RF-MEMS for Single Line-Up Front-End modules

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Outline

• Single Line-Up FEM concept
• High Efficiency amplifier operation
• Band and Load-switching
• High Efficiency dualband GSM amplifier
• Requirements on RF MEMS
• PASSI™ MEMS process
• Power and voltage handling
• Speed and reliability
• Conclusions
Trends in RF Front-End modules

- Convergence to Multi-Band / Mode RF-pipes.
Single Line-Up FEM concept

- Re-use of PA-stages and matching networks saves cost & size.
- Concept demonstrator GSM FEM: F1 = 0.9GHz, F2 = 1.8GHz.
High Efficiency amplifier operation

- High power efficiency requires optimum load impedance levels at fundamental- and harmonic-frequencies. (Inverse class-F)

$$RL_{\text{fund}} = \left(\pi Vcc\right)^2 / (8Pc) \approx 3\Omega$$

$$RL_{\text{Heven}} = \infty$$

$$RL_{\text{Hodd}} = 0$$
• Optimum impedance doubles for every 3dB power reduction.
• Loadline switching improves efficiency at reduced power levels.
Inverse class-F approximations

\[ n \to \infty: \quad \text{PAE}=100\% \]

\[ n = 3: \quad \text{PAE} \approx 90\% \]

- Proper termination up to H3 is sufficient for high efficiency.

\[ n = 3, \text{GaAs HBT: PAE} \approx 80\% \]
Frequency Band Switching

Bandswitching with variable C and fixed L by switching topology.

0.9GHz: low order
1.8GHz: high order

re-configurable network
• Maximize bandwidth by design for equal Q per section.
• Q\text{lowband} and Q\text{highband} are coupled.
• Use of variable shunt capacitance to control real part of ZL.
High Efficiency Dualband GSM Amplifier

<table>
<thead>
<tr>
<th>State / ZL</th>
<th>Vload_switch</th>
<th>Vband_switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>LB_33dBm / 3Ω</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>LB_30dBm / 6Ω</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>HB_30dBm/ 4Ω</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Efficiency Characteristics

PAE_FEM [%]

PL [dBm]

Lowband_LS

Lowband

Highband
• ESR is critical in low impedance applications.
• MEMS technologies allow ESR numbers in the 0.2Ω area.
MEMS CAP Current and Voltage levels

- $I_{rf\_rms} \approx 1...2\text{A} \ (50\Omega \ldots \text{mismatch})$
- $V_{rf\_rms} \approx 10...20\text{V} \ (50\Omega \ldots \text{mismatch})$

Low Z: High current

High Z: High voltage
Switch demands for single line-up FEM

- Low cost
- Capacitance switching ratio $\alpha=C_{\text{on}}/C_{\text{off}}>10$
- Low loss: ESR < 200 mΩ
- RF current handling ~2 A in closed state
- RF voltage handling $V_{\text{rms}} = \sim 20$ V
- Switching time < 100 µs
- Reliability >$10^9$ switches
- Linearity

Capacitive RF MEMS switches are one of the most promising technologies to meet these demands
Low cost PASSITM MEMS process

Industrialized PASSI process for passives on Si:
- Capacitors
- Inductors
- MEMS switches and tunable capacitors.

PASSITM MEMS
Implementation of RF MEMS
Switching ratio

Decoupling capacitor reduces switching ratio

- Switching ratio $\alpha = \frac{C_{on}}{C_{off}} = 20$
- $C_{decoupling} \approx 2C_{MEMS,on}$
- $\alpha_{MEMS+dec.} = \frac{C_{on}}{C_{off}} = (\alpha + 1/2)/(1+1/2) = 13.7$
Current handling

Issues:
• RF losses → efficiency reduction
• Heating → deformations

Solutions:
• Minimize ESR
  • Thick metal
  • Wide, short & many springs
  → ESR < 500 mΩ at 3 GHz, $R_{dc} < 100$ mΩ
• Multiple switches in parallel
• Reduce temperature sensitivity
• Temperature stable design

1 A → $\Delta T_{max} = 86 °C$
→ ~0.5 μm in-plane deformation
Temperature stable design

- Spring designs reduce out-of-plane movement as a result of heating from RF or external power.
- Springs occupy minimal space.

see Nieminen et al., J.MEMS p. 705 (2004)
Voltage handling

- $V_{rms}$ can reach about 20 V
- $V_{PI}$ must be much larger than $V_{RF, rms}$ to prevent RF pull-in
  + large $V_{PI}$ increases speed!
- $V_{bd} > 80$ V breakdown voltage of dielectric
- $V_{PI} = 30$ V $\rightarrow$ DC-DC converter required

Philips DC-DC converter for MEMS

$V_{out}:V_{in} = 35$ V:2.8 V

$P_{DC-DC} = 400$ nJ/switch + 110 $\mu$W standby
Switching speed

- High actuation voltage (31 V) for sufficient speed (<100 µs).
- Bipolar actuation reduces charging, but difficult to implement.
Reliability

Black: after $25 \times 10^3$ switch cycles (10 minutes@40 Hz).

Red: after $230 \times 10^6$ switch cycles (~40 hours@1600-2500 Hz)

Probe frequency: 1 GHz, $V_{\text{act}} = 32$ V

charging main issue
Conclusions

• Single-Line Up FEM concept can reduce cost and size and improve performance of multiband/multimode Front-End modules.

• Concept can be implemented with MEMS switched capacitors:
  – Only 4 MEMS required for dualband operation
  – Improved efficiency by applying load-switching

• Philips MEMS technology is attractive for this concept:
  – Derived from low cost PASSI™ process.
  – Designed for low loss, high current&voltage handling.
  – Sufficient switching time and reliability.
  – MEMS concept promises high linearity.