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RF-MEMS based adaptive antenna matching module

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***Abstract* — To preserve the link quality, in fluctuating operating environments, an adaptive antenna matching module is presented that consists of a 5-bit RF-MEMS switched capacitor array, a bipolar 60/30V MEMS-biasing voltage generator for improved reliability, and an impedance phase detector that provides information on mismatch. It uses an iterative up-down counting algorithm for robust control. Measurements show proper correction of the antenna reactance, even for a VSWR of 10. The switched capacitor array exhibits a large tuning range from 1 to 15 pF and an insertion loss of 0.4 dB. The detector dynamic range equals 35 dB with an accuracy of 8 degrees from 0.8 to 2 GHz. Adaptive matching will make isolators redundant.**

***Index Terms* — Adaptive filters, micro-electromechanical devices, impedance matching, phase detection, power amplifiers, switched capacitor filters.**

I. INTRODUCTION

Link quality of multi-mode, multi-band cellular phones suffers from the narrow bandwidth of miniaturized high-Q antennas as well as from detuning of the antenna resonance frequency by changes in antenna environment [1], [2]. Maximum field strength, modulation quality, receiver sensitivity and power efficiency strongly depend on the antenna impedance, which is commonly assumed to be 50 Ω. Its actual impedance however, is frequency dependent and fluctuates, over a wide range, under the influence of body-effects and changes in phone form-factor [3].

To preserve linearity under antenna mismatch conditions an isolator is often applied between the power amplifier and antenna to absorb reflected power. This solution is not very attractive to set makers because the isolator is a rather bulky and expensive component that cannot easily be integrated with other front-end functions. Moreover, it does not preserve maximum field strength nor receiver sensitivity.

Adaptive antenna matching [4], [5] is an attractive method to maintain the performance under mismatch conditions because it dynamically compensates antenna impedance fluctuations. It preserves maximum field strength and receiver sensitivity and improves the power efficiency of a phone significantly.

In this paper we present an adaptive antenna matching module. RF-MEMS devices are used for the implementation of a 1 to 15 pF variable capacitor that is realized as a 5-bit binary weighted switched capacitor array. We apply bipolar biasing with 60/30 V actuation/hold signals to minimize dielectric charging and thus to improve MEMS reliability. An impedance phase detector provides information on mismatch that is used to minimize the mismatch in an iterative manner.

II. CONCEPT

Most cellular phones make use of planar inverted-F antennas (PIFA) that are series resonant at 900 MHz as well as at 1800 MHz. Body-effects detune the antenna resonance frequencies downwards causing mainly a change in the reactance of the antenna feed impedance. Variations in the real part of the antenna feed impedance are relatively small when properly designed.

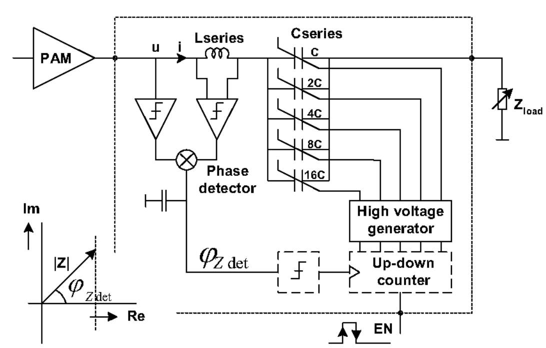

Fig. 1. Block diagram of the adaptive series-LC matching module. It compensates the reactive part of the load impedance by controlling the detected phase φ_{Z_DET} of the matched impedance to zero.

Therefore, we propose to apply a relatively simple series-LC matching network that compensates the reactive part of the antenna impedance variations. The variable capacitor is implemented as a 5-bit binary weighted switched capacitor RF-MEMS array, as depicted in Fig. 1. The MEMS biasing voltages are supplied from the high voltage generator.

Mismatch information is obtained from the phase of the matched impedance φ_{Z_DET}. This phase equals zero when a proper impedance match is achieved. It is given by the phase difference between the matching network input voltage u and its input current i. This phase difference is detected with a Gilbert cell mixer that is driven by hard limited input signals. The phase of the input current i is derived from the differential voltage across series inductor L_{SERIES} that acts as, an almost frequency independent, +90 degrees phase shifter.

The phase detector output signal φ_{Zdet} is fed to a limiter that determines the sign of the phase error. Depending on this sign the counter will either increase or decrease its output value in steps of 1-LSB under control of a base-band enable signal *EN*. Consequently, the loop controls the detected phase of the matched impedance φ_{Zdet} to zero step by step.

The control algorithm, given by the phase detector output limiter and the up-down counter, are actually implemented in HP-VEE software.

III. Design

In this Section we describe the design of two main building blocks: the RF-MEMS switched capacitor array and the high voltage generator.

The 5-bit RF-MEMS array, shown in Figure 2, is designed for a wide tuning range from approx. 1 pF to 15 pF with small steps of 0.5 pF to minimize impedance quantization errors. The four most significant bits (MSBs) are implemented as 4 pF unit capacitors DC isolated by accurately scaled MIM capacitors. It secures good matching of the (40 V) pull-in and (10 V) pull-out voltage over the wide range of capacitor values. The least significant bit (LSB) however, is realized by two 1 pF MEMS devices in series as a compromise between chip area (with associated parasitics) and self-actuation (none-release) that must be prevented under hot-switching conditions. The switched capacitor array is implemented in a passive silicon technology with a 5 kΩ·cm substrate. Wafer level packaging is applied to provide hermetic enclosure of the MEMS devices.

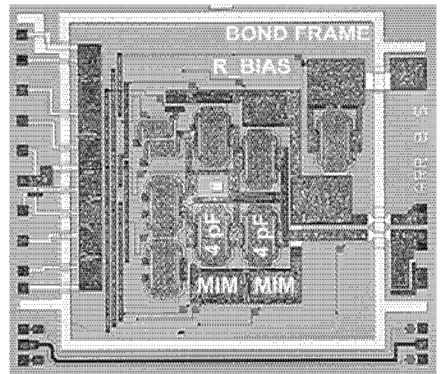

Fig. 2. Die photograph of a 5-bit switched capacitor array using 4 pF RF-MEMS unit cells with integrated DC-block MIM capacitors and bias resistors.

The RF-MEMS switched capacitor array is biased from a high voltage generator that consists of a charge pump, high-voltage output switches, and two output voltage control loops. The charge-pump, switched at 20 MHz, gradually charges a 1 nF buffer capacitor under control of the 60 V stabilization loop. A sudden discharge occurs after actuation of the MEMS array, which causes some ripple in the 60 V output voltage. To minimize dielectric charging of the RF-MEMS devices their bias voltage can be reduced, under control of the 30 V loop, during hold periods in which switching of the array is not required. A full-bridge circuit topology of the high voltage output stages is used for bipolar actuation of the MEMS array, which offers a further reduction in dielectric charging. The high voltage generator is implemented in a 120 V SOI process.

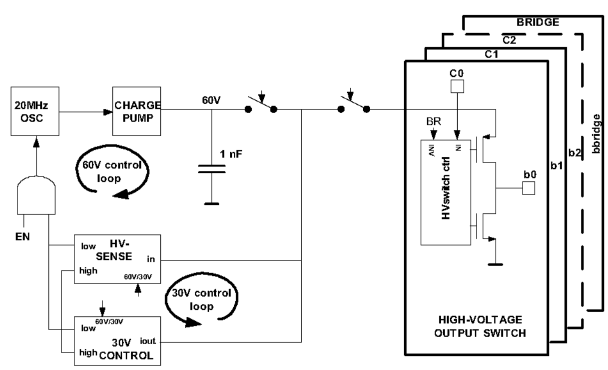

Fig. 3. Block diagram of the high-voltage generator providing a 60 V *actuation* and 30 V *hold* voltage. The *bridge* circuit allows for bipolar actuation of the RF-MEMS devices.

IV. RESULTS

Figure 4 shows SONNET EM-simulation and on-wafer measurement results of the 5-bit switched capacitor array. The capacitance in OFF state (00000) is approx. 1 pF for measurements and simulations. For MSB ON state (10000) the measured capacitance of 10 pF is 20 % larger than the simulated value of 8 pF, which might be caused by a difference in surface roughness. Series resonance occurs due to a parasitic series inductance of approx. 1.5 nH. For the adaptive matching module this inductance is harmless because it can easily be embedded in L_{SERIES}.

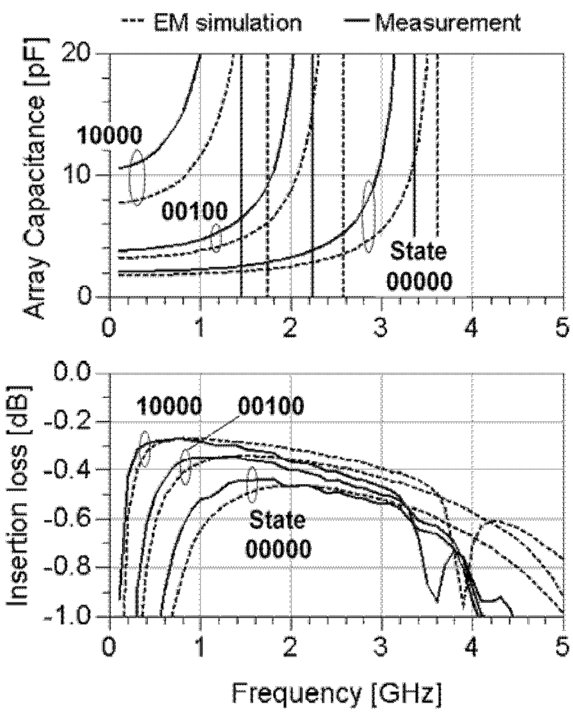

Fig. 4. Simulated and measured capacitance (a) and insertion loss (b) of the 5-bit switched capacitor array for three different capacitor values.

For the various capacitance values, simulations and measurements show an insertion loss in the range of 0.3 to 0.5 dB at 1 to 2 GHz. At lower frequencies the insertion loss increases drastically due to parasitic substrate shunt resistance whereas at higher frequencies skin effects of interconnect lines cause an increase in insertion loss.

In Figure 5 a typical output voltage waveform of the high voltage generator is shown. During a relatively short time interval a 55 V actuation voltage is present at the generator output to switch on MEMS devices if needed, followed by a ramp-down to a hold voltage of 35 V.

We measure a maximum output voltage ripple of approx. 3V, an average supply current of 1 mA, a leakage current smaller than 10 nA, and a total turn on time of approx. 2 ms, as expected.

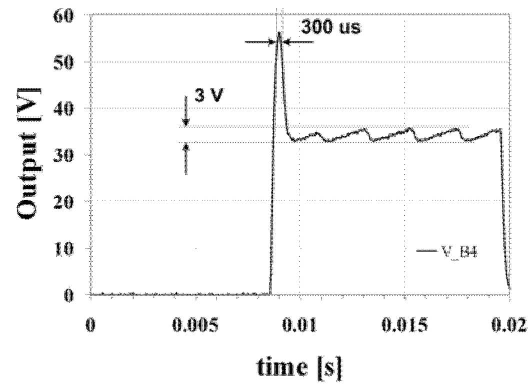

Fig. 5. Measured high voltage generator output voltage waveform.

For evaluation of the impedance phase detector [6] an RF signal is split to the voltage and current input, while a variable phase shifter is included in one of the two signal paths. Figure 6 gives the detector output voltage as function of the phase difference for 870 and 1840 MHz. The 8 degrees off-set at 1840MHz in this saw-tooth shaped detector characteristic seems to be caused mainly by on-chip parasitics. We measured a dynamic range of 35 dB for 800 MHz to 2 GHz.

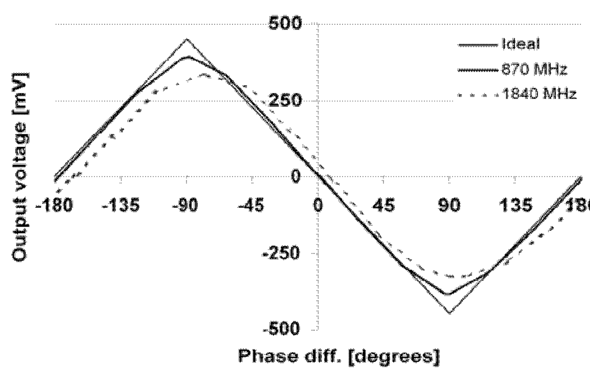

Fig. 6. Measured detector output voltage as function of the phase difference between voltage and current input for 870 and 1840 MHz, and the ideal as reference.

Initial measurements on the complete module have been carried out to prove the concept of adaptive matching. We applied five different load impedances *L1* to *L5*, all with a VSWR of 4, to the module as depicted in Figure 7. For each load condition the loop controls step by step to a steady-state condition. The trajectories of adaptation are visualized by dotted lines. For all five load conditions adaptation starts from initialization state 00000, which results in (un)matched impedances indicated by *Init1* to *Init5* in the Smith chart. Steady-state conditions are found close to the real axis, for inductive loads *L1*, *L2* and *L3*, which indicates that the reactive parts of these load impedances are compensated as expected. The capacitive loads *L4* and *L5* however, cannot properly be transformed to the real axis because they are out of range of the variable LC-network.

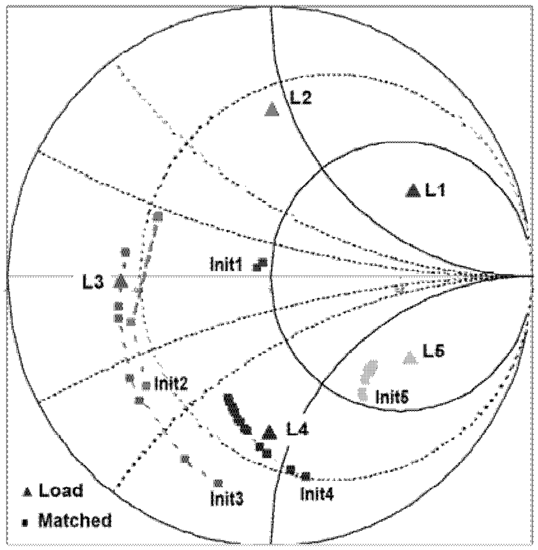

Fig. 7. Impedance adaptation trajectories measured for loads with VSWR of 4. f = 900 MHz.

The photograph in Figure 8 shows the complete adaptive antenna matching module. The capped RF-MEMS die, detector die and high voltage generator die are wire bonded to laminate. The module contains two SMD components: a 1 nF high voltage buffer capacitor and an inductor for ESD protection at the antenna terminal.

V. Conclusions

We presented an RF-MEMS based adaptive series-LC antenna matching module that automatically compensates for fluctuations in antenna reactance. The 5-bit RF-MEMS switched capacitor array exhibits a large tuning range from 1 to 15 pF and an insertion loss of 0.3 to 0.5 dB at 1 to 2 GHz.

For improved reliability of the MEMS devices we proposed a high voltage generator that allows for biasing with a 60 V actuation and a 30 V hold voltage, combined with bipolar actuation accomplished by a full-bridge circuit topology.

The wide-band impedance phase detector, based on a Gilbert cell mixer, has 35 dB dynamic range and a maximum phase error of 8 degrees. Adaptive antenna matching modules are expected to make isolators redundant and will enable the use of smaller sized antennas.

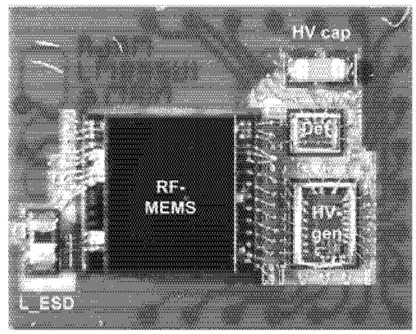

Fig. 8. Photograph of the adaptive antenna matching module showing the packaged RF-MEMS, the high-voltage generator, and impedance phase detector dice.

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