A BI-STABLE ELECTRO-THERMAL RF SWITCH FOR HIGH POWER APPLICATIONS

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ABSTRACT

This paper reports on the development of a bi-stable electro-thermal RF switch which can be operated with zero standby power (and bias) in either latched state. The device includes a bi-stable structure, which electrically shorts the input and output signal lines. Two electro-thermal actuators are used to switch it on and off. The entire structure is fabricated from 27 µm thick electroplated Cu, suspended 3 µm above a glass substrate. Typical actuation of the driving engine is performed by a 20 ms single pulse, corresponding to power and energy consumption of 33 mW and 662 μJ, respectively. Bursts of pulses of 0.1 ms width, used in sets of various durations, can reduce the total switching energy to < 210 µJ. Measurements show that at 2.2 GHz, the device offers –0.5 dB insertion loss and –38 dB isolation, whereas at 3.5 GHz it offers –1 dB insertion loss and –30 dB isolation. Power handling capability tests for cold switching show that the device can be easily switched even after flowing >1 W RF power, suggesting that any micro-welding that may occur does not impede switching.

I. INTRODUCTION

MEMS-based RF switches have been developed extensively for the past decade [1]. However, for normally open switches, power has to be applied for the entire time that the switch is on. While this may not increase the power consumption significantly for electrostatic switches, it has other detrimental effects, such as charging of dielectric layers, which leads to a drift in the actuation voltages. In addition, the transmitted data in a telecommunication network could be lost if the applied power fails. Therefore, exploration of latched RF switches is essential for some applications. In particular, *bi-stable* devices, in which the actuating bias can be turned off after switching, are needed. These are attractive especially when switching is infrequent. While bi-stable electro-magnetic actuation has been reported [2], it requires permanent magnets, which are not easily integrated. Electro-thermal actuators [3], which require low operating voltages and offer high contact forces, have been very successful for RF switching [4]. For these devices, latching is almost essential because they tend to consume more power than electrostatic switches. While latching mechanisms have been proposed for them [5, 6], latching appears to have been only accomplished by pushing with an off-chip manipulator. An electrothermal device, which is held closed by electrostatic force, has been reported [7], but requires a bias to stay on.

Another vital issue is power handling capability, which is related to the impact force of the switch. A large impact force is helpful for RF switches because it breaks through corrosion and contamination on the contact surface, increasing reliability, easing packaging restrictions, and permitting the transmission of large RF power. Therefore, a fully integrated bi-stable RF switch with zero standby actuator power and large signal power handling capacity is still needed.

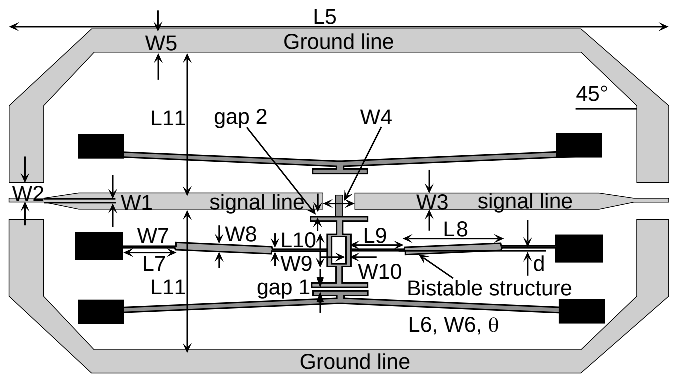

Fig 1: Schematic illustrating the CPW and RF switch.

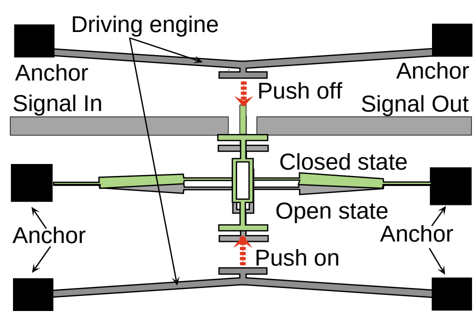

Fig.2: Operation of the bi-stable switch (not to scale).

Table 1: Dimensions of the CPW, switch, and properties of copper, dimensions are in microns and the thickness is 27 μm.

Transmission line portion	W1=50, W2=100, W3=100, W4=150, W5=400, L5=4640, L11=420
Driving engine portion	W6=10, L6=1500, θ6=0.02 radian (two actuators)
Bis-table structure portion	W7=W9=3, L7=L9=150, W8=20, L8=550, W10=5, L10=130, d=12.5
Properties of Cu	Young's modulus E=1.28×10^5 MPa, Poisson's ratio=0.36,CTE=16.8 ppm/K

II. DEVICE DESIGN AND FABRICATION

Device structure and design

Figure 1 shows the schematic of the proposed device, in position within a co-planar waveguide (CPW) that is surrounded by two ground lines. A bi-stable element is positioned to fill the breach in the CPW, and in-plane bent-beam electrothermal actuators [3] are located on both sides of it to push it on and off. The operation of the switch is illustrated in Fig. 2.

Bi-stable structure design

The bi-stable structure is a suspended beam with a shallow lateral bend. A flexible element in the center provides longitudinal compliance so that it can be pushed laterally from side to side. By scaling its various dimensions, the reaction and latching forces of the bi-stable structure can be tuned. Since bent-beam electrothermal actuators are used, forces in the milliNewton range can be achievable.

The calculated potential energy curve of the bi-stable structure shown in Fig. 3 (a) is obtained using the dimensions given in Table 1, assuming that the structural material is copper. The calculation is performed using FEA by ANSYS™ including non-linear analysis. The element type used is BEAM3. It clearly shows that the structure has two energy valleys, which correspond to two stable positions. It should be noted that the two valleys are somewhat asymmetric. Its corresponding reaction force/displacement curve is given in Fig. 3 (b). The reaction force of the bi-stable structure is highly nonlinear with the displacement. The magnitude of the reaction force initially rises to a maximum value F_{min}, beyond which the force decreases to zero at its unstable equilibrium point. In the absence of external forces, the structure could remain at this position. However, any small perturbation could snap the structure into either stable position. After passing this position, the reaction force rises again in the other direction to the other maximum value F_{max}, and then drops to zero at the other stable position. For this design, the peak contact forces are about 12 μN in the absence of residual stress. By modifying the boundary conditions and dimensions of the bi-stable structure, the reaction forces can be scaled readily. From the reliability point of view, care should be taken to keep the peak stress in the structure, which occurs near the anchors, lower than the yield strength of the structural material.

In practice, the electroplated copper has tensile residual strain after the device is released from the substrate. This shifts the two stable positions and also reduces the potential barrier between them, decreasing the reaction force. Figure 3 shows the consequence of 100 μstrain residual tension in the structural material.

There are two ways to switch the bi-stable structure upon impact from the drive engine. One way is to impart sufficient kinetic energy so that the bi-stable structure itself overcomes the potential energy peak and snaps to the other stable position. The other way is to gently push the bi-stable structure with the driving engine until it passes the unstable equilibrium point, thereby falling into the other stable position. In this project, the first method is used.

The impact force between the switch and the signal line is dependent on the force offered by the electrothermal actuators and the velocity of the impact, while the sustained latching contact force is determined by the reaction force of the bi-stable structure at its rest position against the signal lines. The impact force can be scaled up to milliNewton range, which is easily provided by the bent-beam electrothermal actuators. For the design in Fig. 3, however, the maximum latching contact force is 11 μN, available at 22 μm in the absence of residual strain (Fig. 3b). Thus, in order to ensure maximum latching contact force for this specific design, the separation (gap2) between the open position of the switch and signal lines should be 22 μm. It is important to note that this latching contact force can also be easily scaled to milliNewton range by scaling the dimensions of the bi-stable structure.

The contact element attached to the bi-stable structure can be engineered to reduce any bounce that may occur at contact: a larger compliance will reduce the bounce, but will also compromise the contact force to some extent.

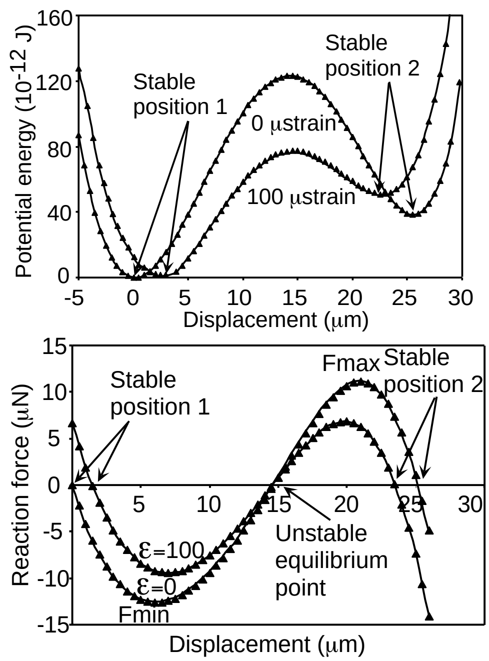

Fig. 3: (a: upper) Calculated potential energy curve for the bi-stable structure; (b: lower) Calculated reaction force curve for two different residual strains of 0 and 100 μstrain.

Driving engine design

The bent-beam electro-thermal actuator is utilized as the driving engine in this RF switch design. The bent-beam electrothermal actuator design used in the device (Table 1) offers 28 μm displacement without loading, and 1.14 mN peak loading force for a uniform temperature change of 25 °C. The gap (gap1) between the bi-stable element and actuator is 5 μm as drawn (Fig. 1). However, in the presence of 100 μstrain residual tension, this increases to 10 μm. Thus, the actuator experiences no external loading for the first 10 μm of displacement. In addition, it must be able to provide sufficient velocity to the bi-stable element upon impact to overcome the 6.3 μN reaction force. By scaling the dimensions of the actuator, the driving force and displacement can be scaled to satisfy specific requirements.

Device Fabrication

Devices were fabricated from 27 μm thick Cu electroplated in an SU-8™ mold on a Pyrex™ glass substrate. A 3 μm thick sacrificial layer of Ti layer was used for suspended elements. The impact forces at milliNewton range of this switch are large enough for unpackaged operation in a laboratory in air despite the use of Cu, which tends to tarnish. For commercial applications, a thin film of Au or packaging in an inert gas environment may be used. Figure 4(a) shows the SEM of the fabricated device, and Fig. 4(b) gives the close-up of the 3 μm wide structures with 27 μm height.

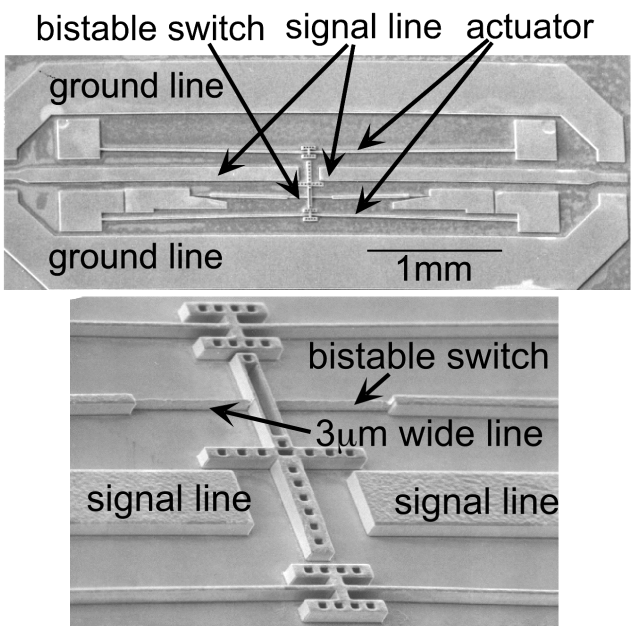

Fig. 4: (a: upper) SEM of the fabricated device; (b: lower) close-up of the device showing the 3 μm structure with 27 μm tall structure.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Electro-mechanical characterization

Figure 5 shows optical micrographs of a switch in open (as fabricated) and latched (on) positions. Our past work [8] has shown that metal actuators, which tend to have very low resistance values, are best operated by pulsed currents. In this effort, typical actuation is by a 20 ms single pulse actuation, power and energy used to close the switch are 33 mW and 662 μJ, respectively. This includes a substantial safety margin. Figure 6 shows measured peak displacements obtained from an unloaded actuator using 5 ms long pulses of varying current levels. The maximum blocking forces are estimated from quasi-static analysis using formulas presented in [8]. Thus, for example, a 5 ms pulse of 275 mA produces a 21 μm displacement or a blocking force of 800 μN.

The impact of varying the pulse width has also been explored. These tests were performed on an actuator of 3000 μm overall length, 10 μm width, and 0.05 radian bending angle. Figure 7 shows that as the pulse width is reduced, the energy consumption, defined as the product of the current flowing through the actuator, the voltage across it, and the duration of the actuation, also reduces. As the pulse width reduces from 5 ms to 1 ms, the energy required to close the switch reduces from 1031 μJ to 343 μJ. Similarly, the energy required to open the switch reduces from about 585 μJ to 220 μJ. The caveat is that the peak current values required to cause these transitions increase as the pulse widths decrease. The peak current increases from 550 mA to 713 mA and from 456 mA to 619 mA to close and open the switch, respectively.

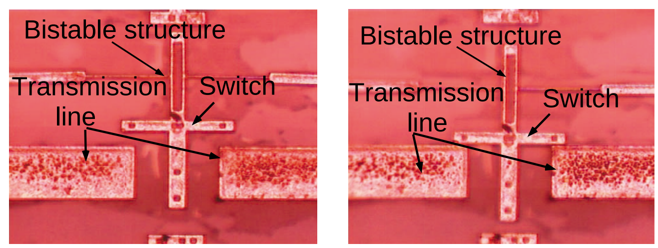

Fig. 5: (a: left) Optical micrograph of the open switch; (b: right) optical micrograph of the closed switch.

The energy efficiency achieved by using actuation pulses of smaller duration motivates the exploration of using bursts of very short pulses to accomplish further savings in energy. These results are also plotted in Fig. 7. Measurements found that with a single pulse width of 1 ms, the power and energy required to turn on the switch are 343 mW and 343 μJ, while using bursts of 0.1 μs pulses, the power and energy are 208 mW and 208 μJ, respectively. The power consumption reduces by about 40%. The peak current for 1 ms pulse was 713 mA, while that for the burst was about 900 mA.

RF test

An HP 8510C vector network analyzer was used to characterize the device. The pad parasitics were removed from the measurements by using on-wafer calibration standards. The measured data in Fig. 8 indicates that at 2.2 GHz, in the closed state of the switch the insertion loss is –0.5 dB; in the open state the isolation is –38 dB. At 3.5 GHz, the insertion loss is –1 dB and the isolation is –30 dB. It should be noted the geometry of the device is not optimized for these frequencies. We envision that the switch can work up to 10 GHz with an optimized RF design, which is under investigation currently.

Power handling test

The device was tested using 1 ms pulses of DC power while the resistance along the signal path was measured with the closed switch (Fig. 9 (a)). This resistance reduced from 0.68 Ω at 6.8 mW transmitted power to 0.13 Ω at 1.5 W. The switches were easily opened by the normal electrothermal actuation even after these high power measurements, indicating that any micro-welding that may have occurred did not impede switching. The measurements also suggest that by local heating between the interface of the switch and the signal lines, the DC resistance of the signal path can be significantly reduced and can be beneficial to the RF performance.

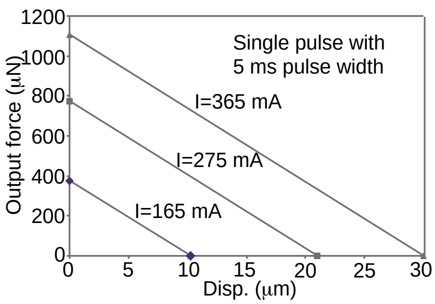

Fig. 6: Measured displacement and calculated force for the actuators.

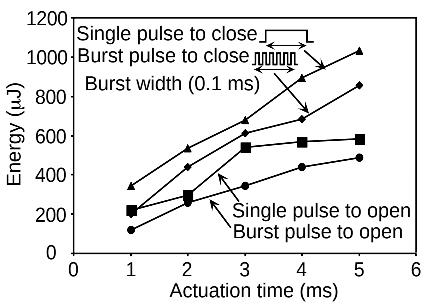

Fig. 7: Actuator energy to close and open RF-switch in single pulse and burst modes.

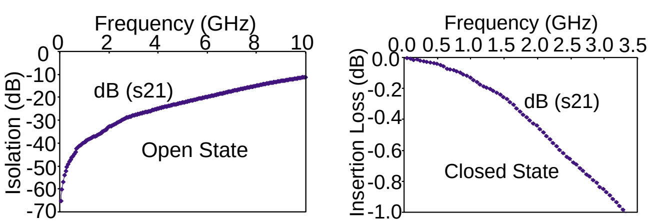

Fig.8: (a: left) Measured isolation, and (b: right) insertion loss.

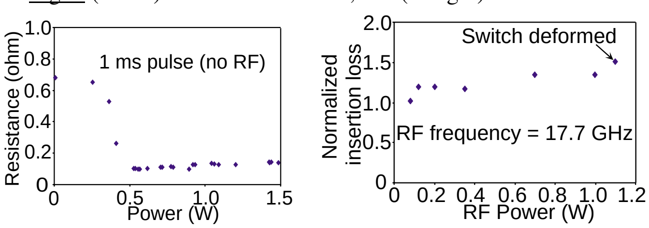

Fig. 9: (a: left) Switch resistance as a function DC power, and (b: right) normalized insertion loss as a function of transmitted power at 17.7 GHz.

Power handling tests have also been performed using RF signals. However, these were constrained by the availability of a high power source that operated only at 17.7 GHz. Cold switching, i.e., switching with the signal off, was performed before and after transmitting signal power upto 1 W without degradation as shown in Fig. 9(b).

IV. CONCLUSIONS

This effort illustrates the development of a bi-stable RF switch for high RF power applications that requires no voltage or power applied to the actuator to maintain either switched state. The switching can be accomplished with < 210 μJ energy and the contact forces are high enough to permit operation of a Cu switch in laboratory conditions without packaging. For all frequencies upto 3.5 GHz, the insertion loss and isolation of the CPW signal line are –1 dB and –30 dB with a closed and opened switch, respectively. RF power up to 1 W can be handled without any degradation under cold switching conditions. Furthermore, it is found that the DC power reduces the resistance of the signal line, benefiting its RF performance. The high force actuators eliminate any problems that might otherwise exist due to micro-welding.

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