RF-MEMS: An enabling technology for Reconfigurable Radio Front-ends

H. Tilmans (IMEC)

Overview

- Mobile phones handsets
  - Intro/Ubiquitous world/Convergence
  - Multiband/Multistandard/Multimedia
  - Challenges for the future/Key drivers for mobile handsets
- Technology trends addressing the handset problem
- RF-MEMS as an enabling technology
  - How can RF-MEMS help?
  - Example of MEMS devices for wireless applications
  - Example of reconfigurable MEMS based functionality (switchable bandpass filter)
  - Passive integration of RF-MEMS
- Conclusions
Wireless Ubiquity: a world where we can access what we want, when we want and where we want..

Source: K. Muhammadand, Front-Ends for Commercial Digitally Controlled Radios”, workshop IMS2007

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A crowded frequency spectrum

- Cellular (GSM-GPRS, UMTS/WCDMA, ...)
- Connectivity (Bluetooth, Wi-Fi, WLAN, WiMAX)
- Broadcast (FM, DVB, ...)
- Positioning (GPS)

Source: M. Brandolini (Broadcom) and F. Svelto, "Reconfigurable Reconfigurable SiSiRF Receiver FrontRF Receiver Front-Ends Ends for Multifor Multi-Standard RadiosStandard Radios", Workshop IMS2007.

Roadmap for RF section in cellular "phones"

Source: EPCOS, "RF-Frontend of Mobile Phones", workshop IMS06
IC trend:
- Miniaturization "More Moore": 90 65 45 32nm (SoC approach)
- New technologies "Beyond CMOS" (e.g., tri-gate, Carbon Nanotube FET)

Packaging trend (SiP is the future):
- Advanced packaging technologies:
  - Smaller pitch (wirebond and flip-chip)
  - Thickness direction integration
    - Stacked die (PiP, PoP,...), 3D packaging
  - Embedded actives (thinned die) in substrate
  - Embedded passives in substrate: Integrated Passive Devices (use of semiconductor processing in stead of surface mount devices)

RF-MEMS technology: a "More than Moore" technology for building RF passives (switches, varicaps, resonators, filters, ...) using semiconductor like technologies

So many discrete passives....
**Integrated Passive Device (IPD)**

Gain 30% board space

**Passive Front-End Module IPD inc.**
Example of Integration of passives:
Philips GSM PA module  Tx Front-End Module

- 2 actives
- 30 SMD passives

Trend towards fully integrated RF radio module

Multiradio: How to fit all these radio’s in the same size (or smaller) handset?

Future: 2G/3G/3.9G (up to 17 bands) together with UWB, WLAN, RFID, Bluetooth, FM Radio, DVB-H, GPS, …
**The Future: The flexible radio (Multi-band/Multi-mode): Introduce reconfigurability**

Multi-band/Multi-mode radio architecture:

*Today: Duplication of part of the front-end*

![Diagram of multi-band/multi-mode radio architecture](image)

**The Future: The flexible radio (Multi-band/Multi-mode): Introduce reconfigurability**

Multi-band antenna + Antenna switch matrix

- 800-900MHz
- 1700-2200MHz
- 2400MHz
- VHF

Headphone +FM antenna

**Direct conversion BASEBAND**

- GSM1800 Rx → LNA1
- GSM900 Rx → LNA2
- WLAN5.2 Rx → LNA3
- GSM1800 Tx → PA1
- GSM900 Tx → PA2
- WLAN5.2 Tx → PA3
- UMTS2.2 → LNA4
- PA4
- PCS1900 → LNA5
- PA5

**Band/TDD/FDD**

- TDD
- FDD

**Tunable Antenna Match**

- Adaptive Antenna Match

**Direct conversion BASEBAND**

- DCS1800 Rx → LNA1
- GSM900 Rx → LNA2
- WLAN5.2 Rx → LNA3
- DCS1800 Tx → PA1
- GSM900 Tx → PA2
- WLAN5.2 Tx → PA3
- UMTS2.2 → LNA4
- PA4
- PCS1900 → LNA5
- PA5

**Introduce reconfigurability**

**Direct conversion BASEBAND**

- PCS1900 T/R → LNA1
- GSM900 T/R → LNA2
- UMTS2.2 → LNA3
- PA3

**Multi-band/Multi-mode radio architecture:**

- Multi-band antenna + Antenna switch matrix
- Mode/Band switch
- TDD
- FDD
- LNA1
- LNA2
- LNA3
- PA1
- PA2
- PA3
- PA4
- PA5

**Direct conversion BASEBAND**

- DCS1800 Rx → LNA1
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**Introduce reconfigurability**

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**Multi-band/Multi-mode radio architecture:**
Where can RF-MEMS be used?

- Large variety of functions (switch, varicap, variometer, filter, resonator, ...)
  replace existing components with cheaper or better MEMS components
- Low loss (high-Q) components
- High linearity
- Reconfigurability is a natural asset for some
  Tunable/adaptive (matching) networks
  Multi-mode/Multi-band switching
- **“Integratability”:**
  - With IPD
  - Above/Below RF-CMOS

**Tunable/Reconfigurable radio front-ends** are needed to satisfy the constraints on size, battery life, functionality and cost;

**RF-MEMS is a key technology enabler:**
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Reconfigurable Radio Front-End
Where can RF-MEMS be used?

Multi-band antenna + Antenna switch matrix

Headphone +FM antenna

Switchplexer

Diplexers

RF-MEMS for Reconfigurable Radio Front-ends
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RF-MEMS functionalities

- **Components:**
  - Switch
  - Tunable capacitor
  - Tunable inductor
  - MEM resonator
  - BAW resonator (FBAR)

- **Circuits:**
  - FBAR filter
  - Switchable filter
  - Tunable matching network

- **Subsystems**
  - Tunable antenna
  - Switched filter bank
  - ....

BAW thin film resonators/filters
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The radio front-end; where can BAW filters be used? diplexer

Multi-band antenna + Antenna switch matrix

Diplexer

SAW filters

DCS1800 Rx

GSM900 Rx

WLAN5.2 Rx

DCS1800 Tx

GSM900 Tx

WLAN5.2 Tx

Ladder-type FBAR filter

Film Bulk Acoustic Resonator (FBAR) (1)

principle of operation/filter structure

- Resonator

\[ f \sim \frac{V}{2d} \]

[AIN: \approx 11,000 \text{ m/s}
2.5\mu m \& 2.2GHz]

\[ Q \approx 1000 \]

- Filter

Ladder-type FBAR filter

Measured filter response

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**FBAR filter**

**Example AVAGO Quintplexer (5 FBAR filters)**

- Single antenna connection for PCS duplexer, Cellular duplexer, and GPS filter
- Eliminates antenna switching
- Miniature size
  - 5 x 8 mm Footprint
  - 1.3 mm Max Height
- High Power Rating
  - 0 +33 dBm Max Tx Power
- Lead-Free Construction

**Features:**

- High Power Rating
- Lead-Free Construction
- 5 x 8 mm Footprint
- 1.3 mm Max Height
- Single antenna connection for PCS duplexer, Cellular duplexer, and GPS filter
- Eliminates antenna switching
- Miniature size
- High Power Rating
- Lead-Free Construction

**Tunable FBAR**

- Actuation voltage (V)
- Load curve
- 24.5 MHz (0.39% tuning)

**AlN layer**

<table>
<thead>
<tr>
<th>Substrate</th>
<th>AlN layer</th>
<th>Signal line</th>
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<tr>
<td></td>
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<td>Top electrode</td>
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**Substrate**

- 800 MHz Band Tx and Rx Rejection
- 2.4 dB
- 3.9 dB
- 55 dB
- 40 dB

**Imec/restricted 2008**
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**FBAR(2): FBAR filter above BiCMOS for use in WCDMA zero-IF Front-end**


FBAR integrated above CMOS
Insertion loss: -3.5dB
Out-of-band rejection: ≈50dB

**Mechanical Resonator**
**Si-MEM resonator**
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Reference resonator (used for LO)

Quartz crystal oscillator (13 MHz)

- advantages: well understood, low cost (<0.5 EUR), temperature stable to 1 ppm, long term stable to 0.1 ppm/year
- disadvantage: significant space consumer on circuit board!

Reference clock/Timing devices:

Quartz crystals   Si MEM resonators

Quartz crystals -- Remarkable properties:
- high spectral purity (low phase noise),
- exceptional frequency stability against temperature variations and aging (for wide temperature range (-45°C to +100°C) stability ∆f/f of XO: 10-50ppm, of TCXO: 1ppm (aging 0.1-1ppm/year) and of OCXO: 0.01ppm)

but also drawbacks:
- Relatively large size
- Not "integratable" (with CMOS)
- Cost

New kid on the block: Si MEM resonator

Square Extensional Mode resonator

Better than:
-130dBc/Hz@Δf=1kHz (=GSM spec)

Noise floor:
-150dBc/Hz

Kajakaari (VTT, 2004)
SiTime
MEMS first resonator (below-CMOS)

- 300µm on the side
- 8" SOI wafers in a 0.18micron CMOS fabrication line (10cents/mm²)
- Encapsulated on-chip: low cost plastic injection molded package
- Performance similar to quartz (Q=75,000; frequency error 75ppm)

RF-MEMS switching devices
Tunable capacitors

- Capacitive
- Ohmic
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The radio front-end: Where can switches/switched caps be used? band switches, T/R switches, matching networks, ...

Multi-band antenna + Antenna switch matrix

Direct conversion BASEBAND

A key element for reconfigurable radio front-ends: (RF-MEMS) Switching device
Switching Devices:
Example 6-7GHz shunt capacitive switch

Imec’s RF-MEMS Technology Platform today:
First step towards an RF-MEMS IPD
RF-MEMS circuitry

Switchable (LC-type) Band Pass Filter

The radio front-end: Where can switchable filters be used? band select filters

Multi-band antenna + Antenna switch matrix

Band/ TDD/FDD

TDD

GPS Rx

Headphone +FM antenna

800-900MHz UHF

Switchable band filters

UMTS2.2

GSM1800 Rx

DCS1800 Rx

Direct conversion BASEBAND

Band/Pillar Tunable/switchable RF filter

Switched filter bank

LNA1

PA1

LNA2

PA2

LNA3

PA3

T/R

DCS1800 Tx

GSM900 Tx

WLAN5.2 Tx

WLAN5.2 Rx

DFD

Adaptive Antenna Match

Coupler

DCS1900  Tx

GSM900  Rx

WLAN5.2  Rx

VHF

UMTS 2.2

GSM900  Rx

800-900MHz

1700-2200MHz

5200MHz

2400MHz

Mobile TV & Radio Rx

2400MHz

VHF

800-900MHz
Example of an IPD:
LC-type BPF (GPS and Galileo)

Source: X. Rotenberg et al., proc. EuMIC2006, Manchester (UK), Sept. 2006

2nd order LC-type BPFs as IPD:
for GPS and Galileo

Source: X. Rotenberg et al., proc. EuMIC2006, Manchester (UK), Sept. 2006

MCM-D IPD:
Two separate filters for both bands increased size

Need for on-chip switchable capacitor
(for C₁ and C₂)

RF-MEMS
Switchable filter in RF-MEMS: between GPS and Galileo bands

Comparison IPD/RF-MEMS
- (+) Reduced size (by factor 2)
- (+) Lower loss
- (-) f_0 (Galileo) is off

Tunable/Switchable BPF
2-COUPLED RESONATOR switchable FILTER by XILM (1)

PARAMETER | DCS 1800 | WLAN
---|---|---
Lr (nH) | 2.6 | 2.6
Cr (pF) | 2.85 | 0.28
Cm (pF) | 0.2 | 0.045
n | 5 | 1.85

ADS simulation
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Tunable/Switchable BPF
2-COUPLED RESONATOR switchable FILTER by IRCOM (2)

Prototype fabricated by XLIM
(on quartz substrate: 525 μm, εr=3.78, tanδ=0.0001) and measured

RF-MEMS on the evolutionary path of passive integration
Technology platform for RF passives:
Stepwise introduction of flexibility/Evolutionary paths

Integration of fixed RF passives
Integrated Passive Device MCM

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Example of RF-SiP reconfigurable front-end

Technology platform for RF passives:
Introduction of flexibility/Evolutionary paths

Integration of fixed RF passives
Preferably serve as a carrier substrate for mounting actives (and other discrete passives)
Next evolutionary path: include RF-MEMS (flexible) passives:

Source: imec
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Technology platform for RF passives: Introduction of flexibility/Evolutionary paths

Integration of fixed RF passives

Preferably serve as a carrier substrate for mounting actives (and other discrete passives)

Integrated Passive Device MCM

Integrated Passive Device MCM

RF-SIP

Next evolutionary path: include RF-MEMS (flexible) passives:

5 Hybrid RF-MEMS SIP

5 Monolithic RF-MEMS MCM/RF-MEMS SIP

Conclusions and outlook

- Mobile wireless communication systems (handsets) are complex embedded systems where all functional blocks are custom-made for mobility. The combination of miniaturization and functionality is unprecedented compared to other consumer products.

- Next-generation mobile handsets will accommodate multiple wireless standards (3G, WiFi, WiMax, DTV, ..) and multiple frequency bands and will be based on software-defined-radio (SDR), asking for
  - A reconfigurable RF interface/architecture
  - Mode/band switching, Tx/Rx switching
  - More and smaller antennas antenna impedance matching
  - More and higher efficient PAs PA impedance matching
  - Tunable/switchable filters
  - ...

- There is a need for reconfigurable/tunable RF components (L's, C's, filter, switch, ...);

- **RF-MEMS is a key enabling (disruptive) technology** for reconfigurable radio front-ends satisfying functionality requirements, miniaturization, reduction of component count, long battery life, improved electrical performance, low cost, ...

- **High integration level** / "Integratability" (with CMOS and/or as passive platform) is one attractive feature of RF-MEMS technology

- The state of RF-MEMS in handsets:
  - BAW fixed frequency filters based on FBAR/SMR have proven themselves; Fixed frequency filters based on mechanical resonators are still very far from industrialization.
  - Silicon (BAW) resonators are emerging to replace quartz crystal resonators, but very tough stability requirements
  - RF-MEMS switch technologies still requires proof for RF applications. There still remains research work to be done in terms of: Packaging, reliability (duration, switch life cycles), power handling, price (low cost wafer process (foundry compatible) and packaging process needed)
  - Implementation of switchable filter banks are hampered by the development stage of MEMS switches
  - Tunable RF filters are still very far from implementation;
  - ...
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