Digital-Type RF MEMS Switched Capacitors

Jad B. Rizk and Gabriel M. Rebeiz

Radiation Laboratory, Department of Electrical Engineering and Computer Science,
University of Michigan, Ann Arbor, Michigan, 49109-2122, USA.
E-mail: jrizk@umich.edu, rebeiz@umich.edu.

Abstract — **This paper presents digital-type RF MEMS switched capacitors built in a coplanar waveguide (CPW) configuration. In this design, a MEMS shunt bridge is fabricated over an MIM capacitor. When the bridge is in the up-state position, the CPW line is loaded mainly by the up-state MEMS bridge capacitance. When the MEMS bridge is pulled down, the line is loaded by the MIM capacitor. As a result we obtain a digital-type switched capacitor suitable for 0.5-6 GHz operation. Switched capacitors of different values (300 fF, 600 fF, 750 fF, 1.5 pF, 2.25 pF) were fabricated and resulted in high-Q (> 100) designs at 1 GHz. Also a 2-bit capacitor array was demonstrated. The values of Q are limited by metal-to-metal contact resistance (0.8 Ω) and the calibration accuracy of the method used.**

I. Introduction

MEMS capacitive shunt switches have been demonstrated extensively in literature [1], [2], [3], [4]. These switches have very low insertion loss and and result in very high isolation. They show a large capacitance ratio (> 30), but the exact value of the down-state capacitance depends on the roughness of the contact area between the bridge metal and the dielectric layer [2]. Therefore they are not suitable to be used as precise switched capacitors. Goldsmith et al. used a series array of MEMS bridges with fixed MIM capacitors to result in a N-bit capacitor array [5], [6]. The design results in excellent performance at 0.1-4 GHz, but suffers from a series inductance due to the t-line lengths used.

This paper presents a new MEMS bridge design that allows a high capacitance-ratio and ensures a fixed down-state capacitance. The design also allows operation to 6 GHz and above with any capacitor resonances. An all-metal MEMS bridge is fabricated over an MIM capacitor. In the up-state position, the effect of the MIM and MEMS bridge in series is dominated by the up-state capacitance of the bridge. In the down state position, the metal bridge touches the upper metal of the MIM capacitor, connecting it using a low inductance to ground. This results in an equivalent fixed MIM capacitance to ground. The quality factor of the switched capacitors is limited by the metal-to-metal contact resistance (0.7-1 Ω). Cascading two or more of these switched capacitors is possible and results in a digital capacitor array.

II. Fabrication

The switched capacitor is fabricated on a 400 μm-thick high-resistivity silicon wafer (2,000-3,000 Ω-cm). The CPW line dimensions under the bridge are G/W/G = 130/100/130 μm. The bridge width over the center conductor is 100 μm and the bridge length is 300 μm. The pull-down electrodes are located in the gaps of the CPW line. The bridge is widened over the CPW gap to increase the pull-down area and therefore reducing the pull-down voltage. Also the geometry of the MEMS bridge results in a low spring constant design, further reducing the pull-down voltage (Fig. 1).

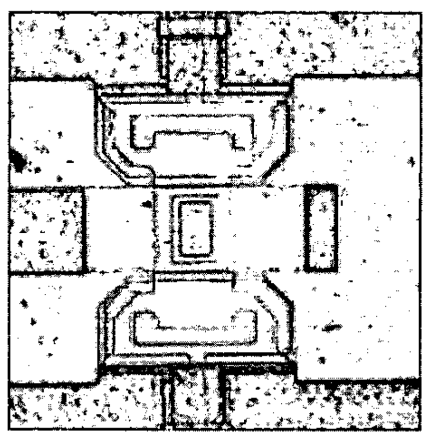

Fig. 1. Switched MEMS capacitor with a 0.75 pF MIM capacitor.

The fabrication steps are as follows: First, the SiCr bias lines and the pull-down electrodes are defined. Then, the first metal layer (6000 Å of Ti/Au/Ti) is

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C_{MIM}	width (μm)	length (μm)
300 fF	40	22
600 fF	60	30
750 fF	60	37
1.5 pF	75	60
2.25 pF	84	80

TABLE I
DIMENSIONS OF THE MIM CAPACITORS.

defined using a lift-off process, and a 2000 Å-thick silicon nitride dielectric layer is deposited and patterned. Next, the upper metal of the MIM capacitor is defined using a lift-off process. The MEMS bridge is fabricated using a 8000 Å-thick sputtered layer of gold using PMMA as sacrificial layer. A series of 5000 Å deep bumps are etched in the sacrificial layer over the MIM capacitor before sputtering of the bridge to insure a good contact resistance between the bridge and the underlying MIM capacitor. Also, the center conductor, the ground planes and the anchors of the MEMS bridge are electroplated with 2 μm of gold. The bridges are finally released using a critical point dryer (CPD) system. The bridge height is 1.5 μm and the pull-down voltage is 15 V. The applied voltage is 20-30 V to result in a good contact resistance. Fig. 1 shows a picture of a MEMS switched capacitor with an MIM capacitor of 0.75 pF.

Different MIM capacitance values were chosen: 300 fF, 600 fF, 750 fF, 1.5 pF and 2.25 pF. The dimensions of the MIM capacitors are easily calculated from the parallel-plate capacitor formula: $C = \epsilon_o \epsilon_r A/d$, where $\epsilon_r = 7.6$ is the relative dielectric constant of silicon nitride, A is the area of the MIM capacitor and d is the silicon nitride thickness (2000 Å). Table I gives the dimensions of the MIM capacitors used.

III. Measurements on Single MEMS Switched Capacitors

Fig. 2 shows a CPW MEMS shunt switched capacitor and its CLR series equivalent circuit. In order to measure the Q of these capacitors, reflection loss measurements of the switched capacitor placed at the end of a CPW line were done. This measurement results in an easy determination of the capacitance and Q of the device-under-test. As noted below, it is limited to a Q of around 80, before small errors in the S_{11} measurements greatly affect the result.

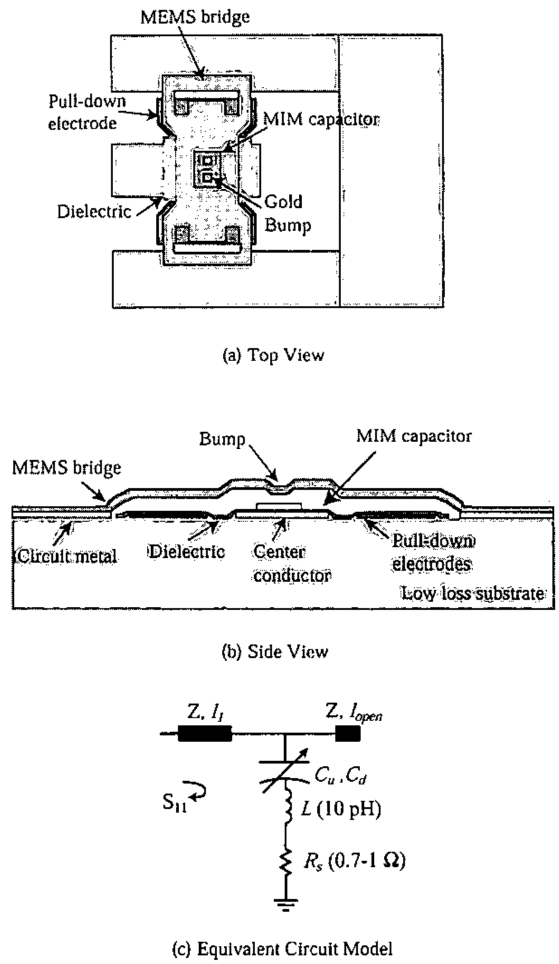


Fig. 2. CPW shunt MEMS switched capacitor and its equivalent circuit model.

In the up-state position, the series combination of the MEMS bridge and the MIM capacitor is dominated by the up-state capacitance of the bridge. The up-state capacitance is measured to be 100-120 fF for the different capacitances listed above. When the bridge is pulled down, the bumps touch the upper metal of the MIM capacitor. This is a metal-to-metal contact and the MIM is connected via the metal bridge to the ground plane. The inductance of the bridge is around 10 pH and therefore its effect is insignificant at 1-6 GHz.

Measurements were done from 1-6 GHz. Fig. 3 shows the measured and fitted reactance of the differ-

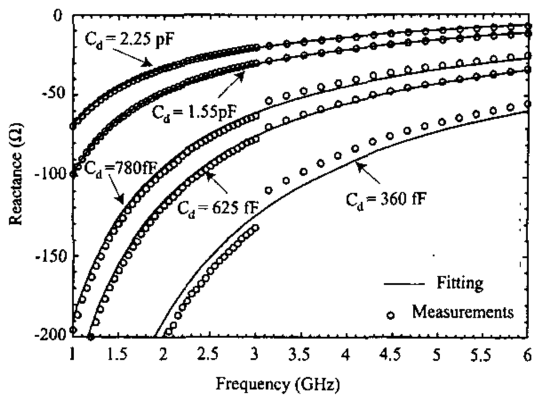


Fig. 3. Measured reactance of the different switched capacitors from 1-6 GHz.

C_{up} (fF)	C_d (pF)	X (1-3 GHz) (Ω)	Q (1-3 GHz)
100 -120	0.36	-400 to -132	>>
100 -120	0.62	-240 to -77	> 170
100 -120	0.78	-196 to -63	> 120 - 75
100 -120	1.55	-99 to -30	100 - 35
100 -120	2.25	-69 to -20	90 - 30

TABLE II
MEASURED QUALITY FACTOR AND REACTANCE AT 1-3 GHZ FOR THE DIFFERENT SWITCHED MIM CAPACITORS.

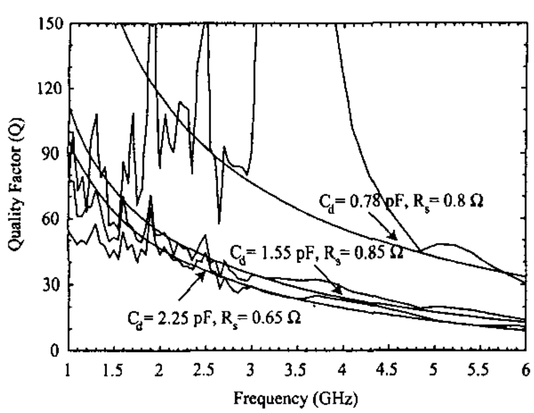


Fig. 4. Measured quality factor (Q) of the different switched capacitors from 1-6 GHz.

ent switched capacitors. The reference plane is defined 100 μm away from the edge of the MEMS bridge. The fitted values are within 5% from the designed values except for the 300 fF design. This is due to the small value of the MIM capacitor used. Since the up-state capacitance is around 100 fF, the MEMS switched capacitors lead to a digital varactor with ratios of (3:1), (6:1), (7.5:1), (15:1) and (22:1). The jump in reactance for 750 fF, 600 fF and 300 fF cases around 3 GHz is due to different calibration standards used for the low frequency range (1-3 GHz) and for the upper frequency range (3-6 GHz).

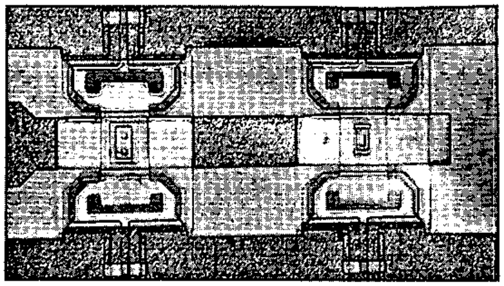
Fig. 4 shows the measured quality factor (Q) for the 2.25 pF, 1.5 pF and 0.75 pF cases versus frequency. The Q varies as 1/f as predicted, since for an RC in series Q = 1/RCω. The quality factor is calculated from the S_{11} measurements by taking the ratio of the imaginary part over the real part of the corresponding input impedance at the reference plane. The quality factor (Q) is fitted to the quality factor of the model in Fig.2 and results in resistance values between 0.65-0.85 Ω. For the 300 fF and 600 fF designs, the Q is very high at 1-3 GHz and could not be measured. This is clearly seen in Fig. 4, where large variations in the measured Q exist for the 0.75 pF case. In fact:

$$Q = \frac{2Im[S_{11}]}{1 - |S_{11}|^2} \qquad (1)$$

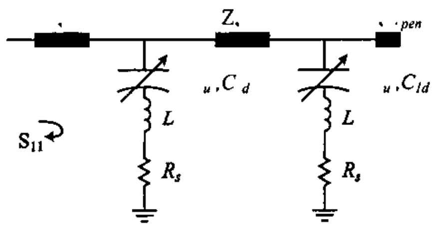
and for a very low loss (high-Q capacitor), $|S_{11}|^2$ is very close to 1. Therefore, any variation in S_{11}, due to noise and calibration errors, will have a drastic effect on the Q, and the method used is valid for $Q < 80$. The measured quality factors and reactance of the switched capacitances at 1-3 GHz are tabulated in Table. II.

IV. 2-bit Switched Capacitor Array

A 2-bit digital capacitor array has been fabricated using the 300 fF and 600 fF switched capacitors. Each bit is addressed individually using separate bias lines. Fig. 5 shows the equivalent circuit model for a 2-bit MEMS switched capacitor array. The CPW line dimensions used are G/W/G = 130/100/130 μm and the distance between the two bridges is 200 μm. The reference plane is defined as 100 μm away from the edge of the first bridge. Fig. 6 presents the measured reactance of the 4 possible combinations in the 2-bit design. The up-state capacitance was fitted to 110-120 fF. The fitted down-state capacitances for the individual switched capacitors are 360 fF and 640 fF. This is in close agreement with the values seen in the single switched capacitor design.



(a)



(b)

Fig. 5. Photomicrograph (a) and equivalent circuit model (b) of the 2-bit MEMS switched capacitor array.

The 2-bit design can be tuned at 2 GHz in a digital fashion from $-j250$ (both bridges up) to $-j130$, $-j90$ and $-j70$ Ω (both bridges down) resulting in impedance ratios of (1.9:1), (2.8:1) and (3.6:1), respectively. The same impedance ratio is achieved at 2.5 GHz (-j200, -j100, -j70 and -j56 Ω) and at 3 GHz (-j165, -j85, -j58 and -j45 Ω). This makes the switched capacitor array design suitable for a digital tunable matching network at 0.5-3 GHz. The high Q of these components make them very attractive since the tunable matching network will have very low loss.

V. Conclusion

This paper presents different digital switched capacitors for frequency range from 0.5-6 GHz. The values covered were from 300 fF to 2.25 pF rendering varactors with ratios ranging from 3 to 20:1. These capacitors have demonstrated a high quality factor. Also, a 2-bit switched capacitor array was built and measured. Different impedance values were achieved at 2-3 GHz over a wide range (1.9, 2.8, 3.6:1). This makes the switched capacitors very suitable for digital tunable matching networks.

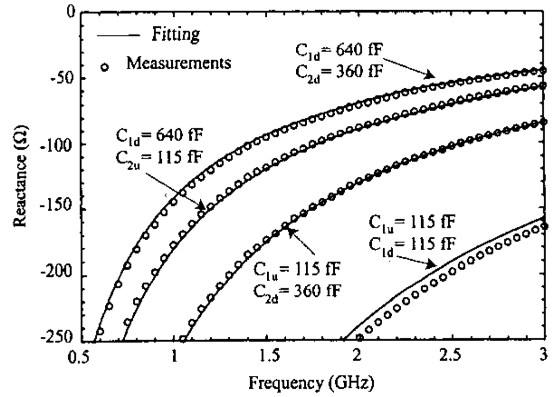


Fig. 6. Measured reactance, X, of the 4 states of the 2-bit switched-capacitors array from 0.5-3 GHz.

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