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Improved MEMS based shunt switches for telecom applications

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Abstract - A novel RF-MEMS capacitive switching device implementing an electrically floating metal layer is proposed. An optimal switch down capacitance is ensured with such a structure. Moreover it allows the down/up capacitance ratio to improve beyond the theoretical maximum value of the conventional RF-MEMS capacitive switches. Simulation and measurement results clearly indicate an improved performance compared to conventional RF-MEMS capacitive switches, in the frequency range from 1 to 30 GHz. The measured down/up capacitance ratio in the novel structure is up to 34 times larger than the same ratio measured on conventional designs with equal size and using the same materials. The advantages of RF MEMS Switch with a combined Series-Shunt-Series architecture are briefly described.

Keywords: RF MEMS, RF Switch, Wireless communication systems.

I. Introduction

RF-MEMS switches offer great potential benefits over GaAs MMICs and PIN diode switches for application in wireless communication systems [1,2]. Prototype RF-MEMS switches display low loss (<0.4 dB), good isolation (>20dB), extremely low standby power consumption, excellent linearity (IP3> 66dBm), compactness and high levels of integration [3,4]. Alternative configurations for RF-MEMS switches have been developed including Series and Shunt switches.
The typical implementation of a shunt switch on a CPW (CoPlanar Waveguide) line has the structure shown in Fig. 1 [5-7]. The switch consists of a suspended movable metal bridge, which is mechanically anchored and electrically connected to the ground of the CPW. To first order, the switch can be modeled as a capacitor between the metal bridge and the signal line. In the RF-ON state the bridge is up, hence the switch capacitance is small, hardly affecting the impedance of the line. By applying a DC bias (superimposed on the RF signal) the bridge is pulled down onto the dielectric, the switch capacitance becomes high and the switch is OFF or in the isolation state. An impor-

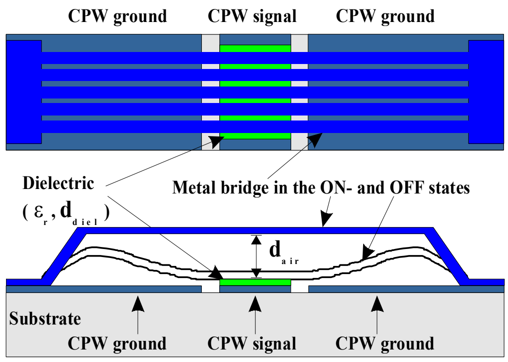

Fig.1: Standard RF-MEMS capacitive shunt switch

tant figure of merit quantifying the RF performance is the down/up capacitance ratio, C_{down}/C_{up}, which can be approximately expressed as

$$C_{down}/C_{up} = \frac{\varepsilon_o \varepsilon_r A_{overlap}/d_{diel}}{\varepsilon_o A_{overlap}/d_{air}} = \frac{\varepsilon_r d_{air}}{d_{diel}}$$

where d_{air} and d_{diel} are the thickness of the air gap and the dielectric, respectively, ε_r is the dielectric constant of the dielectric and $A_{overlap}$ is the overlap area of the bridge and the signal line. The larger the C_{down}/C_{up} ratio the better the switch performance is. Surface roughness in the central part of the switch (see Fig.2(a)) prevents intimate contact between the bridge and the dielectric in the down state. As a result, parasitic air gap capacitances remain in series

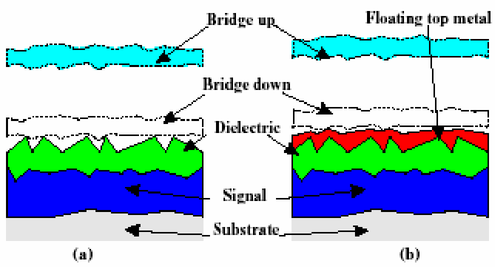

Fig.2: Close-up on the active area showing the parasitic air-gaps as a result of the surface roughness: a) conventional, b) with floating metal

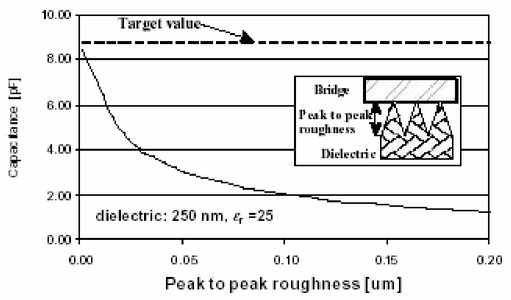

Fig.3: Influence of the roughness on the down capacitance

with the down capacitance needed for efficient switching. Simulation results plotted in Fig.3 show that a peak-to-peak roughness distribution between 0 to 20 nm on a 250 nm thick dielectric with ε_r = 25 (Ta_2O_5) already dramatically reduces the down capacitance by a factor of 2. The commonly pursued solutions to this problem aim at keeping the roughness of the bridge and of the dielectric layer very low, e.g., <5 nm, and to keep the surface free from residues [5-7].
Muldavin *et al.*[6] and Yao *et al.* [5] introduced thin bottom metals in an attempt to reduce the roughness. In particular, in [5], a thin refractory metal layer (e.g., W) was used. This however introduces a high series resistance leading to an increased insertion loss. Moreover, a lower roughness leads to higher stiction forces and thus to a lower reliability. Clearly, in a conventional design as the one shown in Fig. 1, a difficult trade-off must be made between on one hand the need of high isolation requiring a low surface roughness and on the other hand the insertion loss and unreliability problems associated with such a low roughness.

II. New RF MEMS switch with modified shunt configuration: Switch Design

The novel modified RF-MEMS capacitive switch proposed in the present work and sketched in Fig.4 solves the surface roughness trade-off. A close-up of the contact area in this new structure is shown in Fig. 2(b). Key points in the novel design are the use of an electrically floating metal layer covering the dielectric, and the use of separate DC actuation electrodes. The concept of using the floating metal is to ensure an optimal down capacitance without having to resort to very smooth surfaces. The theoretical down capacitance C_{down} is given by $\varepsilon_o\varepsilon_r A_{float}/d_{diel}$, where A_{float} is the area of the floating metal. The theoretical C_{down} is achieved once the bridge pulls-in and touches the floating top metal, even in a small area as there is no air gap between the top floating metal and the dielectric layer. In addition it becomes possible to use a highly conductive, thick (e.g. same thickness as usual CPW lines) and thus low-loss bottom metal layer. The capacitance that can be obtained by this method is very close to the value reached for a perfectly smooth dielectric. Moreover, surface roughness in the contact areas of the moving structures can now be introduced on purpose in order to minimize the contact surface, thus reducing stiction. The only requirement is that the contact impedance (combination of contact resistance and capacitance due to a native oxide layer) from the bridge to the floating metal is low enough not to introduce too high signal losses.

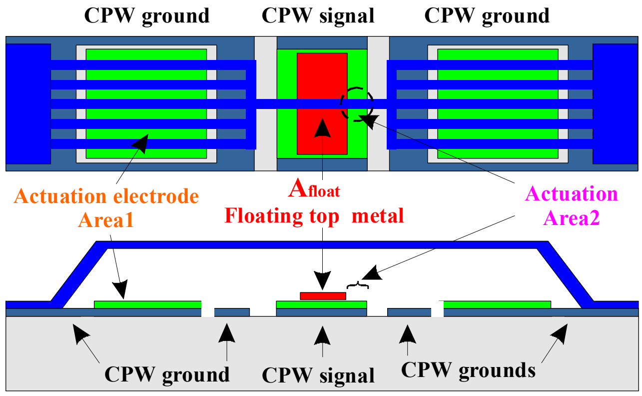

Fig.4: MEMS switch implementing a floating top metal covering the dielectric

Since the areas describing C_{down} and C_{up} in the proposed structure are decoupled, it becomes possible to optimize both capacitance independently. Therefore, in addition to a high C_{down}, C_{up} can be lowered without affecting the down capacitance. This is achieved in the improved switch structure by making the bridge narrower than the floating top metal width.
A separate DC actuation is introduced to cope with the presence of the floating top metal, since covering the standard switch in Fig. 1 with a floating metal would result in an unstable device. Indeed, should the bias be applied to the signal line, the electrostatic force would disappear when the floating top metal becomes charged. The bridge would pull back up to the ON state and remain there. It would in fact be impossible to achieve a steady down state.

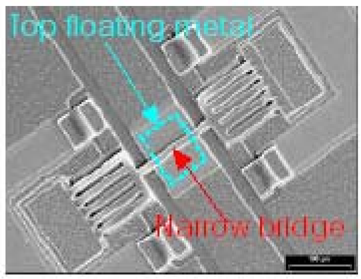

Fig.5: SEM picture of the boosted RF MEMS switch

A SEM picture of the final RF MEMS improved switch structure implementing the floating metal layer is displayed in Fig.5. A boosting geometrical factor of five is obtained in this structure, equal to the ratio between the down-capacitance area (floating metal arear A_{float}) and the up-capacitance area (area of bridge overlapping the signal line).

II. New RF MEMS switch with modified shunt configuration: Simulation and measurements

A. Simulations

Figure 6a and Fig.6b show the simulated S-parameters (S_{21}) using HFSS (High Frequency Structure Simulator) for the various switches in the ON-state and the OFF-state, respectively. In Fig.6a, a simulation of a 600µm CPW line is included for reference purposes. The simulations indicate that the same insertion loss is obtained for the standard and the floating top metal devices, but that the boosted switch brings about the expected improvement in the ON-state (bridge in the up-state). The "naked" CPW line is nearly non-sensitive to the presence of a narrow

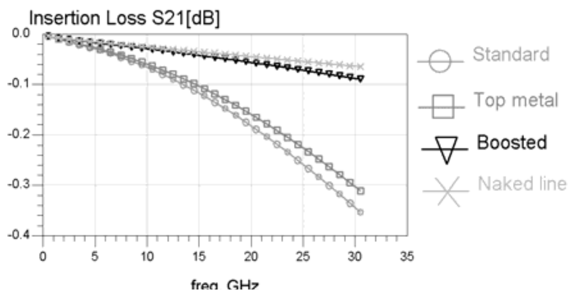

Fig.6a: Simulated HFSS Insertion Loss of standard switch, switch with floating top metal, boosted switch and naked line.

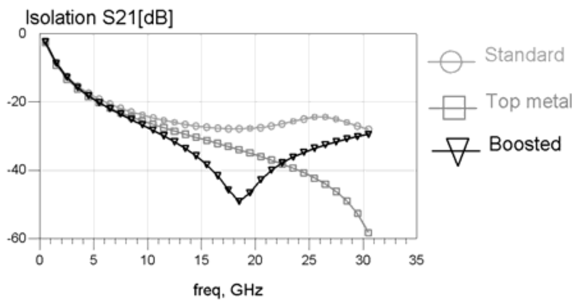

Fig.6b: Simulated HFSS Isolation of standard switch, switch with floating top metal, boosted switch.

bridge. The loss of the boosted device is only slightly higher than the loss of the naked line (0.09dB vs. 0.07 dB at 30GHz for the line).

In the results of Fig.6b (switch in down state) a perfect contact between the bridge and the dielectric is assumed. The dip in the curve is well known and is due to the LC resonance [6]. It is found, that the isolation for all structures is the same at low frequencies (<5GHz). At higher frequencies, the standard switch starts to behave as a number of LC-tanks in parallel, due to the ribbon-like bridge design (see Fig. 1). This broadens the LC resonance dip. The switch with top metal effectively has only a single LC tank giving a single sharp resonance peak. The boosted switch shows similar behavior but the LC resonance occurs at higher frequency due to the higher inductance of the narrow center bridge. Note that tuning of the LC resonance frequency by shaping the bridge offers the opportunity to greatly improve the isolation in a determined bandwidth. This is of interest for the low frequency application where the shunt switch, by nature, has poor performances.

B. Measurements

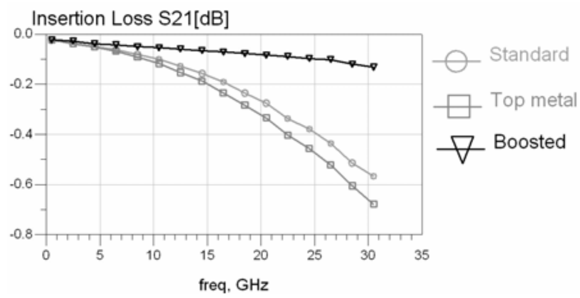

Fig.7a: Insertion Loss measurements

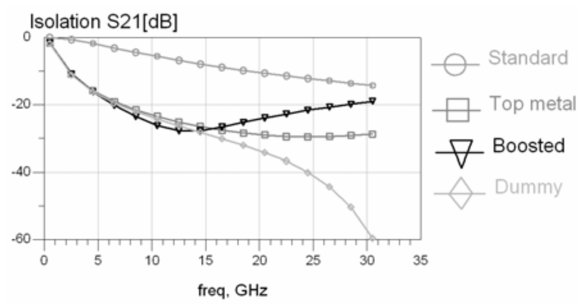

Fig.7b: Isolation Loss Measurements

The insertion loss and the isolation of the various configurations have been measured and are shown in Fig.7a and Fig.7b, respectively. In Fig.7b the curve labelled "dummy" represents the best possible situation used as a reference to evaluate and compare the performance of actual switches. In such a dummy switch, a bridge is permanently fixed during fabrication in the down-state which makes it free from any contact problems and hence represents the optimum shape for a pulled down bridge. The insertion loss measurements show a good agreement with the simulations although different by a factor 2. The source of this discrepancy has not been explained yet. As predicted by the simulation results plotted in Fig.6a, adding a floating top metal only slightly modifies the behaviour of the switch. The boosted switching device shows a much lower loss due to the much smaller up-state capacitance. The loss of the boosted switch is now limited by the losses of the 1µm thick Al CPW line.

The measured isolation plotted in Fig.7b for the standard switch exhibits the typical behavior of a capacitive switch with poor bridge-dielectric contact and clearly differs from the simulated results. The measured isolation for the other structures shows relatively good agreement with the

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simulations, especially in the low frequency range. A difference is observed in the LC resonance characteristics. The dummy structure goes to a sharp LC resonance around 30 GHz, whereas a clear LC resonance is not observed for the other switching devices.

C. Model

A circuit model for the switches is shown in Fig.8. Fitting the experimental results of Fig.7a and Fig.7b using such a model with R, L and C as fitting parameters, and with a fixed model for the CPW line sections leads to the values summarized in TABLE 1.

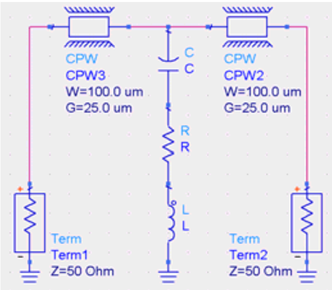

Fig.8: Capacitive shunt switches extraction model

TABLE 1

Measurement extracted fitting parameters.

	C_{up} [fF]	C_{down} [pF]	L_{down} [pH]	R_{down} [Ω]	$\frac{C_{down}}{C_{up}}$
Standard	68	0.90	(2)	(0.22)	13
Top metal	78	7.98	10	1.12	102
Boosted	18	7.98	18	1.33	459
Dummy	-	9.12	10	0.15	-

The up-capacitance of the standard switch and the switch with top metal do not differ significantly. The five times boosted switch displays a 4 times smaller up-capacitance. The down capacitances of the top-metallised and boosted switches are equal, and a factor 9 larger than the down-capacitance of the standard switch. The difference between the 7.98 pF measured on the movable structures and the 9.12 pF measured on the dummy structures is due to the difference in contact areas. For frequencies (much) smaller than the LC resonance, the capacitance dominates the RLC impedance. The extracted R_{down} and L_{down} for the standard switch are poor estimates since its resonance frequency occurs out of the measurement range. For the other configurations, the extracted L- and R-values are more reliable. The inductances for the switch with top metal and the dummy switch are equal, while the boosted switch shows a much higher inductance.

A resistance close to 1Ω has been extracted for the movable devices using top metal (including the boosted switch), while the dummy shows a much smaller resistance of 0.2 Ω. This can be explained by the thicker top metal of the dummy, which is 1 µm Al vs. 0.1 µm thick Al for the other configurations.
Most importantly the calculated capacitance ratio improves from 13 for the standard switch to above 400 for the boosted device.

III. RF MEMS Switch with a Combined Series-Shunt-Series architecture

Series-Shunt-Series MEMS switch is a special architecture which combines series and shunt switches aiming at attaining a better performance over a wide frequency band (1-30 GHz), by benefiting from the advantages of both families of switches A microphotograph of such a structure is shown in Fig.9. The shunt switch takes care of the isolation at higher frequencies while the series switches contribute to the low frequency isolation.
An Insertion Loss of less than 1 dB and an Isolation higher than 40 dB for frequencies ranging from 5 to 20 GHz have been achieved using such a combination switch. The rather high insertion loss is mainly attributed to line losses and not to the switching devices themselves. It is expected, that the losses can be reduced to 0.2 dB through optimisation of the design layout.

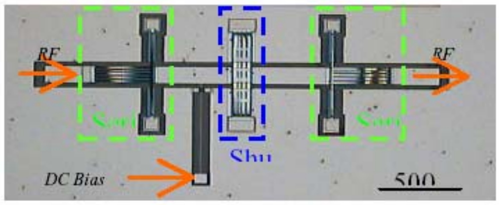

Fig.9: Series-Shunt-Series architecture including biasing circuit and pad.

IV. Summary and Conclusions

A novel RF-MEMS capacitive switching devices implementing a floating top metal layer and a narrow metal bridge has been presented. In the proposed structure the insertion loss and the isolation are independently optimised. This leads to a down-to-up capacitance ratio boost from 13 to 450. The implemented device achieves an insertion loss below 0.06 dB in the range 1-15 GHz (and includes the losses of the 600 µm long lines estimated to be around 0.04 dB), and an isolation higher than 25 dB at 15 GHz. It is expected that optimising the device will lead to further improvements.
Combination switches (Series-Shunt-Series) implementing the novel structure introduced in this paper demonstrated

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promising low losses and high isolation in a large frequency range.

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