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RF MEMS Switches

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Abstract - **An overview of the MEMS technology development and applications is given in this paper. A special attention is paid to the RF MEMS switches. Both series and shunt MEMS switches have been considered. It is also presented a technique for modeling and design of inductively-tuned MEMS shunt switch. Some very important issues for the device maturity e.g. reliability and packaging have been addressed.**

Keywords – **MEMS, switch, series switch, shunt switch, high isolation.**

I. Introduction

*M*icro*E*lectro*M*echanical *S*ystems (MEMS) are the integration of mechanical elements, sensors, actuators and electronics on a common substrate using integrated circuit process sequences [1-6, 9-17]. The electronics are fabricated using standard IC processing, micromechanical components are fabricated using compatible 'micromachining' processes that can selectively etch parts of the substrate, or add sections on to the top surface, leaving free standing structures. A large market already exists for micromachined sensors. In this case the microelectronic integrated circuits can be thought of as the brain of the system and micromechanical section as the 'arms' and 'eyes' of the system, sensing thermal, biological, chemical, optical and magnetic phenomena in the environment. The evolving nature of MEMS means that new applications are continually being reported. In recent years, RF and millimetre-wave MEMS have emerged from sensor based technology, they use the same fabrication techniques and have become an area of significant interest. MEMS based RF circuits could have a large impact on handset applications, because of their inherent small size and good electrical performance.

MEMS switches and other components have been very interesting area for research and development in the last few years [1-6, 9-17]. It is well known that they have excellent performances at microwave to mm-wave frequencies. In comparison with other types of switches (e.g. GaAs-based FET, pHEMT or PIN-diode switches), MEMS switches offer lower insertion loss and higher isolation, zero power consumption, small size and weight and very low intermodulation distorsion. Of course, there are also some disadvantages of this type of switches as low switching speed (µs range) and high actuation voltages. These disadvantages together with improving reliability, packaging and cost issues can be tolerated in many telecommunication applications, such as low-loss high isolation RF switches.

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Two different RF MEMS switches have been developed: the series switch [6] and the shunt switch [1-6.]. The typical shunt MEMS switch consists of a thin metal membrane suspended over the center conductor of a CPW (Coplanar Waveguide) and fixed at both ends to the ground conductor of the CPW. Higher isolation can be achieved with the use of tuned switches [3], with the use of a few MEMS switches placed to each other to add down state capacitance, or with the use of a single inductively-tuned MEMS shunt switch [1, 4, 5, 12].

This paper presents an overview of the latest development in RF MEMS switches. In addition to this, it is also presented a technique for modeling and design of inductively-tuned shunt MEMS switch [12]. Due to the complicated geometry of these switches, a full wave simulation is needed to characterize them. The result of this analysis provides scattering parameters for different switch geometries. Based on this, an equivalent lumped element model can be determined. The values of the circuit elements depend on the physical dimensions of the switch. Analytical form of inductance for inductive-tuned MEMS switch is presented. This procedure can be used for very efficient design of desired high isolation switch.

II. MEMS Technology and Applications

With the increased demand for faster, smaller, highly tunable and cheaper communication systems that consume less power and have wider bandwidths for increased data rates, micromachining techniques and MEMS devices have found a new field of applications. Structures such as low loss and high isolation MEMS switches, reconfigurable antennas, filters and tuners, high-Q passives and resonators, low loss planar THz waveguide components and low loss phase shifters are a few examples of revolutionary RF/microwave components that the implementation of this technology has led to.

The essential idea in RF MEMS is to use miniature mechanical devices and physical motion to achieve the function of a microwave switch or a variable capacitor. The high performance is due to the very low capacitance and contact resistance, which can be achieved using RF MEMS technology as compared to GaAs PIN diodes or FETs. It is possible to build RF MEMS switches with a figure-of-merit cut-off frequency of 30-80THz, which is about 100 times better than GaAs transistors. Also, varactors with a *Q* of 150 were demonstrated at 30GHz and this is approximately 5 times

TABLE I. COMPARISON OF EXISTING SWITCHES WITH MEMS RELAYS

Characteristic	MMR	GaAs FET	PIN diode	EMR PCB	EMR SMA
Size	Small	Very small	Small	Medium	Large
Resistance	0.5Ω	1-5Ω	1-5Ω	0.1Ω	0.5Ω
Switching Power	2W CW	0.5W CW	5W CW	10W CW	35W CW
Breakdown Voltage	Low	Low	Varies	High	High
Speed	0.5-200μs	10-100ns	10-100ns	0.8-10ms	1-40ms
Life Cycle	100 million+	Billion	Billion	0.5-5 million	0.1-2 million
Frequency	Up to 70GHz	Up to 4GHz	Up to 20GHz	Up to 5GHz	Up to 40GHz
Ins. Loss max (dB)	0.25	0.5	0.5	0.4	0.1
Isolation min (dB)	40	30	30	40	80
3rd Order Harmonics	Very good	Poor	Poor	Good	Very good
Power Consumption	Very low	Low	Low	Medium	High
Drive Voltage	5V, 28V, 48V	3V, 5V	3V, 5V	5V, 12V	12V, 28V
Integration Capability	Very good	Very good	Very good	Average	Difficult
Cost – SPDT type	8.00-20.00$	0.50-4.50$	0.90-8.00$	0.85-12.00$	38-90$

better than comparable devices using GaAs techniques. RF MEMS also demonstrates the general fiels of high-*Q* micromachined inductors on silicon and glass wafers, although these devices are static in design and are not tunable.

MEMS is a multidisciplinary technology that involves different fields e.g. materials and fabrication, process and device engineering, microwave engineering, mechanical engineering etc [6].

The ultimate goal in applying RF MEMS is to propagate the device-level benefits all the way up to the system level to attain high system performance, as shown in Fig. 1 [17].

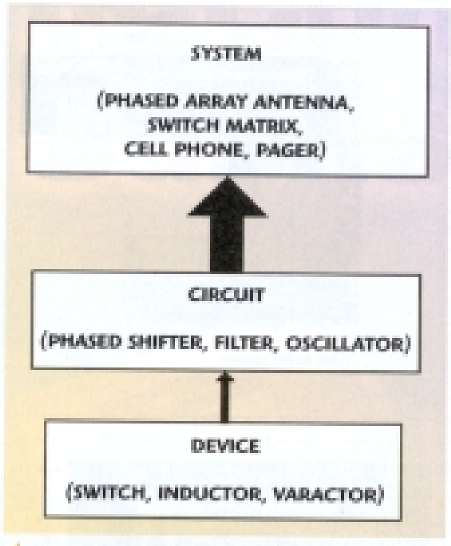

Fig. 1. Typical RF MEMS chain

Many applications demand the lowest insertion loss. Multiple transmitters and receivers in the same mobile phone package also present challenges for RF designers. Global Positioning System (GPS), Bluetooth, HomeRF and wireless LAN systems are just a few of the RF module candidates awaiting integration into the mobile phones. Cell phone vendors are putting two or more simultaneously operating radio transceivers into smaller and smaller mechanical assemblies. Ensuring that these systems work properly together requires careful RF system analysis, tighter filtering, better shielding and higher linearity. These complex RF circuits must not impact overall cellular system performance. The optimum solution lies with MEMS switches. Table 1 compares MEMS micromechanical relays (MMR) performance with solid-state switches and electromechanical relays (EMR) [10]. A schematic of a wireless transmitter and receiver package is shown in Fig. 2, where are shadowed components that can be realized in MEMS technology.

III. SERIES MEMS SWITCH

MEMS switches are devices which operation is based on the use of mechanical movement to achieve a short circuit or an open circuit in the RF transmission line. Electrostatic, magnetostatic, piezoelectric, or thermal designs can be used to obtain required forces for the mechanical movement, but up to date only electrostatic type switches have been used. The advantages of MEMS switches over other traditional switches have already been discussed [6, 9-11]. However, there are also some problems related to RF MEMS switches: low speed, power handling, high actuation voltage, reliability, packaging (MEMS switches need to be packaged in hermetic or near-hermetic seals and packaging costs are high), cost (these switches have potential of very low cost manufacturing, but adding cost of packaging and high-voltage drive chip price is significantly increased). The main applications of MEMS switches are: radar systems for defense applications, automotive radars, satellite communication systems, wireless communication systems, instrumentation systems etc.

The RF MEMS switches developed today, even if quite small, still follow the basic mechanical laws developed a few hundreds of years ago. However, the scale and relative importance of the forces are significantly different from the macro world. Surface forces and viscous air damping dominate over inertial and gravitational forces. The switches have very low mass and therefore are not sensitive to acceleration forces. There are two types of MEMS series

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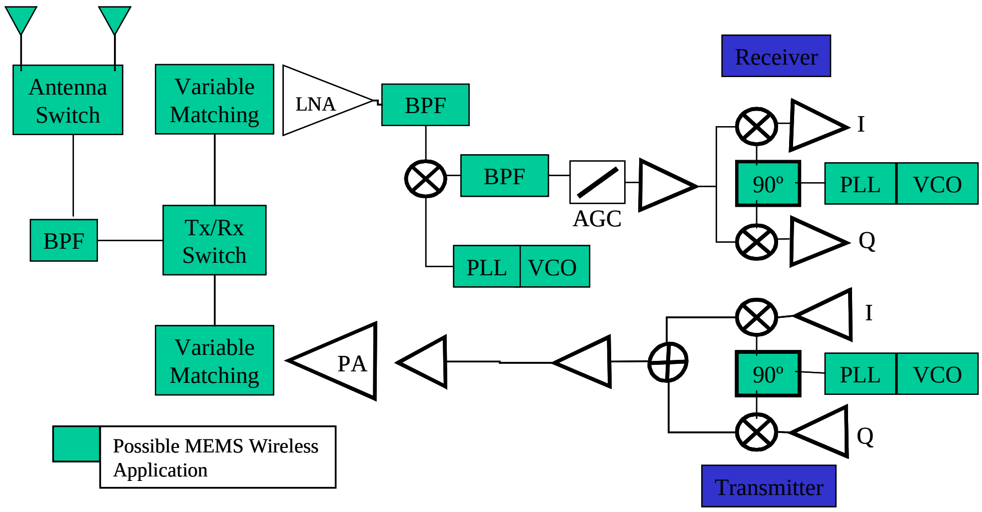

Fig. 2. Schematic of a transceiver with MEMS application

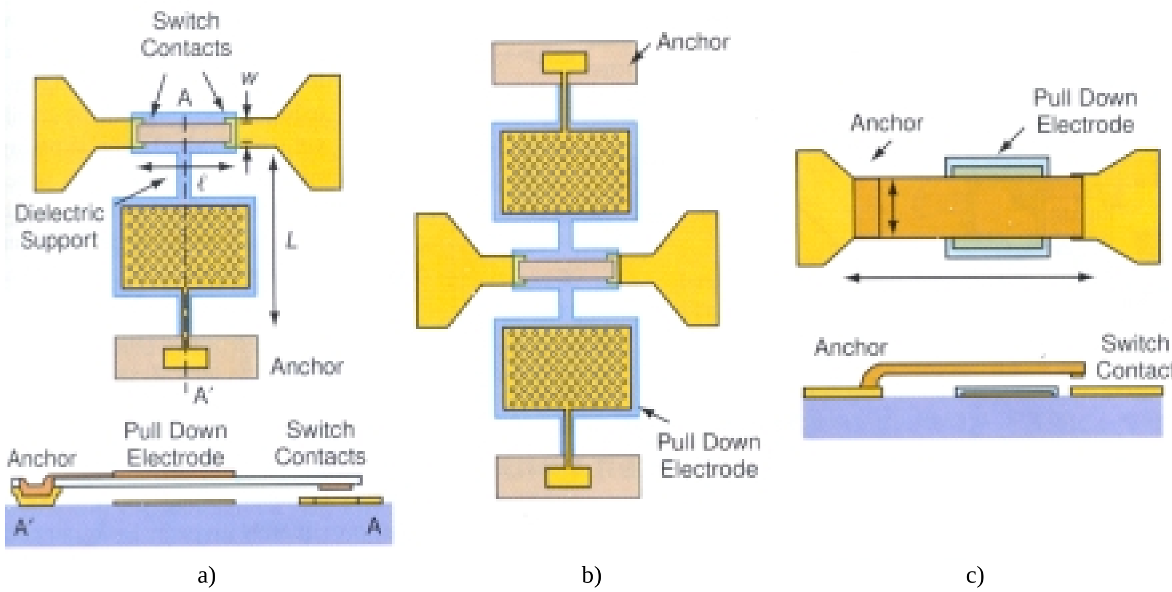

Fig. 3. Broadside series MEMS switch and inline series MEMS switch [9]

switches [9]: the broadside series switch (Fig. 3a) and b)) and the inline series switch (Fig. 3c)). The actuation of the broadside switch is in a plane that is perpendicular to the transmission line, while the actuation of the inline switch is in the same plane as the transmission line. The actuation mechanism is achieved using an electrostatic force between the top and bottom electrodes, and is given by [6, 9]

$$F = \frac{QE}{2} = \frac{CVE}{2} = \frac{\varepsilon A V^2}{2(g + t_d/\varepsilon_r)^2}, \qquad (1)$$

where V, g, and C are the voltage, gap distance, and capacitance between the lower and upper electrodes, respectively, and A is the area of the electrode (Fig. 3 and 4). The bottom electrode is often covered by a dielectric layer (thickness t_d and a relative dielectric constant ε_r) to prevent a short-circuit between the top and bottom plates.

Equation (2) presents a widely cited formula [6, 9, 15] for calculating the required DC actuation voltage, i.e. pull-in voltage of fixed-fixed beams or air bridges

$$V_p = \sqrt{\frac{8K_z g_0^3}{27\varepsilon_0 A}}. \qquad (2)$$

K_z is the equivalent spring constant of the moving structure in the direction of desired motion (typically the *z*-direction), g_0 is the gap between the switch and the actuation electrode, ε_0 is the free-space permittivity, and A is the switch area where the electrostatic force is applied. Equation (2) implies that there are several ways that may decrease the required actuation voltage. For example, reducing g_0 is one way, but it affects the high-frequency off-state switch performance by comprasing the switch isolation or insertion loss. A second approach in lowering actuation voltage is by increasing the actuation area *A*. To be able to create miniaturized circuits this area has to stay small. The third approach, which offers the maximum design flexibility for a low-to-moderate actuation voltage, is to lower the switch spring constant. This is explained e.g. in [15].

The electrical model of a MEMS series switch is a series capacitance in the up-state position and a small resistance in the down-state position. The isolation of a series switch in the up-state position is given by [9]

$$|S_{21}|^2 = 4\omega^2 C_u^2 Z_0^2 , \tag{3}$$

where C_u is the up-state capacitance and Z_0 is the transmission line impedance. The insertion loss is

$$|S_{21}|^2 = 1 - R_S / Z_0 , \tag{4}$$

where R_S is the contact resistance of the switch.

IV. Shunt MEMS Capacitive Switch

There are different types of MEMS shunt capacitive switches, which provide different performances. One example of those switches is given in Fig. 4, and usually shunt switch is based on a fixed-fixed beam design. The anchors are connected to the CPW ground plane, and the membrane is grounded. The center electrode provides both the electrostatic actuation and the RF capacitance between the transmission line and the ground. When the switch is in the up-state it provides the low capacitance to the ground, and it does not affect signal on the transmission line. When the switch is actuated in the down-state, the capacitance to the ground becomes higher and this results in an excellent short circuit and high isolation at microwave frequencies.

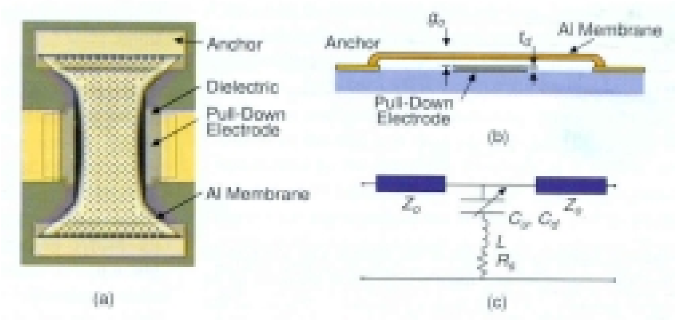

Fig. 4. Raytheon MEMS capacitive shunt switch [9]

The up-state reflection coefficient of a shunt capacitive switch is [9]

$$|S_{11}|^2 = \frac{\omega^2 C_u^2 Z_0^2}{4} , \tag{5}$$

where C_u is the up-state capacitance of the switch. The down-state isolation is

$$|S_{21}|^2 = \begin{cases} \dfrac{4}{\omega^2 C_d^2 Z_0^2}; & f << f_0 \\ \dfrac{4R_S^2}{Z_0^2}; & f = f_0 \\ \dfrac{4\omega^2 L^2}{Z_0^2}; & f >> f_0 \end{cases} , \tag{6}$$

where f_0 is the down-state resonant frequency of the capacitive switch.

V. Inductively-Tuned MEMS Shunt Switch

A special attention will be paid to the modeling of a CPW shunt capacitive switch, which is shown in Fig. 5a). The center conductor of the CPW line is biased with respect to the ground, to accomplish switch actuation. The resulting electrostatic force pulls the membrane towards the center conductor, with a certain pull-down voltage [3, 6, 15]. When the bias voltage is released, the mechanical stresses in the membrane overcome the stiction forces between the membrane and the dielectric and pull the membrane away from the dielectric layer, moving it to the original position.

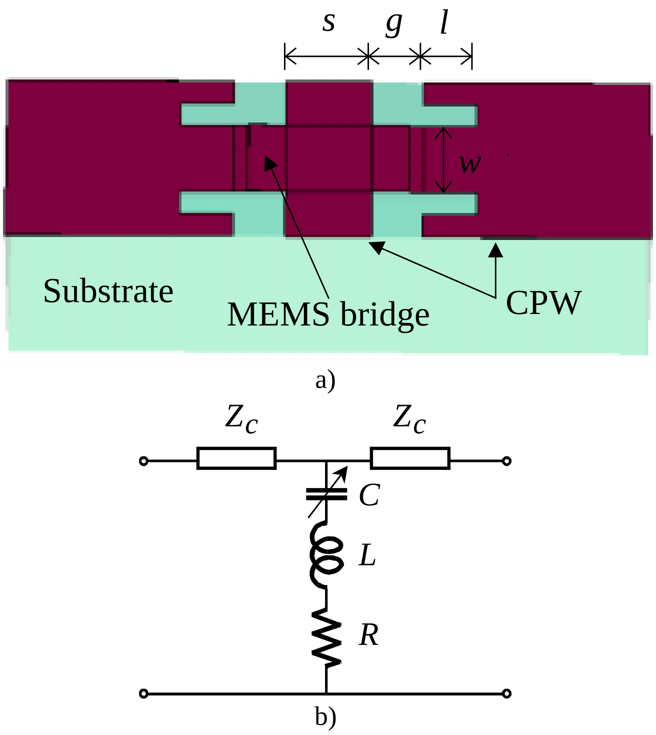

Fig. 5. A typical inductively-tuned MEMS shunt switch a), and an equivalent lumped element model b)

Shunt MEMS switch in the up position behaves mainly as a small capacitance to ground. This up-state capacitance can be modeled well by electrostatic solvers or using full wave analysis. The lumped element model also includes a small inductance and resistance in series with the shunt capacitance, as in Fig. 5b). Since the capacitance is very small and it

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dominates the shunt impedance, it is very difficult to determine the resistance and inductance associated with the model in this up-state. The down-state capacitance is more difficult to model because it depends on the MEMS switch planarization and the surface roughness of the dielectric and metal layers. That is way, sometimes down-state parameters must be extracted from measured data.

The switch shunt impedance is

$$Z = R + j\omega L + \frac{1}{j\omega C}, \quad (7)$$

where capacitance C depends on the position of the switch (up or down). The series resonant frequency of the switch is

$$f_0 = \frac{1}{2\pi\sqrt{LC}}. \quad (8)$$

This lumped element model behaves as a capacitor below the series resonant frequency, and as an inductor above this frequency. The series resonance is very important for the isolation performance of the shunt switch, but unfortunately high isolation can only be achieved around this resonance.

One way to obtain a higher isolation at lower frequencies is to increase the series inductance of the switch to lower the resonant frequency. This can be done by adding a short section of transmission line between the MEMS bridge and the ground plane, as in Fig. 5a) [1, 4, 5, 12]. By properly choosing the length of this line *l*, the series resonant frequency can be pushed down to the desired frequency range. This gives high isolation inductively-tuned MEMS shunt switch without the use of a few additionally switches or tuned designs. This type of switch has less bandwidth than standard shunt switch, but it also has much higher isolation in the vicinity of resonant frequency.

VI. Design Example

The considered MEMS shunt switch should be fabricated using a $Z_c = 50\Omega$ CPW line implementation ($s = 160\mu m$ and $g = 96\mu m$) on a 400µm thick high resistivity silicon substrate with relative dielectric constant of 11.9. The fabrication procedure should be based on a 300µm long, 6000Å thick sputtered gold bridge, suspended 2.5µm above the center conductor. 4000Å thin SiO_2 is sandwiched between CPW and substrate. The middle electrode of CPW, underneath the bridge is covered by a dielectric of 2100Å of silicon nitride, to prevent stiction problems (the device is capacitively rather than resistively coupled). A membrane width is $w = 150\mu m$ and the length of the inductive section of transmission line is in the range $l = 0\mu m$ (no ground indentation) to $l = 200\mu m$. The CPW line and the inductive section are 1.3µm thick.

The full wave electromagnetic simulation of the switch is done using CST MicroWave Studio [7]. In the simulation, the substrate is assumed to be lossless and conductors are treated as perfect conductors. The parameters of the lumped element model in Fig. 5b) are optimized to fit the S-parameters obtained from the full wave electromagnetic simulation. Fig. 6 shows the EM simulated and lumped element model S-parameters of the analyzed switch in the up-state, for no inductive tuning ($l = 0\mu m$). S11 and S21 are reflection and transmission parameters obtained by EM simulation; S33 and S43 are corresponding parameters obtained using lumped element model. Good agreement between those results is obvious. Since the capacitance is very small and it dominates the shunt impedance, it is very difficult to determine the resistance and inductance associated with the model in up state. The capacitance in the lumped element model for this state is $C_u = 117.425\text{fF}$.

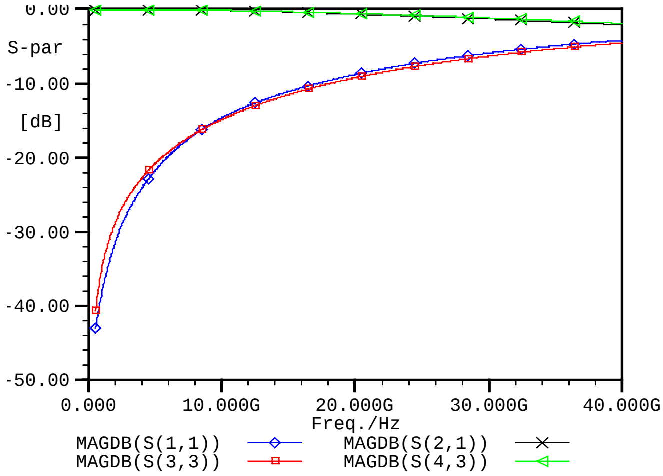

Fig. 6. S-parameters of the EM simulated and lumped element modeled switch in the up-state

When the switch is in the down-state, similar procedure is used and S-parameters obtained from the full wave analysis are compared with those obtained using model. This switch is analyzed for five different lengths of the inductive tuning section in the down position. The lumped element circuit parameters are obtained using optimization procedure in Aplac [8]. Fig. 7 shows the EM simulated and lumped element modeled down-state performance of the switch with $l = 0\mu m$ (higher resonant frequency) and $l = 200\mu m$ (lower resonant frequency) long inductive tuning section.

From the result in Fig. 7 it can be seen that the resonant frequency is shifted from 24.442GHz for the standard case (no inductive tuning) to 15.374GHz in the case of inductively-tuned switch. This gives isolation better than 20dB from 13-18GHz, and in this range there is at the most 8.5dB improvement in the isolation over the standard design.

From the results of the full wave analysis, i.e. lumped element model characteristics, it is observed dependence of the switch inductance in the down state versus the inductive section length. The obtained values for the lumped element modeled inductance in Aplac are given in the second column in the Table 2. For all the chosen lengths of the inductive section resistance and capacitance in the down state lumped element model are $R = 0.05\Omega$ and $C = 1.179\text{pF}$, respectively.

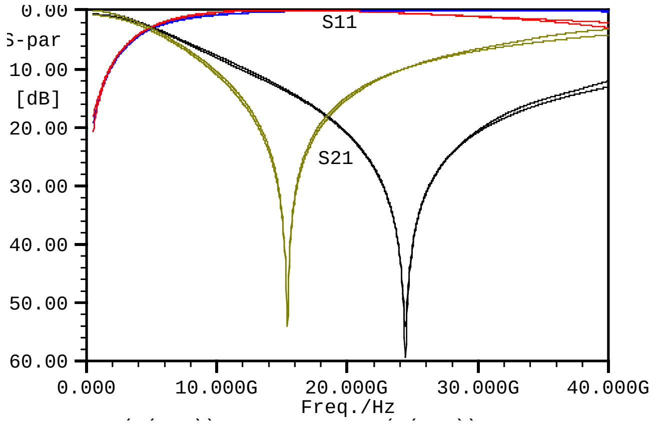

Fig. 7. EM simulated and lumped element modeled S-parameters for the switch in the down-state

TABLE II. INDUCTANCE AND RESONANT FREQUENCY VALUES FOR THE MEMS SWITCH IN THE DOWN-STATE

l[μm]	L[pH] Aplac	L[pH] Eq. (9)	L[pH] Eq. (10)	f_0[GHz] Aplac
0	35.962	34.971	36.076	24.442
50	48.412	48.665	48.112	21.066
100	61.039	62.359	61.254	18.761
150	75.486	76.053	75.501	16.871
200	90.896	89.747	90.854	15.374

Fig. 8 shows the obtained inductance in lumped element model (Aplac) versus inductive section length. From this data, a linear fitting for the switch inductance is obtained in the form

$$L[\mathrm{pH}] = a + bl\,, \tag{9}$$

where $a = 34.9706\mathrm{pH}$, $b = 0.27388\mathrm{pH/\mu m}$ and l should be replaced in μm. A bit better fitting can be obtained using polynomial regression

$$L[\mathrm{pH}] = c + dl + el^2\,, \tag{10}$$

where $c = 36.07631\mathrm{pH}$, $d = 0.22966\mathrm{pH/\mu m}$, $e = 2.21143\cdot 10^{-4}\,\mathrm{pH/(\mu m)^2}$, and l should also be expressed in μm. The calculated values for switch inductance using presented fitting equations are given in the Table 2, for the discrete values of inductive section length. Fig. 8 also involves both fitting curves, and from the presented models a very good agreement between the results can be noticed.

The values of the inductance predicted by the models given here can be efficiently used in addition to the presented procedure, to design a shunt MEMS switch with a high isolation in the desired frequency range.

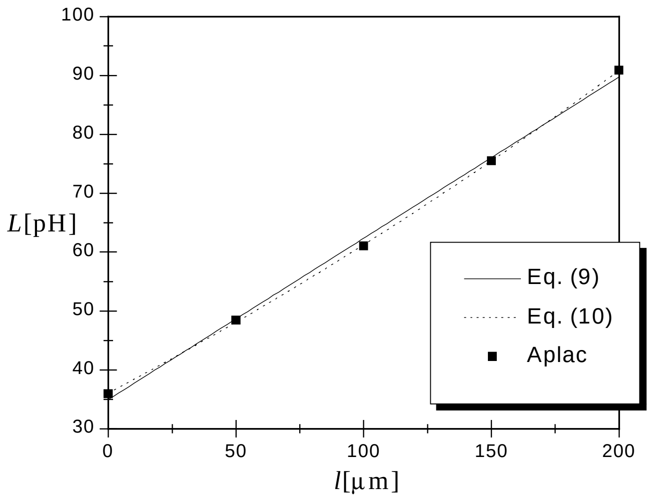

Fig. 8. Inductance of the lumped element model as function of the length of the tuning section

VII. RELIABILITY AND PACKAGING

The reliability of MEMS switches is very important for long-term applications [9-11]. For DC contact switches the failure mechanisms are resistive, and for capacitive switches this is due to stiction. The reliability of the series switch is limited by damage, pitting, organic deposits, and contamination around the contact area. The last two reasons can be eliminated by clean packaging environment. The reliability of capacitive switches is defined by stiction between the dielectric layer and the metal due to the large contact area of the switch. The main stiction force is due to the charging effects in the silicon nitride dielectric layer, and it can cause the switch to either stick in the down state position or results in an increase in the pull-down voltage so that the MEMS switch can not be used anymore.

The most critical part of MEMS switches is the packaging technique. That is the most expensive step in the production chain and determines the cost of the switch. It is possible to package MEMS switches in clean room conditions using proven hermetic packages, but that is very expensive approach. There is currently a large effort to develop wafer-scale packaging techniques which are compatible with MEMS switches [9] (low-temperature hermetic glass bonding, minimal outgassing, gold-to-gold bonding etc.).

The reliability and packaging of MEMS switches are currently the subjects of an intense research effort.

There are some companies putting much effort to the MEMS switch commercialization (e.g. Dow-Key [18] and Teravicta [19]), but still mentioned issues together with high prices are very challenging.

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VIII. CONCLUSION

An overview of MEMS technology, applications and RF MEMS switches is presented in this article. MEMS technology is quite mature at the wafer level and the switch actuation is well understood. MEMS switches development has been progressing very rapidly, and their RF performance is excellent when compared to PIN diode or FET switches. However, there are also several problems relating to the lack of high power RF MEMS switches, long-term reliability, packaging, fabrication cost, high voltage levels and some phenomena, such as stiction, to be solved in the near future. These factors make RF MEMS switches area very challenging.

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