RF-MEMS Technology for High-Performance Passives (Second Edition)

5G applications and prospects for 6G

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This book is dedicated to the people below, without any relationship between the order of appearance and their relevance.

To Brando and Pietro and to their relentless energy and unconditional serenity, with the profoundly heartfelt wish of conserving such treasures to the largest and longest possible extents, across the extraordinary and endless journey unrolling ahead their limpid eyes.

To Moira, for making her way, our way, relentlessly, day after day, in spite of our adversities.

To Rossana and Pietro, with endless gratitude for their unconditional presence and for making everything possible.

To Luisa De Sanctis, in the awareness that wherever she is now, she is beautiful as always.

To Victor Manuel Caraballo, in the awareness that wherever he is now, he is dancing and smiling.

Jacopo Iannacci

Contents

Preface

The scientific area of microsystems, known as Micro-ElectroMechanical Systems (MEMS), has followed an evolutionary path intimately linked to that of semiconductors, albeit with relevant differentiation. MEMS and semiconductor technologies developed together, starting in the 1960s. While the manufacturing process of transistors was becoming more sophisticated, critical fabrication steps, like the patterning of buried conductive/piezoresistive thin-films and deposition of metals, began to be ventured to yield microstructures with mechanical properties. However, if transistors and semiconductors followed a relentless trend to miniaturisation (*More Moore*) across the last five decades and more, microsystems developed increasing and diversifying transduction principles, aiming at broad functionalities in the fields of sensors and actuators (*More than Moore*).

Within the scenario of microsystem technologies, RF-MEMS, i.e. MEMS for Radio Frequency passive components, started being investigated in the 1990s. Passive components for RF applications, such as waveguides, micro-relays, variable capacitors (varactors), as well as tunable filters, reconfigurable phase shifters, impedance tuners, and so on, were demonstrated in the literature. Their characteristics, in terms of low loss, high isolation and wide tunability/reconfigurability, were outstanding if compared both to standard RF/microwave components as well as to semiconductors.

Such remarkable performances triggered, in the early 2000s, inflated expectations around the massive absorption of RF-MEMS components in mass-market applications, especially referring to mobile handsets, which were growing particularly fast in those years, with the 2nd and 3rd generations of mobile communications (2G/3G). In actuality, market forecasts were systematically disappointed for more than a decade, and the foreseen revolution never took place.

More recently, starting from 2014, RF-MEMS commenced making their way into the market landscape, thanks to a need that other technologies were unable to address effectively. Modern 4th generation (4G) smartphones, due to the integration of more and more components, triggered a degradation trend in the quality of communication, which has been mitigated by the wide reconfigurability of MEMS-based RF passives. As a result, adaptive impedance tuners are now the first successful example of the exploitation of RF-MEMS technology in the consumer market segment. Besides, other MEMS components, such as high-performance switches, are starting to consolidate in applications like high-linearity RF Power Amplifiers (PAs) and RF Front Ends (RFFEs).

If this is the quite reassuring recent market snapshot of RF-MEMS, in addition the 5th generation (5G) of mobile communications and services has begun to be deployed in the last few years. Despite the fact that 5G is stepping in compliance with the 4G Long Term Evolution (4G-LTE) and according to a smooth fashion, it will pursue fundamental drivers of network densification and diversification. Compared to 4G-LTE, the full deployment of 5G in the years to come will demand an increase of data volume, up to 1000 times, of connected devices, from 10 to 100 times, as well as reduced End to End (E2E) latency, massive Machine-Type Communication (mMTC) and operation in the millimeter wave (mm-wave) range.

Further ahead, 6G is already starting to gain shape, capitalising on the visions and high-level Key Performance Indicators (KPIs) that are being elaborated in the scientific literature. Keeping as reference the year 2030, 6G is expected to take over 5G, marking a further 1000× increase in terms of data rate and speed, apart from largely increased reliability of communications, and, most of all, massively leveraging Artificial Intelligence (AI) to trigger resilient and self-evolutionary network paradigms.

These harshly stringent system requirements will push for very-high-performance, widely reconfigurable and frequency-agile passive components. RF-MEMS technology holds the fundamental features to be a Key-Enabling Technology (KET) for 5G and future 6G. From a different perspective, 5G/6G could be the killer applicative scenarios for a massive consolidation of RF-MEMS in the mass-market landscape.

The aim of this book is to outline the outstanding intrinsic potential of RF-MEMS technology with reference to future 5G/6G mobile communications and services. The way this objective is pursued is twofold. On one hand, the proper background concerning the characteristics of RF-MEMS is built, together with a definition of target specifications of interest for future telecommunications protocols and standards. On the other hand, practical insight around the design and development of RF-MEMS passive components is provided, by reviewing a few case studies of design concepts, also including multi-physics simulation approaches and techniques. In more detail, the book unfolds, chapter by chapter, as reported in the following.

Chapter 1 develops a comprehensive discussion on MEMS technologies. First, the inception of microsystems is analysed with reference to the evolution of semiconductor technologies, highlighting common features as well as their differentiation. The most diffused technology platforms for microsystems manufacturing are reported. Examples of consolidated (market) exploitations of MEMS sensors and actuators are also provided. Then, RF-MEMS are introduced, explaining their working principles and listing diverse actuation mechanisms. Subsequently, the main categories of RF-MEMS devices are reviewed, focusing both on simple components, as well as on complex high-order reconfigurable networks.

Chapter 2 places the evolution of the RF-MEMS market, since the early days of the technology, under the spotlight. First, fundamental market analysis concepts, like the hype curve and technology push/market pull scenarios, are introduced. Then, the boosted prospects around massive market penetration of RF-MEMS, counteracted, in fact, by fluctuations and disappointments for over a decade, will be studied in-depth. Two sets of reasons, namely intrinsic and extrinsic to RF-MEMS technology, are identified and discussed. Bearing in mind the lesson learned across multiple forecasted and then missed breakthroughs, a sound overview addressing the current state of the RF-MEMS market for mobile applications is provided.

Chapter 3 focuses on present and future mobile communication protocols. Initially, the working principles of mobile networks are introduced. The evolution of services and performance are reviewed, starting from the 1st generation (1G) of mobile communications, launched in the late 1970s, to the 4th generation (4G). Subsequently, the frame of the under deployment and future 5th generation (5G) communications is depicted. The expected performance and services offered to end users are discussed, along with a comprehensive recap of the current state of its roll-out. Concerning the further development of the paradigm, the main drivers of network virtualisation, densification and diversification pushed forth by 5G will also be debated, covering challenges and KETs to make this vision real within a few years. A brief outlook will also be developed on future 6G, with reference to the timeframe of the next decade, highlighting the potential limitations of the current Hardware-Software (HW-SW) systems development approaches in making the current visions turn into reality.

Chapter 4 deals with a few RF-MEMS design concepts, discussed through a quite practical and hands-on approach. First, capitalising on system-level requirements unrolled in the previous chapter, a few classes of passive components and a set of target specifications critical for 5G/6G will be reported. Then, examples of RF-MEMS designs will be studied in detail, with the aid both of electromechanical and electromagnetic multi-physics simulations. Leveraging the aforementioned tools, case study designs will be altered, showing how this influences the RF-MEMS characteristics and how they can be tailored with respect to the requirements.

Chapter 5 builds upon the hands-on modelling and simulation of RF-MEMS passive components. To this end, a purposefully developed software library of compact analytical models of basic MEMS structures will be reported and discussed in detail. The tool is based on the VerilogA programming language, and it can be exploited in any commercial or open source Integrated Circuits (ICs) development environment supporting Hardware Description Language (HDL) syntaxes. Apart from discussing the most relevant details of the implemented mathematical models, the chapter will also focus on practical exploitation examples of the mentioned tool, with reference to physical and experimentally characterised samples of RF-MEMS lumped components and complex networks.

Appendix A enriches the book's content, showing the dynamics of a few RF-MEMS devices by means of experimental videos (acquired through optical microscopy techniques) and simulated animations.

Appendix B completes the book, gathering practical information and hints, according to a user guide fashion, in order to introduce the reader to the practical use of the MEMS compact model library, previously reported in chapter 5, which is also made available for download along with the manuscript (available at https://iopscience.iop.org/book/978-0-7503-4199-8).

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Author biography

Jacopo Iannacci

Jacopo Iannacci was born in Bologna, Italy, in 1977. He received the MSc (Laurea) degree in Electronics Engineering from the University of Bologna, Italy, in 2003, and a PhD in Information and Telecommunications Technology from the Advanced Research Center on Electronic Systems 'Ercole De Castro' (ARCES) at the University of Bologna, Italy, in 2007.

He received the Habilitation as Associate Professor in Electronics from the Italian Ministry of Education, University and Research (MIUR), in 2017, and the Habilitation as Full Professor in Electronics from the Italian Ministry of University and Research (MUR), in 2021.

He worked in 2005 and 2006 as visiting researcher at the DIMES Technology Center (currently Else Kooi Lab) of the Technical University of Delft (www.tudelft.nl), the Netherlands, focusing on the development of innovative packaging and integration technology solutions for RF-MEMS devices. In 2016, he visited as a seconded researcher the Fraunhofer Institute for Reliability and Microintegration IZM (www.izm.fraunhofer.de) in Berlin, Germany, to conduct high-frequency characterisation of RF-MEMS components jointly with the RF & Smart Sensor Systems Department at IZM. Since 2007, he is researcher (permanent staff) at the Center for Sensors and Devices of Fondazione Bruno Kessler (www.fbk.eu), in Trento, Italy.

His research interests and experience fall in the areas of Finite Element Method (FEM) multi-physics modelling, compact (analytical) modeling, design, optimisation, integration, packaging, experimental characterisation and testing for the reliability of MEMS and RF-MEMS devices and networks for sensors and actuators, Energy Harvesting (EH-MEMS) and telecommunication systems, with applications in the fields of 5G, Internet of Things (IoT), as well as future 6G, Tactile Internet (TI) and Super-IoT.

Dr Iannacci has authored more than 100 scientific contributions, including international journal papers, conference proceedings, books, book chapters and one patent. Among them, a few items are going to be mentioned here. The monograph *Practical guide to RF-MEMS*, published by Wiley-VCH (https://onlinelibrary.wiley.com/doi/book/10.1002/9783527680856), in 2013, was adopted in several courses as a reference textbook. The monograph *RF-MEMS Technology for High-Performance Passives—The challenge of 5G mobile applications*, published by IOP Publishing (https://iopscience.iop.org/book/978-0-7503-1545-6), in 2017, along with the articles 'RF-MEMS Technology for 5G: Series and Shunt Attenuator Modules Demonstrated up to 110 GHz' (https://ieeexplore.ieee.org/document/7556311) and 'RF-MEMS Technology for Future Mobile and High-Frequency Applications: Reconfigurable 8-Bit Power Attenuator Tested up to 110 GHz' (https://ieeexplore.ieee.org/document/7726036), published on the IEEE

Electron Device Letters (EDL), in 2016, were among the first contributions in the literature discussing the employment of RF-MEMS technology in the frame of 5G applications.

He was and is currently involved in several international conferences as symposium chair/co-chair, session chair, technical program committee member, international advisory board member, tutorial lecturer and invited speaker, among which the following few are mentioned: IEEE Sensors, SPIE Microtechnologies, ESSCIRC-ESSDERC, ESREF, MNDCS.

Jacopo Iannacci is Senior Member of the IEEE (www.ieee.org), and is currently Associate Editor of the Springer Microsystem Technologies (https://www.springer.com/journal/542) and of the Frontiers in Mechanical Engineering (https://www.frontiersin.org/journals/mechanical-engineering#).

Introduction

Driven by my passion for commercial aviation, I wrote the introduction to the 1st edition of this book, back in 2017, around the incident of the British Airways (BA) Flight 9. The text is entirely reported below, right at the end of this section. When the book was launched, after receiving the green light from Dr John Navas at IOP Publishing, on early December 2017, I decided to publish the BA Flight 9 story in a LinkedIn article, entitled ‘A Lesson Transcending Science’, available at the following link: https://www.linkedin.com/pulse/lesson-transcending-science-jacopo-iannacci.

Nearly four years later, precisely on September 21, 2021, I received an email of appreciation regarding the LinkedIn article. My reaction was twofold. I was happy to read the message, and I jumped on the chair when I reached its end. The sender was Andrew Townley-Freeman, son of Barry Townley-Freeman, Senior Engineer Officer of BA Flight 9.

Since then, I started exchanging messages with Andrew, led by my curiosity for aviation and not only. Moreover, at that time I was working on the 2nd edition of the book, so I asked Andrew if he was available to answer some questions I would have then included in this Introduction. As a matter of fact, Andrew kindly accepted, so I report below my questions and his answers.

Closing the circle of coincidences, I am writing these words in February 2022, just a few months before the 40th anniversary of the BA Flight 9 incident. This is a further motivation for which I want to express my gratitude to Andrew Townley-Freeman for contacting me, as well as to his father, Barry Townley-Freeman, to Roger Greaves and Eric Moody, Engineer Officer, First Officer and Captain, respectively, of BA Flight 9, for what they did that night of June 1982.

Jacopo Iannacci

The story of BA Flight 9—From the Introduction to the 1st edition

On the evening of June 24, 1982, British Airways Flight 9, operated by the Boeing 747 named 'City of Edinburgh', was *en route* from Kuala Lumpur to Perth, in a multiple stopover haul from London (Heathrow), to Auckland. At around 20:40 (Jakarta time) engine number 4 started malfunctioning and failed straight away. According to standard drills, the crew shut it down and armed the fire-extinguishing system. Shortly after, engine number 3 failed for no apparent reason, followed by engines 1 and 2. In a matter of two or three minutes, all four engines were down. It was the first time in the history of aviation that a Boeing 747 lost all four engines.

Starting from the altitude of the engines' failure, Flight 9 had approximately 23 minutes of gliding available before unavoidably touching down. Jakarta airport was within gliding distance, but a mountain in between had to be cleared; however, gaining altitude was not an option with no functioning engines. The only alternative was banking towards the open sea and trying an emergency ditching, even though, in the middle of the night and with no functioning engines at all, it was a very risky manoeuvre. On top of that, it would have been the first time that a Boeing 747 was trying to land on water.

After several minutes, just a steps before the point of no return in which the crew would have had to aim the Boeing 747 nose to the Indian Ocean, engine 4 came back to life. Two minutes later, all four engines were back on track. Flight 9 gained altitude, cleared the mountain and landed safely in Jakarta.

The reason for the failure remained unknown until scientific investigations were carried out. The cause was found to be a cloud of volcanic ash produced by an eruption of Mount Galunggung, in West Java. The particles engulfed the engines, killing their power. It was only when the aircraft significantly lost altitude and the engines cooled down, that the ash solidified and broke off from the fans and rotating parts, allowing them to resume normal operation.

In summary, it was the first time a Boeing 747 had lost all four engines. The crew had absolutely no idea of the reason for such a failure, and found themselves faced with a critical decision: on the one hand, an emergency landing in Jakarta, impossible without engines; on the other, an emergency ditching in the Indian Ocean, at night, with no thrust, attempting a landing that had never been done before with a Boeing 747.

What Captain Eric Moody, First Officer Roger Greaves and Engineer Officer Barry Townley-Freeman kept doing in those endless minutes, was one, and only one thing. They repeated the engines' in-flight starting procedure, time after time, and even with no response at all, they tried again, dozens of times, relentlessly, without caring about the unmistakeable ineffectiveness and uselessness of their actions; without paying too much attention to the hopelessness of the whole situation.

While studying averted and, unfortunately, in other circumstances, unavoidable aviation accidents, I unexpectedly found an invaluable source of cases from which important lessons can be learned. For instance, what the crew of Flight 9 did in a matter of less than 20 minutes, projected on the unrolling of a lifespan—of course without the pressure of imminent disaster—could be the key to success. Pushing forth and trying to do what one feels like doing, against unfavourable circumstances and adverse and sceptical people, as well as, on top of it all, a lack of confirmation, might be a way to reach the target, because, primarily, it is the proof of your own motivation, belief and passion.

In fact, immediately following landing in Jakarta, Moody, Greaves and Townley-Freeman, instead of having champagne (and celebrating) with the cabin crew and passengers, looked through the booklet containing all the flight procedures and emergency drills dozens of times, because they were concerned that the engines' failure could have been their fault.

Now, if someone would ask me to unfold the concept of commitment, I think that this example would sketch quite effectively the meaning that such a term bears.

A few questions to Andrew Townley-Freeman

JACOPO IANNACCI (JI): Andrew, as you recently wrote me, you were the person at home picking up the phone call of Berry from Jakarta. Which is the most vivid memory you have of that moment and of the rest of June 24?

ANDREW TOWNLEY-FREEMAN (ATF): I was getting ready to go to my part time job for the evening and the house phone rang—there were no mobiles then—and, to my surprise, it was my father. Probably because the telephone line wasn't that good, he was speaking very quickly. He said that they had had an incident and when the news breaks, don't worry, they are all ok! I had to go find mum, who was out shopping, and tell her, and also phone the homes of the Captain and First Officer. I didn't think much more about it until I got home from work and mum said that British Airways had called her, and there was a little more to the full story. The next morning, I was sent to the newsagent to buy every newspaper!

JI: Did the spread-out of the BA Flight 9 case, on media and among people, interfere on your daily life and on that of your family, in the weeks/months after it happened?

ATF: No, not at all. I think that in those days, news reporting was a lot less sensational and where this would be a massive story in this era, I don't really recall much being said after the first day or two.

JI: As at the time of this interview it is early 2022, we are very close to the 40 years anniversary of BA Flight 9. Wrapping together these four decades, what is the most relevant lesson you learned, in your personal and/or professional life, from what happened on June 24?

ATF: I don't know if this is driven by the events of that night, or just the sort of person that my father is in general, but what I learned (especially in my professional life) is that you stay calm and do things the right way. Panicking when things get tough is an unhelpful emotion and wastes time—you have to put that aside and solve the problem. I think that it has also instilled the value of team working.

Above all, we all know the difference between being professional and being unprofessional, and I strive to be professional every day. My father's approach to this guides me every day.

JI: Probably I can't help sticking to the idea that in June 1982 I was barely 5 years old, i.e. in that period of life when my father, police officers and airplane pilots were all heroes. If I think to this and to what I am today, the feeling that a lot of time passed, gets stronger and stronger. Differently, if I think that 40 years ago planes were flying as they are today, it seems like yesterday. Having said this, thinking of all the time gone, and reasoning in very general terms, is there one item that gives you the feeling that a huge time has passed, and something else that, on the contrary, makes you think that the journey from 1982 to 2022 was not so long, after all?

ATF: When the event happened, I was just 18 years old so, on the one hand, it's (almost) a lifetime ago. Things have changed, especially in flying. Flight Engineers are no longer needed on today's airplanes and if you look in a flight deck from those days to now, they are hugely different. Closer to your field, when dad called me from Jakarta, they had had to book a telephone line to call the UK and then they were able to call. Today, they would call on their mobile … in fact, the passengers would probably be live streaming the incident!

On the other side, there are things that haven't changed. When problems happen, we still need quick thinking humans to address them. If we think about Covid, the scientists that developed the vaccines have done a modern-day equivalent of the crew of BA009. They stayed calm, evaluated the information that they had available, used the processes that they were familiar with and adapted to the situation.

JI: Lastly, still recalling the common way of attributing the role of heroes to the piloting crew of BA Flight 9, is there a little thing, like a daily habit or anything else, you always observed in Barry, that makes him absolutely human?

ATF: This is difficult to answer because you are asking if there is something that makes the hero seem human, but for me, the human that I had known for 18 years became the hero – my hero. But, that wasn't a different role, it was an additional role. After the event, he returned from his role as a Flight Engineer to his role as a father and husband and really he kept the two as different worlds. Maybe that is the answer to your question—he remained the same person that he always was. Also, he feels that he didn't do anything particularly special—to him, he was just doing the job that he was trained to do.