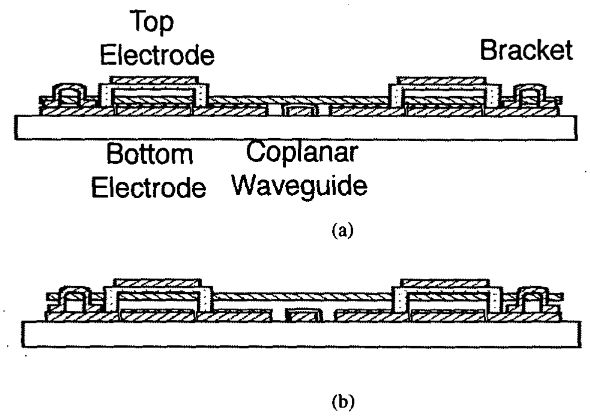


Fig. 1: The schematic cross-sectional side view of RF MEMS switch with hinge configuration for (a) switch 'off' operation and (b) switch 'on' operation, respectively

The input RF signal from one port will short to the ground and no RF signal will flow through the other port. This corresponds to the switch 'off' state. When a voltage is applied to the top electrodes, as shown in Fig. 1(b), the conductive pad is attracted upward. RF signals flow through the output port without much insertion loss. This corresponds to the switch 'on' state. The switching operation can therefore be realized by applying two out-of phase pulses on the top and bottom actuation electrodes. Ideally, the minimum electrostatic force required for actuation is equal to the sum of the weight and the air friction of the conductive pad. The minimum actuation voltage V_{min} required for the switch operation can be estimated by:

$$V_{\min} = \sqrt{\frac{2(mg + F_{friction})}{\varepsilon_o A_{pad}} d} \qquad (1)$$

where

d: the spacing between the conductive pad the electrodes,
mg: the weight of the conductive pad,
$F_{friction}$: the frictional force,
A_{pad}: the area of actuation pad, and
ε_o: the permitivity of the air.

Assume that the conductive pad size is $100\text{X}400\mu\text{m}^2$ and d is 4μm, the minimum actuation voltage will be less than 1 volts if the air friction is ignored.

The "hinged" RF MEMS switches offer several advantages. First, the high actuating voltage due to mechanical stress in MEMS devices can be reduced to less than two volts. Second, the switch is electrically isolated from the actuating voltage. Third, the device size can be relatively small to enable direct scaling to higher frequency applications.

Fabrication Processes

The RF MEMS fabrication processes have been developed to be compatible with MMIC fabrication processes. Surface micromachining techniques are utilized to fabricate the switches on semi-insulating GaAs substrates. A 1-μm thick Au layer is evaporated and patterned to form the CPW and the bottom electrodes. A layer of PECVD silicon nitride is deposited, followed by a via-hole etch. Next, a polymer sacrificial layer is spun on and a 0.6-μm thick Au layer is evaporated to form the conductive pad. Another polymer sacrificial layer is spun on and a 1-μm thick PECVD silicon nitride layer is deposited and patterned. A 0.5-μm Au layer is then evaporated to form the top electrodes. Finally, the sacrificial layers are removed by a plasma etch.

The fabricated hinge RF MEMS switch is shown in Fig. 2. The suspended conductive pad, which is 100 μm in width, hangs across the signal line and ground plane. It shorts the signal line to ground when it is in the "down" position. The coplanar waveguide has a width of 20μm and a gap of 15μm. There are 8-μm holes in the conductive pad and the top electrodes. They serve as undercut access holes for sacrificial layer removal.

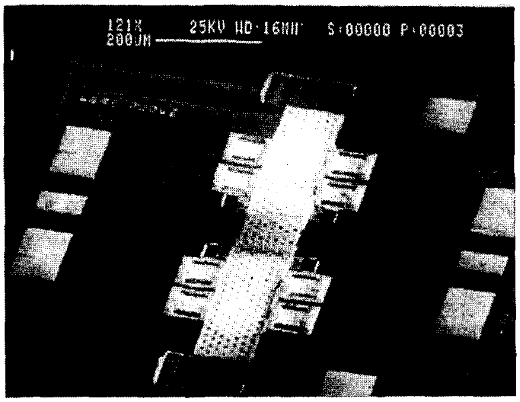
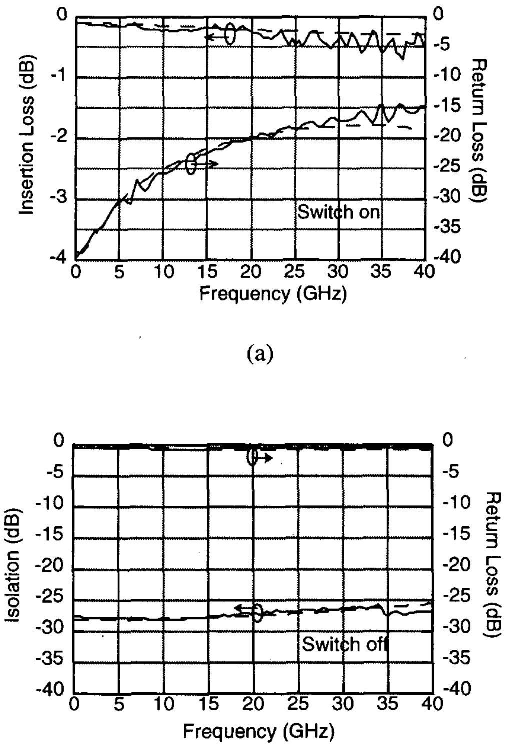


Fig. 2: A SEM photograph of fabricated RF MEMS switch.

Results and Discussion

The S-parameters of the device were measured from 0.25GHz to 40.25GHz using an HP8510C vector network analyzer and Pico probe RF on-wafer coplanar probes with 150 μm pitch. The system was calibrated using a commercially available Impedance Standard Substrate, which has a quartz substrate with short, 50Ω load, and through standards patterned on the surface. When the hinge was in the 'up' position (switch 'on' state) as shown in Fig. 3(a), an insertion loss of 0.25 dB at 20GHz and 0.5 dB at 40GHz with a return loss of –20dB at 20GHz and –15 dB at 40GHz was measured. When the hinge was in the 'down' position (switch 'off' state) as shown in Fig. 3(b), an isolation better than 27 dB over the frequency band from 0.25GHz to 40.25GHz was measured. The wide bandwidth isolation characteristic is due to a low resistance, rather than a capacitance, across the signal line and the ground planes. The actuation voltage is 14-17 volts. To our knowledge, the actuation voltage is among the lowest voltages for RF MEMS switches reported so far. Further reduction in actuation voltage can be achieved by optimizing the processing steps.

The device parameters are extracted from S-parameter measurements and are modeled in a HP Microwave Design System (MDS). The measured results are de-embedded using



(a)

(b)

Fig. 3:The RF performance of MEMS switch for (a) 'switch on' state and (b) 'switch off' state. The experiment data are shown in solid line and simulation data are shown in dashed lines.

a CPW model developed by Shimon (9). The device is decomposed into 2 sections of CPW and the intrinsic switch portion, as shown in Fig. 4.

The de-embedded data is used for the device modeling. The lumped-circuit model for both 'on' and 'off' states is shown in Fig. 5. The lumped circuit model simulates the finite length transmission line embedded in the device and the core portion of the switch. R_{l1}, R_{l2}, L_{l1}, and L_{l2} account for the resistance and the inductance of the finite length transmission line; C_{para} is the parasitic capacitance between the metal plate and the coplanar structure due to non-uniform metal contact. The core portion of the switch consists of a variable capacitance C_s in series with a resistance R_s and an inductance L_s. The L_s includes the effect of the large metal plate hanging across the signal line and R_s accounts for the contact resistance for the 'off' state. C_s is a capacitance which changes as a function of the position of the metal plate.

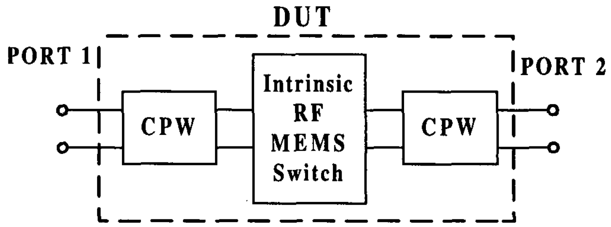


Fig.4: The circuit model used for derivation of device parameters of the intrinsic RF MEMS switch.

The device parameters are listed in Table 1. For the 'on' state, there is capacitance between the signal line and the metal plate. For the 'off' state, the metal plate shorts out the signal line and the ground plane, making C_s zero. The inductances of the signal line, L_{l1} and L_{l2}, are also reduced because part of the signal line is shorted to the ground. The equivalent circuit model is used in predicting the performance of the switch. As shown in Fig. 3, the simulated S-parameters agree well with the experimental data up to 40GHz. The 'on' resistance is 0.3Ω and the 'off' capacitance is 90fF. The figure of merit is around 6000GHz.

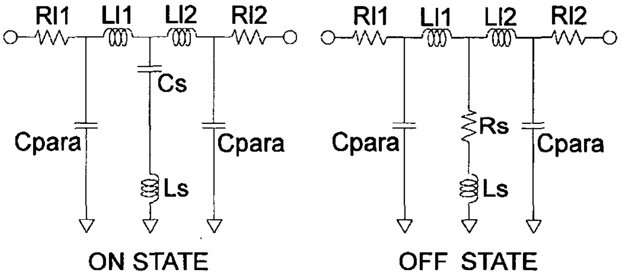


Fig. 5: The equivalent circuit of RF MEMS switch for both 'on' and 'off' states.

Switch State	R_{l1} (Ω)	L_{l1} (nH)	R_{l2} (Ω)	L_{l2} (nH)	C_{para} (fF)	R_s (Ω)	L_s (pH)	C_s (pF)
ON	0.15	0.06	0.15	0.08	45	0	1.2	0.006
OFF	0.15	0.05	0.15	0.07	45	1.05	1.2	0

Table 1: The device parameters of a intrinsic RF MEMS switch

Conclusion

A new class of RF MEMS switch is reported. It possesses wide bandwidth, low insertion loss and high isolation RF characteristics. The potential low actuation voltage operation make the switch the best candidate for integration with monolithic millimeter wave integrated circuits. The RF MEMS switch model has also been developed. This new RF MEMS switch will provide a solution for low voltage and highly linear switching topologies for the next generation of broadband RF, microwave, and millimeter-wave circuits and systems.

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