Getting ready for beyond-5G, super-IoT and 6G at hardware passive components level: a multi-state RF-MEMS monolithic step attenuator analyzed up to 60 GHz

Jacopo Iannacci1 • Girolamo Tagliapietra1

Received: 1 October 2021 / Accepted: 22 March 2022 / Published online: 31 March 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
Looking at 2030, the landscape of technology will be dominated by paradigms like 6G, Super-IoT (Internet of Things) and Tactile Internet (TI). From the perspective of Hardware (HW) components technologies, the turning into reality of such scenarios will demand for a radical reconceptualization of devices, sub-systems and systems, probably modifying the concept of HW itself. Driven by the target of taking initial steps in the direction of such future applications, this work discusses a 4 bit RF power step attenuator entirely realized in RF-MEMS technology. Physical samples are fabricated in a surface micromachining technology and rely on electrostatically actuated cantilevered MEMS ohmic switches to select or short resistive loads placed along the RF line. Fabricated devices are tested and validated up to 30 GHz, while simulations are discussed up to 60 GHz for the full set of allowed configurations. Despite a few technology non-idealities, the network shows levels of attenuation with a flatness as good as 1 dB over 60 GHz frequency span. The measured and simulated data reported in this work offer important indications on how to improve the network concept, both at technology and design level.

1 Introduction

Nowadays, key application scenarios like the Internet of Things (IoT) and the Internet of Everything (IoE) turned to be so widespread, that significant part of R&D in the fields of modern electronics and Hardware (HW) technologies falls under such umbrellas, especially if looking at the area of remote and distribute smart sensing. On a different plane of reference, the 5G covers a role similar to IoT/IoE for whatever involves telecommunications and transmission of data, taking up the challenge of becoming the enabler of pervasivity of the IoT and IoE (Wei et al. 2017). To this end, just mentioning applications like Virtual/Augmented Reality (VR/AR) and Machine-To-Machine (M2M) interaction, frames unprecedented needs in terms of mobile broadband and reliability of communications (Evolving and to fit the 5G future 2021, 5G Network Architecture a High-Level Perspective 2021; The path to 5G: as much evolution as revolution 2021; Osseiran et al. 2014). Nonetheless, despite still in the early days of its deployment, the 5G is already predicted to fail the promise of enabling the so-called Super-IoT (Zhang et al. 2019; Saad et al. 2020) and Tactile Internet (TI) (The Tactile Internet 2021) paradigms, shifting the attention ahead on 6G (Zhang et al. 2019; Katz et al. 2019). This is because the 5G, although its innovations, still relies on classical HW-SW (Software) co-design approaches (Noguera and Badia 2002; Yeniceri and Huner 2020; Wolff et al. 2011). From a different perspective, the future 6G also in light of massive exploitation of Artificial Intelligence (AI), will demand for more separation and symmetry between HW and SW (Ko et al. 2016; Makridis et al. 2020; Saxena et al. 2019; Hu et al. 2019), probably pushing the reformulation of the HW concept itself, as hypothesized in Iannacci (2021).

Narrowing down the discussion around the telecommunications infrastructures and its expected Key Performance Indicators (KPIs), the transition from 5G, to Beyond-5G, and, eventually, to 6G, will demand for a 100 to 1000 times increase of performance (Saad et al. 2020). Among relevant items, nominal data-rates per user are forecasted to transit from the current Gbps frontier, to the Tbps. Moreover, End-To-End (E2E) delay should reduce
from 5 ms, down to below 1 ms, intrinsic radio systems delay will have to pass from 100 to 10 ns, while E2E reliability should step from 99.999 to 99.99999%. Meeting these challenges will necessarily push toward exploitation of higher frequency ranges. To this end, a tentative list of RF devices and technologies pivotal to 6G/TI/Super-IoT is developed as follows:

- Above 6 GHz Radio Frequency (RF) components, devices and systems, including mm-waves (30–60 GHz), beyond mm-waves (up to 100 GHz) and THz (100–300 GHz), for the transition from 5G Small Cells to 6G Tiny Cells (Rappaport et al. 2019). Such a consideration applies both to passive components, like switches, switching matrices, phase shifters and filters, as well as to active transceivers (transmitters/receivers) and to their building elements, like Power Amplifiers (PAs), Low Noise Amplifiers (LNAs), mixers, and so on. Regardless of the specific RF item at stake, very-advanced characteristics in terms of wideband operability, large reconfigurability, wide tunability, low-loss, low-interference and high-linearity (Iannacci 2017a), will be always desirable;
- Transition from classical antennas and emerging 5G massive-Multiple-Inputs-Multiple-Outputs (MIMO), to interaction with the previously mentioned electromagnetic active items and Large Intelligence Surfaces (LISs) (Dardari 2020; Pan et al. 2020).

In light of the just sketched future scenario, this work discusses a miniaturized 4 bit, 1.4 by 1.4 mm² RF power step attenuator realized in RF-MEMS technology. Programmable attenuators, along with phase shifters, are key components to enable advanced beamforming of future 5G/6G antennas (e.g. massive-MIMOs), and the device here reported is tested and validated up to 60 GHz, as discussed in the next sections.

2 RF-MEMS attenuator design concept

The multi-state RF power step attenuator design concept here at stake is implemented within an RF-MEMS technology platform based on a surface micromachining technology performed on 6 inch silicon wafers (Iannacci et al. 2009; Iannacci 2017b). The technology was developed and is available at the Center for Sensors and Devices (SD) of Fondazione Bruno Kessler (FBK), in Italy. It features two conductive layers passivated by oxide, and two above metallizations for realizing waveguides and suspended MEMS structures. The lower conductive layer is a boron doped polycrystalline silicon (poly-si). By driving a selective double dose implantation, parts of such a layer are highly resistive, in the order of 1.5 kΩ/sq, suitable for DC feeding lines and electrodes, while other areas can have a resistivity in the range of 50–200 Ω/sq, ideal for the realization of calibrated RF resistors. The poly-si is then covered with a passivating silicon oxide layer, that locally can be etched, thus allowing electrical continuity with the conductive layers above. Subsequently, an aluminum-based layer is sputtered. Such a level is needed for RF underpasses, and is passivated by a second silicon oxide layer, through which, vertical vias can be opened. Then, a thin-film of gold is evaporated, and typically placed around where vias to the underneath aluminum are opened, with the aim of ensuring contacts’ low-resistance. The actual MEMS structuring, consists of electrodeposition of two stacked gold layers, and elevated membranes (air-gaps) are obtained wherever a photoresist sacrificial layer is patterned. A schematic cross-section of the RF-MEMS fabrication process is reported in Fig. 1.

In the specific design concept here at stake, a bank of resistive loads realized with the poly-si layer, is inserted on the RF line. Such resistors load the line or are selectively shorted, depending on the ON/OFF state of electrostatically driven MEMS ohmic switches. The whole RF-MEMS network is framed within the classical Coplanar Waveguide (CPW) configuration, as reported by the microphotograph in Fig. 2a.

The schematic in Fig. 2b summarizes how the attenuation is implemented. The RF line is split in two parallel branches, individually selected by the MEMS switches \( S_{BU} \) and \( S_{BD} \) (Switch Branch Up/Down). Then, each branch is loaded by three resistors in series, i.e. \( R_{L1}, R_{L2} \) and \( R_{L3} \). Given that the nominal sheet resistance of the poly-si layer is 100 Ω/sq, the resistors are shaped to be 10 Ω, 40 Ω and 200 Ω, respectively.

The three resistors can be selectively shorted on both branches, when the switches \( S_{L1}, S_{L2} \) and \( S_{L3} \) are actuated. Given the just discussed configuration, the RF-MEMS step attenuator realizes 15 different levels of attenuation, plus the THRU and OPEN configurations, when the all the...
switches are ON, or \( S_{BU} \) and \( S_{BD} \) are OFF, respectively. Details of the MEMS switch used in the attenuator are reported in Fig. 3.

Figure 3a shows the 3D profile of a cantilever-based RF-MEMS series ohmic switch, like those visible in Fig. 2a. The electrostatically actuated gold membrane is hinged on one end, while it is suspended on the other. Two fingers, visible in the righthand side of Fig. 3a, short the input/output terminations of the RF line when the switch is ON. The color scale represents the vertical quote of the sample, observed with a white light interferometer. Figure 3b reports the experimental pull-in/pull-out characteristic of the switch, in response to a triangular biasing waveform. The curve is acquired with a dynamic profiling system, and the switch exhibits an actuation and release voltages of 27 V and 21 V, respectively.

3 Experimental RF validation and simulations

This section focuses on the experimental characterization of the step attenuator, Scattering parameters (S-parameters), as well as on the validation and simulation of a Finite Element Method (FEM) model of the device. The S-parameters are measured by means of a Vector Network Analyzer (VNA) and micro-probes on a probe station, up to 30 GHz. The VNA is calibrated with the SOLT (Short-Open-Load-Thru) method. Then, FEM simulations are performed within Ansys HFSS, relying on a full-3D model of the network in Fig. 2a. Starting from the device 2D layout, a full 3D model is generated within the HFSS environment, by importing the design in GDSII format, and assigning a purposely defined technology file, in which layers are vertically extruded, one by one, according to the thickness of each physical staked level. Subsequently, proper materials parameters are assigned both to conductive and insulating layers, along with boundary conditions and excitations. More details on the simulation methodology, setting and procedure are reported in Chapter 4 of Iannacci (2013).

3.1 Experimental validation up to 30 GHz

Before discussing the validation, it has to be stressed that the RF-MEMS samples available for testing come from a fabricated batch exhibiting two relevant non-idealities. In the first place, the boron implanted dose was smaller than nominal. Then, the poly-si is more resistive than expected, exhibiting 250 \( \Omega \)/sq instead of 100 \( \Omega \)/sq, thus yielding loading resistor of 25 \( \Omega \), 100 \( \Omega \) and 500 \( \Omega \).

![Fig. 3](image_url)
More relevantly, an unwanted oxidation of the aluminum based underpass layer occurred in correspondence with vias openings. This leads to the presence of a thin oxide layer wherever there is a vertical transition between gold (CPW level) and the underneath aluminum (underpass). The oxide behaves as a parasitic capacitor affecting the low frequency range, and as a parasitic resistor as the frequency increases, as already observed in Iannacci et al. (2009).

The HFSS 3D model is defined to account for the poly-si sheet resistance of 250 Ω/sq, however neglecting the presence of the parasitic thin-oxide where vertical vias are opened. In light of these considerations, the comparison of the measured and simulated attenuation (S21) is plotted in Fig. 4.

The five measured configurations include the no attenuation state (i.e. THRU), when all the switches are actuated, the maximum attenuation, when just S_BU is ON, plus three intermediate levels of attenuation.

From a qualitative point of view, a disagreement between the measured and simulated traces is visible below 5 GHz, with the experiments showing larger attenuation, highlighting a decreasing trend as the frequency gets higher. This is due to the parasitic capacitive behavior of the residual oxide layer of vertical vias. As the frequency increases and the parasitic capacitors start to conduct (short), the parasitic resistive contribution of such an unwanted layer kicks in, yielding additional loss over the whole range. This brings to the quantitative disagreement visible in Fig. 4, with simulations overestimating the transmission (S21), especially in the THRU state, with a constant difference of 2 dB over the whole frequency range. In light of these considerations, the HFSS model is able to produce accurate predictions of the RF-MEMS network S-parameters behavior, as emerging from the other network configurations in Fig. 4, as well.

A few additional considerations are now due, before moving to the next section. The discussed technology was affected by diverse non-idealities during its development. One of such spreads is the one discussed above, while other encountered were, for instance, the building of excessive residual stress within the suspended gold metallizations, leading to out-of-plane deformation of the structures, entrapment of charges within insulating layers, lossy dielectrics, and so on. It must also be stressed that all the non-idealities exerting non-negligible influence on the nominal characteristics and operability of RF-MEMS devices, were fixed or largely mitigated, by acting both at technology and design level. This considerations is valid also for the unwanted oxidation of opened vias, which brought to the increased losses in the lower frequency range, previously reported in Fig. 4. However, since the attenuator design discussed in this work was not included in other subsequent fabrication batches, it was not possible having at hand other physical replicas exhibiting an S-parameters behavior closer to expectations. In any case, also for the purpose of validating simulations, devices with characteristics closer to the nominal ones were already demonstrated in literature, as discussed in the next subsection. On the other hand, for what concerns all the experimental data reported in this work, that is, pull-in/pull-out (DC) and S-parameters characteristics (RF), measurements were performed on multiple devices, placed in different parts of the wafer, without showing significant differences from one sample to another.

3.2 Simulations up to 60 GHz

Starting from the discussion developed above, the FEM 3D model is now used to analyze the S-parameters characteristics of the RF-MEMS attenuator in all its configurations, accounting for the nominal poly-si resistivity of 100 Ω/sq. Simulations are performed up to 60 GHz, despite the validation in Fig. 4 was done just up to 30 GHz. This is a sensible choice as the same modelling approach was previously validated for similar RF-MEMS structures up to much higher frequencies (Iannacci 2017b; Iannacci and Tschoban 2017; Iannacci et al. 2016), exhibiting accurate results. The plots in Fig. 5 report the S-parameters behavior of the attenuator in the eight resistive load configurations, when both branches are selected (S_BU and S_BD ON).

Figure 5a shows the eight attenuation (S21) levels, including the THRU state (no loads). All the traces exhibit a rather flat behavior over the wide range of 60 GHz, with a variation of about 3 dB in the worst case, and of about 1 dB in the best case. Also relevantly, the Voltage Standing Wave Ratio (VSWR) reported in Fig. 5b has to be analyzed, since it provides important indications in terms of...
fractions of reflected power. To this end, if a maximum VSWR acceptable threshold is set to 2.5, corresponding to around 20% of reflected power, not all the network configurations are to be considered useful to attenuate the RF signal. In this case, just the four configurations in Fig. 5a with less attenuation are viable over the whole range, while the other four are acceptable just above 40 GHz. The other eight network configurations (S BU ON and S BD OFF) are shown in Fig. 6.

The larger resistive loads, due to the involvement of a single branch, yield higher attenuation levels, up to around 12 dB, as visible in Fig. 6a. The two configurations with lower attenuation show a negative peak of the S21 in the 30–40 GHz range, very likely due to the parasitic behavior of the open lower branch. Such a characteristic is not visible in the other configurations, probably because hidden by the larger signal attenuation. However, the traces not affected by the mentioned peak confirm a marked flatness of attenuation up to 60 GHz. Eventually, similar considerations to the previous ones must be developed looking the VSWR in Fig. 6b, confirming that not all the configurations can be in fact exploited to attenuate the input RF signal.

The reported results, despite preliminary, offer relevant sparks on how to improve this and other RF-MEMS-based design concepts, in view of future Beyond-5G and 6G mm-Waves applications. To this end, resistive loads should be reshaped, in order to add lower and intermediated attenuation levels, thus improving the VSWR. Also, the fact of having two branches in parallel should be perfected, in order to avoid unwanted negative resonances.

4 Conclusion
The future scenarios of Beyond-5G, 6G and Super-IoT, along with massive capitalization on Artificial Intelligence (AI), urge for radical paradigm shifts also at Hardware (HW) component level. Driven by the target of getting ready for such scenarios, this work discussed an RF-MEMS multi-state power attenuator, expected to be a key-component, together with phase shifters, for advanced beamforming capabilities.

The RF behavior of the 4 bit programmable network was measured and validated up to 30 GHz, while Finite Element Method (FEM) simulations showed its full characteristics up to 60 GHz. Despite some non-idealities of technology, the network exhibited good characteristics, with flatness of attenuation (S21) as good as 1 dB over 60 GHz frequency span. The reported design concept admits margins of improvement, both at technology and design level, confirmed by the data reported and discussed in this work.

References

5G Network Architecture a High-Level Perspective (2021) https://www.huawei.com/minisite/hwmbbf16/insights/5G-Nework-Architecture-Whitepaper-en.pdf. Accessed 17 May 2021
Agyapong PK, Iwamura M, Staehle D, Kiess W, Benjebbour A (2014) Design considerations for a 5G network architecture. IEEE Commun Mag 52(11):65–75. https://doi.org/10.1109/MCOM.2014.6957145
Dardari D (2020) Communicating with large intelligent surfaces: fundamental limits and models. IEEE J Sel Areas Commun. https://doi.org/10.1109/JSAC.2020.3007036

Evolving LTE to fit the 5G future (2021) https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/evolving-lte-to-fit-the-5g-future. Accessed 17 May 2021

Hu HC, Smith SF, Goldstein R (2019) Cooperative schedule-driven intersection control with connected and autonomous vehicles. In: IEEE international conference on intelligent robots and systems. https://doi.org/10.1109/ROS40897.2019.8967975

Iannacci J (2013) Practical guide to RF-MEMS. Wiley-VCH Verlag GmbH & Co. KGaA, Hoboken

Iannacci J (2017a) RF-MEMS for high-performance and widely reconfigurable passive components—a review with focus on future telecommunications, Internet of Things (IoT) and 5G applications. J King Saud Univ Sci. https://doi.org/10.1016/j.jksus.2017.06.011

Iannacci J (2017b) RF-MEMS technology for high-performance passes the challenge of 5G mobile applications. https://doi.org/10.1088/978-0-7503-1545-6

Iannacci J (2021) The WEAF Mnecosystem (water, earth, air, fire micro/nano ecosystem): a perspective of micro/nanotechnologies as pillars of future 6G and tactile internet (with focus on MEMS). Microsyst Technol. https://doi.org/10.1007/s00542-020-05202-z

Iannacci J, Tschoban C (2017) RF-MEMS for future mobile applications: experimental verification of a reconfigurable 8-bit power attenuator up to 110 GHz. J Micromech Microeng. https://doi.org/10.1088/1361-6439/aa5f2c

Iannacci J, Giacomozzi F, Colpo S, Margesin B, Bartek M (2009) A general purpose reconfigurable mems-based attenuator for radio frequency and microwave applications. In: IEEE EUROCON 2009, EUROCON 2009. https://doi.org/10.1109/EURCON.2009.5167788

Iannacci J, Huhn M, Tschoban C, Potter H (2016) RF-MEMS technology for 5G: series and shunt attenuator modules demonstrated up to 110 GHz. IEEE Electron Device Lett. https://doi.org/10.1109/LED.2016.2604426

Katz M, Matinmikko-Blue M, Latva-Aho M (2019) 6Genesis flagship program: building the bridges towards 6G-enabled wireless smart society and ecosystem. In: Proceedings—2018 10th IEEE Latin-American conference on communications, LATINCOM 2018. https://doi.org/10.1109/LATINCOM.2018.8613209

Ko B, Lee H, Son SH (2016) GPS-less localization system in vehicular networks using dedicated short range communication. In: Proceedings—2016 IEEE 22nd international conference on embedded and real-time computing systems and applications, RTCSA 2016. https://doi.org/10.1109/RTCSA.2016.26

Makridis E, Charalambous T (2020) Towards robust onboard control for quadrotors via ultra-wideband-based localization. In: 2020 international wireless communications and mobile computing. IWCMI 2020. https://doi.org/10.1109/IWCMI48107.2020.9148351

Noguera J, Badia RM (2002) HW/SW codesign techniques for dynamically reconfigurable architectures. IEEE Trans Very Large Scale Integr Syst. https://doi.org/10.1109/TVLSI.2002.801575

Osseiran A, Boccardi F, Braun V et al (2014) Scenarios for 5G mobile and wireless communications: the vision of the METIS project. IEEE Commun Mag 52(5):26–35. https://doi.org/10.1109/MCOM.2014.6815890

Pan C, Ren H, Wang K et al (2020) Intelligent reflecting surface aided MIMO broadcasting for simultaneous wireless information and power transfer. IEEE J Sel Areas Commun. https://doi.org/10.1109/JSAC.2020.3000802

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.