

RF-MEMS: an enabling technology for modern wireless systems bearing a market potential still not fully displayed

J. Iannacci¹ 

Received: 19 June 2015 / Accepted: 12 August 2015 / Published online: 1 September 2015
© Springer-Verlag Berlin Heidelberg 2015

Abstract Since its first discussions in literature during late '90 s, 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. Nonetheless, against the most confident forecasts for 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, first design wins for MEMS-based RF passives have started to be announced just recently. This paper tries to depict and interpret the substantial circumstances that made RF-MEMS technology fail repeatedly, for about one decade, market forecasts. With the graphical support of the hype cycle concept, it will be shown that missed success of RF-MEMS was first caused by intrinsic (i.e. technology-related) factors. Subsequently, extrinsic elements linked to market acceptance and needs of such a technology, not fully weighted since the beginning, caused the second wave of disappointment around RF-MEMS. 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 about one decade ago. This work frames the current state of RF-MEMS market exploitation, also providing highlights on

further expansion in mobile and telecommunication systems. Eventually, a focused state of the art report is developed around recent RF-MEMS research findings driven by requirements imposed by current market applications.

1 Introduction

Radio Frequency MicroElectroMechanical-Systems are widely known and referred to as RF-MEMS. They are Microsystem-based (i.e. MEMS-based) lumped passive components, realising functions of various complexity, meant to condition and/or redirect one or more Radio Frequency (RF) signal(s) within circuits and sub-systems of wireless transceivers (transmitters/receivers). Since their first upsurges in literature contributions during the second half of the '90 s, RF-MEMS were indicated as a key enabling technology able to target both very high performance and low manufacturing cost, with respect to counterpart RF passives implemented in standard semiconductor solutions (Brown 1998; Katehi et al. 1998).

In RF-MEMS, the ability to reconfigure the conditioning function operated on RF signals is always ensured by the physical movement and mechanical deformation of micro-membranes, i.e. the fundamental characteristic of MEMS-based sensors and actuators (Liu 2011). Given this context, whatever is the complexity of the conditioning function operated by a network in RF-MEMS technology, the basic element is constituted by the switch (or relay). Like in traditional electromechanical relays, RF-MEMS switches feature a metallic (or more in general conductive) flexible membrane that, when suitably deformed, closes the electric contact between the input and output terminations, thus letting the RF signal pass through the relay and changing its state from *open* to *closed* (Iannacci 2013a). On the other

✉ J. Iannacci
iannacci@fbk.eu

¹ MicroSystems Technology (MST) Research Unit, Center for Materials and Microsystems (CMM), Fondazione Bruno Kessler (FBK), Via Sommarive 18, 38123 Povo, Trento, Italy

hand, differently from classic devices, RF-MEMS switches are highly miniaturised, and the in-plane dimensions can be as compact as a few tens of μm , with thicknesses (out-of-plane dimension) of just a few μm (or starting from 50 to 100 μm also considering the Silicon substrate). The most common actuation strategy to control the displacement of the movable contact, and therefore to drive the transition of state between open and closed, is the electrostatic attraction. A voltage (i.e. bias) is imposed across the floating part and a fixed counter-electrode, and the attractive force brings the first one in physical contact with the input and output branches, thus shorting them and closing the relay (Liu 2011). Nonetheless, apart from electrostatic force, other actuation mechanisms are possible, like thermoelectric, piezoelectric and electromagnetic (Iannacci 2013b). Moreover, depending on the particular deployment and configuration of input/output electrodes, the switch can be ohmic or capacitive, as well as series or shunt (Iannacci 2013b), thus providing to the designer various degrees of freedom (DOFs) and covering a wide range of performance and characteristics.

In substance, 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 in terms of high isolation, wide frequency range, low insertion loss, pronounced linearity and nearly-zero power consumption, their proper duplication and interconnection enables the realisation of high performance and widely reconfigurable RF-MEMS passive networks (Iannacci 2013a). 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). Reconfigurable RF power attenuators (Iannacci et al. 2010) 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. 2011a; Lu et al. 2005a; Domingue et al. 2010; Larcher et al. 2009). 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-Heikkilä 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 availability of such a wide variety of RF passives with remarkable characteristics nurtured the research and

scientific community in developing visions and strategies about capillary market exploitations of RF-MEMS technology in modern wireless components and systems. To this regard, the contribution provided by Nguyen, with specific focus on MEMS resonators with very high Q-factor (quality factor), is certainly relevant (Nguyen 2001, 2002). According to his vision, RF passives based on MEMS technology were bearing the potential for a twofold impact on radio transceivers. First, lumped RF-MEMS devices, like switches, resonators and variable capacitors (or varactors) could have replaced their standard counterparts in RF circuits, leading to better performance of wireless devices (Nguyen 2002, 2006). On the other hand, realisation of RF-MEMS complex reconfigurable networks, like switching units, tunable filters, reconfigurable LC-tanks and so on, was supposed to make rethink the architecture of transceivers. This would have enabled not only better performance, but also wide reconfigurability of the same platform, extending services and compliance with different standards, as well as reducing hardware redundancy and power consumption (Nguyen 1998, 2006, 2007, 2013).

Despite all these remarkable characteristics that boosted high expectations concerning the impact on commercial applications, the first RF-MEMS design wins were announced just in the last few years, with a delay of about one decade with respect to the market revolution predicted in the first years of the 2000s. This happened because rather critical aspects concerned to RF-MEMS were not fully estimated in the beginning. This contribution will try to isolate and describe those factors, providing also a brief overview of current state of the art in the research and market fields.

The paper is arranged as follows. Section 2 analyses the history of market expectations and forecasts for RF-MEMS, highlighting the causes of their disappointment, as well as the recent encouraging trends enabled by the smartphones market segment. Section 3 reports a state of the art on recent research findings related to RF-MEMS devices, mainly driven by current market applications requirements. Finally, Sect. 4 summarises some conclusive considerations.

2 Market analysis of RF-MEMS: past and present

In order to better understand the trends followed by RF-MEMS since their appearance in the scientific community, the concept of hype curve has to be introduced. Such graphic tool was elaborated by Gartner Inc., an information technology research and advisory company, and depicts the typical acceptance cycle of a new technology, from its first development to the employment in market applications (Gartner 2015). The typical trend of the hype curve is shown in Fig. 1.

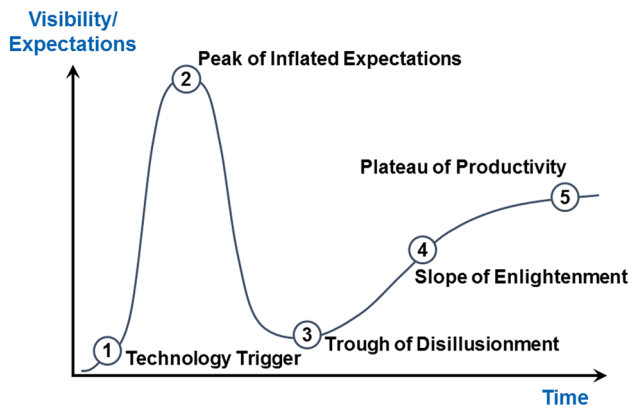


Fig. 1 Typical behaviour of the hype curve, describing the evolution of a novel technology versus time, since its first investigation at research level, to the maturation and employment in the market and in commercial applications

When a novel technology starts to be intensively investigated at research level and its remarkable performance and characteristics are demonstrated (1—*Technology Trigger*), its visibility increases, and together with it, expectations of market placement and outcomes do (2—*Peak of Inflated Expectations*). Nevertheless, when research commences approaching real application cases and scenarios, the aspects of the new technology that were not so relevant for demonstration purposes, but that are critical for the market, start to emerge. Among them, the most important are typically limited in number, and very often the same, i.e. integration/compatibility with other existing technologies, reliability and manufacturing cost. This context causes blown up expectation to drop down (3—*Trough of Disillusionment*). However, such a scenario provides also scientific and industrial community with proper motivation to address and overcome the limitations of the new technology against real application scenarios (4—*Slope of Enlightenment*). Finally, when the technology is mature enough, it starts to be steadily employed and available on the market, leading to the final stage of the hype curve (5—*Plateau of Productivity*). The whole hype cycle has different duration depending on several factors, like, for instance, technology complexity, market’s acceptance and needs, and so on. In any case, the time unit on the horizontal axis in the plot of Fig. 1 is typically the one of years.

Looking at the specific case of RF-MEMS, the evolution of the technology and of expectations linked to it seem to have followed a path more articulated if compared to the one depicted in Fig. 1 and discussed above. This can be inferred after observing the prediction of market forecasts and technology intelligence reports released through years, with specific focus on the expected impact of RF-MEMS technology in the mass production of mobile handsets. In the first RF-MEMS analyses,

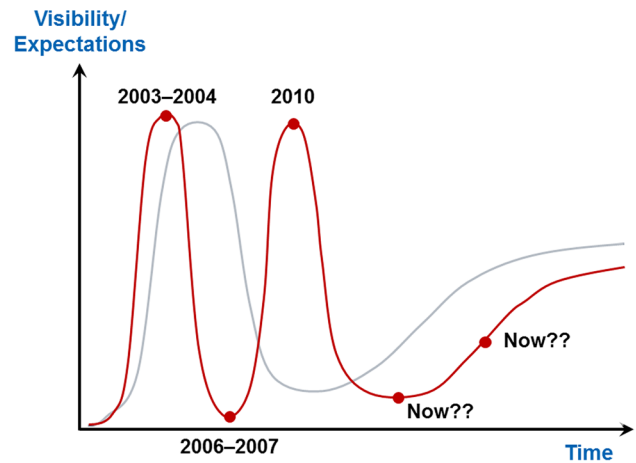


Fig. 2 Behaviour of the hype curve of RF-MEMS technology based upon the market forecasts published through the last decade and the fluctuating expectations for mass-market outcomes

released in 2004–2005, the market volume was expected to reach from 700 \$M (Millions of US Dollars) to 1 \$B (Billions of US Dollars) in 2009 (Bouchaud and Wicht 2005). Nonetheless, stepping forth in time, WTC in 2006 predicted a downsized market volume of RF-MEMS for mobile applications of around 10 \$M in 2009 and 70 \$M in 2011 (Bouchaud and Knoblich 2007). Later, in August 2010, IHS Inc. consolidated the RF-MEMS market figure to a few \$M in 2009, and predicted a volume of 225 \$M in 2014 (MEMS Journal 2010). However, still IHS Inc. in 2012 shrunk down the forecast for 2014 market to less than 100 \$M (McGrath 2012). Again, in 2013 Yole Development estimated a market volume for RF-MEMS of around 50 \$M in 2014 and of less than 350 \$M in 2018 (DeLisle 2014).

By summarising all the just mentioned forecasts and projections, and providing them with a graphical arrangement, the hype curve of RF-MEMS technology, since its introduction to recent years, would exhibit a peculiar behaviour like the one reported in Fig. 2.

It seems that evolution of RF-MEMS experienced two peaks of inflated expectations delayed through time. Providing a straightforward and unique explanation motivating such fluctuations is not a simple task. Nonetheless, by analysing scientific literature, reports and articles, it is possible to build up a reasonable interpretation of RF-MEMS blessings and straits. The double peak of inflated expectations and trough of disillusionment can be attributed to two sets of reasons and issues, the first one (around 2004) being predominantly linked to RF-MEMS technology *intrinsic factors*, while the second one (around 2010) being generated by *extrinsic circumstances*, i.e. not directly linked to the technology itself, but rather driven by market needs and acceptance.

Concerning RF-MEMS technology-related intrinsic factors, the fall of expectations after 2003 can be attributed to three main key elements: (1) reliability, (2) packaging and (3) integration. Right after demonstration of the remarkable performance of RF passives enabled by MEMS technology if compared to standard semiconductor solutions, like high quality factor (Q-factor), wide tunability, low loss, high isolation and good linearity, reliability of RF-MEMS started to emerge as a major issue. Given their coupled electromechanical behaviour, MEMS are exposed to a wide range of malfunctioning and failure mechanisms (reversible and irreversible) that are 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 and micro-welding (Iannacci 2015). This clearly demonstrated 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 importantly, it must be highlighted that significant work has been carried out at research and development level, in order to address one or more of such failure mechanisms, and to improve, in turn, lifetime, operability and performance stability of RF-MEMS devices. To this concern, Table 1 summarises some relevant solutions, proposed and discussed in literature, to improve robustness against specific reliability issues (also listed in the table).

Somehow related to reliability, also the issue of packaging and encapsulation caused the initial enthusiasm around RF-MEMS to be reshaped downward. As MEMS devices are composed by movable micro-membranes, they are very fragile and exposed to harmful environmental factors, like mechanical shocks, moisture, dust particles and contaminants. Therefore, MEMS need to be properly isolated from the surrounding environment by being housed within a protective (possibly hermetic or semi-hermetic) cap (Jourdain et al. 2003; Park et al. 2002, 2003). In the case of RF-MEMS, application of a package increases, on one side, the complexity of technology and the manufacturing cost, the latter one being estimated to be as high as 80 % of the final product price (Cohn et al. 2002). On the other hand, presence of a protective cap puts in jeopardy the outstanding RF performance of MEMS-based passives, and therefore must be carefully designed and counted in as actual part of the device, thus making the design and modelling phases more challenging (Iannacci 2013a, b; Iannacci et al. 2006, 2008; Margomenos and Katehi 2002, 2003).

Finally yet importantly, MEMS technology is typically incompatible with standard semiconductor platforms (e.g. CMOS). Therefore, RF-MEMS 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). In light of all the just listed additional challenges to be faced before getting RF-MEMS technology ready for market, the set of reasons causing the first drop of expectations in Fig. 2 is sufficiently clear. Once the scientific community gained consciousness around these issues, plenty of effort was spent after them, thus reducing significantly the gap of RF-MEMS in terms of reliability, encapsulation and integration/compatibility with standard semiconductor active technologies, and boosting, as a result, expectations and optimism at market level for the following years (see Fig. 2). Nevertheless and unfortunately, struggle for RF-MEMS was not over, yet, when technology gained maturity, towards the end of the first decade of 2000s.

As mentioned above, the second trough of disillusionment of RF-MEMS can be mainly attributed to factors extrinsic to technology (i.e. market related). In 2001, Nguyen provided an inspiring overview on how RF-MEMS technology could have been exploited during the upcoming (at that time) years in the mobile handsets market (Nguyen 2001). To this regard, the super-heterodyne transmitter/receiver (transceiver) architecture was taken as reference. The first commercial exploitation of RF-MEMS technology, according to his forecast, was supposed to be the replacement of low-complexity elements (e.g. switches and LC-tanks) in standard technology, with their Microsystem-based counterparts, as reported in Fig. 3.

The remarkable characteristics of RF-MEMS components, like low loss, high Q-factor, etc., were expected to improve the performance of the whole receiver. Thereafter, Nguyen elaborated a more visionary and extensive exploitation of RF-MEMS technology, as well. In this case, the architecture of the entire receiver was supposed to be rethought based on RF-MEMS, as shown in Fig. 4.

High-complexity RF-MEMS blocks were supposed to replace entire portions of the receiver, as clearly appears confronting Figs. 3 and 4, thus reducing hardware redundancy and need for amplification stages, in light of very low losses enabled by Microsystem-based elements. This sort of revolution was envisaged not only to boost the performance of the entire receiver, but also to extend significantly its reconfigurability, making the same hardware operable according to different and diverse telecommunication standards and services (e.g. GSM, WLAN, and so on).

Despite the enlightenment of Nguyen's vision, market's needs, and especially the constraints it imposes, impaired its turning into reality. Since their wide diffusion in the second half of the '90 s, mobile phones used to work pretty well. The perspective of replacing small transceiver blocks with more expensive RF-MEMS devices (see Fig. 3), also

Table 1 Summary of effective solutions proposed in literature to improve reliability of RF-MEMS devices

Type of RF-MEMS device	Targeted reliability issue/s	Proposed solution	References
Resonator	Long-term stability of resonant frequency	Low-temperature processing of Silicon thin-films	Sousa et al. (2012)
Lateral comb-drive resonator	Performance drifts due to mass and elastic constant changes because of aging, device defects, harsh conditions, etc.	Custom active adaptive controller	Izadian and Famouri (2008)
MEMS with cyclic contact	Contact wear and stiction	Atomic layer deposition (ALD) of thin-film coatings	Ashurst et al. (2004)
Resonator in a vacuum	Decrease of Q-factor due to degradation of the in-package vacuum	Use of getter films within the sealed cavity to absorb gases	Longoni et al. (2006)
RF-MEMS capacitive switch	Charge accumulation in the dielectric film, leading to voltage screening and failure for stiction	Deposition of SiO ₂ /Si ₃ N ₄ double layer dielectric stacks instead of SiO ₂ single layer	Li et al. (2011)
RF-MEMS ohmic switch	Stiction failure due to micro-welding induced by large current densities	Design of an active restoring mechanism (i.e. micro-heater integrated in the MEMS) to be activated with an electric current in case of stiction	Iannacci et al. (2011b)
RF-MEMS capacitive switch	Stiction due to charge accumulation	Toggle design enabling both push and pull active electrostatic control	Solazzi et al. (2010)
Single pole single throw (SPST) ohmic RF-MEMS switch	Contact wear and other mechanical failures induced by the cycled abrupt pull-in contact	Shaping of the voltage waveform applied to the MEMS switch to achieve soft-landing and soft-contact of surfaces at pull-in	Czaplewski et al. (2006)
RF-MEMS capacitive switch	Contact wear and other mechanical failures induced by the cycled abrupt pull-in contact	Resistive and capacitive braking schemes by suitable design of device-intrinsic loading resistor and of capacitor plate geometry	Ankit et al. (2011)
Lateral bulk acoustic resonator (LBAR)	Drift of resonant frequency due to temperature variations	Temperature compensation active control circuitry	Lavasani et al. (2012)
Resonator	Drift of resonant frequency due to temperature variations	Reduction of the resonator temperature coefficient of frequency (TCF) by exploiting heavy n-type and p-type doping	Pensala et al. (2011)

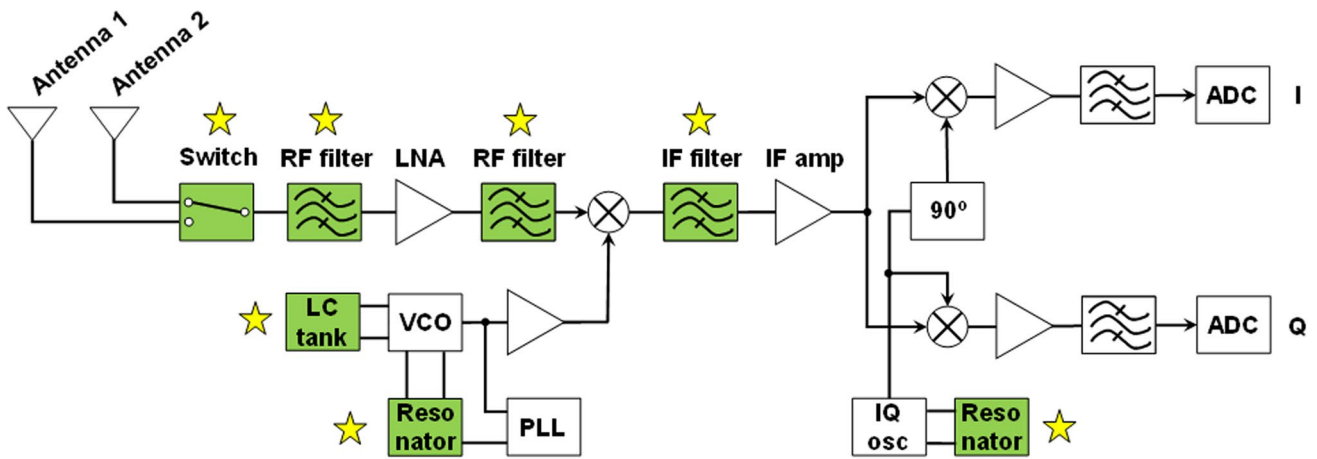


Fig. 3 Block diagram of the super-heterodyne radio receiver, as reported by Nguyen (2001). The *starred* and *coloured* blocks can be realised with passive components based on RF-MEMS technology, thus improving the performance and characteristics of the whole system

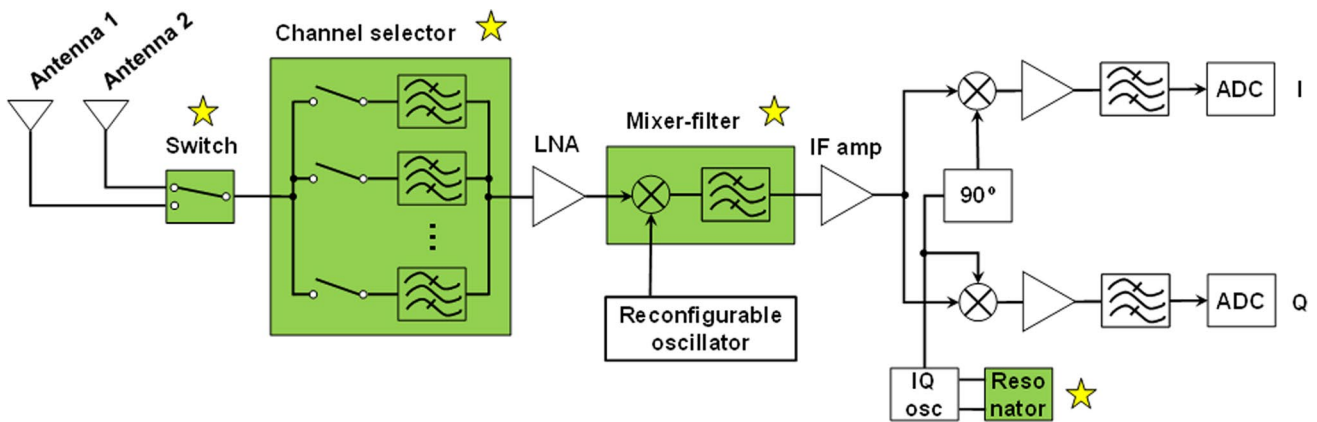


Fig. 4 Block diagram of the super-heterodyne radio receiver, based on a modified architecture that features complex blocks entirely based on RF-MEMS technology (*starred* and *coloured*), namely, a multi-

channel selector, a reconfigurable oscillator, and a mixer-filter, as reported by Nguyen (2001)

rising problems at integration level, just to improve a little the performance of handsets, could not be successful according to market philosophy and drivers. This caused the second trough of disillusionment in Fig. 2 that commenced to be interpreted also as the possible final defeat of RF-MEMS technology in the mass-market arena.

Surprisingly enough, recent development of the large market of smartphones seems to be nurturing once again hope for successful commercial exploitations of RF-MEMS technology. Since the widespread diffusion of mobile phones in mid-‘90 s, voice signal quality has been experiencing a degradation trend, hopping from one generation to the next one (i.e. GSM, 2.5G, and so on). This is clearly stated by Allan (2013) and depicted in Fig. 5.

The increasing use of cellular communications, the introduction of full-screen devices (with touch technology) and the integration of antenna inside the handset, have been

determining the trend in Fig. 5. Moreover, as smartphones become smaller and thinner, it is difficult to integrate proper circuitry to boost performance, counteract dropped

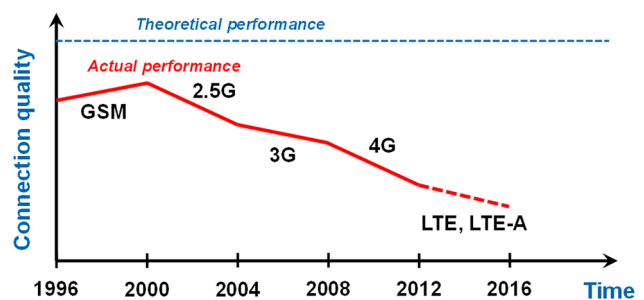


Fig. 5 Decreasing trend in communication quality stepping from one generation to another, as hopping from early mobile handsets in late ‘90 s to modern smartphones (Allan 2013)

calls and improve voice quality. It is estimated that the ratio of theoretical versus actual RF signal quality has been decreasing with a pace of about 1 dB per year for over a decade (Allan 2013). Because of all these factors, antennas of most today's smartphones do not work efficiently, leading to slower download speeds, reduced quality of voice, lower energy efficiency and more dropped calls (Jacobs School of Engineering 2014). Given such a scenario, the characteristics of high performance and wide reconfigurability belonging to RF-MEMS are now very attractive for commercial applications. Nonetheless, having in mind the history of MEMS technology for RF passives in the last 10–15 years as described above, one could reasonably be sceptical and wonder if this is simply another evanescent peak of expectation that soon will reverse its momentum. To this regard, it should be kept in mind that there is a substantial change in the smartphones market of today if compared to the early days of RF-MEMS. While in the first years of the 2000s, despite the soundness of the vision reported in Figs. 3 and 4, there was not a factual need for RF passives with better performance, on the other hand, nowadays the availability of such components can make the difference. In other words, if the early approach to the commercial exploitation of RF-MEMS was mainly *technology push* based, today it is turning into *market driven* scenario (Martin 1994). Very likely, such a metamorphosis of the surrounding context already commenced to draw the line between the lacking and the successful affirmation of RF-MEMS technology in mass-market applications.

One of the first needs to be addressed, as suggested by the decreasing trend in Fig. 5, is to improve the quality of connection in modern smartphones. As stated above, demands for compact and within-device integrated antennas has decreased their efficiency and made them more sensitive to interaction with external items, like the head of the speaker or the hand holding the handset. Therefore, a fixed impedance matching between the antenna and the RF front-end is not anymore an optimal solution, as the characteristic impedance of the transmitting/receiving aerial undergoes slight changes. Availability of high performance reconfigurable impedance matching tuners started to be desirable, and RF-MEMS is demonstrating to be the proper technology solution to realize such complex devices. To this regard, in 2012 the information about the presence of RF-MEMS-based adaptable impedance tuners manufactured by WiSpry Inc. (<http://wispry.com>) within Samsung's Focus Flash Windows smartphone was announced (IHS iSuppli 2012). More recently, in fall 2014, Cavendish Kinetics B.V. (<http://cavendish-kinetics.com>) announced the commercial adoption of their RF-MEMS-based SmarTune™ antenna tuning solution in the Nubia Z7 smartphone, manufactured by the Chinese ZTE Corporation (Cavendish Kinetics 2014). Few months later, Cavendish Kinetics

went public with the information that SmarTune products were adopted in five different Chinese smartphone models, promising signal enhancement of 2–3 dB, resulting in boosted data rates (up to 2×) and improved battery life (up to 40 %) (Cavendish Kinetics 2015a). To demonstrate that it is not just a flash in the pan, ZTE Corporation is now investing on innovative RF-MEMS-based dual antenna tuning (Cavendish Kinetics 2015b), while DelfMEMS (<http://delfmems.com>) with its FreeFlex™ RF-MEMS technology is nearly ready to deliver commercial low-cost and reliable solutions for modern handsets (DelfMEMS 2015).

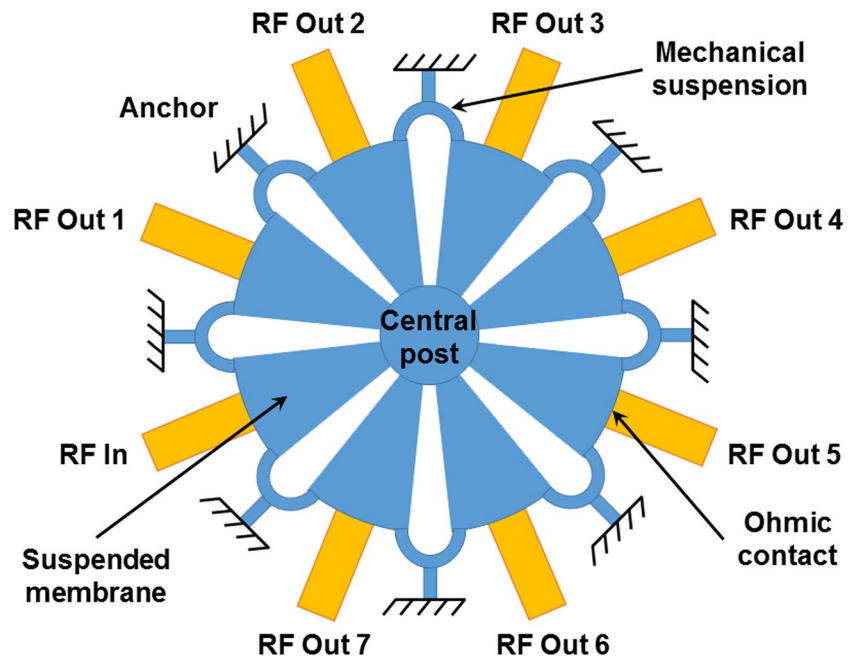
In conclusion, signals suggesting a robust market acceptance of RF-MEMS technology have been growing stronger in very recent years, finally suggesting concrete exploitation perspectives for Microsystem-based RF passives. Coming back for a moment to the vision of Nguyen (2001), previously discussed in Figs. 3 and 4, it seems that it is somehow taking place, despite according to a reversal development. The first market exploitation of RF-MEMS technology is related to complex reconfigurable networks (i.e. impedance tuners at first), that was supposed to be *phase two* of Microsystem RF components (see Fig. 4). Spreading of such networks is increasing the demand for high-performance, reliable and low-cost basic RF-MEMS components (mainly switches and tunable capacitors), thus pushing advanced research and engineering of such building blocks, as well.

3 Current state of research in RF-MEMS technology

As briefly discussed in Sect. 1, in early years of RF-MEMS the research followed rather scattered and diverse directions, basically all combined by the urge to demonstrate the remarkable performance and reconfigurability achievable with Microsystems with respect to RF passives realised in standard semiconductor technologies. Nowadays the scenario has significantly changed. In light of the evolution described in Sect. 2, research on RF-MEMS technology is now focused around a reduced set of topics, if compared to years ago, and is more specialised on aspects that are crucial for product commercialisation. Among them, reliability and integration play an important role, as well as targeting of performance figures that are imposed by specific applications, rather than being general purpose, like frequently happened in the past. Having outlined such a scenario, the target of this section is to provide a brief state of the art report on recent research activities related to RF-MEMS, highlighting topics and issues to be solved that are attractive today.

Starting from basic RF-MEMS switching devices (i.e. the building blocks of more complex networks), current

Fig. 6 Schematic of the circular and compact SP7T RF-MEMS-based design concept proposed in Yang et al. (2015a). The suspended circular slices are anchored both externally and in the centre to a common post. Depending on which slice is actuated, the RF input signal can be driven to any of the 7 outputs



research aims at very compact relays, with improved performance in terms of reliability, stability versus time and cycling, power handling and robustness. To this regard, a significant contribution is reported in Yang et al. (2015a), where a circular and compact design of SPMT ohmic RF-MEMS device is proposed. The SPMT is shown in two different configurations, i.e. with 7 and 11 output lines (SP7T and SP11T, respectively). The schematic of the SP7T is depicted in Fig. 6.

The design concept is based on a circular arrangement of sliced suspended metal membranes that are anchored both on the outer ends, as well as centrally to the post that is common to all the clamped–clamped MEMS switches. Each membrane can be independently actuated (electrostatic actuation by means of a fixed bottom electrode not visible in Fig. 6), thus establishing ohmic contact with the RF line termination placed below it. Depending on which membrane is actuated, the RF input signal can flow toward any of the 7 outputs. The whole switching unit is rather compact ($0.61\text{ mm} \times 0.61\text{ mm}$) and presents contact forces as high as 0.3–0.4 mN. This enables insertion loss in the 0.3–1.7 dB range, from 0.1 to 10 GHz. On the other hand, isolation ranges between 50 and 17 dB in the same frequency span. Reliability in terms of cycling (cold switching condition) showed that it is possible to reach more than 10^8 cycles with both SP7T and SP11T configurations, with power levels in the 0.1–1 W range. Furthermore, the particular shape in Fig. 6 enables improved robustness of the switch against residual stress and stress gradient effects (Yang et al. 2015a). Other recent and significant contributions of high-order switching solutions based on RF-MEMS are discussed in literature, as well.

For instance, the work discussed in (Diaferia et al. 2014; Lucibello et al. 2015) encompasses the realisation of a 12×12 switch matrix that integrates SPDTs in RF-MEMS technology with low temperature co-fired ceramic (LTCC) hermetic package for satellite applications, leading to high-performance and reduced weight, if compared to standard technology solutions. Another design solution, despite not verified yet with physical samples, is discussed in Ilkhechi et al. (2015). Such a solution exploits a rotary circular electrostatically actuated structure to redistribute RF signals among the available terminations. It promises below -1 dB insertion loss up to 90 GHz, driving voltages around 50 V, and switching time in the order of 100 μs . Differently, a robust design concept of capacitive switch with remarkable power handling performance and insensitiveness to stress gradients is discussed in Yang et al. (2015b) and is shown schematically in Fig. 7.

The switch is composed by four square-like cantilevers that are kept suspended by means of a surrounding beam fixed to a mechanical anchoring point in the external edge (see Fig. 7). The four cantilevers are then joined together by means of a central patch. The whole mechanical structure is suspended above a fixed electrode, whose footprint is sketched in figure (dashed line). The capacitive switch is actuated electrostatically and when pulled-in, minimum air gap of 0.3 μm is ensured by the presence of dimples, not shown in the schematic in Fig. 7. All these features make the switch concept particularly robust against non-idealities, like stress gradient and stiction. The capacitive relay exhibits remarkable power handling characteristics, it being able to withstand 12 W RF signal in hot switching conditions (Yang et al. 2015b). Reliability and stability of

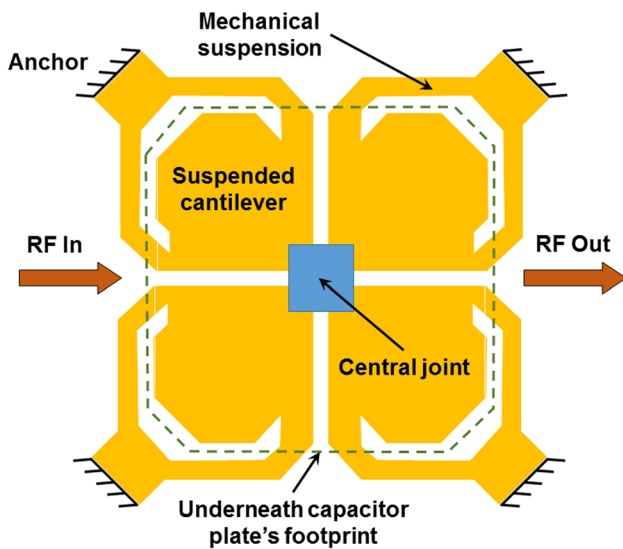


Fig. 7 Schematic of the RF-MEMS capacitive switch discussed in details in Yang et al. (2015b). The four square-like cantilevers with surrounding mechanical suspensions and the central joint boost insensitiveness of the membrane to stress gradients effects. The footprint of the fixed electrode placed below the suspended membrane is sketched (dashed line)

operation are crucial requirements for RF-MEMS. To this regard, numerous measures are employed at design and material/technology level in order to make devices more robust against malfunctioning and failure modes, as discussed in the previous examples. All these solutions can be classified as *passive measures*, as they are meant to reduce as much as possible the likelihood of failure. In addition, the literature reports some examples of *active measures* to counteract RF-MEMS malfunctioning, as well. This is the case of MEMS devices provided with mechanisms that can be activated only when failure occurs, in order to restore normal device functionality. The work reported in Iannacci et al. (2011a), Tazzoli et al. (2011) and Kuenzig et al. (2012, 2014) discusses the design concept of RF-MEMS ohmic switches in cantilever and clamped–clamped membrane configuration, respectively, with an active restoring mechanism to counteract stiction induced by charge accumulation and/or micro-welding. The layout of both switches is schematically depicted in Fig. 8. In particular, Fig. 8a, b refer to the cantilevered ohmic switch configuration (Iannacci et al. 2011b; Tazzoli et al. 2011), while Fig. 8c, d to the clamped–clamped ohmic switch device (Kuenzig et al. 2012, 2014).

The active mechanism consists of high-resistivity serpentine-like conductive lines, embedded underneath the anchoring area of the MEMS suspended membrane. This is visible for the cantilever (Fig. 8a) and clamped–clamped switch (Fig. 8c), in Fig. 8b, d, respectively, where the above-Silicon MEMS structure is hidden in order to allow

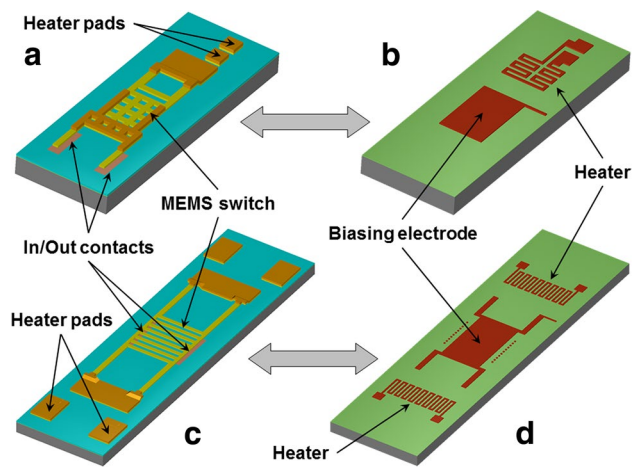


Fig. 8 Schematic views of RF-MEMS ohmic switches provided with active restoring mechanism. **a** Cantilevered switch discussed in Iannacci et al. (2011b) and Tazzoli et al. (2011); **b** view of the buried serpentine-like micro-heater; **c** clamped–clamped switch discussed in Kuenzig et al. (2012, 2014); **d** view of the buried serpentine-like micro-heaters

the view of the buried serpentine. When stiction occurs, i.e. the switch does not recover its rest position, because of accumulated charge or of joints formed in the metal-to-metal contacts (micro-welding), an electric current is driven through the serpentine. Because of its resistance, the meandered conductive path behaves as a micro-heater. Increase of temperatures leads, on one side, to faster dispersion of charges entrapped in the dielectric layer. On the other hand, heating of the metal MEMS membrane causes its physical expansion that induces shear forces on the ohmic contacts, thus helping break welded joints and recover device operability. In (Iannacci et al. 2011b; Tazzoli et al. 2011) micro-welding stiction is intentionally induced in a physical cantilevered RF-MEMS sample by means of Transmission Line Pulsing (TLP) technique. Subsequent activation of the micro-heater with pulsed current induces shear forces able to break the joints and bring the MEMS back to normal functioning. Other recent findings related to robust and highly reliable RF-MEMS switches are reported in Zhu et al. (2014).

Moving now the focus on complex networks based on RF-MEMS building blocks, the scientific literature reports recent contributions that are tailored to performance and requirements imposed by actual applications with commercial interest today. To this regard, it must be highlighted that currently the main fields of application driving research on RF-MEMS complex network are those of radars and steering antennas rather than mobile handset and smartphone industry. As extensively discussed above, indeed, nowadays the main commercial application of RF-MEMS networks concerns impedance tuners for smartphone antennas, and



Fig. 9 Schematic view of the reconfigurable RF-MEMS-based phase shifter presented in Bakri-Kassem and Mansour (2013). The network employs RF-MEMS capacitive switches with 7 different lengths of

the clamped–clamped suspended membranes labelled from “A” to “G” (longest and shortest membrane, respectively)

this is driving research on robust and reliable RF-MEMS switches and switched capacitors. Nonetheless, the interest for other types of complex networks in RF-MEMS technology will likely start to increase, as soon as the commercial exploitation of impedance tuners will consolidate, thus realising somehow the scenario predicted by Nguyen (2001) and reported in Fig. 4. On the other hand, maturation of research in RF-MEMS networks for high-frequency applications (e.g. radars and telecommunication systems for defence and space applications working in the K band) is seamlessly progressing. This is, for instance, the case of the reconfigurable phase shifter reported in Bakri-Kassem and Mansour (2013). As is known, several papers were published in the past concerning RF-MEMS phase shifters with remarkable characteristics in terms of reconfigurability, however without covering appropriately issues like dimensions of the network and complexity of operation. In this work, both aspects are effectively addressed. Concerning device compactness, a corrugated design of the Coplanar Waveguide (CPW) RF ground lines was chosen. This brings to the realisation of a slow wave transmission line (length of 7 mm), that enables an effective electrical length that is equivalent to a physically longer traditional CPW (Bakri-Kassem and Mansour 2013). Another drawback of most RF-MEMS-based phase shifters is that the larger is the number of capacitive switching stages to achieve different phase shifts, the larger is the number of DC controlling signals that have to be imposed to actuate them. In most cases, it happens that each RF-MEMS switch is independently controlled with respect to the others. Therefore, if the phase shifter employs 10 switching stages (i.e. 10 bits), it needs 10 independent DC signals to cover all the span of reconfigurability it implements, leading to significant increase of complexity of the controlling electronics and at integration level. This issue is also solved rather

effectively in this contribution, as clamped–clamped RF-MEMS capacitive switches are all connected and therefore controlled by a unique DC signal. Nonetheless, the length of the suspended MEMS membranes is varied according to the pattern schematically reported in Fig. 9.

The whole network employs 7 different switching stages with varied length, labelled from “A” to “G”, with reference to the longest and shortest MEMS membrane, respectively. The different membranes are deployed along the CPW according to the pattern reported in Fig. 9. Given the modified geometry of the RF-MEMS switches, their elastic contact varies and, in turn, the pull-in voltage as well. In particular, the longest switch (“A” type) will exhibit the lowest actuation voltage, while the shortest switch (“G” type) will actuate at the highest voltage. Therefore, simply by sweeping the DC signal applied to all the MEMS membranes, it is possible to induce progressive collapse of switches, from “A” to “G”, thus realising 8 different phase shift configurations (i.e. from no voltage applied, to all 7 types of switches actuated) by means of a unique bias. More in detail, the switches are designed to have pull-in of “A” type devices at 10 V, of “B” type devices at 15 V, and so on with steps of 5 V. Experimental characterisation performed on fabricated physical samples showed an achievable phase shift range of 106° , with worst insertion loss and return loss of 1.7 and 13 dB at 30 GHz, respectively. Additional recent design and technology solutions for high-performance reconfigurable RF-MEMS-based phase shifters are discussed in Huang et al. (2015) and Chakraborty et al. (2014).

Another example of reconfigurable RF-MEMS-based complex network class of devices concerns tunable filters. To this regard, particular interest has been oriented in recent years toward evanescent mode 3D cavity-based filters, as discussed in (Yang and Peroulis 2014). In this case,

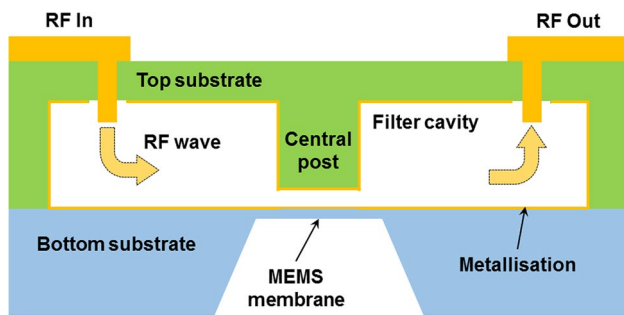


Fig. 10 Schematic cross-section of a generic implementation of a 3D cavity evanescent mode RF tunable filter. The RF signal is radiated at the input within a metallised cavity, whose structure behaves for the wave as an LC filter, and is then collected at the output line. The filtering function operated by the cavity is reconfigured by tuning the capacitance between the central fixed post and the underlying deformable MEMS membrane

the RF signal, rather than being guided through a CPW-like structure and filtered by lumped reactive elements (i.e. inductance— L and capacitance— C), is radiated within a cavity with metallised walls in order to keep the signal confined within it. The filtering function is operated on the radiated RF wave by the cavity, according to a continuous and distributed fashion. A general schematic cross-section of a cavity-based filter is reported in Fig. 10.

In details, the cavity is *seen* by the radiated wave as an inductive element (L). On the other hand, the central post realises a parallel plate capacitance (C). The interaction between the L and C reactive behaviour realises a filtering function for the RF wave that is then collected at the outlet and brought out of the cavity through the output line (see Fig. 10). MEMS technology is particularly suitable to make such a concept reconfigurable, and one of the possible solutions at technology level is depicted in Fig. 10. The bottom electrode of the capacitor is made by a thin membrane, realised by deep etching of the back-side of a Silicon substrate. By applying a DC bias between the MEMS membrane and the post above, it is possible to tune the capacitance, and therefore to modify the filtering function operated by the whole structure. The advantages of the 3D cavity-based filter solution compared to planar devices are relevant. At first, better Q -factor can be achieved due to reduced losses. Moreover, exploitation of evanescent modes requires fractional cavity dimensions compared to the wavelength of the filtered signal. This allows reducing significantly the volume of the device. Eventually, having a 3D structure eases filter's mounting and integration with other circuits and systems. The work reported in Yang and Peroulis (2014) discusses a two-pole (i.e. two capacitive posts) tunable band-pass filter. Tuning of capacitance is ensured by two micro-corrugated MEMS diaphragms that are independently controlled with DC bias up to 140 V. The

filter's tuning range is rather wide, as it goes from 23 to 35 GHz. Losses are in the range from 4.2 to 1.5 dB, and the Q -factor from 530 to 750. From the point of view of reliability, tunable MEMS membranes have been tested up to 140 million cycles without observing any failure. Other recent achievements concerning the realisation of 3D reconfigurable filters exploiting RF-MEMS technology are discussed in Stefanini et al. (2013) and Pagazani et al. (2015).

4 Conclusions

In this work, the evolution of RF-MEMS (i.e. MicroElectroMechanical-Systems for Radio Frequency applications) technology was analysed, since its first discussion in literature, dated back to the second half of the '90 s, until today. Particular focus was spent around market analysis of RF-MEMS, as rather inflated expectations and forecasts were repeatedly disappointed in about one decade, from the first years of the 2000s until 2010–2011. According to a rather singular path, RF-MEMS technology used to be so animated by nearly revolutionary expectations concerning its impact on radio and wireless systems market applications, that managed to undergo two disappointment phases. Initially, important intrinsic (i.e. technology-related) factors were not properly addressed, despite their critical relevance in commercialisation of products. Among them, reliability, packaging and integration are undoubtedly the most important ones. Once research started to address effectively such issues, other extrinsic factors impairing the success of RF-MEMS were to be faced. In substance, the market need for high performance and wide reconfigurability typical of RF-MEMS was not strong enough to pull such a technology in. Nonetheless, the scenario has rather changed in recent years, and the smartphones market segment is now generating clear needs for RF passives with the characteristics enabled by MEMS solutions. After such analysis, the paper discusses the current state of RF-MEMS market exploitation, also providing perspectives for its further expansion. To this regard, a rather synthetic state of the art was developed around recent research findings in the field of MEMS-based RF passive devices and networks. Compared to early days of RF-MEMS technology, research is currently focused on a limited number of aspects, but with a definitely more pronounced sensitivity toward specifications and requirements imposed by real market applications. This proves not only the maturation of RF-MEMS technology itself, but also of its acceptance and collocation within important market segments, that very likely will lead relatively soon to the success that was expected more than one decade ago.

References

- Allan R (2013) RF MEMS switches are primed for mass-market applications. <http://mwr.com/active-components/rf-mems-switches-are-primed-mass-market-applications>. Accessed 29 May 2015
- Ankit J, Nair PR, Alam MA (2011) Strategies for dynamic soft-landing in capacitive microelectromechanical switches. *IAP Appl Phys Lett* 98:1–3. doi:10.1063/1.3598960
- ark Y-K, Park H-W, Lee D-J, Park J-H, Song I-S, Kim C-W, Song C-M, Lee Y-H, Kim C-J, Ju BK (2002) A novel low-loss wafer-level packaging of the RF-MEMS devices. In: IEEE international conference on micro electro mechanical systems, pp 681–684. doi:10.1109/MEMSYS.2002.984362
- Ashurst WR, Jang YJ, Magagnin L, Carraro C, Sung MM, Maboudian R (2004) Nanometer-thin titania films with SAM-level stiction and superior wear resistance for reliable MEMS performance. In: Proceedings of the IEEE international conference on micro electro mechanical systems MEMS, pp 153–156. doi:10.1109/MEMS.2004.1290545
- Bakri-Kassem M, Mansour RR (2013) A novel self collapsed corrugated MEMS phase shifter. In: European microwave integrated circuits conference (EuMIC), pp 360–363
- Bouchaud J, Knoblich B (2007) RF MEMS switches deliver on early promise. <http://www.memsjournal.com/2007/10/rf-mems-switches.html>. Accessed 20 May 2015
- Bouchaud J, Wicht H (2005) RF MEMS: status of the industry and roadmaps. In: IEEE radio frequency integrated circuits (RFIC) symposium, pp 379–384. doi:10.1109/RFIC.2005.1489818
- Brown ER (1998) RF-MEMS switches for reconfigurable integrated circuits. *IEEE Trans Microw Theory Tech* 46:1868–1880. doi:10.1109/22.734501
- Cavendish Kinetics (2014) Nubia adopts Cavendish Kinetics' smart-une™ antenna tuning solution for its new Z7 LTE smartphone. <http://www.cavendish-kinetics.com/index.php/news-media/press-releases/nubia-adopts-smartune/>. Accessed 5 June 2015
- Cavendish Kinetics (2015) Cavendish Kinetics adds design wins and ramps shipments of RF MEMS tuners. <http://www.cavendish-kinetics.com/index.php/news-media/press-releases/ck-adds-design-wins/>. Accessed 5 June 2015
- Cavendish Kinetics (2015) Cavendish powers nubia Z9: world's first smartphone with dual antenna tuning. <http://www.cavendish-kinetics.com/index.php/news-media/press-releases/cavendish-powers-nubia-z9/>. Accessed 5 June 2015
- Chakraborty A, Gupta B, Sarkar BK (2014) Design, fabrication and characterization of miniature RF MEMS switched capacitor based phase shifter. *Microelectron J* 45:1093–1102. doi:10.1016/j.mejo.2014.05.009
- Cohn MB, Roehnel R, Xu J-H, Shteinberg A, Cheung S (2002) MEMS packaging on a budget (fiscal and thermal). *Int Conf Electron Circuits Syst ICECS* 1:287–290. doi:10.1109/ICECS.2002.1045390
- Czaplewski DA, Dyck CW, Sumali H, Massad JE, Kuppers JD, Reines I, Cowan WD, Tigges CP (2006) A soft-landing waveform for actuation of a single-pole single-throw ohmic RF MEMS switch. *IEEE J Microelectromechanical Syst* 15:1586–1594. doi:10.1109/JMEMS.2006.883576
- De Angelis G, Lucibello A, Marcelli R, Catoni S, Lanciano A, Buttiglione R, Dispenza M, Giacomozzi F, Margesin B, Maglione A, Erspan M, Combi C (2008) Packaged single pole double thru (SPDT) and true time delay lines (TTDL) based on RF MEMS switches. *CAS Semicond Conf* 1:227–230. doi:10.1109/SMICND.2008.4703376
- De Silva AP, Hughes HG (2003) The package integration of RF-MEMS switch and control IC for wireless applications. *IEEE Trans Adv Packag* 26:255–260. doi:10.1109/TADVP.2003.818056
- DelfMEMS (2015) DelfMEMS announces that its breakthrough, SP12T, RF-MEMS ohmic switch has passed the one billion operations milestone. http://www.delfmems.com/press_release/delfmems-announces-its-breakthrough-sp12t-rf-mems-ohmic-switch-has-passed-one-billion. Accessed 5 June 2015
- DeLisle J-J (2014) The future of connectivity: mobile & automobiles. <http://mwr.com/systems/future-connectivity-mobile-automobiles>. Accessed 20 May 2015
- DeNatale J, Mihailovich R (2003) RF MEMS reliability. In: 12th International conference on solid-state sensors, actuators and microsystems TRANSDUCERS, vol 2, pp 943–946. doi:10.1109/SENSOR.2003.1216922
- Domingue F, Fouladi S, Mansour RR (2010) A reconfigurable impedance matching network using dual-beam MEMS switches for an extended operating frequency range. In: IEEE MTT-S international microwave symposium digest (MTT), pp 1–1. doi:10.1109/MWSYM.2010.5515472
- Entesari K, Obeidat K, Brown AR, Rebeiz GM (2007) A 25–75-MHz RF MEMS TUNABLE Filter. *IEEE Trans Microw Theory Tech* 55:2399–2405. doi:10.1109/TMTT.2007.908674
- Gartner, Inc (2015) Interpreting technology hype. <http://www.gartner.com/technology/research/methodologies/hype-cycle.jsp>. Accessed 19 May 2015
- Gil I, Martin F, Rottenberg X, De Raedt W (2007) Tunable stop-band filter at Q-band based on RF-MEMS metamaterials. *IET Electron Lett* 43:1153–1153. doi:10.1049/el:20072164
- Gong S, Shen H, Barker NS (2011) A 60-GHz 2-bit switched-line phase shifter using SP4T RF-MEMS switches. *IEEE Trans Microw Theory Tech* 59:894–900. doi:10.1109/TMTT.2011.2112374
- Huang Y, Bao J, Li X, Wang Y, Du Y (2015) A 4-bit switched-line phase shifter based on MEMS switches. In: Proceedings of IEEE 10th international conference on nano/micro engineered and molecular systems (NEMS), pp 405–408. doi:10.1109/NEMS.2015.7147454
- Iannacci J (2013a) Practical guide to RF-MEMS. Wiley-VCH, Weinheim
- Iannacci J (2013b) RF MEMS passive components for wireless applications. In: Uttamchandani D (ed) Handbook of MEMS for wireless and mobile applications, 1st edn. Woodhead Publishing, Cambridge, pp 100–135
- Iannacci J (2015) Reliability of MEMS: a perspective on failure mechanisms, improvement solutions and best practices at development level. *Elsevier Disp* 37:62–71. doi:10.1016/j.displa.2014.08.003
- Iannacci J, Tian J, Sosin S, Gaddi R, Bartek M (2006) Hybrid wafer-level packaging for RF MEMS applications. In: International wafer-level packaging conference IWLPC, pp 106–113
- Iannacci J, Bartek M, Tian J, Gaddi R, Gnudi A (2008) Electromagnetic optimization of an RF-MEMS wafer-level package. *Elsevier Sensors Actuators A Phys* 142:434–441. doi:10.1016/j.sna.2007.08.018
- Iannacci J, Faes A, Matri F, Masotti D, Rizzoli V (2010) A MEMS-based wide-band multi-state power attenuator for Radio Frequency and Microwave Applications. *Proc NSTI Microtech* 2:328–331
- Iannacci J, Masotti D, Kuenzig T, Niessner N (2011) A reconfigurable impedance matching network entirely manufactured in RF-MEMS technology. In: Proceedings of SPIE Smart Sensors, Actuators, and MEMS, vol 8066, pp 1–12. doi:10.1117/12.886186
- Iannacci J, Faes A, Repchankova A, Tazzoli A, Meneghesso G (2011b) An active heat-based restoring mechanism for improving the

- reliability of RF-MEMS switches. Elsevier Microelectron Reliab 51:1869–1873. doi:10.1016/j.microrel.2011.06.019
- Ilkhechi AK, Mirzajani H, Aghdam EN, Ghavifekr HB (2015) A novel electrostatically actuated spdt rotary RF MEMS switch for ultra-broadband applications. In: Proceedings of the 23rd Iranian conference on electrical engineering (ICEE), pp 1175–1179. doi:10.1109/IranianCEE.2015.7146392
- IHS iSuppli (2012) IHS iSuppli teardown analysis service identifies first use of RF MEMS part, set to be next big thing in cellphone radios. <http://press.ihs.com/press-release/design-supply-chain/ihs-isuppli-teardown-analysis-service-identifies-first-use-rf-mems>. Accessed 4 June 2015
- Izadian A, Famouri P (2008) Reliability enhancement of MEMS lateral comb resonators under fault conditions. IEEE Trans Control Syst Technol 16:726–734. doi:10.1109/TCST.2007.912233
- Jacobs School of Engineering (2014) RF MEMS: new Possibilities for smartphones. <http://www.jacobsschool.ucsd.edu/pulse/winter2014/page5.sfe>. Accessed 29 May 2015
- Jourdain A, Ziad H, De Moor P, Tilmans HAC (2003) Wafer-scale 0-level packaging of (RF-)MEMS devices using BCB. In: Symposium on design, test, integration and packaging of MEMS/MOEMS, pp 239–244. doi:10.1109/DTIP.2003.1287044
- MEMS Journal (2010) Cell phone antenna troubles? RF MEMS come to the rescue. <http://www.memsjournal.com/2010/09/cell-phone-antenna-troubles-rf-mems-come-to-the-rescue.html>. Accessed 20 May 2015
- Katehi LPB, Rebeiz GM, Nguyen CT-C (1998) MEMS and Si-micromachined components for low-power, high-frequency communications systems. In: IEEE MTT-S international microwave symposium digest, vol 1, pp 331–333. doi:10.1109/MWSYM.1998.689386
- Kuenzig T, Schrag G, Iannacci J (2012) Modeling and simulation of an active restoring mechanism for high reliability switches in RF-MEMS technology. Elsevier Microelectron Reliab 52:2235–2239. doi:10.1016/j.microrel.2012.06.137
- Kuenzig T, Muschol T, Iannacci J, Schrag G, Wachutka G (2014) Analysis of RF-MEMS switches in failure mode: towards a more robust design. In: International conference on thermal, mechanical and multi-physics simulation and experiments in microelectronics and microsystems (EuroSimE), pp 1–6. doi:10.1109/EuroSimE.2014.6813812
- Larcher L, Brama R, Ganzerli M, Iannacci J, Margesin B, Bedani M, Gnudi A (2009) A MEMS reconfigurable quad-band class-E power amplifier for Gsm standard. In: IEEE 22nd international conference on micro electro mechanical systems MEMS, pp 864–867. doi:10.1109/MEMSYS.2009.4805520
- Lavasani HM, Pan W, Harrington BP, Abdolvand R, Ayazi F (2012) Electronic temperature compensation of lateral bulk acoustic resonator reference oscillators using enhanced series tuning technique. IEEE J Solid State Circuits 47:1381–1393. doi:10.1109/JSSC.2012.2192657
- Li G, Hanke U, Cheng Z, Min D, San H, Chen X (2011) Si₃N₄/SiO₂ dielectric stacks for high reliable capacitive RF MEMS switch. In: Proceedings of the IEEE conference on nanotechnology IEEE-NANO, pp 496–499. doi:10.1109/NANO.2011.6144348
- Lisec T, Huth C, Wagner B (2004) Dielectric material impact on capacitive RF MEMS reliability. In: 34th European microwave conference, vol 1, pp 73–76
- Liu C (2011) Foundations of MEMS. Prentice Hall, Upper Saddle River
- Longoni G, Conte A, Moraja M, Fourier A (2006) Stable and reliable Q-factor in resonant MEMS with getter film. In: Proceedings of the IEEE international reliability physics symposium, pp 416–420. doi:10.1109/RELPHY.2006.251254
- Lu Y, Katehi LPB, Peroulis D (2005) A novel MEMS impedance tuner simultaneously optimized for maximum impedance range and power handling. In: IEEE MTT-S International microwave symposium digest, pp 1–4. doi:10.1109/MWSYM.2005.1516775
- Lu ACW, Chua KM, Li HG (2005) Emerging manufacturing technologies for RFIC, antenna and RF-MEMS integration. In: IEEE International workshop on radio-frequency integration technology: integrated circuits for wideband communication and wireless sensor networks, pp 142–146. doi:10.1109/RFIT.2005.1598895
- Lucibello A, Capocchia G, Proietti E, Marcelli R, Margesin B, Muloni V, Giacomozzi F, Vitulli F, Scipioni M, Bartolucci G (2015) Reliable response of RF MEMS LTCC packaged switches after mechanical and thermal stress. In: Springer microsystem technologies, pp 1–7. doi:10.1007/s00542-015-2577-5
- Mahameed R, Rebeiz G (2010) A high-power temperature-stable electrostatic RF MEMS capacitive switch based on a thermal buckle-beam design. IEEE J Microelectromechanical Syst 19:816–826. doi:10.1109/JMEMS.2010.2049475
- Margomenos A, Katehi LPB (2002) DC to 40 GHz on-wafer package for RF MEMS switches. In: IEEE topical meeting on electrical performance of electronic packaging, pp 91–94. doi:10.1109/EPEP.2002.1057890
- Margomenos A, Katehi LPB (2003) High frequency parasitic effects for on-wafer packaging of RF MEMS switches. In: IEEE MTT-S international microwave symposium digest, vol 3, pp 1931–1934. doi:10.1109/MWSYM.2003.1210536
- Martin MJC (1994) Managing innovation and entrepreneurship in technology-based firms. Wiley, Hoboken
- Martinez J, Blondy A, Pothier A, Bouyge D, Crunteanu A, Chatras M (2007) Surface and bulk micromachined RF MEMS capacitive series switch For watt-range hot switching operation. In: European microwave conference, vol 1237–1240. doi:10.1109/EUMC.2007.4405424
- McGrath D (2012) Teardown finds RF MEMS in samsung handset. http://www.eetimes.com/document.asp?doc_id=1260917. Accessed 20 May 2015
- Melle S, Flourens F, Dubuc D, Grenier K, Pons P, Pressecq F, Kuchenbecker J, Muraro JL, Bary L, Plana R (2003) Reliability overview of RF MEMS devices and circuits. In: 33rd European microwave conference, pp 37–40. doi:10.1109/EUMA.2003.340820
- Nguyen CT-C (1998) Microelectromechanical devices for wireless communications. In: Proceedings of international workshop on micro electro mechanical systems (MEMS), pp 1–7. doi:10.1109/MEMSYS.1998.659719
- Nguyen CT-C (2001) Transceiver front-end architectures using vibrating micromechanical signal processors. In: Topical meeting on silicon monolithic integrated circuits in RF systems, pp 23–32. doi:10.1109/SMIC.2001.942335
- Nguyen CT-C (2002) RF MEMS for wireless applications. In: Device research conference (DRC), pp 9–12. doi:10.1109/DRC.2002.1029485
- Nguyen CT-C (2006) Integrated micromechanical circuits for RF front ends. In: Proceedings of the European solid-state circuits conference ESSCIRC, pp 7–16. doi:10.1109/ESSCIR.2006.307523
- Nguyen CT-C (2007) MEMS technology for timing and frequency control. In: IEEE transactions on ultrasonics, ferroelectrics, and frequency control, vol 54, pp 251–270. doi:10.1109/TUFFC.2007.240
- Nguyen CT-C (2013) MEMS-based RF channel selection for true software-defined cognitive radio and low-power sensor communications. IEEE Commun Mag 51:110–119. doi:10.1109/MCOM.2013.6495769
- Nishino T, Kitsukawa Y, Hangai M, Lee S-S, Soda S-N, Miyazaki M, Naitoh I, Konishi Y (2009) Tunable MEMS hybrid coupler and L-band tunable filter. In: IEEE MTT-S international microwave symposium digest, pp 1045–1048. doi:10.1109/MWSYM.2009.5165879

- Ocera A, Farinelli P, Mezzanotte P, Sorrentino R, Margesin B, Giacomozzi F (2007) Novel RF-MEMS widely-reconfigurable directional coupler. In: European microwave conference, pp 122–125. doi:[10.1109/EUMC.2007.4405141](https://doi.org/10.1109/EUMC.2007.4405141)
- Pacheco S, Zurcher P, Young S, Weston D, Dauksher W (2004) RF MEMS resonator for CMOS back-end-of-line integration. In: Topical meeting on silicon monolithic integrated circuits in RF systems, pp 203–206. doi:[10.1109/SMIC.2004.1398203](https://doi.org/10.1109/SMIC.2004.1398203)
- Pagazani J, Lissorgues G, Mehdaoui A, Schropfer G, Vinh-Dinh T, Pasquet D, Nicole P (2015) A RF tunable Agile filter: from component to system design. In: Proceedings of the symposium on design, test, integration and packaging of MEMS/MOEMS (DTIP), pp 1–6. doi:[10.1109/DTIP.2015.7160974](https://doi.org/10.1109/DTIP.2015.7160974)
- Park Y-K, Kim Y-K, Hoon K, Lee D-J, Kim C-J, Ju B-K, Park J-O (2003) A novel thin chip scale packaging of the RF-MEMS devices using ultra thin silicon. In: IEEE international conference on micro electro mechanical systems, pp 618–621. doi:[10.1109/MEMSYS.2003.1189825](https://doi.org/10.1109/MEMSYS.2003.1189825)
- Patel C, Rebeiz GM (2010) An RF-MEMS switch with mN contact forces. In: IEEE MTT-S international microwave symposium digest (MTT). doi:[10.1109/MWSYM.2010.5518064](https://doi.org/10.1109/MWSYM.2010.5518064)
- Pensala T, Jaakkola A, Prunnila M, Dekker J (2011) Temperature compensation of silicon MEMS resonators by heavy doping. In: Proceedings of IEEE international ultrasonics symposium IUS, pp 1952–1955. doi:[10.1109/ULTSYM.2011.0486](https://doi.org/10.1109/ULTSYM.2011.0486)
- Reines I, Park S-J, Rebeiz GM (2010) Compact low-loss tunable X-band bandstop filter with miniature RF-MEMS switches. IEEE Trans Microw Theory Tech 58:1887–1895. doi:[10.1109/TMTT.2010.2050621](https://doi.org/10.1109/TMTT.2010.2050621)
- Reinke J, Wang L, Fedder GK, Mukherjee T (2011) A 4-bit RF MEMS phase shifter monolithically integrated with conventional CMOS. In: IEEE 24th international conference on micro electro mechanical systems (MEMS), pp 748–751. doi:[10.1109/MEMSYS.2011.5734533](https://doi.org/10.1109/MEMSYS.2011.5734533)
- Rizk JB, Chaiban E, Rebeiz GM (2002) Steady state thermal analysis and high-power reliability considerations of RF MEMS capacitive switches. In: IEEE MTT-S international microwave symposium digest, vol 1, pp 239–243. doi:[10.1109/MWSYM.2002.1011602](https://doi.org/10.1109/MWSYM.2002.1011602)
- Shalaby M, Wang Z, Chow L-W, Jensen B, Volakis J, Kurabayashi K, Saitou K (2009) Robust Design of RF-MEMS cantilever switches using contact physics modeling. IEEE Trans Industr Electron 56:1012–1021. doi:[10.1109/TIE.2008.2006832](https://doi.org/10.1109/TIE.2008.2006832)
- Solazzi F, Tazzoli A, Farinelli P, Faes A, Mulloni V, Meneghesso G, Margesin B (2010) Active recovering mechanism for high performance RF MEMS redundancy switches. In: Proceedings of the European microwave conference EuMC, pp 93–96
- Sousa PM, Chu V, Conde JP (2012) Reliability and stability of thin-film amorphous silicon MEMS resonators. IOP J Micromechanics Microengineering 22:1–8. doi:[10.1088/0960-1317/22/6/065030](https://doi.org/10.1088/0960-1317/22/6/065030)
- Stefanini R, Chatras M, Pothier A, Guines C, Blondy P (2013) High-Q 3D tunable RF MEMS filter with a constant fractional bandwidth. In: Proceedings of the European microwave integrated circuits conference (EuMIC), pp 312–315
- Stehle A, Georgiev G, Ziegler V, Schoenlinner B, Prechtel U, Schmid U, Seidel H (2009) Broadband single-pole multithrow RF-MEMS switches for KA-band. In: German microwave conference, pp 1–4. doi:[10.1109/GEMIC.2009.4815911](https://doi.org/10.1109/GEMIC.2009.4815911)
- Tazzoli A, Iannacci J, Meneghesso G (2011) A positive exploitation of ESD events: Micro-welding induction on ohmic MEMS contacts. In: Electrical overstress/electrostatic discharge symposium (EOS/ESD), pp 1–8
- Th Rijks GSM, van Beek JTM, Ulenaers MJE, De Coster J, Puers R, den Dekker A, van Teeffelen L (2003) Passive integration and RF MEMS: a toolkit for adaptive LC circuits. In: European solid-state circuits conference ESSCIRC, pp 269–272. doi:[10.1109/ESSCIRC.2003.1257124](https://doi.org/10.1109/ESSCIRC.2003.1257124)
- Thakur S, Sumithra Devi K, Ranjitha I (2009) Performance of low loss RF MEMS fixed-fixed capacitive switch characterization. In: Applied electromagnetics conference (AEMC), pp 1–4. doi:[10.1109/AEMC.2009.5430610](https://doi.org/10.1109/AEMC.2009.5430610)
- Uno Y, Narise K, Masuda T, Inoue K, Adachi Y, Hosoya K, Seki T, Sato F (2009) Development of SPDT-structured RF MEMS switch. In: International solid-state Sensors, actuators and microsystems conference TRANSDUCERS, pp 541–544. doi:[10.1109/SENSOR.2009.5285381](https://doi.org/10.1109/SENSOR.2009.5285381)
- Van Caekenberghe K, Vaha-Heikkilä T (2008) An analog RF MEMS slotline true-time-delay phase shifter. IEEE Trans Microw Theory Tech 56:2151–2159. doi:[10.1109/TMTT.2008.2002236](https://doi.org/10.1109/TMTT.2008.2002236)
- Varadan VK (2002) RF MEMS and their applications. John, Hoboken
- Diaferia F, Deborgies F, Di Nardo S, Espana B, Farinelli P, Lucibello A, Marcelli R, Margesin B, Giacomozzi F, Vietzorreck L, Vitulli, F (2014) Compact 12 × 12 switch matrix integrating RF MEMS switches in LTCC hermetic packages. In: Proceedings of the 44th European microwave conference (EuMC), pp 199–202. doi:[10.1109/EuMC.2014.6986404](https://doi.org/10.1109/EuMC.2014.6986404)
- Vorobyov A, Sauleau R, Fourn E, Oberhammer J, Baghchehsaraei Z (2011) MEMS based waveguide phase shifters for phased arrays in automotive radar applications. In: Proceedings of the 5th European conference on antennas and propagation (EUCAP), pp 2087–2090
- Yang ZA, Peroulis D (2014) A 23–35 GHz MEMS tunable all-silicon cavity filter with stability characterization up to 140 million cycles. IEEE MTT-S International Microwave Symposium (IMS) 1–4. doi:[10.1109/MWSYM.2014.6848663](https://doi.org/10.1109/MWSYM.2014.6848663)
- Yang H, Yahiaoui A, Zareie H, Blondy P, Rebeiz GM (2015a) Symmetric and compact single-pole multiple-throw (SP7T, SP11T) RF MEMS switches. IEEE J Microelectromechanical Syst 24:685–695. doi:[10.1109/JMEMS.2014.2344694](https://doi.org/10.1109/JMEMS.2014.2344694)
- Yang H, Zareie H, Rebeiz GM (2015b) A high power stress-gradient resilient RF MEMS capacitive switch. IEEE J Microelectromechanical Syst 24:599–607. doi:[10.1109/JMEMS.2014.2335173](https://doi.org/10.1109/JMEMS.2014.2335173)
- Y-q Zhu, Han L, Qin M, Q-a Huang (2014) Novel DC-40 GHz MEMS series-shunt switch for high isolation and high power applications. Elsevier Sensors Actuators A Phys 214:101–110. doi:[10.1016/j.sna.2014.04.024](https://doi.org/10.1016/j.sna.2014.04.024)
- Zhang QX, Yu AB, Yang R, Li HY, Guo LH, Liao EB, Tang M, Kumar R, Liu AQ, Lo GQ, Balasubramanian N, Kwong DL (2006) Novel monolithic integration of RF-MEMS switch with CMOS-IC on organic substrate for compact RF system. International Electron Devices Meeting IEDM 1–4. doi:[10.1109/IEDM.2006.346890](https://doi.org/10.1109/IEDM.2006.346890)
- Ziegler V, Siegel C, Schonlinner B, Prechtel U, Schumacher H (2005) RF-MEMS switches based on a low-complexity technology and related aspects of MMIC integration. European Gallium Arsenide and Other Semiconductor Application Symposium EGAAS 289–292