RF MEMS: Benefits & Challenges of an Evolving RF Switch Technology

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Micromachining provides a new dimension to the fabrication of RF devices for high performance and low cost. The use of surface micromachining techniques combined with conventional microwave integrated circuit processing enables a new class of RF devices with unique and improved performance. The benefits of these devices include ultra-low loss, very high linearity, and negligible current consumption. These devices are typically operated with electrostatic forces. The geometry and material properties of the switches determine the actuation voltage, usually in the range of 30-50V. As the device is essentially a switched capacitor, it draws no quiescent current other than a very small leakage current. The low loss dielectrics and high conductivity metals used to construct these switches enables them to have low losses, typically less than 0.1 dB through 40 GHz [1]. At frequencies up through at least 20 GHz, the loss is primarily due to ohmic losses within the metals. The effective resistance through the switch is roughly 0.25 ohms.

The inherent low loss of these switches has been exploited to fabricate phase shifters with very low loss. At X-band, 4-bit phase shifters exhibit 1.2 dB of average loss [2]. At Ka-band, the loss increases to approximately 2.25 dB for 4-bits [3]. Both of these phase shifters have significantly lower loss than obtainable with *p-i-n* diode or transistor switches. The loss within the phase shifters is primarily due to ohmic losses, the main contributors being that of the switches and transmission lines.

The primary application of RF MEMS phase shifters is in electronically scanned antennas. Putting an RF MEMS phase shifter behind every antenna element enables the T/R module to be moved back behind a first layer of manifolding. By feeding 8 or 16 antenna elements with each T/R module, the high cost of the modules can be amortized over many antenna elements. While this technique will not work in systems that need high peak power per element, it does work with many systems which operate at lower power levels. There are several classes of radar and communications antennas that are applicable to this technique [4].

RF MEMS switches have also been used to develop a new class of tuned L-C filters that operate at frequencies up through 3 GHz. Since the MEMS switches are actually bi-stable, switched capacitors, they can be cascaded to create multi-bit, digitally selectable varactors [5]. These varactors, in turn, can be used to create multi-pole filters. By designing redundant components into the filter in the form of impedance inverters, the filter network can be designed such that the inductors are equal and remain a fixed value while the filter is tuned. This enables capacitor-only tuning, with series capacitors tuned to adjust bandwidth and shunt capacitors tuned to set the resonant frequency. A five-pole filter at 806-917 MHz with on-board inductors tunes in sixteen 7-8 MHz steps and has a loss of 6-7 dB. Interestingly, it is the loss of the inductors (due to their low-Q) that is the main determinant of the filter loss. Similarly, a six-pole filter was constructed which tuned 110-160 MHz in sixteen 3-4 MHz steps. This filter possessed off-chip, wire-wound inductors (Q~50 at frequency of interest). The resulting loss was 3-5 dB across the tuning range [6]. These tunable filters, and others like them, result in substantial size (60x) and weight (150x) reductions compared to conventional fixed filters with switch networks. This enables significant reductions in packaging for receiver front-ends.

Presently, neither capacitive membrane nor ohmic contact switches are limited in lifetime by mechanical considerations. In ohmic contact switches, the mechanism that limits lifetime is degradation of the contacts with repeated actuations. Typical lifetimes are on the order of 1-100 million cycles, depending on the load current carried by the contact [7]. In capacitive membrane switches, the limiting mechanism is charging within the switch dielectric layer. The exact physics of dielectric charging within RF MEMS switches is not presently understood. There are several scenarios by which charges can migrate and become trapped on the surface or within the bulk of the dielectric. Under typical bias conditions (1-3 MV/cm of electric field across the dielectric), it is possible for charges to tunnel into the dielectric with a phenomenon similar to Frenkel-Poole emissions in insulating films. Once charges tunnel into the device, they become trapped within the dielectric, where there is no convenient conduction path. The recombination time for these charges can be very long, on the order of seconds to days. As charge becomes trapped within the dielectric, it tends to screen the applied electric fields used to control the actuation and release of the switch. The end result is that this screening voltage builds up within the dielectric and hinders operation of the switch. Most commonly, this results in the switch being stuck down [8].

Recent improvements in reliability have focused on operating the switches with reduced actuation voltage. This requires lower pull-down voltages, which means controlling the geometry and stresses of the metal films. Significant efforts have also been underway to reduce the magnitude and variability of the pull-down voltage through tight control of the core MEMS fabrication processes. This has reduced the typical pull-down voltage of the switches by more than 20 volts. It has also reduced the standard deviation of pull-in voltage across a wafer from 4-5 volts to 1-2 volts. This reduction in the magnitude and variance of the pull-down voltage has resulted in orders of magnitude improvement in switch lifetime. Currently, large numbers of MEMS switches are under lifetest with operating lifetimes in the billions of cycles.

RF MEMS technology is a new technology that is already finding niche applications in radar and communications systems. Its low power, high performance, and tunability enables potential cost, size, and/or weight improvements in several systems. Emphasis is no longer focused on RF performance, as that aspect is well established. Currently, efforts are underway to establish and improve the reliability of the devices. As with any maturing technology, there is much room for improvement. However, results to date show continuing improvement in lifetime and provide an argument that these devices will eventually have very long lifetimes (> 10^{11} cycles).

References

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