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ANALYSIS OF LINEARITY DEGRADATION IN MULTI-STAGE RF MEMS CIRCUITS

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ABSTRACT

This paper reports for the first time on RF nonlinearity analysis of complex multi-device RF MEMS circuits. The nonlinearity analysis is done for the two most commonly-used RF MEMS tuneable-circuit concepts, i.e. digital MEMS varactor banks and MEMS switched capacitor banks. In addition, the nonlinearity of a novel MEMS tuneable capacitor concept by the authors, based on a MEMS actuator with discrete tuning steps, is discussed. This paper presents closed-form analytical formulas for the IIP3 (nonlinearity) of the three MEMS multi-device circuit concepts, and an analysis of the nonlinearity based on measured device parameters (capacitance, gap), of the different concepts. Finally, this paper also investigates the effect of scaling of the circuit complexity, i.e. the degradation of the overall circuit linearity depending on the number of stages/bits of the MEMS-tuning circuit.

INTRODUCTION

RF MEMS components are especially of interest for reconfigurable/tuneable circuits for frequency-agile front end applications, due to their near-ideal signal handling behaviour, ultra-low power consumption, large bandwidth and easiness of integration, since fabrication is compatible to integrated circuits. The parallel-plate capacitive tuning principle is very widely used implementation for RF MEMS tuneable devices. Such MEMS tuneable capacitors are near-ideal tuning elements in filters, phase shifters, voltage-controlled oscillators, antennas and impedance-matching networks. RF circuits, including mobile phones, often operate up to power levels of 1W [1], and thus require high linearity to avoid signal degradation, in particular for the complex modulation schemes in modern, high data throughput, communication systems. High RF power implies high electrostatic forces on the mechanically-compliant MEMS-tuning mechanisms, which introduces intermodulation distortion (nonlinearity). Although these distortions may be quite small for a single device, they grow significantly for complex, multi-device RF MEMS circuits. For instance, WiSpry's current generation mobile phone antenna tuner has an 80-element MEMS-switched capacitor bank [2].

The present paper reports for the first time on RF nonlinearity analysis of complex multi-device RF MEMS circuits. Previous nonlinearity reports were done for single-stage devices only [1], [3]. However, state-of-the-art RF MEMS circuits are composed of an increasing number of MEMS tuneable/switched stages, and it is important to analyse the overall nonlinearity of the entire RF MEMS circuit. In addition to digital MEMS varactor bank [4] and MEMS switched capacitor bank, the nonlinearity of a novel MEMS tuneable-capacitor concept by the authors [5], based on multiple discrete and well-defined steps, implemented by in-plane moving of the ground side-walls of a 3D micromachined coplanar

waveguide transmission line is discussed. The paper also presents the closed-form analytical formulas for determining the overall IIP3 for any operation state the three discussed multi-device RF MEMS circuit concepts.

ANALYTICAL FORMULAS

This section includes the derivations of the IIP3 for the most commonly used multi-device RF MEMS capacitor circuits.

The analytical derivation of IIP3 of a single RF MEMS shunt capacitor loaded on a transmission line is provided in [1]

$$IIP3 = \frac{2kg^2}{\phi CZ_0} = \frac{4kg^2}{\omega C^2 Z_0^2} \quad (1)$$

where k is the spring constant, g is the gap between the electrodes, ω is the angular frequency, C is the capacitance and Z_0 is the characteristic impedance. Since modern RF MEMS circuits are composed of many MEMS tuneable/switched stages, the above model need to be extended to describe RF MEMS circuits with multiple devices, each contributing to the overall circuit nonlinearity. Firstly, the model is extended to two equal stages having similar capacitance, spring constant and gap values loaded on the same transmission line (i.e. both tuneable capacitances having the same configuration) which reduces the overall IIP3 by half compared to the previous case

$$IIP3 = \frac{2kg^2}{\phi CZ_0} = \frac{2kg^2}{\omega C^2 Z_0^2} \quad (2)$$

This case is then extended to a more general case of two capacitors with unequal stages, i.e. unequal capacitance, spring constant and gap values, resulting in

$$IIP3 = \frac{4k_1 g_1^2 k_2 g_2^2}{\left[\omega C_1^2 (k_2 g_2^2) + \omega C_2^2 (k_1 g_1^2) \right] Z_0^2} \quad (3)$$

This leads to the derivation of the closed form analytical formula for IIP3 calculations utilizing N-stage capacitor with unequal stages, or stages in different operation states:

$$IIP3 = \frac{4}{\omega Z_0^2} \left(\frac{1}{\sum_{i=1}^N \frac{C_i^2}{k_i g_i^2}} \right) \quad (4)$$

Figure 1: 3D illustration and equivalent capacitor model: (a) Digital MEMS varactor bank; (b) MEMS switched capacitor bank; and (c) multi-step MEMS capacitor

This can then be used as the basis for the derivation of IIP3 for another most common circuit type where N-stages switched capacitors with fixed series capacitors are loaded on the transmission line to have a better control of the capacitance achieved in various states of the RF MEMS circuit.

$$IIP3 = \frac{4}{\omega Z_0^2} \left(\frac{1}{\sum_{i=1}^N \frac{C_{Si}^2}{k_i g_i^2} \left(\frac{C_{Fi}}{C_{Si} + C_{Fi}} \right)^3} \right) \quad (5)$$

Table 1: Summary of parameters of digital MEMS varactor bank (circuit type A) used for linearity analysis, based on [4].

Parameter	Capacitor I	Capacitor II	Capacitor III
C_{up} (fF)	63	45	38
C_{down} (fF)	205	145	80
g_{up} (μm)	1.5	1.5	1.5
g_{down} (μm)	0.5	0.5	0.5
k_{up} (N/m)	12	12	12
k_{down} (N/m)	55	55	55

ANALYSIS OF CIRCUIT EXAMPLES

Figure 1 shows the three investigated RF MEMS-tuneable circuit concepts, (A) digital MEMS varactor bank which is used in distributed MEMS transmission line (DMTL) circuits, (B) MEMS switched capacitor bank which is extensively used in tuneable filters, and (C) multi-step MEMS capacitor which is a novel capacitor concept developed by the authors.

A. Digital MEMS Varactor Bank

The data for the analysis of digital MEMS varactor

bank is based on a published RF MEMS circuit from [4]. The varactors have two discrete positions each with a capacitance ratio of around 3. The total capacitance of the circuit can be tuned from 146 fF to 430 fF in eight discrete states. Table 1 shows the device parameters used for the calculation of the IIP3 for each state. Equation (4) is used to calculate the IIP3 of the varactor bank in each of the 8 states. Figure 2 show the calculated IIP3 at 2.5 GHz for all 8 states of the two 3-bit MEMS-tuneable circuit concepts. The non-linearity is increasing (i.e. IIP3 is decreasing) with increasing number of activated stages, weighted by the capacitance/gap (C/g) ratio of the individual stages.

Figure 2: IIP3 analysis and measured capacitance for each state of the digital MEMS varactor bank (circuit type A).

B. MEMS Switched Capacitor Bank

The MEMS switched capacitor bank with a metal-air-metal fixed capacitor in series with each MEMS capacitive switch is shown in Figure 1(b). This example uses a 3-bit MEMS switched capacitor bank where three MEMS switch and fixed capacitor combinations are arranged along the length of the transmission line. The values of the fixed capacitors are binary coded, i.e. doubled from the smallest to the next higher stage. The device

parameters used for the nonlinearity analysis are shown in Table 2. Equation (5) is used to calculate the IIP3 of the switched capacitor bank in each of the 8 states. Figure 3 shows the calculated IIP3 for various states of the bank. It can be seen here that the non-linearity is increasing with increasing number of activated stages, weighted by the capacitance/gap (C/g) ratio of the individual stages.

Table 2: Summary of parameters of digital MEMS varactor bank used for linearity analysis (circuit type B).

Parameter	Capacitor I	Capacitor II	Capacitor III
$C_{S,up}$ (fF)	88.5	88.5	88.5
$C_{S,down}$ (fF)	885	885	885
C_F (fF)	160	320	640
$g_{S,up}$ (μm)	2	2	2
$g_{S,down}$ (μm)	0.2	0.2	0.2
k_{up} (N/m)	32	32	32
k_{down} (N/m)	586.5	586.5	586.5

Figure 3: IIP3 analysis and capacitance for each state of the MEMS switched capacitor bank (circuit type B).

Table 3: Summary of parameters of multi-step MEMS capacitor used for linearity analysis (circuit type C).

Parameter	State I	State II/III	State IV
C_L (fF)	20.27	20.27	30
C_R (fF)	20.27	30	30
g_L (μm)	4.4	4.4	2
g_R (μm)	4.4	2	2
k_L (N/m)	5.8	5.8	5650
k_R (N/m)	5.8	5650	5650

C. Multi-step MEMS Capacitor

For the discrete multi-step MEMS capacitor previously published by the authors [5] and shown in Figure 1(c), the non-linearity analysis is shown in Figure 4, based on the measured parameters given in Table 3 [5]. This capacitor utilizes a 3D-micromachined transmission line embedded tuning mechanism, where integrated MEMS actuators are moving the sidewalls of the 3D-transmission line, resulting in a modulation of the capacitive loading of the line. The mechanical springs are completely decoupled from the RF signal, i.e., the RF ground signal is coupled capacitively from the fixed ground layer to the moving ground sidewall, and the mechanical springs are connected to isolated islands behind the moving sidewalls. This result in low series

resistance, and thus low insertion loss and high Q of 88 measured at 40 GHz in a weakly-coupled transmission line resonator, which is very high for a tuneable device. The ground sidewall section is moved uniformly over its entire length. The device is actuated by applying a voltage between the actuation electrode and the anchors connected to the springs, i.e. no DC bias or reference ground is shared with any RF potential, neither the RF ground nor the signal line. More actuator stages can also be integrated for this design resulting in additional states of the capacitor and extended tuning range [6]. The fabricated prototype is shown in Figure 5. For this circuit, the calculated IIP3 values at 2.5 GHz are much higher due to the much smaller C/g ratio of this concept. In addition to the calculated IIP3 from the measured RF capacitances, the IIP3 of this device was measured using dual-tone measurement technique, but the measurement setup had an upper limitation of 68.5 dBm for all states as shown in Figure 6, and the expected IIP3 are clearly above that limit.

Figure 4: IIP3 analysis and measured capacitance for each state of the multi-step MEMS capacitor (circuit type C).

Figure 5: SEM picture of the fabricated multi-step MEMS capacitor (circuit type C).

SCALING OF LINEARITY WITH CIRCUIT COMPLEXITY

Finally, the effect on the IIP3 when scaling the circuit complexity was analysed for the digital MEMS varactor bank and MEMS switched capacitor bank. Figure 7 shows

the signal power limit for tolerating a nonlinearity degree of 1% intermodulation for circuits with 1 to 5 stages (=bits), shown for the worst-case bit combination i.e. shown for the operation state of the circuit which has the worst linearity. The signal power allowed for limiting the non-linearity distortion is significantly decreasing with increasing number of stages, which has to be taken into account in multi-devices RF MEMS circuit designs.

Figure 6: Measured dual-tone fundamental and intermodulation levels with IIP3 point of the two-stage multi-step MEMS capacitor (circuit type C).

Figure 7: Scaling of 1%-intermodulation power (for worst-case state), for increasing circuit complexity from 1 to 5 bits (for A, B).

CONCLUSION

Closed form analytical formalisms have been derived and presented for calculating the IIP3 for various multi-device

RF MEMS circuits. The RF nonlinearity analysis for three different multi-device RF MEMS circuits i.e. digital MEMS varactor bank, MEMS switched capacitor bank and multi-step MEMS capacitor, was performed along with IIP3 measurements on the prototype of a novel multi-step MEMS capacitor. Finally, the scaling of the linearity with the circuit complexity was analysed.

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