Quasi-Analog Multi-Step Tuning of Laterally-Moving Capacitive Elements Integrated in 3D MEMS Transmission Lines

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Abstract. This paper reports on multi-position RF MEMS digitally tuneable capacitor concept resulting in quasi-analog tuning with large tuning range. The capacitors are integrated inside a coplanar transmission line whose tuning is achieved by moving the sidewalls of the 3D micromachined transmission line, with the actuators being completely embedded and shielded inside the ground layer.

Devices with symmetrical two and three-stage actuators have been fabricated in an SOI RF MEMS process. A tuning range of C_{max}/C_{min}=2.41 with a total of 7 discrete tuning steps from 44 to 106 fF was achieved for the three-stage tuneable capacitors. Devices with actuator designs of different mechanical stiffness, resulting in actuation voltages of 16 to 73 V, were fabricated and evaluated. The robustness of the actuator to high-power signals has been investigated by a nonlinear electromechanical model, which shows that self actuation occurs for high-stiffness designs (73 N/m) not below 50 dBm, and even very low-stiffness devices (9.5 N/m) do not self-actuate below 40 dBm.

1. Introduction

Most RF MEMS capacitors are based on a switched or tuned, surface-micromachined, parallel-plate configuration [1]-[2]. However, such architectures are limited to low tuning range (analog tuning) or require large areas, as digitally tuning requires multiple devices, and require relatively complex fabrication. The devices presented in this paper are based on laterally moving structures fabricated in robust monocrystalline siliconon-insulator (SOI) device layer, already utilized by the authors for fabricating laterally moving switches [3]. The basic concept of utilizing such a technology for tuneable capacitors has recently been presented by the authors [4].

In the present paper, this process is utilized for a concept of multi-step quasi-analog tuneable capacitors utilizing laterally-moving multi-stage MEMS actuators.

2. Concept and Design

Fig. 1 shows the basic concept of the multi-stage tuneable capacitors. The sidewalls in a section of the ground plane of a 3D micromachined coplanar waveguide can be moved laterally and are thus changing the capacitive load of the transmission line [4].

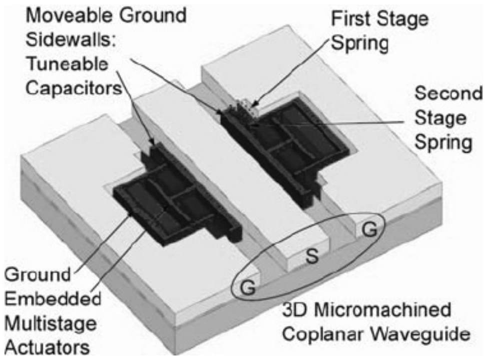

Fig. 1. 3D illustration of ground sidewall integrated multistage tuned capacitors.

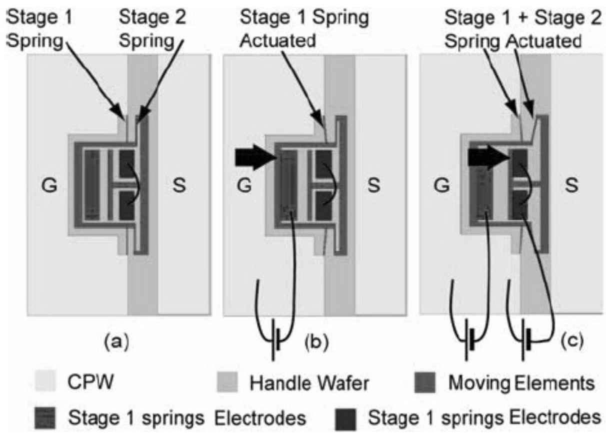

Fig. 2. Operation states of a two-stage actuator (only one side of the coplanar transmission line illustrated): (a) nonactuated; (b) stage 1 actuated (half displacement); (c) stage 1 and stage 2 actuated (full displacement).

The tuning range of the devices in this paper is much larger than conventional parallel-plate tuneable capacitors, as the actuation electrodes are de-embedded from the RF electrodes. Furthermore, a special multistage actuator is implemented, which offers large displacement at acceptable low voltages by splitting the total movements into smaller parts, which is achieved by a series of actuators which are sequentially operated, as shown in Fig. 2 for a two-stage design. For actuating a stage at low actuation voltage, all previous stages must already have been actuated. The tuning elements of one side are duplicated symmetrically in the ground layer of the other slot, and thus the number of possible states is higher than the number of actuator stages, as the transmission line can be loaded slightly unbalanced.

The advantages of this concept, over conventional electrostatic actuator based MEMS tuneable capacitors, are summarized as follows:

- moving sidewalls low-parasitic tuning concept;
- multi-step digital tuning with extended tuning range;
- ground layer-embedded, electrically shielded actuators;
- de-embedded RF and actuation electrodes;
- 3D micromachined transmission lines;
- all-metal actuators and metal-air-metal capacitor;
- single-mask fabrication.

3. RF and Actuator Evaluation

Fig. 3 and 4 show SEM pictures of fabricated two and three-stage devices respectively. The two ground sidewalls of a CPW can be tuned independently, resulting in additional states, as listed in Table I, together with the corresponding capacitance values extracted from S-parameter measurements (shown in Fig. 5) via an equivalent circuit model in Agilent Advanced Design System (ADS). The two-stage device has a total of 5 discrete states with capacitance values ranging from 48 to 105 fF (C_{max}/C_{min}=2.18), for a **capacitance gap from 6 to 2 µm**. The three-stage device has **7 discrete states** with capacitance values ranging from **44 to 106 fF (C_{max}/C_{min}=2.41)**.

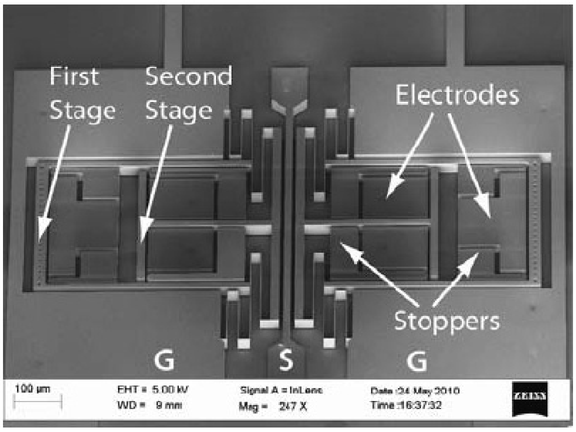

Fig. 3. SEM picture of a fabricated two-stage Tuneable capacitor.

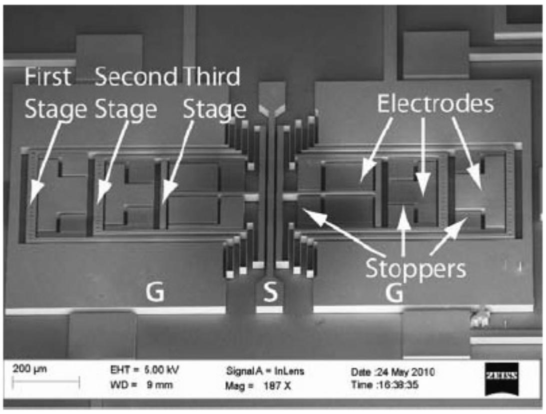

Fig. 4. SEM picture of a fabricated three-stage tuneable capacitor.

Table 1. Actuation states and corresponding capacitances Extracted from S-parameter measurements

Actuated stages (left) 12 21(right)	**Capacitance [fF] (measured)**
00 00	48
10 00	62
10 01	70
11 01	88
11 11	105

a) two- stage device

Actuated stages (left) 123 321(right)	**Capacitance [fF] (measured)**
000 000	44
100 000	47
100 001	50
110 001	58
110 011	64
111 011	86
111 111	106

b) three- stage device

The capacitive behavior and the varying capacitance is clearly visible in the measured return loss (S11) of the 50 Ω transmission line piece containing the tuneable capacitors, plotted in Fig. 5 for all states of the two and three-stage devices. The S-parameters could only be measured up to 40 GHz with our measurement setup.

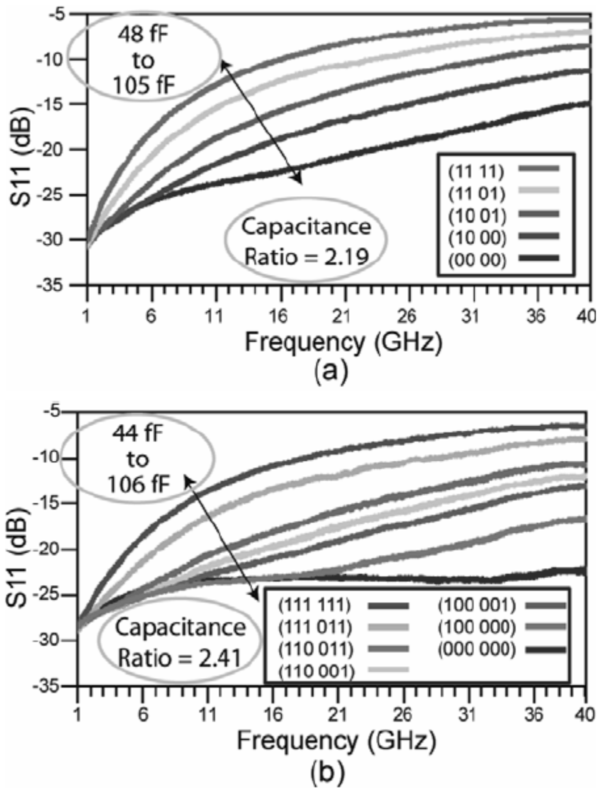

Fig. 5. Measured return loss (S11) of fabricated devices for all actuation states as listed in Table 1: (a) two-stage device; (b) three-stage device.

Fig. 6 shows the results of the actuator characterization, *i.e.* pull-in and release voltages for each stage of the two and three-stage devices, for 10 device designs with different mechanical spring constants. The actuation voltages for the different implemented spring designs are between 16 and 73 V. The overall device design is extraordinarily robust, since relatively stiff springs can be employed as the full tuning range is split up between different actuators, in contrast to conventional tuneable capacitors. This robustness is demonstrated by simulation results of a nonlinear electromechanical model in Agilent Advanced Design System (ADS) shown in Fig. 7, showing that selfactuation, *i.e.* pull-in resulting from very high signal power, occurs for the high-k designs only above 50 dBm, and even for the lowest-k devices not below 40 dBm.

The mechanical resonant frequency of one of the devices was measured to be 11.05 kHz. The fabrication process flow require only one photolithographical step, one metal deposition step, a deep-silicon etch step and wet-etching.

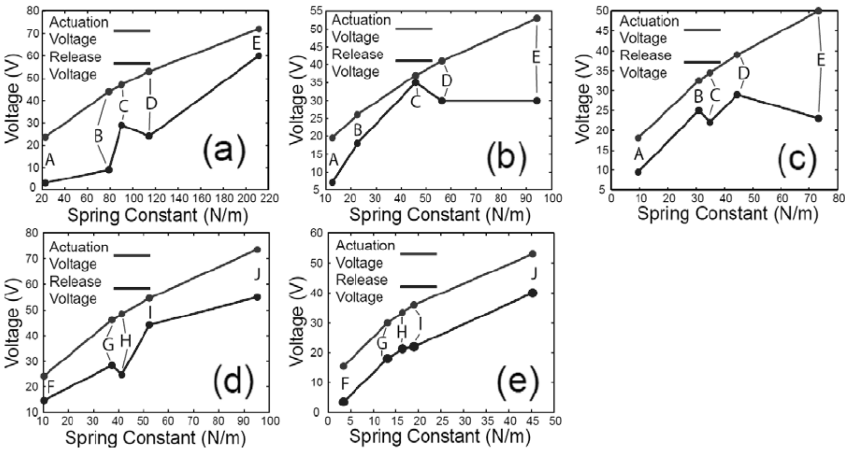

Fig. 6. Actuation and release voltages versus spring constants of 10 different actuator designs of varying mechanical stiffness, plotted or the individual stages of three-stage (A..E) and two-stage (F..J) devices: (a), (b), (c) three-stage devices, stages 1, 2, and 3, respectively; (d), (e) two-stage devices, stages 1 and 2, respectively.

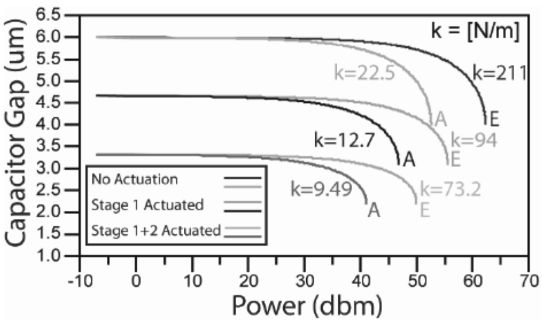

Fig. 7. Simulated self-actuation robustness for three-stage devices A (low k) and E (high k) from Fig. 7.

4. Conclusion

A novel concept of RF MEMS tuneable capacitors has been presented which offers the following advantages: multi-position digitally tuning; large tuning range; number of states independent on required transmission line length; low insertion loss by moveable sidewalls and by embedding the actuators inside the shielding ground layer; low-loss 3D micromachined transmission line; high self-actuation robustness; single-mask fabrication.

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