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RF-MEMS for high-performance and widely reconfigurable passive components – A review with focus on future telecommunications, Internet of Things (IoT) and 5G applications

Jacopo Iannacci

Fondazione Bruno Kessler (FBK), Center for Materials and Microsystems (CMM), Via Sommarive, 18–38123 Povo–Trento, Italy

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ABSTRACT

Since its first discussions in literature during late '90s, RF-MEMS technology (i.e. Radio Frequency MicroElectroMechanical-Systems) has been showing uncommon potential in the realisation of high-performance and widely reconfigurable RF passives for radio and telecommunication systems. Nevertheless, against the most confident forecasts sparkling around the successful exploitation of RF-MEMS technology in mass-market applications, with the mobile phone segment first in line, already commencing from the earliest years of the 2000s, the first design wins for MEMS-based RF passives have started to be announced just in late 2014. Beyond the disappointment of all the most flattering market forecasts and, on the other hand, the effective employment of RF-MEMS in niche applications (like in very specific space and defence scenarios), there were crucial aspects, not fully considered since the beginning, that impaired the success of such a technology in large-market and consumer applications. Quite unexpectedly, the context has changed rather significantly in recent years. The smartphones market segment started to generate a factual need for highly reconfigurable and high-performance RF passive networks, and this circumstance is increasing the momentum of RF-MEMS technology that was expected to take place more than one decade ago. On a broader landscape, the Internet of Things (IoT) and the even wider paradigm of the Internet of Everything (IoE) seem to be potential fields of exploitation for high-performance and highly reconfigurable passive components in RF-MEMS technology.

This work frames the current state of RF-MEMS market exploitation, analysing the main reasons impairing in past years the proper employment of Microsystem technology based RF passive components. Moreover, highlights on further expansion of RF-MEMS solutions in mobile and telecommunication systems will be briefly provided and discussed.

1. Introduction on RF–MEMS technology

MicroElectroMechanical–Systems for Radio Frequency applications, commonly known as RF–MEMS, have been investigated by the research community starting from the late '90s. Microsystem (MEMS) technologies, at that time already exploited with a certain maturity in sensors and actuators applications (Bernstein et al., 1993; Zengerle et al., 1992; Aratani et al., 1993), commenced to be ventured for prototyping RF passive components. At first, miniaturisation of microwave and millimetre–wave transmission lines and their implementation in micromachining technologies based on Silicon, emerged as a rather promising research field already at the beginning on '90s (McGrath et al., 1993), thanks to the outstanding performance figures in terms of low–loss and compactness, if compared to traditional solutions (Katehi et al., 1993). The possibility to integrate fixed RF signal manipulation functions, e.g. through the realisation of stubs (Weller and Katehi, 1995), appeared as an additional strength of Silicon–based waveguides.

Subsequently, the exploitation of the mechanical deformability, typical of MEMS, within the just mentioned miniaturised waveguides, posed the bases for the inclusion of a crucial characteristic of passive RF components in Silicon–based technologies: tunability/reconfigurability. To this regard, it must be recalled here that from the functional point of view, the multi–physical coupling

E-mail address: iannacci@fbk.eu

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through which the mechanical behaviour of movable RF–MEMS parts is controlled (and their characteristics reconfigured) can take place basically according to four different actuation principles: electrostatic (Liu, 2011; Lee et al., 2004), electromagnetic (Cho et al., 2005), piezoelectric (Safari and Akdoğan, 2008; Kawakubo et al., 2005), and thermoelectric (Daneshmand et al., 2009; Iannacci et al., 2011a, 2010a).

This is how reconfigurable transmission lines and, more appropriately, RF–MEMS, started to draw increasing attention in the research scenario (Brown, 1997). Shortly after, MEMS technology was demonstrated for the realisation of micro–switches (Goldsmith et al., 1998) and variable capacitors (varactors) (Feng et al., 1999), as well as tunable filters (Katehi et al., 1998), resonators (Katehi et al., 1998) and programmable phase shifters (Malczewski et al., 1999). Fig. 1 shows the microphotograph of a typical varactor configuration realised in RF–MEMS technology (Goldsmith et al., 1998).

The varactor is framed in a Coplanar Waveguide (CPW) structure. A metal overpass (realising an air–gap) crosses the RF line, connecting the two RF ground planes. When no DC bias is imposed between the suspended metal plate and the underlying fixed electrode (i.e. underpass), the shunt capacitance to ground is minimal. Differently, when the DC voltage drop between the two electrodes crosses the pull–in level, the suspended metal membrane collapses onto the underlying electrode, and the shunt capacitance to RF ground reaches its maximum value. In between the two ON/OFF configurations, the vertical position of the MEMS can be controlled in an analogue fashion, by driving the DC bias, thus enabling the continuous tuning of the capacitance, in a range of vertical displacement equal to the 33% of the initial (OFF state) air–gap (Iannacci et al., 2010b).

The remarkable characteristics in terms of low–loss, high–isolation, high quality factor (Q–factor), good linearity and, also importantly, tunability/reconfigurability, indicated since the early days RF–MEMS as a key enabling technology for next generations of radio platforms, spanning from handsets and mobile communications (Nguyen, 1998) to radar systems (Brown, 1998). Fig. 2 shows the schematic block diagram of an RF transceiver (transmitter/receiver), where all the circled components were envisaged to be replaced with MEMS/RF–MEMS implementations, thus enabling better performance of the whole system (Nguyen, 1998).

As visible in Fig. 2, the variety of passives to be realised in RF–MEMS technology is quite broad, ranging from switches and varactors, to reconfigurable filters and LC–tanks. Given these premises, the research community has been driven through the years to put significant effort in demonstrating the outstanding performance achievable by means of thoughtful design of basic and complex passives in RF–MEMS technology.

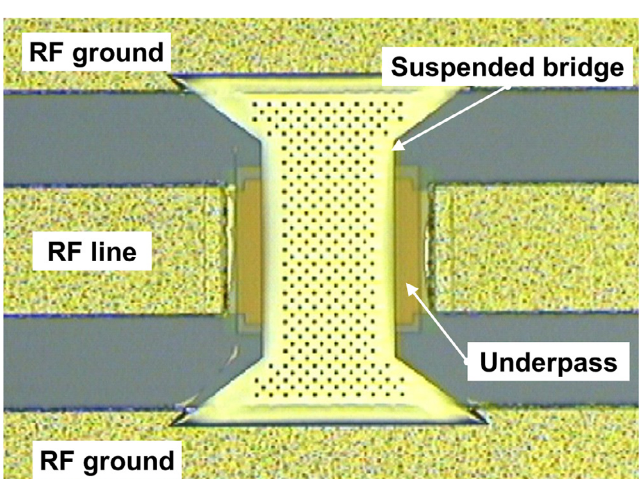

Fig. 1. Microphotograph of an RF-MEMS varactor in Coplanar Waveguide (CPW) configuration (Goldsmith et al., 1998).

Starting from basic reconfigurable elements, i.e. ohmic (Patel and Rebeiz, 2010; Shalaby et al., 2009) and capacitive (Mahameed and Rebeiz, 2010; Thakur et al., 2009; Martinez et al., 2007) micro–relays with superior characteristics, their proper replication and (cross-)interconnection enabled the realisation of high–performance and widely reconfigurable RF–MEMS passive networks (Iannacci, 2013). Thereafter, switching units ranging from Single Pole Double Throws (SPDTs) (Uno et al., 2009) to more complex Single Pole Multiple Throws (SPMTs) and switching matrices were successfully demonstrated in literature (Gong et al., 2011; Stehle et al., 2009). Fig. 3 shows the Scanning Electron Microscopy (SEM) image of the 60 GHz switched lines proposed and discussed by Gong et al. (2011).

The network is realised in CPW configuration. The RF input branch can be redirected on four output lines, by means of a star–like central multiple switching unit, relying on ohmic RF–MEMS switches, that implements a Single Pole Four Throw (SP4T). The network reconfigures the phase shift of the output RF signal with respect to the input one, depending on the length of the selected output branch. Reconfigurable RF power attenuators (Iannacci et al., 2010c) and splitter/couplers (Nishino et al., 2009; Ocera et al., 2007) can also be entirely implemented in RF–MEMS technology, as well as impedance matching tuners covering significant portions of the Smith chart and realising a wide number of different states (Iannacci et al., 2011b; Lu et al., 2005a; Domingue et al., 2010; Larcher et al., 2009). Fig. 4 shows the microphotograph of the RF–MEMS reconfigurable power attenuator reported by Iannacci et al. (2010c).

The device, based on a surface micromachining process and framed in a CPW configuration, exploits buried Polycrystalline Silicon (Poly–Si) resistors placed in series on the RF line to attenuate the RF signal flowing across the network. Ohmic contact electrostatically controlled MEMS switches, can selectively short each Poly–Si resistor when actuated (pulled–in), thus reconfiguring the load resistance and, in turn, the attenuation of the RF signal. The experimental testing of the device exhibited rather flat attenuation levels in the range from nearly–DC up to 30 GHz.

Furthermore, RF–MEMS technology was proven to be a key enabling solution also in the realisation of reconfigurable phase shifters (Reinke et al., 2011; Vorobyov et al., 2011) and True Time Delay (TTD) lines (De Angelis et al., 2008; Van Caekenberghe and Vaha-Heikkila, 2008) for electronic antenna steering and radar systems, as well as in the micro–fabrication of tunable filters (Varadan, 2002) for various RF applications (Entesari et al., 2007; Gil et al., 2007; Reines et al., 2010).

The afore–mentioned examples leverage on surface micromachining manufacturing processes, which is proven to be a viable solution for the realisation of highly–reconfigurable RF–MEMS devices. Of course, there exist other technology platforms and solutions, like the so–called bulk micromachining. Since the detailed discussion of pros and cons of each solution steps beyond the purposes of this article, a few references reporting in–depth technology–related discussion are listed (Del Tin et al., 2007; Giacomozzi et al., 2011; Iannacci et al., 2010c; Gao and Gong, 2016).

Despite the focus of this work is mainly aimed to RF–MEMS featuring switching elements, another category of devices that is worth to be mentioned is the one of the so–called Surface Acoustic Wave (SAW), Bulk Acoustic Wave (BAW) filters and (thin-)Film Bulk Acoustic Resonators (FBARs). The just listed classes of devices exploit forth and back transduction between electrical and mechanical (i.e. acoustic) domain, respectively, in order to realise very pronounced filtering functions, and are currently exploited

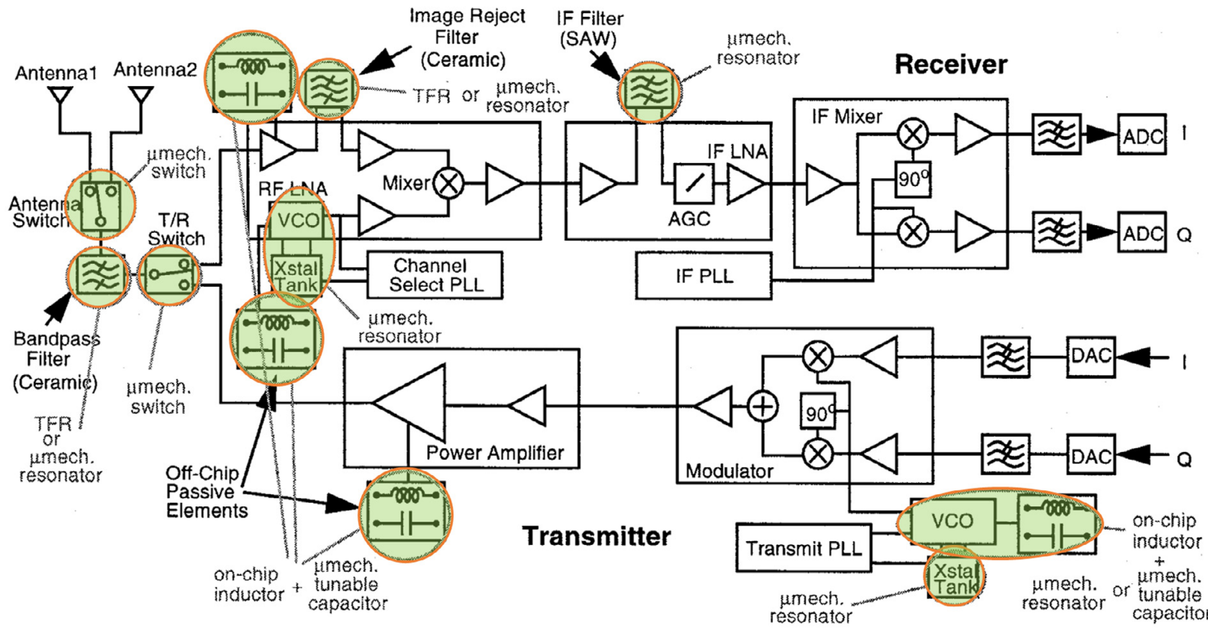

Fig. 2. Schematic block diagram of an RF transceiver (transmitter/receiver). All the circled components were envisioned to be replaced with MEMS and RF-MEMS implementations, thus boosting the performance of the whole system (Nguyen, 1998).

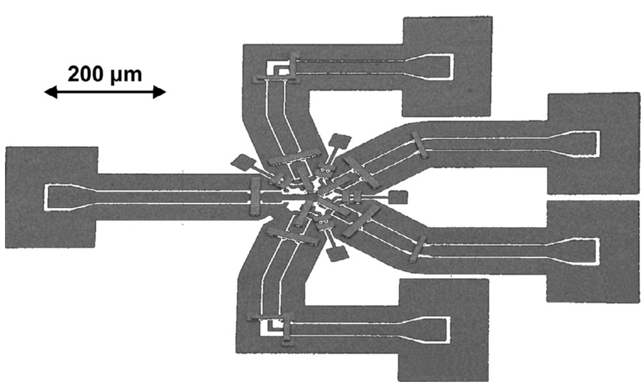

Fig. 3. Scanning Electron Microscopy (SEM) image of the reconfigurable RF-MEMS switched line reported by Gong et al. (2011).

quite frequently in commercial applications. The literature on this topic is wide, therefore just a valuable works are mentioned in this article (Piazza et al., 2007; Gong and Piazza, 2013, 2014; Gao et al., 2016).

2. Market exploitation of RF–MEMS: early vision and actual limiting factors

Such a variety of high–performance RF passives stimulated the research and scientific community to picture strategies around market exploitations of RF–MEMS technology in modern wireless systems. To this end, the contribution of Nguyen, with focus on high Q–factor MEMS resonators, is certainly relevant (Nguyen, 2001, 2002). Based on his vision, RF–MEMS passives were bearing the potential for a twofold impact on radio transceivers (transmitters/receivers). First, lumped devices, like switches, resonators and varactors, were meant to substitute standard counterparts in RF circuits, enabling better performance of wireless devices (Nguyen, 2002, 2006), as previously shown in Fig. 2. On a different level, RF–MEMS complex reconfigurable networks, like switching units, tunable filters, reconfigurable LC–tanks and so on, were supposed to make rethink the architecture of transceivers. This would had enabled not only better performance, but also wider reconfigurability of the same platform/terminal, extending services and compliance with different standards, as well as reducing hardware and power consumption (Nguyen, 1998, 2006, 2007, 2013).

Nonetheless, despite the high–expectations triggered in the beginning by RF–MEMS, issues concerned to reliability, packaging and integration, impaired their breaking into large market applications. The just mentioned aspects are going to be briefly discussed in the following.

MEMS are exposed to a wide range of malfunctioning and failure mechanisms (both reversible and irreversible) that are very common in material and mechanical engineering, but rather unknown in the community of electronic and RF engineers. Among them, the most important are fatigue, creep, plastic deformation, corrosion, fracture, stiction (i.e. the missed MEMS release after zeroing the biasing signal) and micro–welding (Iannacci, 2015a, b). All this highlighted explicitly that RF–MEMS technology was demanding for significant further development before being adoptable in market applications (DeNatale and Mihailovich, 2003; Lisec et al., 2004; Melle et al., 2003; Rizk et al., 2002).

Also related to reliability, the issue of packaging and encapsulation emerged as a relevant aspect. MEMS need to be properly isolated from the surrounding environment, by being housed within a protective (hermetic or semi–hermetic) housing (Jourdain et al., 2003; Park et al., 2002, 2003). In the RF–MEMS frame of reference, the application of a package increases the complexity at technology level and the manufacturing costs, as well. The latter ones were estimated to be as high as 80% of the final product price (Cohn et al., 2002). Furthermore, the presence of a protective cap worsens the outstanding RF performance of MEMS passives, because of additional parasitic effects due to capacitive couplings, inductance and resistance of signal underpasses, etc. Therefore, the package must be carefully conceived and counted in as actual part of the device, thus making the design and modelling phases more challenging (Iannacci, 2013; Iannacci et al., 2006, 2008; Margomenos and Katehi, 2002, 2003).

Finally, yet importantly, in several cases MEMS technology is incompatible with standard semiconductor platforms (e.g.

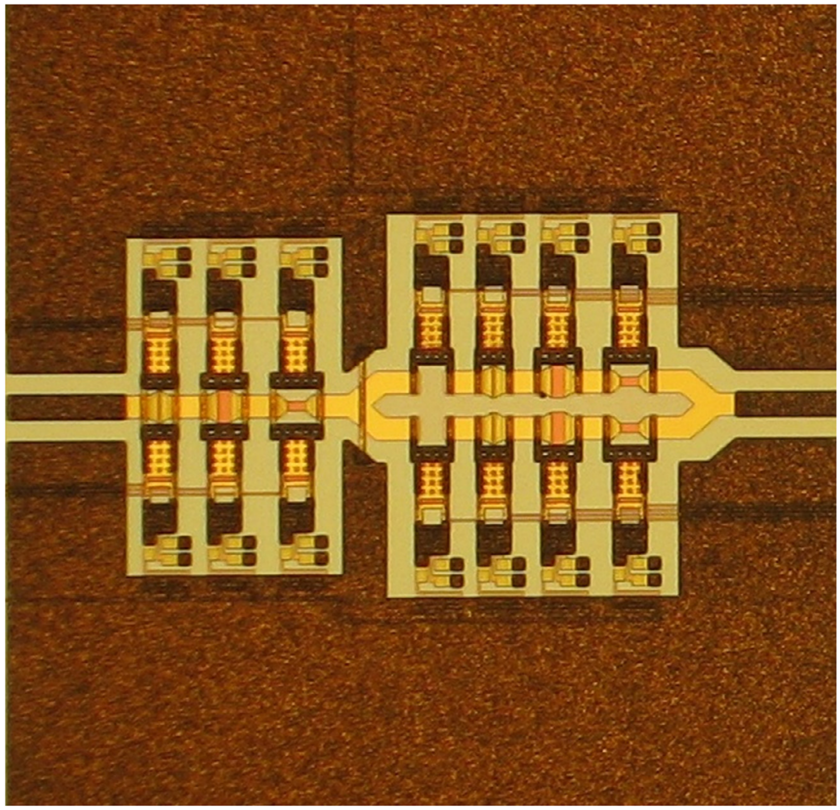

Fig. 4. Microphotograph of the RF-MEMS reconfigurable power attenuator discussed by Iannacci et al. (2010c).

Complementary Metal Oxide Semiconductor – CMOS). This happens, for instance, when metals like Gold are used for the MEMS structural parts, or when the thermal budget of the CMOS and MEMS part are significantly different. In–package passive components need to be integrated with active electronics, e.g. through Surface Mount Technologies (SMTs), and ad–hoc circuitry must be developed and deployed, as well, in order to operate them, rising, also in this case, complexity and costs (De Silva and Hughes, 2003; Lu et al., 2005b; Pacheco et al., 2004; Th Rijks et al., 2003; Zhang et al., 2006; Ziegler et al., 2005).

Bearing in mind the just depicted scenario, RF–MEMS started to be gazed across the scientific community as a technology suitable to demonstrate remarkable performance in research–related topics and very–limited niche applications (e.g. space and defence), but at the same time inappropriate for medium/large volume market applications, and, above all, consumer electronics, i.e. mobile phones. Despite the reasons of such a disappointment were attributed to all the additional efforts at reliability, packaging and integration level, necessary to spill out market products from RF–MEMS technology, there exists a more consistent underlying motivation that impaired their spread since the beginning.

In the first years of the 2000s, despite the technical soundness of the vision reported by Nguyen (2001, 2002, 2006, 2007, 2013), there was not a factual need for RF passives with better performance. In other words, the early approach to the commercial exploitation of RF–MEMS was mainly technology push based, rather than market driven (Martin, 1994; Iannacci, 2015a,b).

To conclude this section, a summary of advantages and disadvantages of RF–MEMS technology with respect to standard technologies (both CMOS/semiconductor and miniaturisation e.g. via micro–milling techniques) is reported in Table 1.

In order to provide the reader with a more quantitative understanding of how RF–MEMS technology places with respect to other solutions, Table 2 reports the comparison between micromechanical and semiconductor–based switches (DeLisle, 2015).

Table 1
Summary of advantages and disadvantages of RF-MEMS technology versus standard technologies.

Advantages	Disadvantages
Good linearity	Fragile (need package)
Large tuning range	Large controlling voltages required (CMOS not compatible)
High Q-factor	Need ad-hoc electronics to be controlled
Virtually no power consumption (for controlling the device)	Technology often incompatible with standard CMOS process (i.e. need to be packaged/integrated)
Good isolation	
Low-loss	
Small dimensions and reduced weight	
High-complexity achievable	

Following a similar approach, a comparison between RF–MEMS and semiconductor–based variable capacitors (varactors) is shown in Table 3 (Elshurafa and Salama, 2013).

3. Market exploitation of RF–MEMS: current situation and perspectives

In fact, the recent rapid diffusion of 4th Generation-Long Term Evolution (4G–LTE) smartphones enabled an unwanted degradation trend in voice signal and data transmission quality, due to the integration of the antenna with many other components (Allan, 2013) (see Fig. 5).

Such an unprecedented context made room for exploitation of RF–MEMS characteristics, especially in terms of tunability. To this

Table 2
Performance and characteristics comparison between MEMS and solid state switches (DeLisle, 2015).

Switch type	MEMS	Solid state		
		FET[a]	PIN[b]	Hybrid
Frequency range	DC to max frequency		1–10 MHz to max frequency	From kHz
Insertion loss	Low	High	Medium	High
Isolation	Good across all frequencies	Good at low-end frequencies	Good at high-end frequencies	
Return loss	Good			
Repeatability	Good	Excellent		
Switching speed	Slow	Fast		
Settling time	Slow	Good < 350 µs	Excellent < 50 µs	Good < 350 µs
Rise/fall time	ms	µs	ns	µs
ON to OFF switching time	ms	µs	ns	µs
Power handling	High	Low		
Operating life	Medium	High		
ESD[c] immunity	High	Low	Medium	Low
Sensitive to	Mechanical vibrations	Temperature extreme and RF power extreme		

[a] Field Effect Transistor.
[b] P-type, Intrinsic, N-type semiconductor.
[c] Electrostatic Discharge.

Table 3
Performance and characteristics comparison between MEMS and solid state variable capacitors (varactors) (Elshurafa and Salama, 2013).

CMOS varactors	MEMS varactors
Leakage currents	No significant leakages
Typical Q–factor of 30–40, in a few cases up to 50–60	Typical Q–factor of 200–300
Decreasing tuning range (C_{max}/C_{min}) due to continuous downscaling. Maximum ration of about 3 in the millimetre-wave range	Tuning ranges typically spanning between 5 and 50
Rather lossy in the millimetre-wave range	Always low-loss

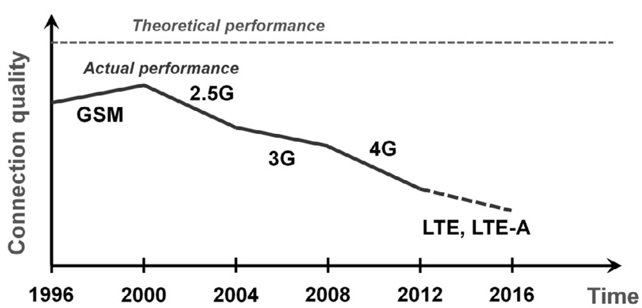

Fig. 5. Decreasing trend in communication quality stepping from one generation to another, as hopping from early mobile handsets in late '90s to modern smartphones (Allan, 2013).

regard, employment of analogue impedance tuners between the smartphone antennas and the RF Front Ends (RFFEs), enables optimal adaptive matching. Thus, RF–MEMS implementation of impedance tuners is one of the first commercial uptakes of such a technology (Cavendish Kinetics, 2014).

The emerging world of 5G appears to be a field of convergence for diverse demands and challenging requirements as rarely the research and industrial community witnessed before. After all, since the massive diffusion of mobile handsets roughly two decades ago, the trend to integration of more wireless services supported by the same device was relentless. And its pace, rather than linear, has been following an exponential law. To this regard, 5G systems are predicted to deliver up to 1000 times the capacity of current mobile networks (Baldemair et al., 2015). For instance, broadband wireless applications, like high–resolution video streaming and Tactile Internet (Moskvitch, 2015), will urge for data rates that could be 10–100 times wider compared to what 4G wireless networks are able to offer (Fettweis, 2014; Osseiran et al., 2014).

At higher level of abstraction, the Internet of Things (IoT) paradigm portrays an ongoing technology development path through which any object and environment belonging to our daily life experience, earns its own identity in the digital world, by means of the Internet (Econocom, 2016; Uckelmann et al., 2011). Given the IoT frame of reference, 5G mobile systems are expected to accommodate a wider range of wireless connections, supporting emerging applications like Machine–To–Machine (M2M), and, in turn, all the more stringent requirements they bring, in terms of Quality of Service (QoS), concerning reliability, spectral and energy efficiency, and so on (Wu et al., 2011; Bhushan et al., 2014; Boccardi et al., 2014). To this regard, the scenario of smart connected cars for road safety, helps understand how critical delay and reliability constraints might be. In light of the just depicted scenario, it is straightforward that there will be no unique enabling technology capable of addressing all the challenging and often conflicting requirements of next generation 5G applications (Le et al., 2015). From a general point of view, innovation and re–engineering of network architecture and algorithms will be necessary. This, of course, will demand both for novel hardware and software solutions. More in details, just to mention some of the current limitations that will have to be overcome at architectural and implementation level, the currently in use Orthogonal Frequency Multiple Access (OFDM) waveform (exploited in 4G applications) will need to be replaced by more efficient solutions. Moreover, network diversification, employment of large–scale Multiple Input Multiple Output (MIMO) units and use of mmW spectrum to ensure Gigabit (Gb) communications, will have to be ventured (Le et al., 2015).

Bearing in mind the previously discussed market pull scenario that started making RF–MEMS solutions successful (up to now for impedance matching tuners), it is envisaged that 5G communication protocols will demand for higher operation frequencies (e.g. well above 6 GHz) and large reconfigurability to cover different services, while reducing hardware redundancy and power consumption. In order to target these challenges, it is necessary to leverage on passives with boosted characteristics (low–loss, high–isolation, etc.), and RF–MEMS technology is indicated as one of the more promising candidates, both for what concerns 5G smartphones (i.e. RFFEs), and base stations (Lapedus, 2015). Of course, there will be important challenges to be addressed in terms of frequency operation. To this regard, the backhaul portion of the infrastructure closer to end users, is supposed to work at millimetre–wave frequency (60–70 GHz). This is the case of the so–called 5G small cells, which will bring very–wide data rate access (up to the Gbps range) to individual users in confined areas. As discussed below in this paper, RF–MEMS devices featuring micro–relays operating at frequencies as high as 110 GHz and exhibiting good characteristics have already been demonstrated in literature. Further effort will have to be directed towards operation at higher frequencies for resonant classes of MEMS devices, as filters based on electromechanical transduction mechanisms.

From a different perspective, regardless of the specific technology employed for the realisation of RF components, they always need to be packaged and integrated into more complex sub–systems and systems. If, on one side, the primary role of the package is to protect devices from potentially harmful (environmental) factors, like shocks, contaminations, moisture, dust particles, and so on (Jin et al., 2010), it has been realising, on the other hand, more and more functionalities (Kuang et al., 2010). As a matter of fact, the massive growth of RF systems for mobile communication taking place since years, has been driving miniaturisation, high–integration density and low–cost fabrication solutions.

Nowadays, RF Systems on Chip (SoCs) employ hundreds of passive components and only few tens of Integrated Circuits (ICs) (STATS ChipPAC, 2017). Given that such components are often manufactured in diverse, incompatible and non–monolithic technologies, it is easy to understand that their successful integration can only take place through high–performance and high–density Wafer Level Packaging (WLP) solutions. Of course, designing and realising a package that ensures high–reliability (Iannacci, 2015a,b), high–density integration and very–low impact on the performance of RF passive (MEMS and non–MEMS) components (Lahti et al., 2013; Iannacci et al., 2008) is a rather challenging task. This is the reason why, as mentioned above, the packaging/integration phase, in some cases can be more expensive than the realisation of the actual RF components to be packaged.

4. Recent findings in the RF–MEMS state of the art research scenario

Since the first years of 2000, the literature on RF–MEMS started to be populated by a few research items reporting high–performance devices and networks working at frequency ranges as high as W–band (i.e. above 75 GHz). The study around the development of such components was mainly driven by the need of demonstrating and disseminating the outstanding characteristics achievable with RF–MEMS technology. For instance, high–isolation RF–MEMS switches (Rizk et al., 2001) and switch–based phase shifters (Stehle et al., 2008) were proven to exhibit high–performance in the range from 70 GHz up to 110 GHz. An interesting solution to improve isolation in the switch OFF state and reduce the losses in the switch ON state is reported by Baghchehsaraei et al. (2012). It is based on a waveguide switch, composed by laterally moving fingers able to short the electric field lines, therefore implementing the OFF state. The 3D schematic of the switch in both ON/OFF states is reported in Fig. 6.

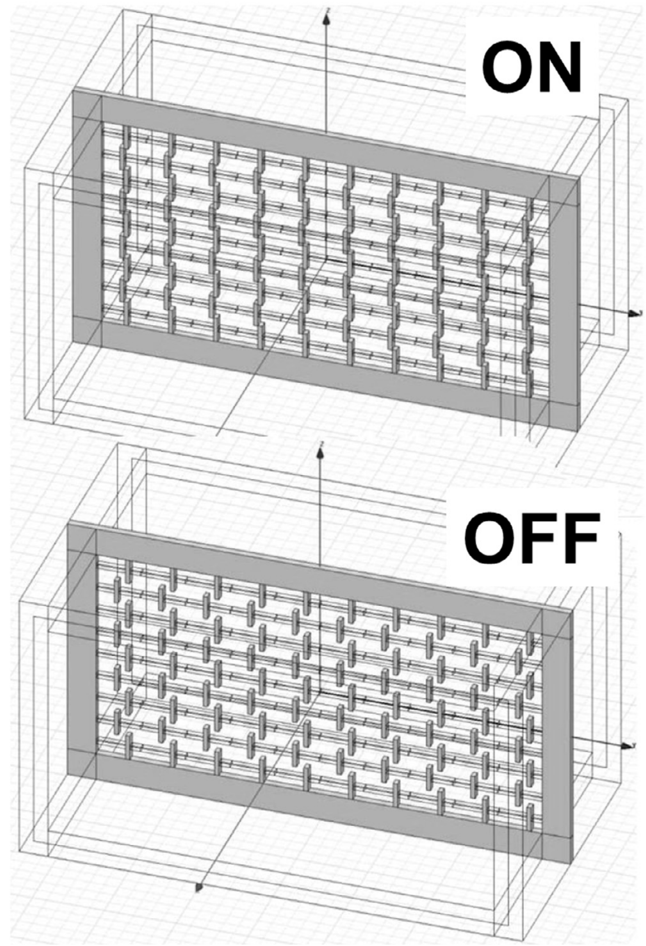

Fig. 6. 3D schematic of the waveguide RF-MEMS switch proposed by Baghchehsaraei et al. (2012), in both ON/OFF configurations.

The tested samples exhibited losses better than 1 dB and isolation better than 20 dB in the frequency range from 62 GHz to 75 GHz. More recently, RF–MEMS started to be indicated as a key enabling technology for future 5G applications, both for what concerns basic elements (Iannacci et al., 2016a,b) and complex networks (Iannacci et al., 2016c; Iannacci and Tschoban, 2017). This suggests that the interest for high–frequency operating RF–MEMS devices is growing not only in research and niche activities, but in the consumer market segment, as well.

5. Conclusions

MicroElectroMechanical–Systems for Radio Frequency applications, i.e. RF–MEMS, after fluctuations about their potential employment as commercial products, are now indicated as a key enabling technology for the next generation of mobile communications. As a matter of fact, 5G communication protocols will demand for higher operation frequencies (e.g. well–above 6 GHz) and large reconfigurability to cover different services, while reducing the hardware redundancy and power consumption. In order to target these challenges, it is necessary to leverage on passives with boosted characteristics (low–loss, high–isolation, etc.), and RF–MEMS technology is indicated as one of the most promising candidates, both for what concerns 5G smartphones, i.e. RF Front Ends (RFFEs), as well as for base stations. On a broader landscape, the Internet of Things (IoT) and the even wider paradigm of the Internet of Everything (IoE) seem to be potential fields of exploitation for high-performance and highly reconfigurable passive components in RF-MEMS technology.

This work framed the current state of RF-MEMS market exploitation, analysing the main reasons impairing in past years the proper employment of Microsystem technology based RF passive components. Moreover, highlights on further expansion of RF-MEMS solutions in mobile and telecommunication systems were provided and discussed.

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