Passive Intermodulation and Power Handling for High Power RF MEMS Switches

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***Abstract* — This paper describes the theory and demonstrates the feasibility of implementing a high power, low loss and high linearity RF switch on fused silica substrate through RF MEMS technology. Commercial two-tone intermodulation test shows IMD3 90~110dBm at 850MHz and 90dBm at 3.6GHz.**

***Keywords* — linearity, microwave devices, dielectric substrates, glass, microswitches, ohmic contacts, silicon-on-insulator, silicon-on-sapphire**

I. INTRODUCTION

Low insertion loss, high linearity, high isolation, and high-power handling capability are always key parameters of RF and microwave switches. There are several major semiconductor technologies that have been developed over past decades. Among them, Gallium arsenide (GaAs) and LDMOS (Laterally Diffused Metal Oxide Semiconductor) are the most mature technologies, especially for low frequency and high power. In recent years Gallium Nitride (GaN) has found its way into various high demanding applications [1] and Silicon-on-Insulator (SOI) or Silicon-on-Sapphire (SOS) has had considerable success in mobile antenna switch applications [2]. However, the electrical conducting mechanisms of all the above technologies are based on minority carriers in semiconductors, which poses a contradictory design direction for high power, high frequency, and high isolation. The advancement of process technology nodes (for smaller geometries), semiconductor materials (high mobility and high voltage), and substrate material [3] (e.g. sapphire to cut down coupling, therefore providing higher isolation) can only improve one or two aspects of product performance but not all. Starting from the late '90s, researchers began looking into Micro-Electro-Mechanical Systems (MEMS) technology to build miniaturized mechanical switches with the ability to operate up to millimeter wave frequencies [2]. The high conductivity of the metal contacts provides much lower insertion loss, lower heat generation, and higher power handling capability than semiconductor counterparts.

There are two main types of MEMS switch architectures, capacitive and ohmic contact. The capacitive switched gained traction in low power antenna tuning applications for its low insertion loss and high isolation. However, it lacks the broadband RF power handling and linearity of Ohmic contact RF MEMS switches. In order to get the best possible off-state isolation and high linearity, MEMS researchers have leveraged findings from their semiconductor peers [4] and have started to migrate ohmic contact switches from regular silicon to Ceramic, High Resistivity (HiRes) Si, and Glass substrates [5] [6] [7].

This paper presents the analysis, characterization results, and high-power linearity performance of RF MEMS switches fabricated on a fused-silica substrate.

II. SOURCES OF NON-LINEARITY FOR TRANSISTOR, PIN DIODE, AND MEMS SWITCHES

For a semiconductor switch device, the most significant non-linear effects come from saturation of on-resistance and modulation of off-capacitance by high powered signals.

When transistors are used to achieve a switching function there are multiple transistors required in series to withstand the high voltage application, e.g. at the antenna. The number of stacked transistors in series is determined by the drain to source breakdown voltage (V_{DS}) of a transistor relative to the maximum voltage swing at the antenna port. When a transistor is fully ON, the non-linearity is mainly contributed by the transistors ON resistance. When a transistor is OFF, the linearity is influenced by not only the OFF capacitance but also other parasitic mechanisms traditional to semiconductors. A secondary effect occurs when the higher power levels create a high voltage swing at the antenna port. This high voltage swing can excite the off-state transistors closest to the antenna port (exceeding the VDS breakdown), through a significant amount of voltage imbalance, i.e. the voltage drop is not evenly distributed across each transistor in a chain [8].

When PIN diodes are used to achieve a switching function there are factors to ensure that the circuit can withstand the peak voltage application at the antenna. The voltage rating and thermal resistance are important parameters for diode switches. Other diode parameters, such as series resistance, junction capacitance, and intrinsic layer thickness, are also contributing factors to the determination of maximum power handling and linearity [9].

MEMS switch devices are fundamentally different compared to semiconductor switch devices in the way they give rise to non-linear energy. MEMS switch non-linearities originate from a combination of mechanical and electrical non-linear effects. These effects transfer energy from the fundamental signal into other frequency bands, where they interfere with other signals. A real-world example is when two in-band transmit signals mix and transfer energy into the adjacent receive band where it interferes with the received signal.

For the MEMS ohmic contact switch, the traditional loss mechanisms associated with semiconductors do not exist on the MEMS structure. The limiting factors of MEMS switch linearity will depend on the substrate material properties, metallurgical interfaces, and structural mechanical characteristics as shown in Fig. 1. The substrate resistance and coupling capacitance determine the RF small signal performance. The resulting small signal performance of an ohmic contact test structure built on fused silica vs. 3000 Ω·cm HiRes silicon is shown in Fig. 2. At 20 GHz, the switch built on fused silica exhibits 0.2 dB lower insertion loss and 6 dB higher isolation. For high power applications fused silica exhibits fewer non-linearity effects than HiRes silicon.

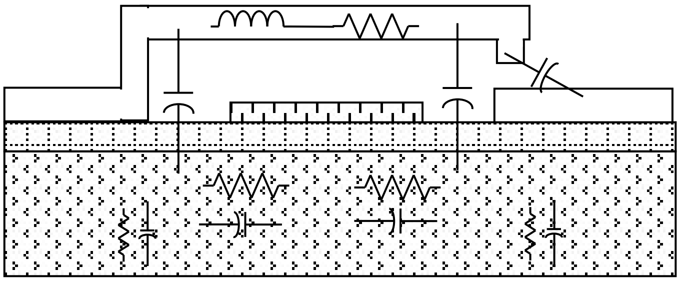

Fig. 1. The parasitic elements around MEMS substrate and in the substrate.

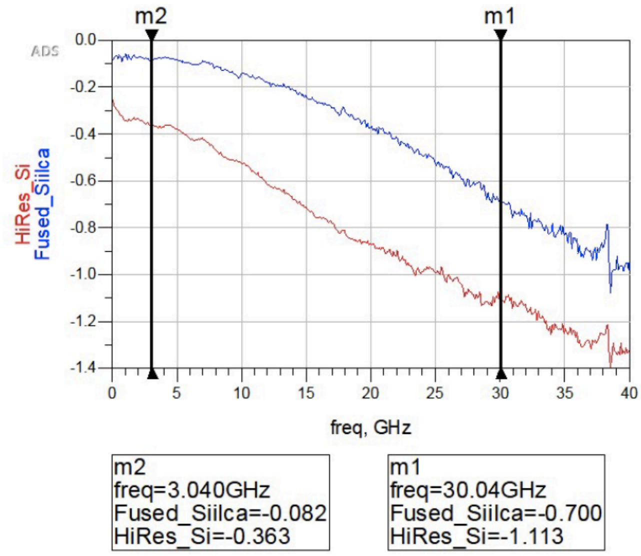

Fig. 2. Measurement results of the same layout built on fused silica (Red Line) and 3000 Ω·cm Si (Blue Line) substrate.

For a MEMS switch in the closed state the rectifying effects where signal voltage modulates the contact force results in mainly second harmonic products. With both positive and negative voltage leading to increased contact force, this creates a contact force varying at twice the rate of the input signal. At frequencies above the MEMS mechanical resonance frequencies, this source of non-linearity is generally very small [10] as the mass of the MEMS switch beam acts as low pass filter providing mechanical damping.

Similarly, for a MEMS switch in the open state, these rectifying effects displace the MEMS beam at twice the rate of the input signal. The slight change of capacitance during this displacement is a contributing source of the non-linear effect in the open switch state.

Another contributor to non-linearity, are effects originating from the electrical and magnetic field penetrating into the substrate. This results in second and third harmonic products. For a MEMS switch device, this component is often the limiting factor for linear performance. Fused silica was chosen as a base substrate material for the MEMS ohmic switch to significantly limit the non-linear contributions.

While most mechanical non-linearity effects occur at low frequencies, care must be taken when applying multiple high-frequency carriers with close frequency spacing. This may result in envelope effects which, if strong enough, may excite the low-frequency mechanical non-linearities. This usually is manifested as degradation in third order intermodulation product (IM3), or in other multi-tone linearity measurements. The same non-linear effects can also be triggered by amplitude modulated signals. See Fig. 3 for an illustration of this phenomenon.

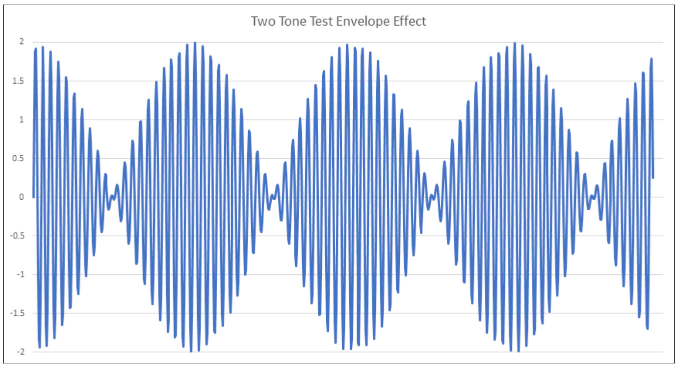

Fig. 3. The envelope effect shown by adding two high-frequency signals creating a low-frequency component or beat frequency

III. Technology Comparisons

Table 1 compares the relevant merits of the common switch technologies used in today's communication systems.

Table 1. Technology comparisons of MEMS-based switches against semiconductor-based switches

Characteristics	**MEMS Ohmic contact**	**Semiconductor Switch**			
	Ohmic contact	**SOI**	**GaAs**	**GaN**	**PIN**
Physics of Ron	Electrons in a metal conductor	Minorities (holes/electrons) in semiconductors			
Physics of Coff	~10 fF/unit cell @ 150 V	*(> 100 fF /gate @ 10 V)			
Typical IP3	> 90 dBm	< 75 dBm			
Typical Power Handling	>2 W/beam	< 2 W/Transistor			
Typical H3 @ +35 dBm	-120 dBc	See Measurements			

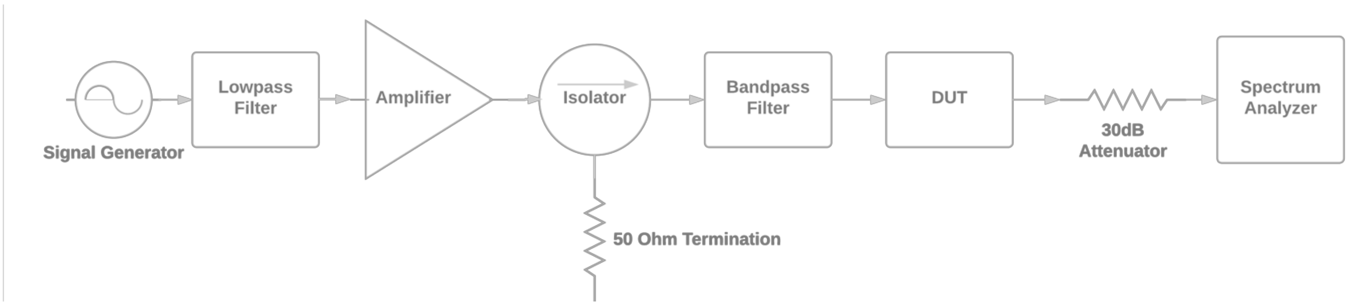

Fig. 4 Block diagram of benchtop harmonic response test set up

IV. Bench Testing of MEMS and Other Devices

A. Harmonics Testing

The harmonic signal to noise ratio is a measurement of overall system/signal distortion. As an established method of linearity performance testing, the 2nd and 3rd harmonic are normally reported to evaluate device linearity. This metric is very important for system design to ensure signal integrity. Traditionally harmonic peaking is mitigated with filtering. Due to superior harmonic performance of the MEMS switch several system benefits may be realized: remove filtering, path loss reduction, increased system efficiency, and lower part count.

Fig. 4 details the general harmonic test set up. A signal generator is used to provide the desired input signal, a lowpass filter is then used to ensure the harmonic cleanliness of the signal input to the power amplifier. The power amplifier output is then routed through an isolator and bandpass filter to the Device-Under-Test (DUT). The isolator ensures reflections do not cause mixing products at the amplifier output and the bandpass filter further ensures the harmonic cleanliness of the signal input to the DUT. A 30 dB attenuator is used at the DUT output to reduce the signal power to an acceptable level at the spectrum analyzer input. For harmonic vs. Voltage-Standing-Wave-Ratio (VSWR) measurements, a programmable tuner is used between the DUT and the attenuator. This allows for the VSWR to be modified from 1:1 through 5:1 and the phase to be controlled through 0-360°.

Measured harmonic response vs. input power of the MEMS switch is shown in Fig. 5 along with data from other devices. Measured harmonic vs. VSWR data for the MEMS switch is shown in Fig. 6, this is worst case measurement at each VSWR point as the phase is swept through 360°.

As shown in the in Fig. 5**,** the metal MEMS 2nd harmonic measurement is limited by the test system limits. The metal MEMS 2nd harmonic performance at 30dBm input power shows an 8 – 10 dB improvement vs. the semiconductor devices. The metal MEMS 3rd harmonic performance at 30dBm input power shows an 18-dB improvement vs. the semiconductor devices. A property observed in the ohmic switch measurements is its lower rate of harmonic distortion at higher input power levels. This result will enable the RF MEMS switch to scale more favourably than other solid-state technologies across the power spectrum. This phenomenon is more pronounced when comparing the 3rd harmonic. This high-power behavior is a combination of the intrinsic benefits of the metal-to metal contact and the fused silica substrate.

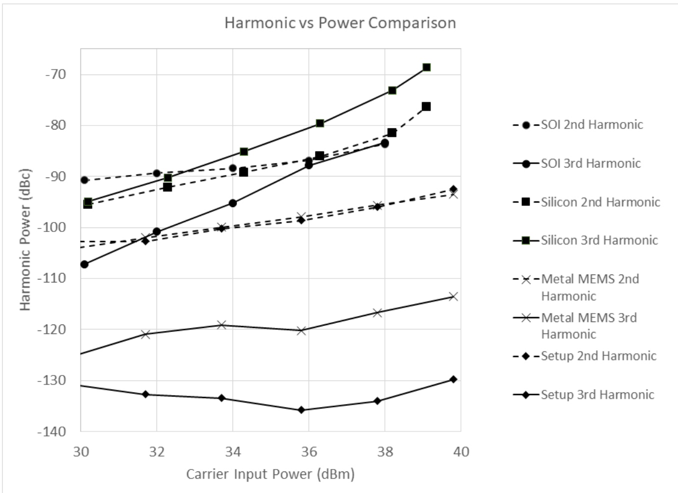

Fig. 5 Harmonic response power relative to carrier against input power level

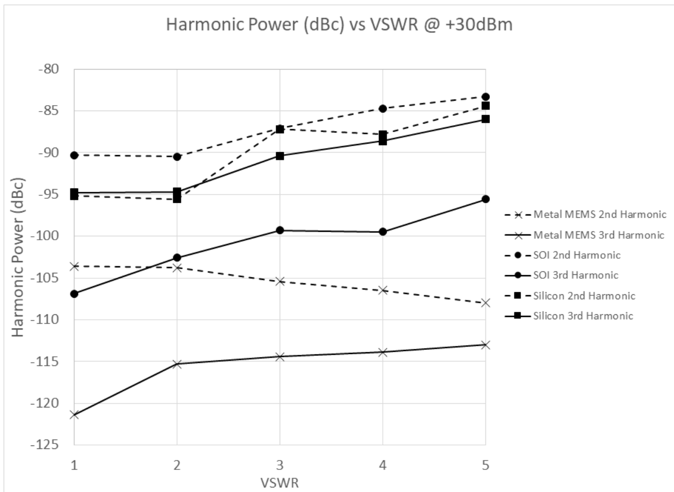

Fig. 6 Harmonic response power relative to carrier against VSWR

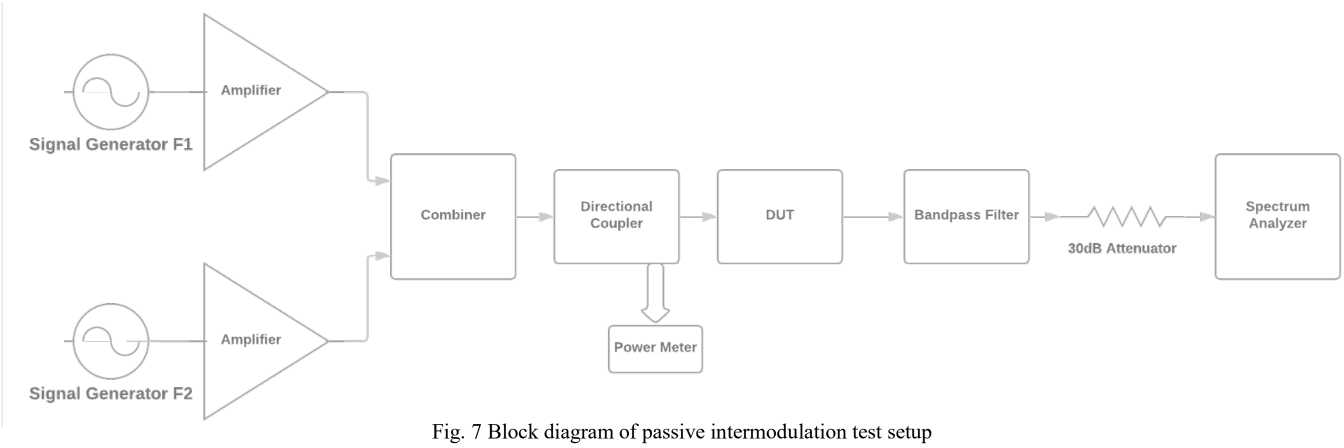

Fig. 7 Block diagram of passive intermodulation test setup

B. Passive Intermodulation (PIM) Testing

Intermodulation between frequency components will form additional components at frequencies that are not only at harmonic frequencies (integer multiples) of either, like harmonic distortion, but also at the sum and difference frequencies of the original frequencies and at sums and differences of multiples of those frequencies. Intermodulation is undesirable as it creates unwanted signals, often in the form of sidebands. For radio systems, this increases the occupied bandwidth, leading to adjacent channel interference.

Fig. 7 details the IMD3 test set up. This is a two-tone test that requires a signal generator and amplifier chain for each tone. The tones are then combined and filtered to ensure sufficient isolation between them, the composite signal is routed to the DUT via a directional coupler and power meter so that signal power level may be monitored. A bandpass filter to reject the two tones and pass the IMD tone along with a 30 dB attenuator is used at the DUT output to limit the power to an acceptable level at the spectrum analyzer input.

The IP3 data presented in Fig. 8 is calculated from IMD3 measurements detailed in (1). The carrier tones are +30 dBm at 1764 MHz and 1834 MHz. The metal MEMS structure data is close to the test system limits and are 10 dB and 15 dB better IP3 than silicon and SOI, respectively. The MEMS device was also measured in the 800 MHz band with +43 dBm tones resulting in an IP3 of +94 dBm. Improved IP3 allows higher order modulation schemes to accommodate the increased band proliferation of current and future communication systems.

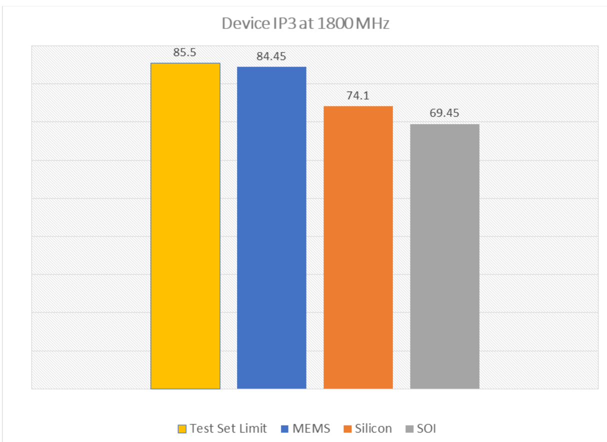

Fig. 8. IP3 for MEMS and other technologies

$$IP3\ (dBm) = P_{IN} - \frac{IMD_3(dBc)}{2} \quad (1)$$

V. Conclusion

As presented in this paper, an ohmic contact MEMS device avoids many of the non-linear effects associated with switch devices at high power levels. Mechanical non-linear effects are introduced that the designer must be aware of to take full advantage of the ohmic MEMS switch

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