

RF MEMS for Ubiquitous Wireless Connectivity:

Part 2—Application

*Héctor J. De Los Santos,
Georg Fischer, Harrie A.C. Tilmans,
and Joost T.M. van Beek*

The application of microelectromechanical systems (MEMS) technology to radio-frequency (RF)/microwave systems is on the verge of revolutionizing wireless communications [1]. Indeed, the fact that RF MEMS enables superior passive devices, such as switches, switchable (two-state) capacitors, tunable capacitors (varactors), inductors, transmission lines and resonators, makes it a prime candidate to enable a plethora of wireless appliances operating in the home/ground, mobile, and space spheres [2], such as handsets, base stations, and satellites. The quintessential properties with which these systems are endowed are those of low power consumption and reconfigurability. It is for these reasons that RF MEMS is believed to be a key technology to enable ubiquitous wireless connectivity. In this context, it is the aim of this article to expose the impact and status of the application of RF-MEMS switchable capacitors, varactors, and switches in the three elements of this paradigm, namely, handsets, base stations, and satellites. In particular, issues such as system-level motivation/justification for RF MEMS, device requirements, high-volume manufacturing, packaging, and state-of-the-art performance and reliability, are presented.

Part one, the preceding article, presented a discussion on the fundamentals of RF-MEMS technology, in

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Héctor J. De Los Santos (NanoMEMSLLC@aol.com) is with NanoMEMS Research, LLC, Irvine, CA 92604 USA. Georg Fischer is with Lucent-Bell Labs Europe in Nuremberg, Germany. Harrie A.C. Tilmans is with Inter-University Microelectronics Center (IMEC) in Leuven, Belgium. Joost T.M. van Beek is with Philips Research Laboratories, in Eindhoven, The Netherlands.

particular, fabrication (surface and bulk micromachining) techniques, and their limitations, comparing key physical actuation mechanisms upon which RF-MEMS devices may be predicated, and device-level packaging. Part two is organized as follows.

- “RF MEMS for Wireless Handsets” outlines current trends, in particular, convergence of functionality and the RF radio in view of size and power efficiency constraints; miniaturization of the RF radio, in view of issues regarding the integration of passive components, in general, and of RF-MEMS switches and variable capacitors in particular; RF-MEMS manufacturing options, in particular, mainstream [complementary metal-oxide semiconductor (CMOS)-compatible] processing of RF MEMS, reliability and actuation voltage issues, and the concept of system-in-package (SiP) for small form factor packaging and assembly.
- “RF MEMS for Base Stations” describes the need for reconfigurable base station architectures, including pertinent requirements for switches and varactors, as well as recent progress on RF MEMS-enabled circuits.
- “RF MEMS for Space Applications” discusses satellites and nanosatellites, including requirements for switches, and recent progress on RF-MEMS phase shifters.

RF MEMS for Wireless Handsets

Trends in Wireless Handsets

Wireless handsets have come a long way since their introduction. Traditional mobile phone functions—voice calls and messaging services—make up an ever-smaller part of the handset hardware. Instead, additional functions such as cameras, gaming, and music players account for many of the components and an increasing share of the value of a mobile phone.

At the same time, voice calls have become just one of the many purposes for the transfer of RF data. This is so because an increasing number of frequency bands and communication protocols are entering the handset’s RF radio. Today, in fact, a variety of communication “pipes” can be distinguished through which the transfer of RF data may be established. Some of these pipes are incorporated in mobile phones that are currently on the market, while others are expected to find their way into the handset in the near future.

In general, three different RF communication pipes can be distinguished that may be present in a handset, namely, the cellular pipe, the interconnectivity pipe, and the broadcast data transfer pipe. The cellular pipe, in particular, is the most mature communication pipe of the three. Its most important property being its large area coverage. The cellular pipe was originally used only for voice calls, but currently it also supports messaging service and internet access. This

pipe covers such standards as global system for mobile communications (GSM), general packet radio service (GPRS), digital cross-connect system (DCS), personal communications services (PCS), and wide-band code-division multiple access (W-CDMA). The cellular and interconnectivity RF pipes differ in that the latter does not make use of a large area cellular network and is used mainly for making local wireless connections between individual devices. Examples of this pipe are such communication standards as Bluetooth, Zigbee, and IEEE 802.11. In the broadcast data transfer pipe, the handset is only used for receiving information. Examples of this are FM radio and, in the near future, TV reception. Global positioning systems (GPS) fall within this last category as well.

It is expected that each pipe will converge towards a single, multiband radio. For the cellular pipe, this can already clearly be observed in present-day handsets, e.g., through the incorporation of highly integrated quad-band RF modules. Similar developments are expected to occur for the other pipes as well.

For successful convergence of the RF radio, two clear conditions should be met, namely, reduced size and power consumption. In particular, the physical size of the handset should be maintained or even reduced. The importance of this condition is exemplified by the fact that the addition of a simple FM radio requires about 150 mm² of board space. Furthermore, for every RF pipe or communication protocol that is added to the handset, the demands on power supply will grow accordingly. Therefore, as the amount of available power for a battery-fed handset is finite, the urgency to minimize power consumption will become more and more prominent.

In this context, MEMS ohmic contact (metal-metal contact) switches and variable capacitors could very well be the missing link between convergence of the RF radio on the one hand, and circuit miniaturization combined with increased power efficiency on the other. MEMS ohmic switches and variable capacitors have excellent low loss and highly linear properties unprecedented in any other semiconductor technology. These properties are key enablers for the convergence of the RF communication pipes through the use of low-loss reconfigurable RF networks. In this way, a reuse of circuitry is established that will reduce the amount of board space needed to incorporate the different pipes. Furthermore, intraband power efficiency can also be improved by making use of the MEMS’ adaptivity, low loss, and high linearity.

Miniaturization of the RF Radio

The first step in miniaturizing the handset radio starts with taking a close look at passive components. Passives account for 75–85% of all components used in a mobile phone today. In comparison, only 5% of the components are actives [i.e., integrated circuits (ICs) and discretes]. In a state-of-the-art multimedia phone,

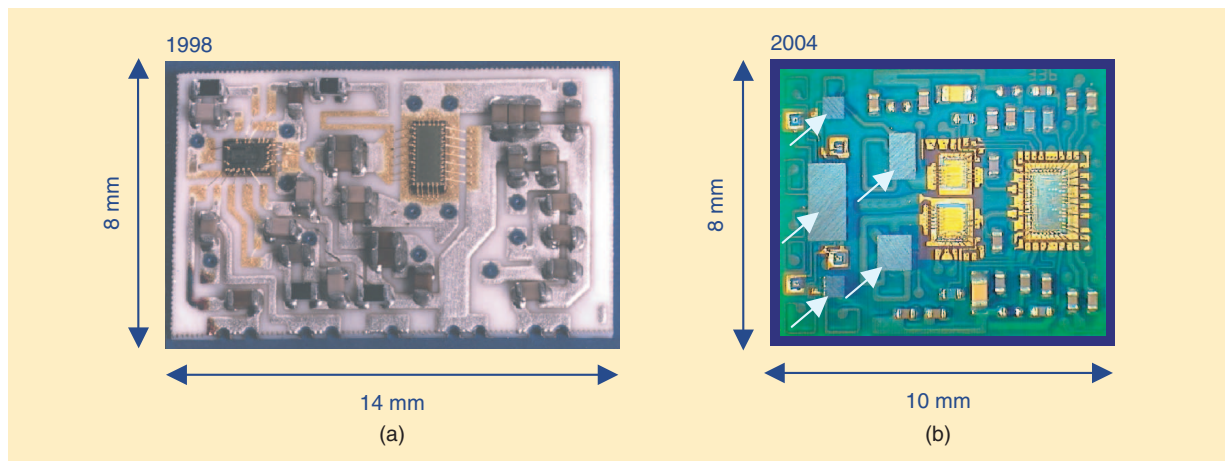


Figure 1. (a) Single-band GSM PA module (Philips, BGY241) from 1998. (b) Quad-band transmit module from 2003 integrating two PAs and an ASW (Philips, BGY504). The arrows indicate PASSI passive integration chips integrating two impedance matching circuits, two low-pass filters, and a diplexer.

several hundreds of capacitors are used, of which approximately 30% are in the RF radio. Apart from their physical size, the total area that is taken up by the passive components can, for the most part, be attributed to the minimum clearance around each component that is required for assembly. When reducing the board space taken up by the RF radio, it is, therefore, obvious that one should focus on reducing the number of discrete passives. This can be achieved by integrating the passives.

An illustrative example demonstrating the ongoing trend of modularization and miniaturization of the RF front-end using integrated passives is shown in Figure 1. On the left, a single-band GSM power amplifier (PA) module (Philips, BGY241) from 1998 is shown, which measured $8 \times 14 \text{ mm}^2$. The Philips BGY241 contained two actives and 30 passives, mainly capacitors. It can

be seen that the amount of passives outnumbered the amount of actives by far. Six years later, the single-band GSM PA has evolved to the module on the right; a dual-/quad-band T_x front-end module (Philips, BGY504), which measures $8 \times 10 \text{ mm}^2$. The BGY504 not only integrates the GSM PA, but also the PA line-up for the DCS-PCS frequency band, and an antenna switch (ASW) incorporating pin-diodes, a diplexer, and two low-pass filters. While smaller in size, the functionality of the BGY504 has increased dramatically. The integration of passive components is a key enabler to size reduction while, simultaneously, adding functionality to the RF module. It can be seen that the amount of surface-mount device (SMD) passives in the BGY504 has decreased from 30 to 26 compared to the BGY241. The reduction of the number of passives is possible through passive integration technology. In this case, many of the discrete SMD capacitors used in the BGY241 are integrated in the BGY504 using a proprietary Philips' passive integration process, called PASSI [3]. The five flipped PASSI dies visible in the BGY504 integrate the capacitors needed for impedance matching, low-pass filtering, and diplexing. A further reduction in size is accomplished by embedding the inductors in the multilayer laminate carrier substrate. The PASSI process is fully CMOS-compatible and enables the processing of inductor-capacitor networks with component accuracy better than a few percent. High Q -factors are achieved through the use of high-resistivity Si substrates and thick metal interconnects.

The ultimate RF module in terms of miniaturization would be one that integrates the complete radio section into one single package, as is indicated in Figure 2 [4]. It is obvious that RF modules will shrink in size. When a certain module, e.g., the PA, has reached a critical minimum size, it will be combined with other modules, such as the ASW forming a T_x front-end module (T_x -FEM, such as BGY504). In the end, the whole radio

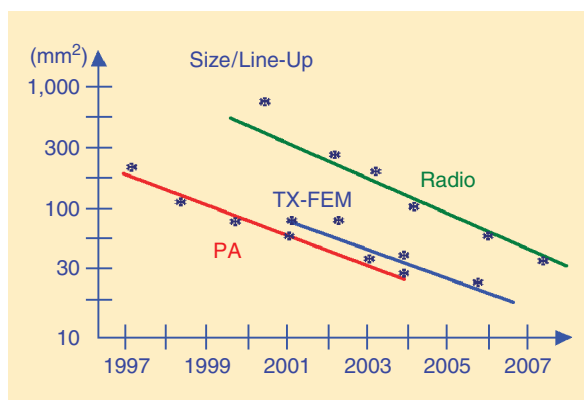


Figure 2. Trend towards a miniature, fully integrated RF radio module. When a certain module, e.g., the PA, has reached a critical minimum size, it will be combined with other modules, such as the ASW forming a T_x -FEM. In the end, the whole radio section will be integrated into one single module: the multiband radio module. The level of module miniaturization that is predicted can only be achieved through the integration of passive components.

section will be integrated into one single module: the multiband radio module. The level of module miniaturization that is predicted in Figure 2 can only be achieved by abandoning the conventional SMD mounting of discrete passives and moving to some form of passive integration.

The next big step in miniaturizing the RF radio will be the incorporation of MEMS ohmic switches and variable capacitors into passive networks. MEMS exhibit very low loss and high linearity and are, therefore, near ideal “adaptive passives.” Using these MEMS elements it is possible to reconfigure passive networks, such as impedance-matching networks and tank circuits, without introducing significant signal loss. This will be especially beneficial when the RF module is more complex and serves many RF communication protocols and frequency bands. In other words, the use of RF MEMS will be more advantageous when radio convergence progresses. In order to illustrate this, a fully converged RF front-end of a third-generation (3G) cellular communication pipe is shown in Figure 3. The use of MEMS variable capacitors and/or ohmic switches in combination with fixed inductors and capacitors allows for the synthesis of a single, reconfigurable impedance match and antenna switch block. It is expected that this type of MEMS reconfigurable network will lead to a smaller footprint of the RF front-end, since a single circuit will be reused for the different frequency bands and protocols.

Apart from the ability to merge different frequency bands into a single adaptive circuit, MEMS can also offer an

intraband improvement of power efficiency. To illustrate this, we consider the impedance matching network between the PA and the antenna with a fixed antenna impedance of $50\ \Omega$, as is depicted in Figure 4 [5]. The value of the optimum load impedance Z_{in} of the PA’s final stage transistor varies with the transmitted power. The impedance-matching network without MEMS is normally designed to give the lowest insertion loss for a value of the optimum load impedance when the transmitted power is at its maximum. In this example, the optimum load impedance is $Z = 2\ \Omega$ when the maximum output power is $P = 3.7\ \text{W}$. However, the optimum load impedance changes to $Z = 4 + 3j\ \Omega$ when the output power is lowered to $P = 1\ \text{W}$. For a low power level, this results in a less than optimum impedance match and associated loss of PA efficiency. In Figure 4, this is manifested in a higher insertion loss when assuming a source impedance of $4 + 3j\ \Omega$ for the impedance-matching network. By adding a MEMS variable capacitor to the final stage of the impedance-matching network, the load impedance

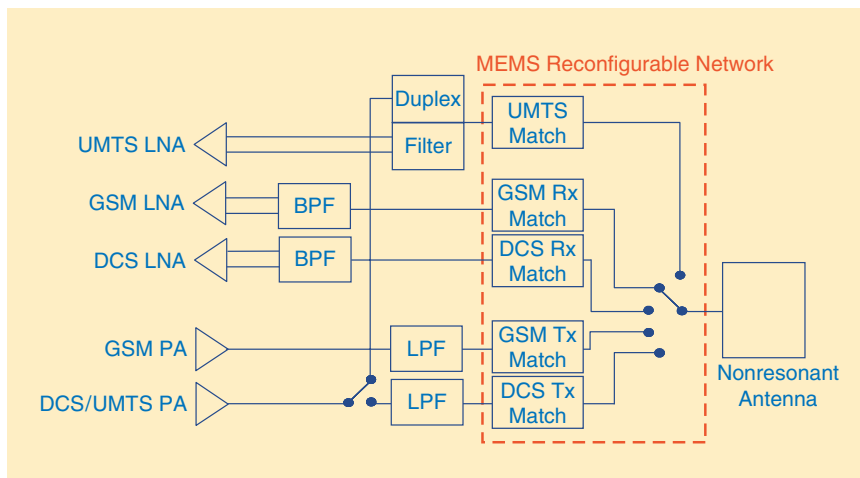


Figure 3. RF front-end of the cellular pipe of a 3G handset. The red box integrates the impedance matching circuitry for different frequency bands and the antenna switch into one functional block using MEMS enabled reconfigurable inductor-capacitor network.

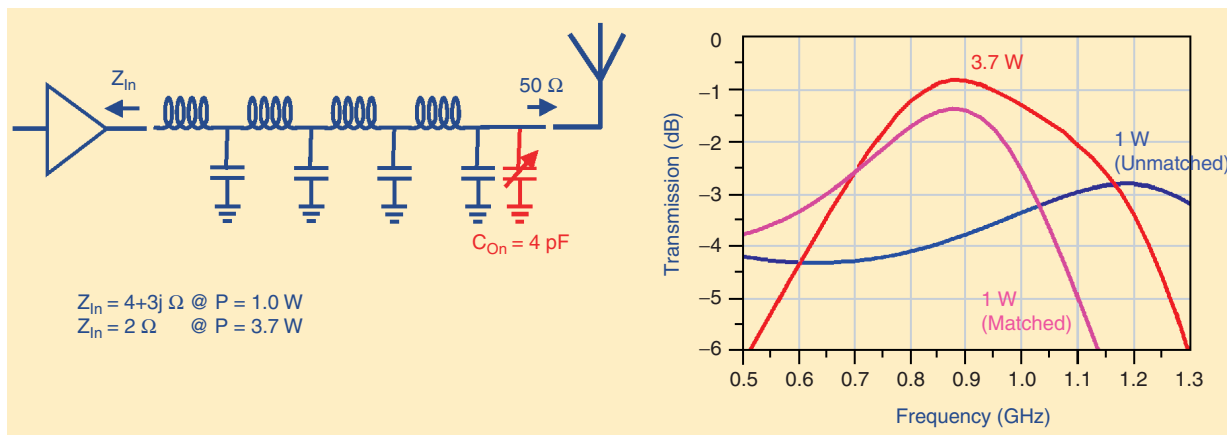


Figure 4. An adaptive 900 MHz PA output impedance matching network accommodates for variations in the optimal transistor load impedance, which is a function of transmitted PA power.

can be switched when the PA is transmitting at 1 W. It can be seen from Figure 4 that with the incorporation of a single MEMS capacitor the insertion loss is reduced from 2.8 to 1.4 dB, again assuming a source impedance

The most promising attribute of RF MEMS for both base stations and handsets is their capability for realizing frequency-agile RF/wireless systems capable of serving multiple frequency bands.

of $4 + 3j\Omega$. This indicates that the load impedance is closer to the optimum load impedance when the MEMS capacitor is switched on. The efficiency at low power can be further improved when incorporating more than one MEMS capacitor in the matching network. The same loss mechanism also plays a role at the antenna side of the impedance match. The impedance of the antenna is 50Ω only under nominal conditions, but can vary considerably, e.g., when the antenna is close to the human body. Also in this case, adaptive impedance matching using MEMS capacitors can improve the power transmission (and reception) efficiency.

Mainstream Processing of RF MEMS

An important aspect that differentiates the handset market from other potential RF-MEMS markets is its enormous size. For example, 500 million handsets were shipped in 2003 compared to only 1.4 million base stations. When developing RF-MEMS manufacturing processes for the handset market one should realize that RF MEMS will be produced in very large quantities. For this reason, processing technology should be as compatible as possible to mainstream IC (CMOS) processing. This allows for the utilization of the vast

CMOS manufacturing infrastructure that exists today.

Attention should be paid to several aspects when adapting CMOS-compatible materials and processes for the manufacturing of RF MEMS. First, the MEMS device should preferably be processed on Si wafers in order to be compatible with mainstream processing equipment. Unfortunately, standard Si wafers have a resistivity in the $m\Omega\cdot\text{cm}$ to $\Omega\cdot\text{cm}$ range, which causes significant loss to the RF signal, thereby severely deteriorating the low loss property of RF-MEMS switches and capacitors. One way of suppressing this loss is to use a highly conductive ground plane between the wafers and the MEMS device thereby effectively shielding the Si substrate. Another method is to use a Si substrate that resembles an insulator as much as possible. Float-zone Si wafers can be mass-produced with a resistivity larger than $4\text{ k}\Omega\cdot\text{cm}$ and have been successfully used for the fabrication of low loss passives and RF MEMS [6].

A second aspect that deserves special attention is the use of CMOS-compatible metals for the fabrication of the freestanding beam element. Aluminum and copper are the metals of choice used in almost all back-ends of existing IC processes. As a result, the processing of aluminum and copper films is well mastered on an industrial scale. Aluminum in its pure form is known to be a very ductile material prone to elastic deformation and creep and, therefore, is not suitable as mechanical layer in MEMS. However, alloys of aluminum are known to have far better mechanical properties [7] and are even used for commercial micro opto-electromechanical systems (MOEMS) applications today [8]. Copper is an interesting material because of its very good conductivity and the ease of processing thick, low-resistivity layers through electroplating. However, copper is very sensitive to corrosion and, as a result, freestanding copper layers are not stable in air without surface passivation. The higher melting temperature of copper indicates a higher hardness and, therefore, a higher yield stress compared to aluminum. However, very limited information is available about the use of copper in MEMS. In

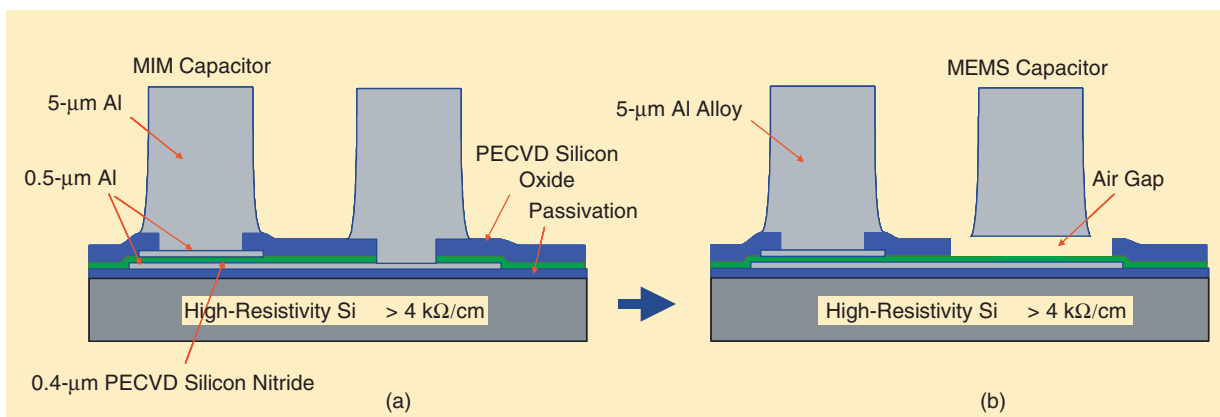
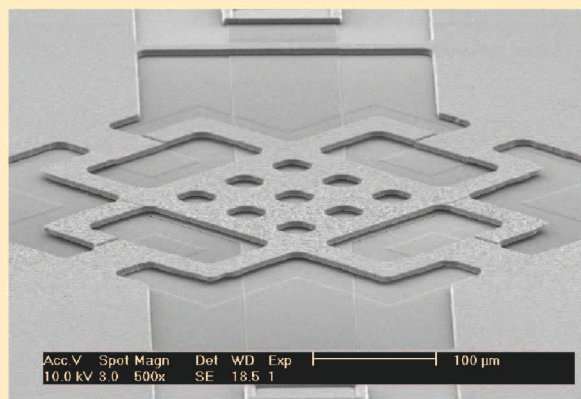
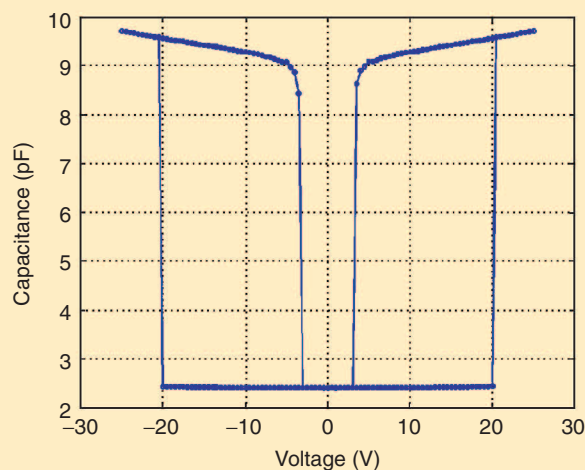


Figure 5. (a) Cross section of the Philips' PASSI technology for the integration of high-Q inductor-capacitor networks. (b) PASSI process extension that also includes variable MEMS capacitors, which allows for the monolithic integration of adaptive inductor-capacitor networks.



(a)



(b)

Figure 6. (a) A SEM image of a variable MEMS capacitor realized in Philips' PASSI technology. (b) Measured CV curve of a PASSI MEMS capacitor.

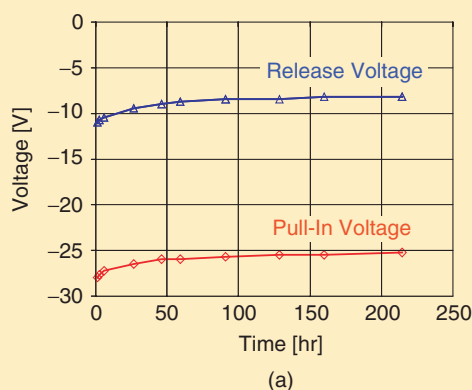
any case, neither aluminum nor copper are suitable for the fabrication of ohmic MEMS switches due to their non-conductive native oxide and, therefore, do not permit a low resistance metal-to-metal contact. The use of CMOS-compatible metals is, in our view, limited to the manufacturing of MEMS variable capacitors.

In most applications, the RF MEMS are combined with high Q -factor inductors and capacitors to form adaptive passive networks, as was explained in the previous paragraph. For this reason, it makes sense to extend existing passive integration technologies for the manufacturing of RF MEMS. For example, Figure 5 shows schematically how the Philips PASSI process is extended for the fabrication of MEMS variable capacitors using a surface micro-machining technique. Figure 6 shows an scanning electron microscope (SEM) image and capacitance/voltage (CV) curve of a temperature-compensated [9] MEMS switchable capacitor made in the Philips PASSI process. In this way, the MEMS extended PASSI process allows for the monolithic integration of a variety of adaptive inductor-capacitor networks. For example, incorporating MEMS switchable capacitors in impedance-matching circuits will allow for low-loss adaptive impedance matching, as was described earlier. Furthermore, the replacement of a solid-state variable capacitor by a tunable MEMS capacitor will in-

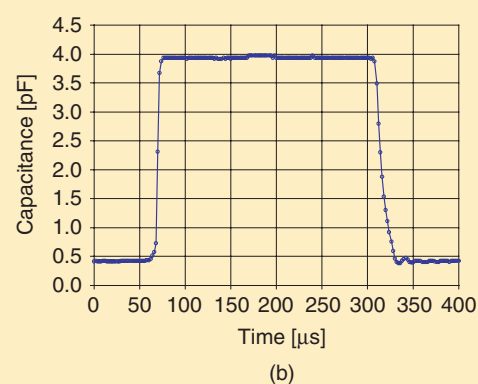
crease the linearity, the Q -factor, and tuning range of tank circuits used in voltage-controlled oscillators (VCOs). Another example is the monolithic integration of capacitive series-shunt antenna switches with low insertion loss and high isolation. All the examples just mentioned serve their own purpose in facilitating convergence of the RF radio as well as in increasing its power efficiency.

Issues: Reliability and Actuation Voltage

The reliability of MEMS ohmic switches and variable capacitors is of major concern when introducing them in a wireless handset. In ohmic switches, the reliability is strongly related to the metal contact used and is limited by damage, pitting, hardening, or welding of the metal contact area, leading to a permanent open or



(a)



(b)

Figure 7. (a) Drift of pull-in and release voltages of a Philips PASSI MEMS capacitor as a function of time when device is continuously dc biased at +40 V. The amount of voltage drift is well below the absolute values of the pull-in and release voltage and saturates over time allowing for reliable operation. (b) Transient capacitance of a Philips PASSI MEMS capacitor at ambient pressure using a 50-V actuation voltage. Closing and opening times of approximately 20 μ s are realized, which is fast enough for, e.g., GSM antenna switching.

short after a certain number of switching cycles. The reliability of MEMS variable capacitors is limited by dielectric charging of the capacitor dielectric, leading to a shift of pull-in and release voltage, ultimately resulting in stiction of the freestanding beam [10]. At present, it is believed that MEMS variable capacitors have an inherently better reliability when driven at high power levels, due to their large contacting surface area, as well as the fact that no significant amount of charge is crossing contacting interfaces. In Figure 7, pull-in and release voltage drifts are plotted for a Philips PASSI MEMS capacitor that is continuously dc biased at +40 V for more than 200 hours in dry nitrogen ambient. It is shown that during this period the amount of voltage drift due to charging of the capacitor dielectric is well below the absolute values of the pull-in and release voltages and saturates over time. It is, therefore, concluded that MEMS capacitors can operate reliably under high voltage/high power conditions using appropriate dielectric materials and ambient conditions.

Both MEMS ohmic switches and variable capacitors exhibit low loss and high linearity—properties that are especially beneficial at high power levels. The expected superior reliability of MEMS variable capacitors at high power levels combined with the benefits of linearity and low loss, leads to the conclusion that the use of MEMS variable capacitors has more potential in handsets compared to ohmic switches. In particular, the incorporation of MEMS variable capacitors in the T_x path seems most promising. However, it must be mentioned that the dynamic impedance range of a MEMS ohmic switch cannot be reached with a MEMS variable capacitor. Therefore, ohmic switches might be the only MEMS

option available, e.g., when isolating the T_x from the R_x path or separating different frequency bands with sufficiently high isolation.

Reliability of electrostatically driven MEMS capacitors and switches can be improved by increasing their mechanical stiffness. This inevitably leads to a higher actuation voltage. A sufficiently high switch speed and the occurrence of self pull-in at high power levels are other important reasons that prohibit the use of a low actuation voltage. The switching speed of MEMS capacitors is primarily limited by air damping. Actuation voltages of tens of volts are required at atmospheric pressure in order to achieve switching speeds suitable for, e.g., antenna switching. Figure 7 shows the transient capacitance at one atmosphere of a Philips PASSI MEMS capacitor, which is switched using a 50-V actuation voltage. It is demonstrated that switching speeds of 20 μ s can be realized, which is fast enough for GSM antenna switching. Unfortunately, voltages in the 50-V range are well above the battery voltage. Additional measures for the generation of these high dc voltages within the handset might turn out to be a necessity for the reliable and fast operation of MEMS capacitors and switches. However, high voltage generation can easily be accomplished using a low power dc-dc converter such as a charge pump.

Small Form Factor Packaging and Assembly: System-in-Package

Since RF MEMS allow for miniaturization through circuit reuse, it goes without saying that, when packaging the MEMS component, this advantage should be maintained. For this reason, the package should be as compact as possible and preferably be an integral part of the RF module. This leads to so-called SiP concepts.

Figure 8 shows two viable RF-SiP module concepts that incorporate a MEMS package. In the first concept, the MEMS form an integral part of the passive integration platform. Caps are placed over the MEMS device and can be an integral part of the module's flip-chip assembly when caps are placed using a solder seal technique. In the second concept, dedicated MEMS dies are placed on carrier substrate that might contain integrated passives. Also, in the second concept, the MEMS package forms an integral part of the module's flip-chip assembly when MEMS dies are placed using a solder seal technique.

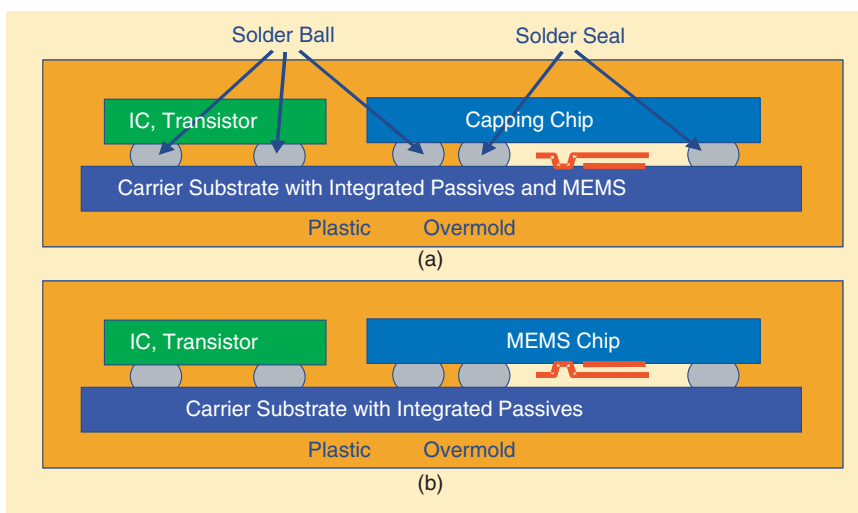


Figure 8. Two examples of an RF system-in-package approach that incorporate the packaging of RF MEMS. (a) Caps are placed over the MEMS device. (b) Dedicated MEMS dies are placed on a carrier substrate that contains integrated passives. In both approaches, the MEMS package forms an integral part of the module's flip-chip assembly when the MEMS package is solder sealed.

Projections and Conclusions

Convergence of the handset's RF radio seems inevitable, although clear boundary conditions have to be met. MEMS switchable capacitors, varactors, and ohmic switches might very well be the missing link between full RF radio convergence on one hand and miniaturization and power efficiency on the other. In particular, the integration of low-loss passive components in combination with RF MEMS opens the way for the realization of a large variety of highly integrated, reconfigurable, and low-loss RF circuits.

The mobile-phone market is by far the largest market for RF MEMS. This aspect should be taken into account when considering RF-MEMS manufacturing for the handset market. Wherever possible, the processing of RF-MEMS switches and variable capacitors should make use of materials, processing, and equipment that is compatible with existing mainstream (CMOS) manufacturing infrastructure. For this reason, high-resistivity Si substrates and aluminum alloys for the MEMS capacitor beam element should be utilized. For the fabrication of ohmic switches, it seems that nonmainstream contact metals need to be used. For incorporation into a handset, the MEMS package should be as compact as possible in order to maintain the size reduction of the RF module that is achieved through RF-MEMS enabled circuit reuse. As a result, the MEMS package will most likely be an integral part of an RF-SiP.

Although very promising, RF MEMS is just one of the technologies available today for the realization of a reconfigurable RF radio. Competing technologies, such as GaAs HBT switch technology, should also be considered. However, it seems unlikely that these alternative semiconductor technologies will deliver the same level of performance in terms of loss, linearity, and integrability in RF-SiPs.

RF MEMS for Base Stations

Base Station Architectures

Today, an infrastructure vendor has to offer a great variety of base station products to meet network operator needs. Besides various air interface standards, like GSM, universal mobile telecommunications system (UMTS), and CDMA, there are also various frequency bands where the systems can operate. Furthermore, there are also various RF power classes. Assuming

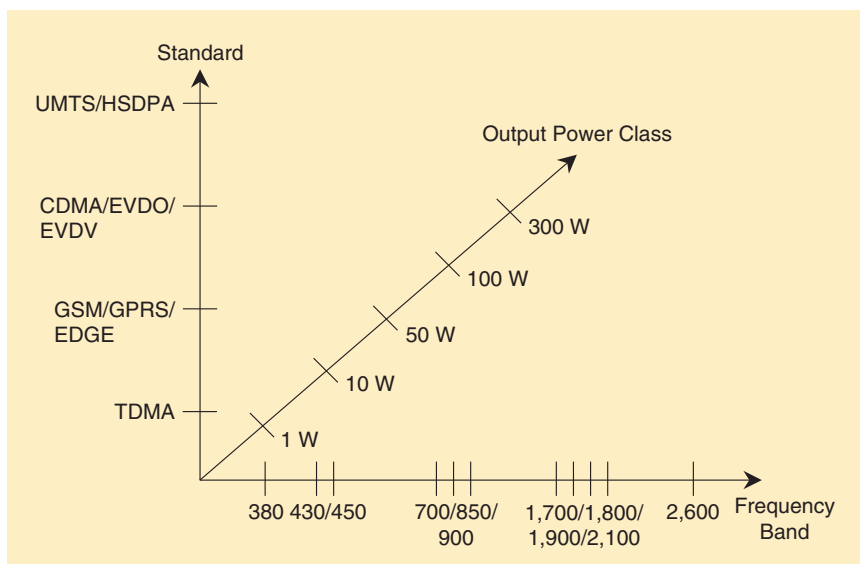


Figure 9. Base station variants.

four air interfaces, 11 frequency bands and five output power classes, there would be 220 different products as depicted in Figure 9. Of course, a great fraction of all these potential combinations has no relevance for the market or are not reflected in the standards. Assuming 85% of the combinations can be dropped, the remaining 15% still implies 33 different variants.

From the supply-chain perspective, it is highly desirable to achieve a great level of commonality between those remaining variants, as the classical approach to design a dedicated base-station product for each specific scenario misses a lot of synergistic effects.

Examining the remaining variants, it can be surmised that the greatest variants are in the frequency bands. The variants along the "Standards" axis may be limited to two big standards for the future only, which will be UMTS and CDMA, including their evolutions high-speed downlink packet access (HSDPA) and evolution data only (EVDO). Anyhow, UMTS and CDMA belong to the same family of code multiplex systems, with differences mainly reflected in the baseband processing and limited differences at the radio side. With respect to power classes, a limit to two classes might also be acceptable.

Ultimately, this means that the axis "Frequency band" is the greatest contributor to the variants. This, in turn, forces an infrastructure vendor to seek technologies that facilitate a unified radio that can serve multiple frequency bands. "Serve" here means that one or another frequency band can be selected. It doesn't mean that different bands have to be supported at the same time. In the literature, this is called a reconfigurable radio. Reconfiguration means that the RF characteristics can be redefined, preferably by software, not by a manual modification or tuning. From that perspective, one may say that such a radio is a software radio but in analog domain. This is a wider under-

standing of the term software defined radio (SDR) to allow for the software-wise definition of the properties of signal processing stages, not only in the digital, but also in the analog (RF) domain [11].

In order to distinguish the classical understanding of software radio technology, focusing mainly on the digital part of a radio, from the new understanding of SDR, including now also the analog stages, a further term is settling in literature, namely, that of "frequency agile radio" or "reconfigurable radio". Frequency agility focuses on the multiband capability of a radio, whereas SDR in the past mainly looked at multistandard capability. So multiband capability is mainly reflected in the radio and multistandard capability is mainly reflected in the baseband. The RF output power capability is then defined by the size of the power amplifier.

In the context of a base station, it is highly desirable that not only the radio, but also other RF stages offer frequency agility. This also means that the power amplifier and the filters, like duplexers, should be frequency-agile or, in other words, reconfigurable [12].

Figure 10 shows the concept of a frequency-agile base station.

If all RF related stages are reconfigurable by software, then also a remote reconfiguration of a base stations' operational frequency band becomes feasible. In the case of base stations, visiting of a site to do reconfiguration should be avoided as this implies huge costs and causes long downtimes while the base station is out of service.

Several levels of reconfiguration can be imagined:

a) *Reconfiguration on shipment*

This means that on shipment a base station is configured to operate at one frequency band and later reconfigurations are not possible. This would be comparable with burning an array of fuses with converter calibration. So this is equivalent to a one-time reconfiguration.

b) *Reconfiguration by reboot*

This means that a base station has to be rebooted to come up supporting another frequency band. Such a reboot can be done multiple times. However a reboot means going out of service and may take some limited time.

c) *Reconfiguration on a per call basis*

This is the highest level of dynamics with reconfiguration. However, this entails a tremendous effort,

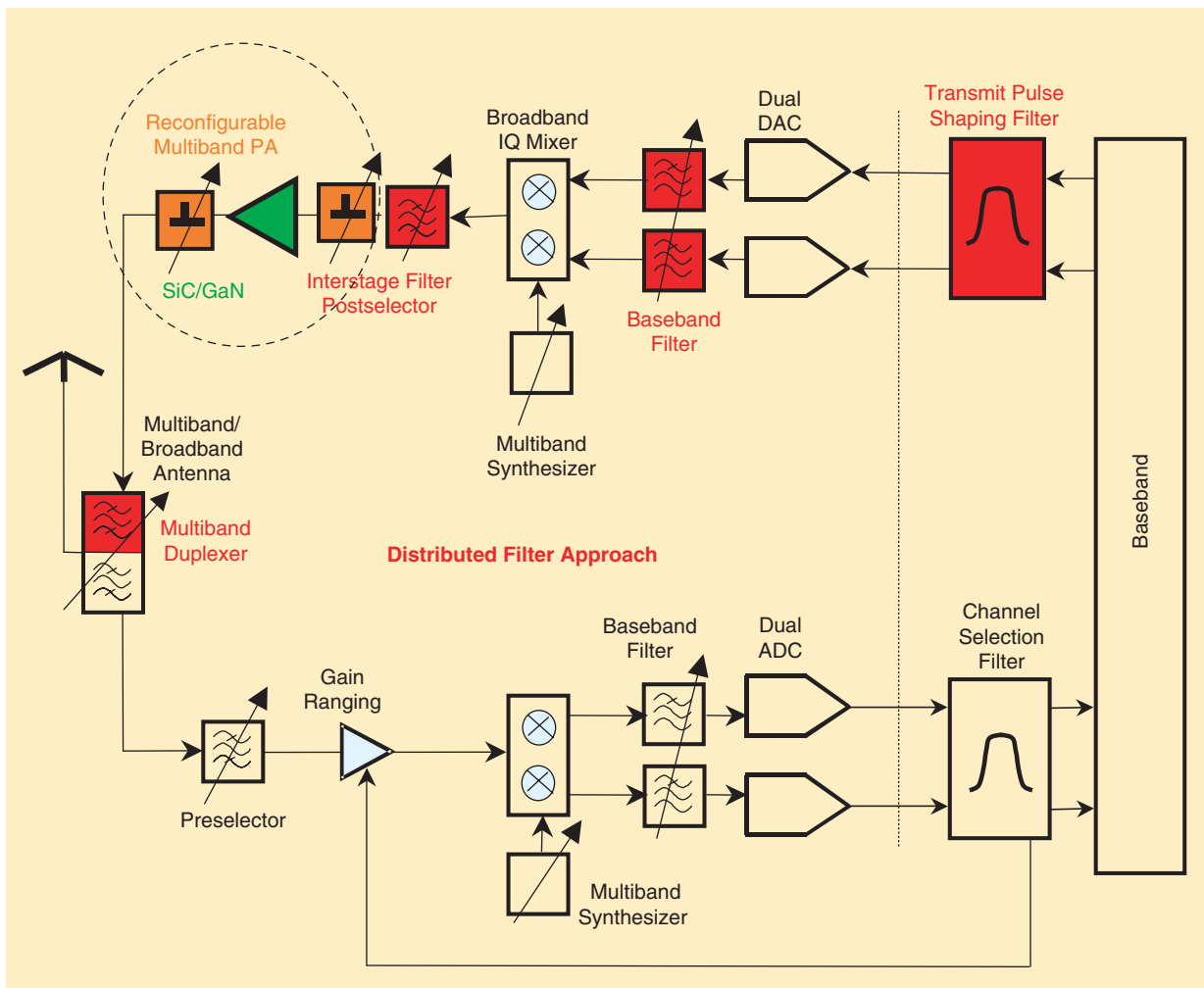


Figure 10. Architecture of a frequency-agile base station.

which likely cannot be justified by the benefits. Network operators are interested in coverage and capacity guarantees, and, therefore, careful network planning is performed and network changes are made seldom in order not to risk network stability. So reconfiguration, for network optimization reasons, wouldn't be done frequently. And if a reconfiguration is needed, an operator typically can wait until the night, where traffic is low and downtime is less critical.

For terminals, the situation is different, it is advantageous to operate at another air interface without having to reboot or switching on/off.

A reconfiguration by reboot is a reasonable approach for base stations on the infrastructure side. This affords an interesting flexibility to network operators. Mergers and license exchanges between operators happen throughout the world, and new frequency bands are being licensed continuously to match the increasing demand in wireless data traffic. Therefore, network restructuring would be facilitated even remotely from a central operation and maintenance center (OMC) without huge costs for sending out technicians to every base station.

Nevertheless, it appears that the real motivation for reconfigurable frequency-agile base stations is on the infrastructure vendor's side, not on the network operator side. This is a drastic shift from the classical motivation for software radio. Detailed analysis have shown that the cost increase due to reconfigurability is more than balanced by the savings that come with a higher level of commonality. Savings are obtained, for instance, by:

- one common PCB board for all bands
- a single development effort with moderate increase versus plenty of development efforts in parallel
- faster certification, compliance testing
- simplified documentation
- simplified quality management
- a unified test platform
- extreme fast reaction to new market needs, e.g., a new frequency band is opened up
- future safe design for new bands, however, this may have some limits
- support of network operator spectrum migration strategies.

Specific logistical gains that can be achieved include the following:

- higher volume of components and PCB $\Rightarrow$ reduced price
- highest production flexibility, order independent
- smaller component data-base
- less production setup times
- reduced design and development effort
- unified field-support and maintenance
- reduced test and certification effort

- simplified documentation and specification effort
- less excess material $\Rightarrow$ reduced risk
- common handling in production, repair, and delivery.

In summary, this can easily lead to savings on the order of several million dollars for an infrastructure vendor. There remains the question now on how this flexibility in the analog RF domain be achieved. We think that RF-MEMS technology is the answer to this request for flexibility, as it has unique properties that make it perfectly suited to perform the necessary manipulations to the RF chain and to address different frequency bands.

At a high level we can exploit the following benefits of RF MEMS:

- low loss/high isolation switching (the ideal switch)
- great tunability with varactors (wide tuning)
- a separation of control and RF path is possible (similar to relays).

In the following, various examples for the use of RF-MEMS to realize certain reconfigurable RF functions with a frequency-agile base station are given and discussed in more detail.

Switch Requirements and State-of-the-Art Performance

In a frequency-agile radio, RF-MEMS switch matrices may be used, e.g., to switch filters as shown in Figure 11.

In this arrangement, the unselected filters are switched to ground at their output. This improves stop-band attenuation as nearly a short is provided at the input within each unselected filter's passband. A practical realization of the filter is shown with Figure 12.

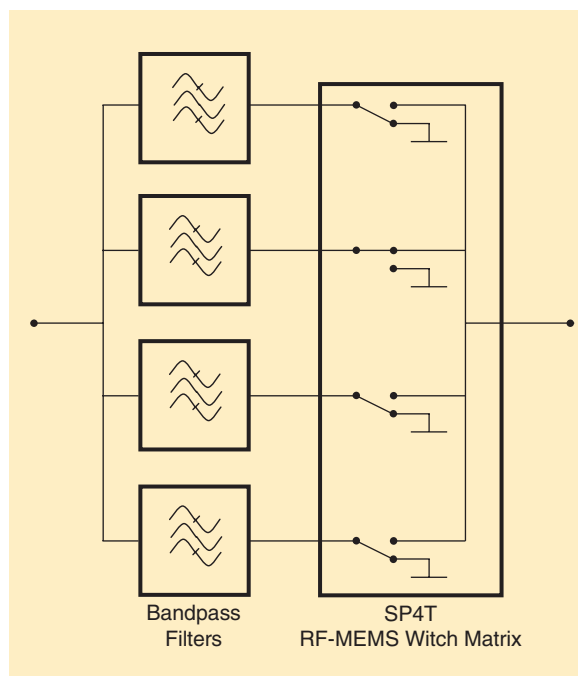


Figure 11. A reconfigurable filter.

For the application as a reconfigurable filter, a good switch to ground at each unselected filter's output is important to profit from additional stopband attenuation by the unselected filters. Here, the typical low loss of RF-MEMS switches when closed is beneficial. The typical low contact resistance ensures a good grounding.

From a cost perspective, the overhead incurred by including filters that may end up not being selected if the base station is never reconfigured over its lifetime, may be a concern. However, since additional stopband attenuation is provided by the unselected filters, the requirements for the selected filters can be relaxed. Therefore, instead of one expensive fixed filter with a classical design and no frequency agility, several filters of moderate performance and cost are sufficient to realize frequency agility. A reconfigurable filter with four different settings doesn't, therefore, imply four times the cost.

A further problem becomes evident. It is not sensible to package each filter and the MEMS matrix individually, as shown in Figure 12, as this implies greater packaging costs as with a multichip modules where all filters and the MEMS matrix reside in one package. Of course, a wafer-level packaging technique for the MEMS matrix would be advisable then. Such a shared package would also avoid long microstrip lines between a filter and its corresponding switch. If the microstrip line is a quarter-wavelength long, then there is the problem that the switch to ground is transformed into an open circuit at an unselected filter's output. By this, the additional stop band attenuation is lost. What would be acceptable would be half-wavelength long

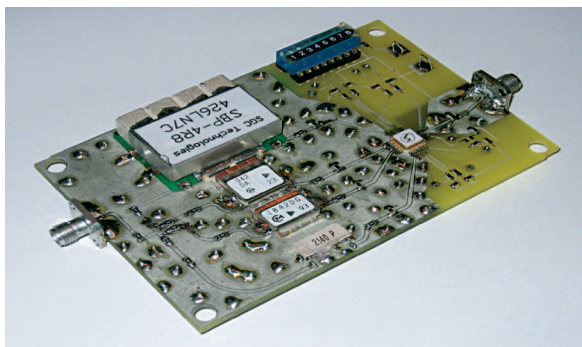


Figure 12. A reconfigurable filter with four different passbands.

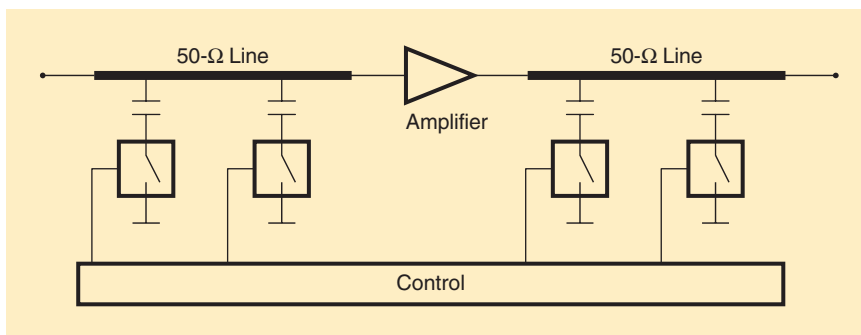


Figure 13. A reconfigurable amplifier.

microstrip with respect to each filter's passband. But this implies different line lengths between the filters and each corresponding switch.

Another use of MEMS switches may be the reconfiguration of matching structures with reconfigurable multiband amplifiers, as depicted in Figure 13.

In such an arrangement MEMS switches should provide a perfect open or short circuit. However, practical studies showed that at die level a good alteration between open and short is produced, and when packaged this behavior is strongly degraded. The reason for this is that typical packages have dimensions much larger than the die size, so some line transformation exists inside the package. This may lead to an open circuit behavior even if a switch is turned on (closed) and provides a connection to ground. In a straight-line arrangement, where RF is switched off and on, this kind of parasitic causes no problem and doesn't hurt the good figures of low loss and high isolation switching, but in the context of reconfigurable matching structures, this is a serious problem. Clearly, this problem pertains to the realm of RF-MEMS packaging, not to MEMS itself, as the typical performance at die level is superior. In order to overcome this problem, one may also consider wafer-level packaging and direct bonding of MEMS components to a soft substrate inside an amplifier module. This looks reasonable as the active devices inside a power module are already mounted directly without individual packages and bonded directly to a soft substrate. By a power module approach, parasitics of active and MEMS device packages would disappear.

Besides these challenges in MEMS packaging, it should be mentioned that the separation of control and RF lines with a MEMS switch is highly beneficial in the context of reconfigurable matching structures as bias tee networks are avoided. The parasitics by the bias tees under real conditions would be of the same order as the matching elements to be switched themselves. Furthermore, it can be assumed that at least two switches are needed at the input and output for each frequency band. If a reconfigurable amplifier has to support four bands, this would imply 16 switches. If 16 bias networks would also be needed, the design would become very complicated, and parasitics by the bias tees would be difficult to control.

Another challenge is the power handling capability of MEMS devices. Due to circulating currents in the matching networks, the RF currents may easily rise up to 1 or 2 A. Of course, the matching topology is a key factor defining the maximum currents through the MEMS switches. It appears

that high voltages across a MEMS switch with impedance transformation are easier to handle than high RF currents. Today's RF-MEMS switches offer around 1–5 W, which maps to maximum current handling in the order of a few hundred milliamps. Some effort should be spent to increase the current handling. Perhaps other actuation mechanisms, like piezoelectric or magnetic, should be preferred as greater contact forces can be realized. Greater contact force should result in lower contact resistance, which then leads to greater current or RF power handling.

In the context of reconfigurable base stations the number of switching cycles is of less relevance as reconfiguration occurs very seldom. The ability of a base station to be reconfigured is a protected investment for network operators, however it may happen that a base station is once configured, on shipment, and never reconfigured during its lifetime. Typically we assume two reconfigurations per year, which would mean 30 cycles assuming a lifetime of 15 years. So 10^2 cycles should be enough. However, even if it is assumed that reconfiguration is done more often accounting for varying traffic over the day, say four switches per day, then this would result in 10^5 cycles (four reconfigurations per day $\times$ 365 days $\times$ 15 years). Such a number can easily be met by today's MEMS switches. For comparison, a TX/RX switch in a GSM handset would require 10^{10} to 10^{11} cycles. It can, therefore, be concluded that for reconfiguration purposes the number of switching cycles for base-station applications is a less critical parameter. Furthermore, the actuation voltage or actuation power is less critical with base stations as they have mains supply, and battery saving is less of an issue compared to handsets.

As mentioned earlier, reconfiguration of a base station occurs seldom and will likely require a reboot, so switching time is also of no relevance.

Varactor Requirements and State-of-the-Art Performance

Instead of using switches with reconfigurable matching structures, one may also consider varactors as depicted in Figure 14. This has the advantage that the matching can be designed to be very narrowband. A narrowband behavior may serve as an additional filter in the transmitter's line up and contribute to a distributed filter approach.

Selectivity at each stage in the transmitter line up, in this case with the amplifier, reduces wideband noise. Wideband noise generated in the transmitter has to be filtered in the duplexer (see Figure 10) in order not to desensitize the receiver. A base station also has to transmit and receive at the

same time for time multiplexed systems. So it has to be of full duplex type.

The distributed filter approach relaxes the requirements of the typical high-performance duplex filter by introducing several tunable filters of moderate performance along the transmitter chain, like the interstage or postselector filter in Figure 10. Duplex filters with base stations typically run off coaxial resonators with a Q factor in the order of several thousands. But this comes at the price of big form factors, big weight, and high costs. Currently, it is not feasible to realize such filters in MEMS. However, multiple small filters along the transmit chain with the distributed filter approach, look promising for a MEMS implementation. Savings will then be obtained through significantly smaller form factor and less costly duplex filters. The next section deals with such filters more specifically.

Using MEMS varactors for tunable matching structures to realize selectivity suffers from the same problem as that of matching structures incorporating RF-MEMS switches. The currents through the MEMS varactors may become very high especially as there are circulating currents. Some techniques to improve power handling capabilities of MEMS varactors would, therefore, be needed.

Another application of MEMS varactors is in wide tuning VCOs. Figure 15 shows such a wide tuning VCO as part of a wide tuning synthesizer.

Very large tuning ratios of capacitance have been demonstrated so far, with moderate figures being about 1:4, and a record figure, demonstrated by Philips, of 1:17 [13].

In the context of VCOs, a further benefit can be obtained from RF MEMS-based varactors. Classically, varactor diodes are used by VCOs, but these are active devices and result in flicker or shot noise. In contrast, RF MEMS-based varactors are strictly passive components, so they don't exhibit flicker noise. Also, the separation of control and RF port in the case of MEMS varactors is an attractive feature as, with varactor diodes, the bias tee needed degrades the Q -factor of the resonant tank. Furthermore, as RF-MEMS devices have certain mechanical inertia properties, the degrees of freedom present with the mechanical design can be exploited to realize mechanical low pass behavior. This mechanical low pass behavior can be designed jointly with the regular electrical loop filter in a phase-locked loop (PLL)

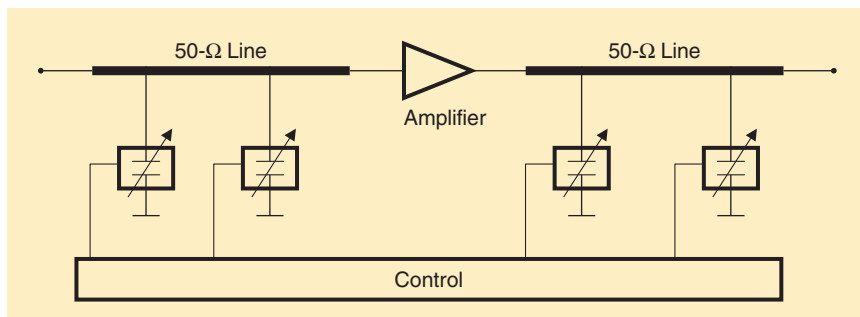


Figure 14. A reconfigurable amplifier with MEMS varactors.

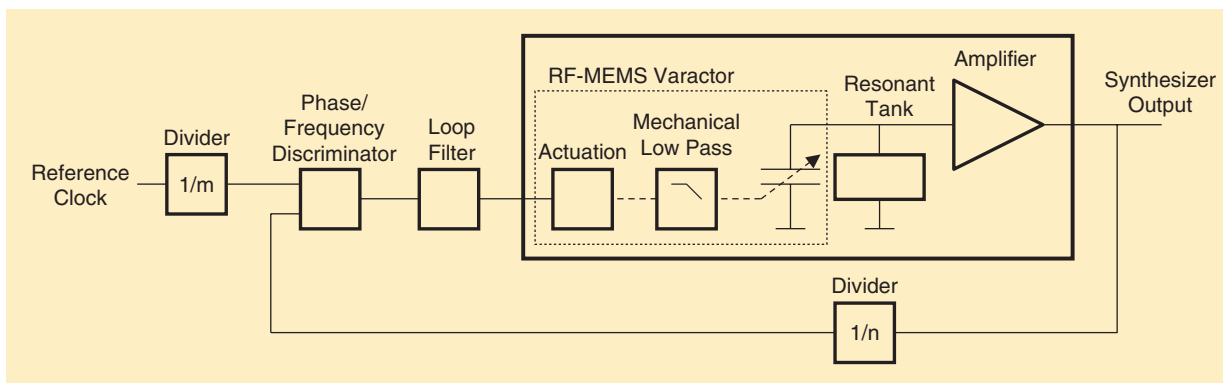


Figure 15. A synthesizer comprising a wide tuning VCO relying on a wide tuning RF-MEMS varactor.

arrangement. This has the advantage that the control line into the VCO becomes very robust against crosstalk problems. Any crosstalk, e.g., by digital clocking signals on the radio board, are filtered by the mechanical stiffness of the MEMS varactor.

One may now ask, what about microphonic effects, since the MEMS device incorporates moving mechanical parts? Analyses in this area were performed and it was found that the frequency modulation introduced by a vibration table according to the specifications is canceled by the PLL. The reason for this is that the moving mass is really low.

Progress on RF MEMS-Enabled Circuits

As stated above, the distributed filter approach mandates selectivity along each stage of the transmitter chain. This selectivity may be realized through RF MEMS-based resonant lumped electrical circuits comprising RF-MEMS varactors and variometers (variable inductors) as shown in Figure 16.

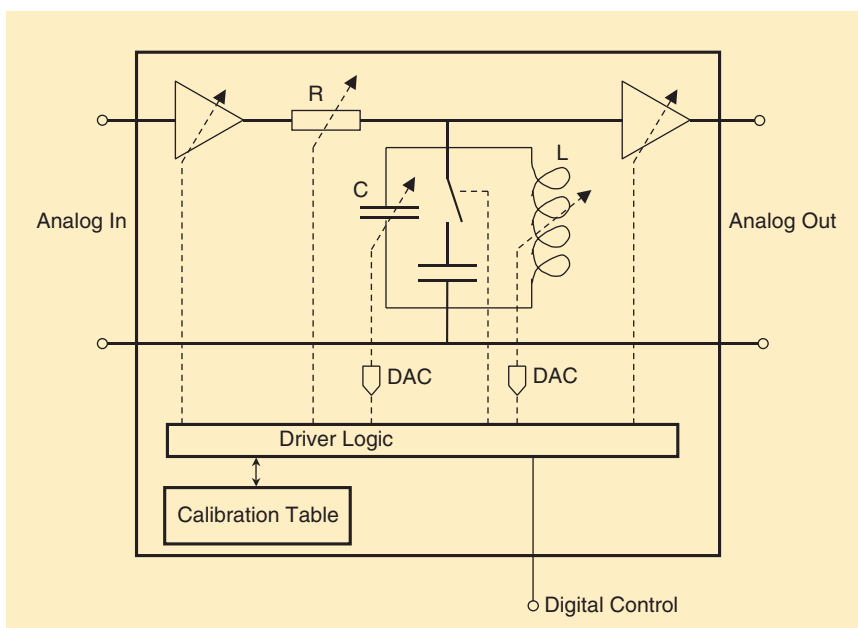


Figure 16. A reconfigurable filter with various MEMS devices.

Both MEMS varactors and variometers are needed because, in a distributed filter approach for a frequency-agile multiband/multistandard radio, both the resonance frequency and the bandwidth need to be tuned to account for different bands and different channel raster.

So far, only few results on continuously-tunable RF-MEMS variometers have been published [14]. However, the use in flexible filters is expected to stimulate more intensive work in this area. Other groups have also worked on big banks of fixed MEMS filters realized in film bulk acoustic resonator (FBAR) technology combined with MEMS switches [15]. However, this concept is not flexible enough within a frequency-agile base station, given the multitude of bands and of standards, each corresponding to a different channel raster.

Within a distributed filter approach, it is essential that the wideband noise in the transmitter chain be kept low. In particular, wideband noise must be precluded from entering the power amplifier and being amplified. A huge effort has to be spent in the TX branch of the

duplexer to attenuate noise at receive frequencies that could leak over to the receive port of the duplexer and desensitize the receiver. As the frequency gap between the uplink and down-link frequency band is typically small, on the order of a few megahertz, it is essential that the highly selective filters in the transmit chain, like the inter-stage filter, be kept narrow. For UMTS, with 5 MHz channel raster, a passband around 7 MHz width would be sufficient.

Preliminary calculations for a flexible filter topology, based on lumped elements, indicate that a Q factor on the order of 200–300 is needed. Today's passive devices exhibit a Q around 50–70. Therefore, more

work to improve the Q -factor is needed. Alternatively, one could think of active filter topologies that perform some Q -factor enhancement. Q -factor enhancement is not a new technology; it was already implemented with Audion short-wave tube receivers that incorporated an adjustable positive feedback. However, some noise problems may arise.

A reconfigurable filter, as depicted in Figure 16, combines RF MEMS with various other technologies like RFIC, logic, bus systems, and digital-to-analog (D/A) converter technology for driving the variable MEMS elements. But in the end, this combination of various technologies leads to a flexible analog function, whose properties can be defined in a digital way. It may, therefore, be called a radio function block (RFB). Since various other RF functions may also be envisioned, besides flexible filters and wide tuning synthesizers, RFBs may be interpreted as the key elements to create a software-defined analog radio. Developing a reasonable packaging strategy, such as creating SiPs, however, is a challenging task.

Projections and Conclusions

Starting from the approach of frequency-agile base station systems, RF MEMS is a powerful technology with various advantages. Besides the low-loss/high-isolation switching, the separation of control and RF ports and the degree of freedom with the mechanical design to realize mechanical filter behavior are attractive features. The maximum number of switching times is a less critical parameter if RF MEMS is used for reconfiguration purposes. Neither are critical in a base station since the required actuation voltage or actuation power operates from mains supply. Further improvements of the RF-MEMS technology are needed in the area of Q -factor magnitude and power handling capability. From the packaging perspective, techniques for reducing the parasitics and, especially, the line transformation inside the package are needed. With respect to RF subsystems of greater complexity with digital control, an efficient technique for combining different MEMS components, like switches and varactors, is needed. In order to also facilitate very flexible filters, a technique to realize wide tuning variometers is needed.

In this section we have addressed RF-MEMS applications to base stations. Next, we consider satellite applications.

RF MEMS for Space Applications

Satellites and Nanosatellites

Communications satellites are the ultimate enablers of global wireless connectivity (Figure 17). Representing one of the highest-capacity nodes of the wireless information grid, satellites must process the aggregate of information originating in the home/ground, mobile, and space realms, in the context of limited available power generation and storage capabilities. Thus, as a technology that conserves energy and minimizes power consumption, RF-MEMS switches, with their superior transmission and standby power consumption attributes, have become critical to increasing satellite capabilities while minimizing launch mass. This is particularly important, not only in traditionally large satellites employing phased-array antennas and switching matrices, such as those deployed in constellations where, to downlink data, they need to use the constellation itself to do packet-switched communications [16], but also in the case of nanosatellites. These are very small and lightweight [with a launch mass under 10 kg (22 lb)] spacecrafts containing microelectronic equipment, components, and payloads. These nanosats are attractive due to their cheaper, lightweight construction; versatility of launching means; and applicability to national security missions, either as single units or as clusters working cooperatively. For example, as single units, they may perform inspection, repair, refueling or sentry missions for larger satellites. As a cluster of three to ten units, they may function as

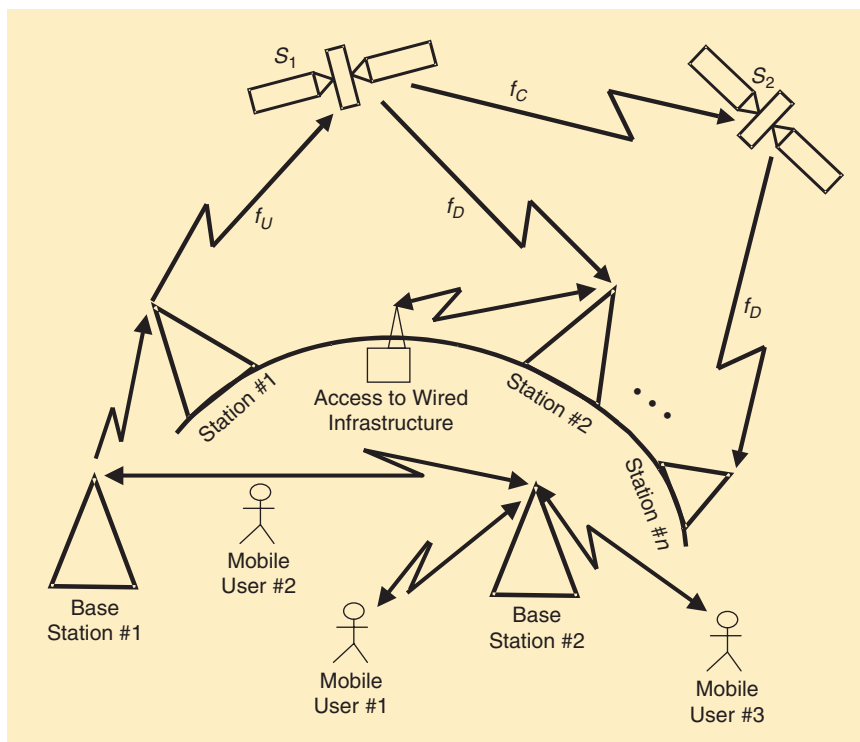


Figure 17. Ubiquitous wireless connectivity paradigm.

Table 1. RF MEMS switch requirements for space-based applications [18].

	Reconfigurable Apertures	Phase Shifters	Switched Antenna	Filters
Insertion Loss	<0.7 dB	<0.7 dB	<0.3 dB	<0.3 dB
Isolation	–20 dB	–20 dB	–20 dB	–20 dB
Return Loss	–15 dB	–15 dB	–15 dB	–15 dB
Switching Time	1 ms	s	s	s
Lifetime Cycles	0.5 B	0.5 B	>20 B	>400 B
Minimum Dwell	1 ms	1 ms	5 ms	0.1 ms
Maximum Dwell	1–10 s	10 ms	500 ms	1 ms
Frequency	UHF-Ka	Ka	X	X
RF Power	>50 mW	>50 mW	>100 mW	>1 W
Hot Switching	No	No	No	No
Events/s	2–50	200	500	10000

smart distributed apertures for the geolocation of a downed pilot in enemy territory. Finally, as a constellation of tens of units, they may enable Internet-in-the-sky applications and continuous reconnaissance of a geographical area during a military operation [17].

Switch Requirements and State-of-the-Art Performance

A good index of requirements for RF-MEMS switches employed in space-based applications are those pursued by the Defense Advanced Research Projects Agency (DARPA) [18], shown in Table 1.

Results of a number of efforts are underway, particularly under DARPA's RF MEMS improvement program to meet the above requirements. The currently available state-of-the-art RF-MEMS switch performance is given in Table 2 [19].

While these results are clearly impressive, work continues to extend consistency over multitudes of samples, not just a handful.

Progress on RF-MEMS Phase Shifters

One of the primary motivations for pursuing RF-MEMS technology, was the presumption that it would enable

phase shifters (PSs) with unprecedented low loss due to the inherent low-loss properties of MEM switches. This low-loss PSs would, in turn, enable low power consumption space-based phased array antennas of unprecedented size and performance. An examination of the current state-of-the-art in MEMS-based PSs, in light of the competing GaAs-FET-based PS technology, ratifies this initial presumption; see Table 3 [20].

Similar to what was said about MEMS switches in the previous section, further work is needed in the area of PS reliability.

Conclusions

For the last decade, research on RF-MEMS switchable capacitors, varactors, and ohmic switch technology has been the subject of intense efforts. While research in some areas, such as switches for space-based applications, continues unabated, due to the more exacting

nature of their lifetime requirements, the achieved level of performance for other applications, such as handsets and base stations, seems sufficient for insertion. The most promising attribute of RF MEMS for both base stations and handsets is their capability for realizing frequency-agile RF/wireless systems capable of serving multiple frequency bands. For the handset, this will eventually lead to a smaller footprint combined with low power consumption of the RF radio. For the base station the benefit lies in ability for reconfiguration of the air interface, which leads to high logistical savings for infrastructure vendors through a reduction in the number of product variants. Reconfigurable frequency-agile radios are a perfect addition to reconfigurable baseband processing. Both together form the basis of a realistic and reasonable approach to realize software radios.

Over the years steady progress has been made concerning the reliability of switched capacitors, varactors, and ohmic switches. There are indications that for ohmic switches high power handling (up to ~1 W) is within reach when the device is operated under "cold-switching" conditions. For switchable capacitors and varactors it is demonstrated that charging of the dielectric can be sufficiently suppressed even at high voltage

Table 2. Consistent state-of-the-art packaged RF MEMS switch data [19].

RF Performance ⁺				Lifetime Cycles [*]	
Insertion Loss	Isolation	Return Loss	Actuation Voltage	Cold Switching @20 dBm ¹	Cold Switching @30 dBm ²
<0.5 dB	23 dB@10 GHz	<15 dB	90 V	1 B	2.9 B
DC-35 GHz	18 dB@36 GHz	DC-38 GHz			

⁺This performance was attained by hundreds of devices.

^{*}Testing Conditions: RF at 10 GHz, 10-kHz cycling, three pulses during ON cycle, one pulse during OFF cycle to measure switch isolation, 10-μs pulsewidth, 50% duty cycle. Cold switching means that the power is switched during every switch cycle, but it is removed prior to either making or breaking the contacts.

¹This level of switching cycles was attained by only three devices possessing one contact.

²This level of switching cycles was attained by only two devices possessing two contacts.

Table 3. Average on-wafer loss for RF MEMS and GaAs FET 3-b PSs [20].

Frequency(GHz)	RF MEMS Phase Shifter Loss(dB)	GaAs FET Phase Shifter Loss(dB)
X-band (10)	−0.9 to −1.0	−3 to −4
Ka-band (35)	−1.7 to −2.0	−6 to −7
V-band (60)	−2.3 to −2.6	−8 to −9
W-band (90)	−2.6 to −3.0	−9 to −10

levels (tens of volts) using appropriate dielectric materials and ambient conditions.

Packaging is recognized as an important factor determining the parasitic behaviour and overall size of the RF-MEMS device. However, techniques such as SiP may well become the avenue that will enable the vision of RF MEMS for ubiquitous wireless connectivity *now*.

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