High-Isolation CPW MEMS Shunt Switches—Part 2: Design

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***Abstract*—In this paper, the second of two parts, the equivalent *RLC* model of the shunt switch is used in the design of tuned two- and four-bridge "cross" switches from 10 to 40 GHz. The cross switch attained an insertion loss of less than 0.3–0.6 dB, a return loss below −20 dB from 22 to 38 GHz in the up state, and a down-state isolation of 45–50 dB with only 1.5 pF of down-state capacitance (C_d). Also, an X-band microelectromechanical system (MEMS) switch with an insertion loss of less than 0.2 dB and an isolation of 35 dB is presented. This is done by inductively tuning the *LC* series resonance of the shunt switch. The MEMS bridge height is 1.5–2.5 μm, resulting in a pull-down voltage of 15–25 V. Application areas are in low-loss high-isolation communication and radar switches.**

***Index Terms*—Low loss, MEMS, micromachining, microwave, millimeter wave, switches.**

I. INTRODUCTION

THIS PAPER focuses on the design and implementation of coplanar-waveguide (CPW) shunt-capacitive-switch-tuned configurations for high-isolation applications from 20 to 40 GHz. The capacitor–inductor–resistor (CLR) model of the shunt switch circuit is used in the design of tuned high-isolation switches. The advantages of a tuned configuration are reduced reflection loss and wide-band operation in the up state, and increased isolation in the down state. A two-bridge-tuned switch and a four-bridge "cross" implementation with high isolation are presented in this paper. Also, a high-isolation switch is obtained by designing the series resonance frequency of the microelectromechanical systems (MEMS) switch to be in the X-band frequency range. This is done using a short transmission-line stub, and is labeled as "inductive tuning."

The tuned designs allow for a compact circuit and simple fabrication, which is crucial for low-cost applications, and results in a lower insertion loss than standard designs. The applications are in high-isolation switches for X-, Ku-, and Ka-band systems. The techniques can easily be applied up to 100 GHz.

II. TUNED TWO-BRIDGE Ka-BAND MEMS SWITCHES

The model for the single MEMS membrane switch can be used to design a high-isolation low-insertion-loss reflective-tuned switch. One of the simplest tuned structures is the two bridge switch (Fig. 1), which consists of two single MEMS shunt switches separated by a short length of high-impedance transmission line. The length of midsection line is chosen such that the reflection from the first membrane and the reflection from the second membrane cancel at the input port when the switch is in the up state. This is a standard design used extensively in p-i-n diode switches [1]. Ignoring the inductance and resistance of the membranes, and setting the cancellation frequency to be ω_r, the electrical length of the midsection line is calculated as

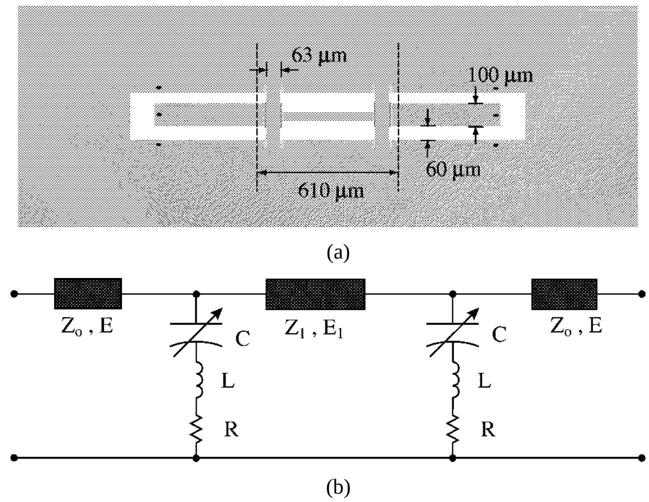

Fig. 1. (a) Physical implementation and (b) equivalent-circuit model for the two MEMS bridge switch.

$$\tan\beta\ell = \frac{2C\omega_r Z_1 Z_o^2}{Z_1^2 - Z_o^2 + (C\omega_r Z_1 Z_o)^2} \tag{1}$$

where $\beta\ell$ is the electrical length of the midsection line of impedance Z_1, C is the bridge capacitance, and Z_o is the port impedance of the switch. If Z_1 is chosen to be higher than Z_o, the midsection physical line length can be reduced. Setting the midsection line impedance equal to the port impedance $(Z_1 = Z_o)$, the equation becomes

$$\tan\beta\ell = \frac{2}{CZ_o\omega_r}. \tag{2}$$

By taking advantage of the reflection null of the tuned MEMS switch, the up-state capacitance of the bridges in the tuned switch can be increased as compared to a typical single MEMS switch. This can be done by increasing the area of the bridge, or lowering the nominal gap height, or a combination of both. Increasing the area will increase the down-state isolation and lowering the nominal gap height will lower the pull-down voltage at the expense of a smaller capacitance ratio (C_d/C_u).

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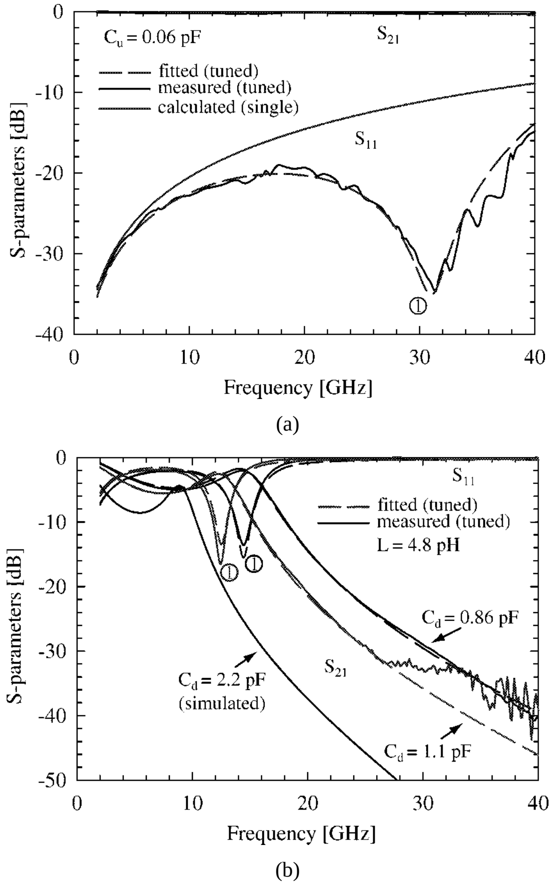

Fig. 2. Measured and fitted two bridge S-parameters in the: (a) up state and (b) the down state for two different values of C_d. The return loss of a single up-state bridge is shown in (a) for comparison.

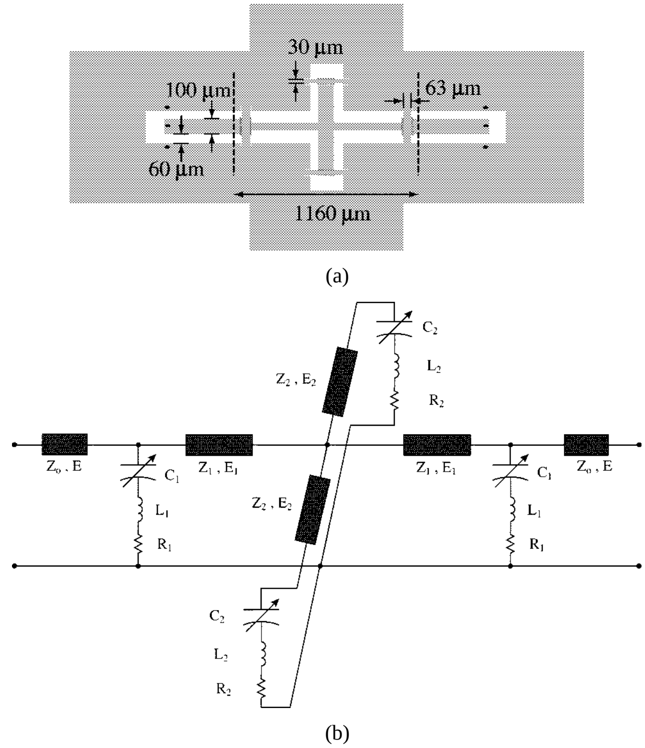

Fig. 3. (a) Physical implementation and (b) equivalent-circuit model for the cross switch.

We have chosen to lower the nominal gap height from 3.5 to 1.5 μm, thereby decreasing the pull-down voltage from 50 to 15 V for a typical 300-μm-long Au bridge, having the same mechanical spring constant. This results in a theoretical C_d/C_u ratio of 40–45 (2000-Å Si_xN_y, $\epsilon_r = 7.6$), depending on the fringing capacitance, instead of $C_d/C_u = 80$ to 90 for a 3–4-μm gap.

The measured and simulated up- and down-state S-parameters for a typical tuned switch are shown in Fig. 2. The measurements were performed using the National Institute of Standard's (NIST's) Multical[1] thru-reflection-line (TRL) calibration with on-wafer standards and reference planes, as shown in Fig. 1. The up-state capacitance of the individual bridges is 55–60 fF, and the midsection line impedance Z_1 is 66 Ω with a length of 400 μm. The capacitance ratio C_u/C_d is 15–19, due again to the surface roughness, and the fitted bridge inductance is only 4.8 pH, due to a bridge thickness of 3 μm. The insertion loss of the switch in the up state is 0.2–0.4 dB from 20 to 40 GHz. The up-state S-parameters for a single membrane switch with a nominal gap height of 1.5 μm are also provided for comparison, showing that the up-state return loss can be lowered over a 50% bandwidth. The isolation after 30 GHz in Fig. 2 was limited by substrate isolation and probe-to-probe coupling (see Fig. 4 for typical isolation measurements). Fig. 2(b) shows the isolation if a capacitance ratio of 40 is achieved. It is evident that a down-state capacitance of 2.2 pF results in a very high isolation at 20–40 GHz while still maintaining a pull-down voltage of 15 V.

[1]Multical v1.00, NIST, Boulder, CO, 1995.

III. Ka-Band Cross Switch

In an effort to further increase the bandwidth and down-state isolation of the tuned switch, a novel "cross" switch was developed. The physical implementation and equivalent–circuit model of the switch are shown in Fig. 3. The in-line section consists of two bridges separated by lengths of high impedance transmission line. The shunt sections are open-ended stubs loaded at the ends with a smaller MEMS switch. These in-line and shunt sections produce two independent reflection nulls [see Fig. 4(a)]. In the up state, the CPW line impedances and electrical lengths can be optimized to give an excellent return loss over a wide bandwidth. In the down state, the reflection nulls are lowered in frequency and the two shunt capacitively loaded stubs present a good RF short circuit at the cross node, resulting in very high isolation. The switch requires a single-bias voltage to pull all four MEMS switches to the down state. The only complication of this implementation is the associated parasitics of the cross junction, which can be modeled using modern electromagnetic (EM) simulation tools.

The measured and simulated S-parameters of a typical cross switch design are shown in Fig. 4. The midsection line impedance Z_1 is 66 Ω with a length of 350 μm and the shunt section line impedance Z_2 is 50 Ω with a length of 170 μm. The MEMS bridge height is again 1.5 μm, resulting in a pull-down voltage of about 15 V. The up-state capacitance of the in-line membranes ($w = 63$ μm) is $C_{u1} = 0.066$ pF and is $C_{u2} = 28$ fF for the MEM's bridges in the shunt sections. The

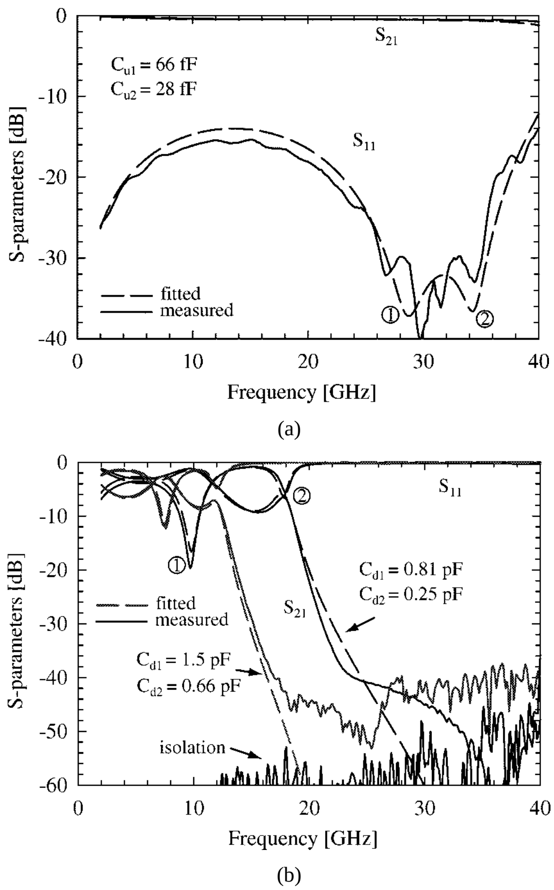

Fig. 4. Measured and simulated: (a) up- and (b) down-state S-parameters of a MEMS cross switch. The location of the nulls in the return loss [labeled (1) and (2)] are controlled by the in-line and parallel resonant structures, respectively.

equivalent circuit model, shown in Fig. 3(b), does not account for the cross-junction parasitics.

The tuned cross switch results in an up-state reflection coefficient of less than -20 dB from 22 to 38 GHz, with a measured insertion loss of 0.3–0.6 dB, respectively. The up-state reflection loss of the cross switch is below -16 dB from dc to 40 GHz. The down-state capacitance C_{d1} of the in-line membranes is a function of surface roughness, and is about 0.5 of the parallel-plate estimate ($C_d/C_u = 22$ instead of 45). Even with the nonoptimal down-state capacitance, the cross switch attained greater than 40-dB isolation from 17 to 40 GHz, for a $C_{d1} = 1.5$ pF, $C_{d2} = 0.66$ pF, with inductances of $L_1 = 9$ pH and $L_2 = 12$ pH. We believe that the measurements above 32 GHz are limited by substrate and coupling effects. The isolation was determined by connecting the probes to CPW short or open circuits on the wafer after calibration and measuring S_{21}.

Another advantage of the cross switch is the relatively high isolation at low (16–20 GHz) frequencies with a small down-state capacitance as compared to a typical single MEMS switch. If a higher down-state capacitance ratio $(C_r/C_d = 45)$ was achieved, the cross design would produce an isolation greater than 50 dB from 12 to 40 GHz.

IV. Inductively Tuned High-Isolation X-Band Switches

One way to obtain a higher isolation at X-band frequencies is to increase the series inductance of the switch so as to lower the resonant frequency. Fig. 5 shows the isolation of a MEMS switch with $C_d = 2.7$ pF and $R_s = 0.35\ \Omega$ for varying inductance values ($L = 8$–64 pH). It is seen that the LC resonance frequency can be lowered to X-band frequencies with the use of a 40–60-pH inductance. Inductively tuned MEMS shunt switches result in less bandwidth than standard shunt switches, but with higher isolation around the resonant frequency. This is especially true at X-band frequencies since the Q of the LC resonance is $Q = wL/R_s$ and L is 40–60 pH.

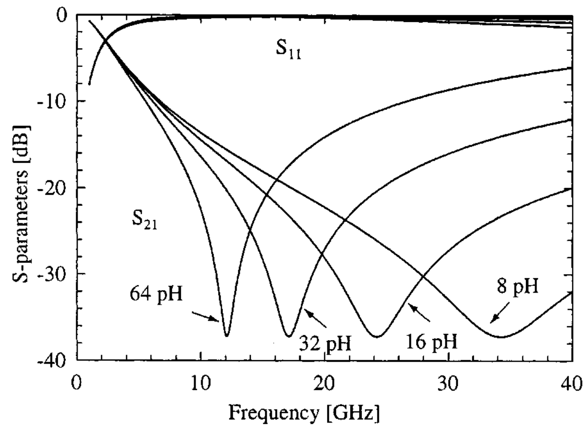

Fig. 5. Simulated S-parameters of a MEMS shunt switch with a down-state capacitance of 2.7 pF and various values of inductance.

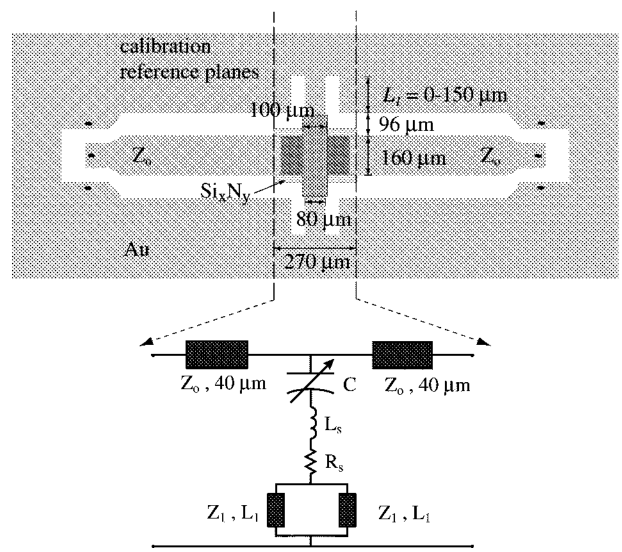

Fig. 6. MEMS shunt switch implementation with inductive tuning and its equivalent-circuit model.

The MEMS bridge inductance is limited to 15–20 pH even with the use of a very small bridge width over the CPW gaps [2, Table II]. However, a large series inductance can be easily synthesized by adding a short high-impedance section of transmission line between the MEMS bridge and the ground plane (Fig. 6). By properly choosing the length of this line, the series resonant frequency can be pushed down to the X-band frequency range. This results in high-isolation shunt X-band MEMS switches without the use of an additional MEMS switch or the tuned designs shown above.

An inductively tuned MEMS shunt switch has been fabricated for X-band operation using a 50-Ω CPW line implementation

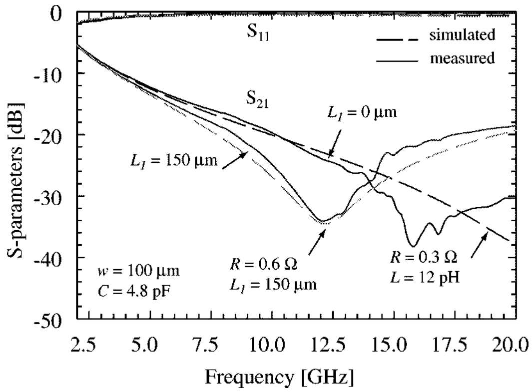

Fig. 7. Simulated and measured S-parameters for MEMS shunt switches with $w = 100$ μm and $L_1 = 0$ and 150 μm.

(96, 160, 96 μm) on a high-resistivity silicon substrate. The fabrication procedure is based on a 300-μm-long 6000-Å thick *sputtered* gold bridge, suspended 2.5 μm above the center conductor. In this case, the metallization underneath the bridge is a smooth layer of 2000-Å-thick refractory metal covered by a dielectric of 2100 Å of silicon nitride. The width of the capacitive section (portion over center conductor of the CPW) of the MEMS bridge is 100 μm. The length of the inductive section of transmission line is either 0 (no ground indentation) or 150 μm. The CPW line and inductive section are composed of sputtered Au that is 1.3-μm thick.

The measurements are based on an on-wafer TRL calibration [3] and are referenced to 40 μm from either side of the MEMS bridge, as shown in Fig. 6. Fig. 7 shows the measured and fitted performance of a 100-μm-wide bridge in the down state. The fitted parameters for no inductive tuning are $C = 4.8$ pF, $L = 12$ pH, and $R_s = 0.3\ \Omega$. This results in a resonant frequency of 21 GHz. The resonance with a 150-μm-long inductive transmission-line section is shifted to 12 GHz, and the isolation is better than -30 dB from 11 to 13 GHz. The 150-μm-long inductive transmission-line section is, therefore, equivalent to a series inductance of 37 pH around 12 GHz. At 10–12 GHz, there is an 8-dB improvement in the isolation over the standard design. The fitting of the inductively tuned bridge is done by taking the C, L values of the MEMS bridge and adding two short sections of 56-Ω CPW transmission line using Libra.[2] For both switches, the up-state insertion and return losses up to 13 GHz were less then 0.2 dB and -15 dB, respectively.

V. Conclusion

This paper has presented tuned switch designs incorporating two or more membrane switches from 10 to 40 GHz. The measurements show the advantages of the tuned approach for high-isolation switches in the down state and excellent return loss in the up state. Also, inductively-tuned bridges have been shown to result in much higher isolation at X-band frequencies than standard MEMS shunt switches. The techniques presented in this paper can be directly applied to millimeter-wave (40–100 GHz) switches, with a good knowledge of the switch CLR model.

[2]Libra, Series IV 6.6, Hewlett-Packard Company, Santa Rosa, CA, 1997.

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Prof. Rebeiz received the 1991 National Science Foundation Presidential Young Investigator Award and the 1993 URSI International Isaac Koga Gold Medal Award for Outstanding International Research. He received the 1995 Research Excellence Award presented by The University of Michigan at Ann Arbor. Together with his students, he has received Best Student Paper Awards presented by the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) (1992, 1994–1999), and the IEEE Antennas and Propagation Society (IEEE AP-S) (1992, 1995) and the 1990 *Journees Int. Nice Antennes* (JINA) Best Paper Award. He received the 1997 Electrical Engineering and Computer Science Department Teaching Award, the 1998 College of Engineering Teaching Award, and was selected by the students as the 1997–1998 Eta–Kappa–Nu Electrical Engineering and Computer Science Professor of the Year. In 1998, he received the Amoco Foundation Teaching Award, given yearly to one (or two) faculty at The University of Michigan at Ann Arbor, for excellence in undergraduate teaching. He is also the corecipient of the IEEE 2000 Microwave Prize for his work on MEMS switches and phase shifters.