Novel MEMS Devices and Silicon Micromachined Components for High Frequency Circuits

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ABSTRACT

This paper discusses recent developments in MEMS devices and Si-micromachined circuits. Specifically, the issue of poor isolation in individual MEMS switches is addressed in the context of creative designs that lead to the development of very-high isolation MEMS switch architectures operating in a very broad frequency range. Furthermore, Si-micromachined circuits appropriate for use in modern communications systems are described, and novel K- thru W-band three-dimensional multi-layer architectures are presented.

1.0 SUMMARY

1.1 Introduction

Communications needs of future systems require increasing functionality and performance endurance to allow for successful insertion of new highly integrated MEMS sensors and instruments, now commonly planned for the new generation of wireless sensors. To maximize data transfer, reduce size and minimize operation cost, communications RF front-ends are forced to move to higher frequencies. Circuit miniaturization can be achieved by implementing a number of enabling technologies, which will allow the development of novel low-energy/low-cost and high-performance RF devices. These technologies include new circuit and component architectures, low-cost adaptive and re-configurable phased array antennas, millimeter-wave devices, advanced materials and novel integration techniques, integrated systems on a chip, and new packaging methods for high-frequency electronics. RF micromachining and MEMS technology promise to provide an innovative approach in the development of effective and low-cost circuits and systems, and are expected to have significant application in the development of low-cost antenna arrays and re-configurable apertures.

With better selectivity provided by MEMS, transceivers will now be able to function in a variety of environments, since co-site and other interferers will be much less of a problem. The use of high-\(Q\) passive components in transceivers allows one to relax the design specifications for the surrounding transistor circuits. In particular, dynamic range and phase noise specifications can be greatly relaxed, allowing not only substantial power reduction (as described above), but also making possible the use of less expensive technologies for certain functions. In a fully integrated system using a merged circuits/MEMS technology, packaging costs can also be reduced, since board-level assembly may no longer be needed. With these new RF MEMS-based architectures, the key enabler is the outstanding performance of RF MEMS devices, particularly switches.
and filters and the ultimate ability of these devices to be fabricated on a variety of heterogeneous materials such as plastics (kapton), thereby allowing flexibility and configurability and reducing the cost per unit area of the RF systems and components. MEMS switches of either capacitive or metal-to-metal contact type have demonstrated modest isolation at the operating frequency range due to the switch capacitance and coupling capacitance and inductance formed between the MEMS switch and the RF circuitry circuitry around it. This isolation reduces with high frequency for both metal to metal and capacitive switches to less than 20dB at 40GHz.

High circuit performance cannot be achieved without the use of novel integrations and packaging techniques. Silicon (Si) micromachining provides a comprehensive technique to microwave and millimeter wave circuit integration with a very large degree of functionality on a single substrate with extremely high density and at a relatively low cost. The micromachined circuit is essentially self-packaged, without the need for external carriers or external hermetic packaging. Since the components are completely shielded by the micromachined structure, there is neither significant electromagnetic coupling nor spurious resonances caused by the package. In addition, the vertically layered structure of the micromachined circuit presents an excellent opportunity for three-dimensional integration, resulting in the potential for substantial reductions in size. This paper will present recent advances in Si MEMS devices and and micromachined circuits.

1.2 High Isolation Switches

One of the well-known applications of micro-electro-mechanical systems (MEMS) is the field of the microwave switches. Many different types of shunt or series capacitive and metal-to-metal MEMS switches on microstrip or coplanar waveguide (CPW) transmission lines have already been reported [1-4]. Capacitive or metal-to-metal contact shunt or series switches using electrostatic actuation [1,2,3] are among the most useful cases, although others using electrothermal actuation have been reported too [4, 5]. Most of the previously reported designs use the variation in the capacitance ratio between the on and off stages of the device for the switching operation. In case of capacitive switches this ratio is of the order of 60 to 100, but in the case of metal-to-metal contact this ratio becomes very large due to the direct contact and very high capacitance values realized when the switch is in the down position (theoretically infinite). However, taking into account only the capacitive part of the switch does not necessarily result in correct modeling of the RF performance, due to the parasitic inductance and resistance [4, 6] of the device (see Figure 1). MEMS switches of either capacitive or metal-to-metal contact type have demonstrated modest isolation at the operating frequency range due to the switch capacitance and coupling capacitance and inductance formed between the MEMS switch.
and the RF circuitry around it [6]. This isolation reduces with high frequency for both metal to metal and capacitive switches to less than 20dB at 40GHz. Preliminary work has shown that appropriate design of the switch inductance and capacitance can provide single MEMS switches with very special RF characteristics.

It has been demonstrated that the switch inductance can be designed to trigger a series electric resonance, which improves the isolation between the input and output ports of the switch. In particular, single capacitive switches connected in a shunt configuration have been designed to resonate at a specified frequency as discussed above and have shown improved isolation. In addition, combinations of these switches connected in parallel have demonstrated the ability to achieve even higher isolation at the frequency range of interest. In all of these designs, bandwidth has been achieved between 5GHz and 40 GHz. In the following we will discuss recent demonstrations of successful designs of resonant switches and switch packets operating from 5 GHz to 40GHz.

Typical values of this inductance \( L \) range from 0.2 to 6 pH depending on the switch geometry. Recent work has demonstrated that appropriate switch design can result in a much higher value of \( L \) (up to 50 pH measured) giving the advantage of tunable switches. In addition, control of both \( C_D \) and \( L \) gives more design goal flexibility since the resonant frequency and the bandwidth can be changed simultaneously. The value of the inductors mentioned above is mainly determined by the geometry of the connecting beams and can either be found by a full wave electromagnetic solver, or from measured S-parameters. Since the up-state switch capacitance is usually very small, the response of the switch in the up-state is almost independent of the inductive connecting beams. Therefore S-parameters showing the switch isolation should be used to accurately extract the inductance value.

In many applications, higher isolation and broader bandwidth than the ones achieved with a single switch are desired. Recent work has shown that a network of four parallel switches has been designed and fabricated as shown in Figure 2. Each single switch has a different connecting beam and thus a different resonant frequency. The switches are connected with small inductive sections so that their reflection coefficients cancel when the switches are up. The down capacitance for the switches in Figure 2 is around 2.9 pF and it is the same for all of them, while the series inductances are: \( L_1 = 50\, \text{pH}, \, L_2 = 43\, \text{pH}, \, L_3 = 31\, \text{pH}, \, L_4 = 27\, \text{pH} \). Finally, the inductive sections between the switches are 190 and 90 micron long, giving equivalent inductances of 115 and 55 pH respectively. The performance of the circuit is shown in Figure 3. The maximum theoretical isolation that such a network can achieve is very high and is greater than 90 dB from 13 to 20 GHz and greater than 60 dB from 12 to 40 GHz. However, these values were below the noise floor and could not be measured. Nevertheless, it is obvious that the measured isolation is greater than 45 dB from 11 to 40 GHz. Capacitive
Four-Switch Packet Measurements

**Switches are ON**
- Measured Isolation > 45 dB (11 to 40 GHz)
- Simulated Isolation > 60 dB (from 12 to 40 GHz)

**Switches are OFF**
- Return loss < -20 dB from 2 to 40 GHz
- Loss < 0.6 dB from 2 to 40 GHz

Figure 3: Measured response of the switch packet of Figure 4.

and metal-to-metal contact switches in arrangements of this type demonstrate good performance above 1 to 5 GHz, while at frequencies below 5 GHz, isolation is very poor and worse than -10 dB. In the case of metal-to-metal contact switches, while the packet performs very poorly below a few GHz, the single switch itself, when in the down position, behaves as a high-pass filter giving isolations of the order of -50 dB.

1.3 Application of Three-Dimensional Integration to a Power Combining Network

Three-dimensional vertical integration can significantly reduce the horizontal line lengths required to reach across all the MMICs in the planar integration because they can be vertically stacked directly above and below each other. In this integration concept, the MMICs are stacked on separate substrate layers above and below the Wilkinson combiners (see Figure 4). Transmission lines make the vertical transitions to the substrate level of the Wilkinson combiners on slanted sides of anisotropically etched apertures in the 100 m thick silicon substrate [8-11].

Figure 5 shows the improved performance of the combining network starting with a single MMIC at the top surface. For a 50% combining efficiency, the vertical stacking architecture allows five combining stages, for a total of 32 combined amplifier MMICs. The total loss is less than that for the micromachined 2-dimensional planar approach,
even though the low loss micromachined lines cannot be used along the slanted faces in the 3-D vertical stacking approach. Another advantage of the 3-D stacking approach is that the reduced horizontal footprint of the circuit. The horizontal footprint of 5 stages of the planar combined circuit (32 amplifiers) is 7.16 mm x 159.5 mm or about 1142 mm$^2$, while for the vertically stacked circuit the footprint of 5 stages is only 10.13 mm x 8.65 mm or about 88 mm$^2$, a factor of 13 reduction. All finite ground coplanar (FGC) based circuit components are optimized to suppress parasitic effects generated by the presence of multiple dielectric layers and the proximity of extended conducting planes. Using a Si-micromachined 3-D architecture, high-density is achieved by integrating wafers vertically and by utilizing both sides of the wafer for printing the circuit components. To achieve on-wafer packaging while integrating multiple circuit functions, the same wafers carry the circuit components in addition to the monolithic fabricated cavities that provide shielding and good circuit isolation. In addition to packaging, the shielding cavities are utilized to reduce parasitic mechanisms generated by the stacking of the wafers and the close proximity of extended metallic planes. However, the ability to integrate in three dimensions can accomplish more than just increasing the density of circuit integration and reducing costs. It can provide added performance that cannot be achieved in a conventional planar circuit architecture. This can be illustrated through a concept study of a power combining network.

Micromachined silicon integrated circuits have the potential for providing an overarching circuit integration technology which can significantly reduce the size, weight, and cost of microwave and millimeter wave components. The capability to integrate diverse substrate technologies opens the door for real multifunction chips, combining analog, digital, RF, and opto-electronic functions. This natural approach to three-dimensional vertical integration not only can provide higher density circuits, but by freeing RF circuit design from the tyranny of the two-dimensional layout, can reach levels of performance not possible in a planar geometry.

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