Characterization of High-Q Laterally Moving RF MEMS Tuneable Capacitor

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Abstract—This paper investigates an implementation of RF MEMS tuneable capacitors based on the lateral displacement of the sidewalls of a three-dimensional micromachined coplanar transmission line. The concept achieves high Q since the mechanical actuation elements are completely de-coupled from the RF path, which is achieved by capacitive coupling of the ground signal to the moving sidewall. The fabricated capacitor has a tuning range of 40.53 to 60 fF ($C_{\text{max}}/C_{\text{min}} = 1.48$) in three discrete steps. This paper reports for the first time on Q-factor measurements, reliability, self-actuation robustness measurements, and linearity analysis. The Q-factor was determined by a transmission-line resonator as 88 at 40 GHz, resulting in a $Q \times f$ product of $3.52 \times 10^{12}$ which is higher than of any previously reported tuneable capacitor. Measurement data demonstrates high self-actuation robustness of 41.5 dBm at actuation and release voltages of 30.7 V and 21.15 V, a pull-in time of 60 μs, and a mechanical resonance frequency of 5.3 kHz. The linearity of the device has been determined to an IIP3 of 71.4, 74.4 and 91.0 dBm for the three states of the capacitor. Reliability tests up to 1 billion cycles show no detectable performance degradation of this all-metal tuneable capacitor concept.

I. INTRODUCTION

Tuneable capacitors form an integral part of frequency-agile microwave systems. Solid-state varactors typically have low self-resonance frequencies, high loss, limited linearity and a very small tuning range [1]. MEMS tuneable capacitors have shown the potential to replace solid-state varactor diodes in applications including phase shifters, voltage controlled oscillators, tuneable filters and impedance matching networks because of their near ideal signal handling behaviour, low power consumption, high self-resonance frequency, low loss and large bandwidth [2].

Quality factor and tuning range are key parameters for tuneable capacitors. As the Q-factors scale inversely with the frequency (~1/f), the $Q \times f$ product is an important benchmark parameter. The discrete position capacitor design in [3] achieved a capacitance ratio of 1.9 and a Q-factor of 95-100 at 34 GHz ($Q \times f = 3.4 \times 10^{15}$). The high power and high reliability capacitor in [4] resulted in a capacitance ratio of 1.5-2 and a Q-factor of over 225 in the X to Ku bands ($Q \times f = 3.75 \times 10^{15}$). The miniature RF MEMS switched capacitor in [5] has a capacitance ratio of 3 and a Q-factor over 90 at 20 GHz ($Q \times f = 1.8 \times 10^{15}$). The CMOS-MEMS 3-bit digital capacitor in [6] has a capacitance ratio of 63 and a Q of 160 at 1 GHz ($Q \times f = 1.60 \times 10^{15}$).

This paper presents a new concept of MEMS capacitor tuneable in multiple discrete and well-defined steps, implemented by in-plane moving of the ground side-walls of a 3D micromachined coplanar waveguide transmission line, with the MEMS actuators completely embedded in the ground layer side-walls. The basic concept of moving-sidewalls devices has been shown previously by the authors [7] but did not achieve high-Q factors. For the capacitor described in the present paper, the actuation mechanism is completely decoupled from the RF signal path. The authors have previously reported on filter circuits based on this concept, which indicate a high Q factor [8]. This paper reports for the first time on the high quality factor measured by a transmission-line resonator, measured reliability data, as well as linearity analysis and self-actuation robustness measurements.
II. CONCEPT AND DESIGN

The basic design of the MEMS-tuneable capacitor is shown in Fig. 1. The capacitive loading of a three-dimensional micromachined coplanar waveguide transmission line is tuned by a laterally moveable section of the ground layer sidewall, which is moved by integrated MEMS actuators which are completely embedded in the ground layer, thereby not adding any additional discontinuity. The 3D-micromachined transmission line results in reduced substrate losses, beneficial for a high-Q design. The whole device, including the RF and the MEMS actuation functions, is composed of a pure metal-air-metal (MAM) geometry which avoids dielectric charging, i.e. the design is done for high reliability and actuation voltage repeatability. Stopper geometries are used to avoid actuation-electrode short circuit. A further reliability-enhancing feature is the utilization of monocrystalline silicon as the core-structural material for all moving parts, which is then metalized. In contrast to many conventional MEMS tuneable capacitors, the signal line of the transmission line is not used for DC-biasing, neither is there a need for biasing lines crossing the transmission line slots, as the actuators are completely embedded in the ground layer and thus shielded.

The major advantage of the design presented in this paper over moving-sidewall tuneable capacitor concepts previously presented by the authors [7] (see concept drawings in Fig. 1), is that the mechanical springs are completely decoupled from the RF signal, i.e. the RF signal is not routed via any mechanical suspension geometry, which resulted in high loss and Q-factor degradation in the previous concept. The separation of RF and mechanical elements is achieved by capacitive coupling of the RF ground signal from the fixed ground layer to the moving ground sidewall. The mechanical springs are connected to isolated, floating islands behind the moving sidewalls. This concept results in reduced series resistance and parasitic inductance, and thus low insertion loss and high Q. Fig. 2 shows HFSS surface current simulations on the coupling mechanisms of a design of [7] compared to the new design. For the new design, the multiple folded spring suspension, even connected to floating islands, is clearly field-free. A SEM picture of a fabricated prototype device with the dimensions is shown in Fig. 3.

The tuning is achieved in well-defined discrete tuning steps. As there is a separate actuator on each side, a total of three discrete tuning steps is achieved (2 symmetrical and one asymmetrical). Fig. 4 shows the actuation principle of the tuneable capacitor with single-stage actuator. The device is actuated by applying a voltage between the actuation electrode and the anchors connected to the springs. More actuation stages can also be integrated resulting in additional states of the capacitor and extended tuning range.

III. CHARACTERIZATION

A. RF Measurements

Fig. 5 shows the insertion and return loss for the unactuated and all-actuated capacitor states. Extracted from the S-parameters, the capacitances are 40.53 fF (unactuated) and 60 fF (double-side actuated), resulting in a $C_{\text{max}}/C_{\text{min}}=1.48$. 

![Fig. 3 SEM picture of fabricated tuneable capacitor with single-stage MEMS actuator (3 tuning states).](image)
The quality factor of the capacitor was measured using a specifically designed weakly coupled 40 GHz transmission line resonator, loaded with the tuneable capacitor. An unloaded reference design $Q_r$, i.e. without the tuneable capacitor, was measured to be 14.88. The unloaded Q is equal to the loaded Q ($Q_l = Q_0$) for $S_{21} < -20$ dB. The unloaded capacitor Q is then calculated as in [2]. Fig. 6 shows the frequency response of the resonator loaded with the tuneable capacitor in the actuated and non-actuated state, resulting in an extracted $Q_u$ of the tuneable capacitor of 88 and 75 for the two states, respectively, at a frequency of 40 GHz. The $Q\times f$ product of this tuneable capacitor is thus $3.52\times10^{12}$.

![Fig. 5 Measured S-parameters for fabricated capacitor for the unactuated and symmetrically actuated states.](image)

Fig. 6 Q-factor characterization for the fabricated capacitor.

B. Actuator Measurements

All displacement measurements for actuation voltage, resonance frequency and response time were performed using a Veeco Wyko NT9300 white-light interferometer, with the chip being placed in a slanting position underneath the lens of the profilometer. Fig. 7 shows the measured actuation and release curve for a single-side actuator with a mechanical spring of $k=5.8$ N/m, compared to the simulated curve with COMSOL Multiphysics. The measured average pull-in voltage of 20 successive cycles is 30.70 V with a standard deviation of 1.08 V. The average and standard deviation of the releases voltage is 21.15 V and 1.71 V, respectively. It can be seen that there is good agreement of the measured displacement of a complete cycle with COMSOL Multiphysics simulations based on the measured, fabricated geometry.

![Fig. 7 Measured and simulated DC-actuation hysteresis for the fabricated capacitor with a spring constant of 5.8 N/m.](image)

Fig. 8 shows the measured mechanical resonance responses of two fabricated devices with different spring constants. For a spring constant of 5.8 N/m the mechanical resonance frequency was measured to be 5.3 kHz, and a spring constant of 27.7 N/m results in a mechanical resonance frequency of 17.2 kHz.

The actuator pull-in time to the first bouncing event is 60 μs, and the settle time for the bouncing to drop below 8% of the gap is 140 μs. The release is followed by multiple oscillation events implying that there is very low damping of the unpackaged device. The oscillation frequency is in good agreement with the measured mechanical resonance frequency of the device.

C. Power Handling, Linearity and Reliability Measurements

The self actuation robustness was determined by applying a 60 kHz low frequency power signal, while measuring actuator movement with a white-light interferometer. Self-actuation pull-in occurs at 41.5 dBm and 47.8 dBm for two devices with $k=5.8$ N/m and $k=27.7$ N/m respectively, as shown in Fig 9. In principle, the stoppers of the actuator should limit any movement in the pull-in state, but it was noted that at high signal power levels beyond 40 dBm, there is a risk for the moving sidewall to tilt which creates an even non-reversible short-circuit to the signal line.

![Fig. 10 shows the calculated IIP3 at 2.5 GHz for the device in its three discrete states, derived from the measured capacitances, measured sidewall displacements and simulated spring constants of the three states, using the equations provided in [2]. The IIP3 was determined to be 71.4, 74.4 and 91.0 dBm for the three discrete states. It was attempted to measure the linearity characteristic (IIP3) with two signal sources (centre frequency 2.5 GHz, 12 MHz offset). Despite using a narrow notch-filter for filtering the signal sources, the IIP3 measurement limit of the setup was measured with a reference line to be 68.5 dBm, which is below the calculated and thus expected IIP3 of the tuneable capacitor.](image)

Lifetime measurements were performed on an unpackaged tuneable capacitor with a spring constant of 5.8 N/m in an uncontrolled atmospheric environment ($V_{AC}=34$ V; unipolar square waveform; 35% duty cycle; 1.6 kHz cycle frequency).
The pull-in and pull-out voltages were determined in an automated setup by measuring complete cycle hysteresis after each decade of actuation cycles, to derive the pull-in and pull-out voltages over the lifetime. The measurements were stopped after 8 days (22 hours of accumulated pull-in time), when reaching one billion cycles, shown in Fig. 11. No failure, fatigue, or altered pull-in hysteresis was observed. Neither the stoppers nor other actuator elements showed any signs of wear when inspected in the SEM after the lifetime measurements.

Fig. 8 Measurements of mechanical resonance frequencies for two fabricated capacitors with spring constants of 5.8 and 27.7 N/m, using a white-light interferometer.

Fig. 9 Measurement of self-actuation behaviour using a 60 kHz high-power signal on the RF transmission line, on two fabricated capacitors with spring constants of 5.8 and 27.7 N/m.

Fig. 10 Calculated IIP3 for the three states of the device (f = 2.5 GHz), derived from measured capacitances, and the geometries of the fabricated device, and the simulated spring constants.

IV. CONCLUSION

This paper has demonstrated the concept of a RF MEMS tuneable capacitor based on moving ground sidewalls of a 3D-micromachined coplanar transmission lines with integrated MEMS actuators, with the RF path completely de-coupled from the DC actuation. Extraordinary high-Q, high reliability, high linearity, and high self actuation robustness at medium actuation voltages is reported.

REFERENCES


