RF MEMS for Ku and K band Frequency Agile Circuits for Communication and Radar Applications

Umer Shah, *Member, IEEE*, and Joachim Oberhammer, *Senior Member, IEEE*

***Abstract*—This document provides a brief summary of the outcome of the project for which I was awarded the 2014 IEEE MTT-S Graduate Fellowship Award. The main goal of the project was to design, fabricate and measure novel RF MEMS devices enabled by three-dimensional micromachining. The research activities have resulted in seven journal articles with four articles as main author and several conference papers. Three of the seven articles were published during the time of the award. The latest results have also been accepted for oral presentation at the International Microwave Symposium (IMS) 2015.**

***Index Terms*—RF MEMS, micromachined transmission line, coplanar waveguide, tunable directional coupler, tunable capacitor, tunable filter, phase shifter, magnetic materials, micromachined inductors, intermodulation distortion.**

I. Introduction

THE success of wireless and communication technologies is evident in the success of cellular telephony, cellular data transfer, wireless local area networks, wireless sensor networks, and wireless computer interface etc. The evolution in wireless standards is governed by the growth in consumer demands and the expectations from wireless appliances are getting higher. The steep requirements place stringent specifications on the conventional RF technology. MEMS is a powerful technology enabling devices to overcome the limitations of conventional RF technology because of their ability of near ideal signal handling behavior, low power consumption, low loss and large bandwidth [1].

RF MEMS provides the opportunity for miniaturization and cost reduction by offering integrated solutions that can be batch fabricated and has the potential to replace the conventional off-chip discrete passive components whose performance is yet to be matched by integrated solutions. Typical RF MEMS devices include RF MEMS switches, tunable capacitors, micromachined inductors and resonators. These basic devices are used to build integrated complex multi-device RF MEMS circuits such as phase shifters, tunable filters, impedance matching circuits, and reconfigurable antennas. Research in RF MEMS is maturing towards providing batch fabricated packaged integrated solutions with the future of RF MEMS research concentrating more on reliability, packaging and system integration.

This project report includes novel research in the field of RF MEMS. The project focuses on the concept and design of three-dimensional micromachined coplanar waveguide transmission line embedded tunable capacitors and actuators for filter and directional coupler applications, respectively. The project further investigates intermodulation distortion in multi-device RF MEMS circuits and the usage of multilayer ferromagnetic composite for permeability enhancement of on-chip integrated inductors.

II. Project Outcomes

The concept of RF MEMS tunable capacitors based on the lateral displacement of the sidewalls of a 3-D micromachined coplanar waveguide transmission line has been shown [2]. The tuning of a single device is achieved in multiple discrete and well-defined tuning steps by integrated multi-stage MEMS electrostatic actuators that are embedded inside the ground layer of the transmission line. Embodiments of different device concepts were successfully demonstrated, achieving high-Q, high reliability, high linearity, and high self-actuation robustness at medium actuation voltages. A tunable filter created in a 3-D micromachined coplanar transmission line has also been implemented using the movable-sidewall tunable capacitor concept.

Two new concepts of area-efficient, ultra-wideband, MEMS reconfigurable coupled line directional couplers have been implemented [3]. The coupling is tuned by mechanically changing the geometry of the coupled transmission lines utilizing integrated MEMS electrostatic actuators. Concept 1 is based on changing the coupling of each signal line to the ground. Concept 2, on the other hand, is based on simultaneously varying both the ground coupling and the coupling between the two signal lines. The measured isolation is better than 40 dB and the return loss is better than 15 dB over the entire bandwidth from 10 to 18 GHz for any actuation state of both the couplers. The directivity are better than 20 dB over the whole frequency range.

RF nonlinearity analysis of complex multi-device RF MEMS circuits is performed [4]. It has been shown that the IIP3 of a multi-device RF MEMS circuit can be significantly lower than the IIP3 of a single device, which requires an analysis of the overall circuit IIP3 rather than just for a single stage. It has also been shown that the IIP3 of complex RF MEMS circuits is very different when compared to a single switch stage and even very different when compared to the

U. Shah and J. Oberhammer are with the Department of Micro and Nanosystems, KTH Royal Institute of Technology. Stockholm, Sweden. (e-mail: umers@kth.se, joachimo@kth.se).

same number of switch stages in simple parallel combination. Closed-form expressions for the IIP3 of multi-device RF MEMS circuits are derived. This is followed by the IIP3 analysis of different RF MEMS tunable-circuit concepts, i.e., digital MEMS varactor banks, MEMS switched capacitor banks, MEMS impedance tuners and MEMS tunable filters. The degradation of the overall circuit linearity with increasing number of device stages is also investigated. Finally, design rules are presented so that the mechanical parameters and thus the IIP3 of the individual device stages can be optimized to achieve a highest overall IIP3 for the whole circuit. In order to achieve the maximum IIP3 for a multi-device RF MEMS circuit, the circuit should be designed such that each stage has the same IIP3.

Unpatterned ferromagnetic NiFe/AlN multilayer composites used as advanced magnetic core materials for on-chip and interposer integrated inductances were proposed. The proposed composite structure reduces RF induced currents and thus pushes the permeability cutoff to beyond 3.7 GHz, which is by a factor of 7.1 higher than for homogeneous NiFe layers of same thickness. To the best of my knowledge, we achieve the highest effective relative permeability of 28 at 1 GHz, highest ferromagnetic resonance frequency and highest inductance enhancement factor above 1 GHz ever reported for devices based on on-chip unpatterned NiFe magnetic cores. A single loop inductor is also implemented as a technology demonstrator, achieving an inductance enhancement of 4.8 and a quality factor enhancement of 4.5 at 400 MHz [5].

A 500-600 GHz submillimeter-wave MEMS-reconfigurable phase shifter was designed, fabricated and measured. It is the first ever RF MEMS component reported to be operating above 220 GHz. The phase shifter is based on a micromachined rectangular waveguide which is loaded by 9 E-plane stubs, which can be individually blocked by using MEMS–reconfigurable surfaces. The phase-shifter is composed of three metallized silicon chips which are assembled in H-plane cuts of the waveguide. The measurement results of the first prototypes of the MEMS reconfigurable phase shifter show a linear phase shift of 20° in 10 steps (3.3 bit) and have a return loss better than 15 dB from 500-600 GHz. The insertion loss is better than 3 dB up to 540 GHz, and better than 5 dB up to 600 GHz for all phase states, of which the major part is contributed by the assembly of the microchips between waveguide flanges which has a reproducibility error between 2 and 6 dB measured for reference chips. The results of this final part of the project will be presented at the International Microwave Symposium 2015 (IMS 2015).

III. Career Plan and Fellowship Impact

I would like to thank the IEEE Microwave Theory and Techniques Society for granting me the 2014 IEEE Graduate Fellowship Award. The award provided my research with the recognition which helped to push my research career in the right direction. The financial support I received helped me to focus more of my efforts on my research rather than worry about personal finances. This also helped me to attend the International Microwave Symposium 2014 which provided me with the opportunity to see the state of the art research activities of the other RF and Microwave research groups from around the world and also brought me in contact with other young researchers in the field.

The research activities during the time of the grant also resulted in two papers which will be presented at the International Microwave Symposium 2015.

My future plan is to continue with a postdoc and continue my research in the field of RF/Microwave MEMS leading to a faculty position at an accredited university. Finally, I would like to mention that the MTT-S Graduate Fellowship award has encouraged me to continue my research and motivated me to work even harder to fulfill my career goals.

References

[1] G. M. Rebeiz, RF MEMS Theory, Design, and Technology. NewYork: Wiley, 2003.

[2] U. Shah, M. Sterner, and J. Oberhammer, “Multi-position RF MEMS tunable capacitors using laterally moving sidewalls of 3-D micromachined transmission lines,” *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 6, pp. 2340–2352, Jun. 2013.

[3] U. Shah, M. Sterner, and J. Oberhammer, “High-Directivity MEMS-tunable directional couplers for 10–18-GHz broadband applications,” *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 9, pp. 3236–3246, Sep. 2013.

[4] U. Shah, M. Sterner, and J. Oberhammer, “Analysis of Linearity Deterioration in Multidevice RF MEMS Circuits,” *IEEE Trans. Electron Devices*, vol. 61, no. 5, pp. 1529–1535, May. 2014.

[5] U. Shah, J. Liljeholm, T. Ebefors, and J. Oberhammer, “Permeability Enhancement by Multilayer Ferromagnetic Composites for Magnetic-Core On-Chip Inductors,” *IEEE Microw. and Wireless Comp. Lett.*, vol. 24, no. 10, pp. 677–679, Oct. 2014.