MEMS/CMOS TRADE OFFS FOR ANTENNA TUNERS

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RF Front End Challenges for 4G

Challenges
- Different standards
- Different band combinations
- Different mobile operators
- More PAs, filters, duplexers and switches

Some Solutions
- Multi-mode, multi-band PA
- Broad band PA
- Supply modulator
  - APT
  - ET
4G: dramatic increase of frequency bands
### 4G COMMON BANDS FOR CARRIER AGGREGATION

#### Specifications for CY14 devices

<table>
<thead>
<tr>
<th>Region</th>
<th>Bands</th>
<th>CA Bands</th>
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</thead>
</table>
| **US** | 2G/3G: 1,2,4,5,8  
          LTE: 2,4,5,13,17,29  
          Roaming LTE: 1,3,7,20 | 4+17,  
                                2+17,  
                                2+29,  
                                4+29,  
                                2+13, 4+13 |
| **EU** | 2G/3G: 1,2,4,5,8  
          LTE: 2,3,4,7,8,20,40  
          Roaming LTE: 12,17,28 | 3+20,  
                                7+20, 3+7,  
                                3+8 |
| **ROW** | 2G/3G: 1,2,4,5,8  
           LTE: 1,3,5,7,8,11,21,28,39,40,41  
           Roaming LTE: 17,20 | 3+7, 3+8,  
                                3+5, 3+28,  
                                7+28 |

#### Specifications for CY15+ devices

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                                      2+29,  
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                                      4+12 |
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          Roaming LTE: 12,17,28,41 | 3+20, 7+20,  
                                      3+7, 3+8,  
                                      2+4, 3+3,  
                                      4+4, 40+40 |
| **ROW** | 2G/3G: 1,2,4,5,8  
           LTE: 1,3,5,7,8,11,19,21,28,39,40,41  
           Roaming LTE: 17,20 | 1+3, 1+7,  
                                3+7, 3+8,  
                                3+5, 1+28,  
                                3+28, 7+28,  
                                1+19, 1+21, 
                                11+18,  
                                39+39,  
                                40+40, 41+41 |
Why we need added performance

Mobile Data Consumption Continues to Grow Exponentially

66% CAGR 2012–2017
Exabytes / Month

- 1 EB = $10^{18}$ bytes = = 1 billion gigabytes.

Source: RFMD Cellular Group
Key Issue for Rel 9 Carrier Aggregation 4G Standards

EXAMPLE: B17 AND B4 RX CARRIER AGGREGATION

- We need 4 receivers at the same time
- We need a linear transmitter chain during RX CA
IIP3 REQUIREMENTS FOR 4G NETWORKS

- 4G Standards require unprecedented levels of component linearity
- All components in the Front End chain need to be appropriately spec’ed
- 88-90dBm IIP3 requirements at critical components where TX/RX co-exist
- RF Tuners and TR switches most affected by such requirements

*Source: Intel Mobile Corporation, “Challenges for Radios Due to Carrier Aggregation Requirements”, Nov 2012
4G Cellular Front End Challenges for 90dBm IP3

- Critical switch components where IP3=90dBm is potentially required for 4G
- In FDD modes, wherever TX can cause desense on RX, thereby dropping call
Integration Flowchart: SIP vs SOP for Cellular FEM

LESSONS LEARNED

System in Package

Is Integration technically feasible?

NO

YES

System on Chip

Is Integration required by the application?

YES

YES

Does Integration add to final cost?

YES

NO

Curt Barratt – ex-VP GaAs operations RFMD
Stay aware of Advanced Packaging Technologies

Embedded Die Module

Thru-Module-Via / Stacked Modules

Wafer Level Fan out with PoP

‘aggressive’ Copper Pillar roadmap

Advanced Packaging may cancel out many integration benefits!
Gartner Hype Cycle for RF SOI / RF MEMS in cellular applications

LEARN WHERE YOU ARE IN THE HYPE SCALE!

>20 years typical
Gartner Hype Cycle for RFSOI / RF MEMS in cellular applications
Substrate Induced Harmonics

- High RF voltages in the circuit induce a Parasitic Conduction Layer in the silicon/STI interface

- RF Signals will couple to this parasitic layer and modulate its electrical conduction characteristics => generates harmonics!

- This effect needs to be mitigated by:
  - Proprietary Interface Treatments
  - Interface Trap-Rich Layer
  - RF Ground Shields
  - Utilization of an ideal dielectric substrate (glass/sapphire)

Substrate-Induced Harmonics

- HR Silicon substrates under metal lines generate HARMONICS at high power levels!
- Trap Rich poly-silicon layers dramatically reduce harmonic levels caused by the substrate
- Technique readily implemented in the RFSOI industry
- MEMS on silicon must also handle this problem in some manner or they will lag RFSOI in linearity!
RFSOI Switched Capacitor: basic building block

N x stacked FETs

MIM capacitor

HR SOI handle
RFSOI MIM Capacitors Trends

- MOS Capacitors not generally used due to non-linear behavior
- Single (High Density) or Double (High Voltage)
- Stacked Double MIMs available (saves metal layers)
- Silicon Nitride-based films; still no viable high $\varepsilon$ dielectric commercially available!
- MOM capacitors: few metal layers in process generally make MOMs too large or unfeasible
RFSOI Stacked FET in Switched Caps

- Stack number / FET selection carefully determined by voltage handling in OFF state
  - FOM 230fs => 150fs => <100fs in 2016
- Careful RDSON-W tradeoff depending on switched branch capacitance
  - Rseries => Q of switch MIM
- Unlike RF switches, no shunt paths for isolation improvement
- Many configurations need to be investigated to optimize overall Q / tuning ratio / impedance coverage
RFSOI PAC’s (Programmable Cap)

- Effective Q of programmable capacitor depends on Switch Branch Resistance (internal MIM Cap Q is fairly high Q!)

- MIM Capacitors may need to be stacked to handle high Vrms voltage levels

MIM capacitors in CMOS are implemented with square vias to a top plate.
Switched Capacitor Q vs FOM in RFSOI (Whatley et al)

\[ C_{\text{min}} = \left(2^{\text{bits}} - 1\right) \frac{C_{\text{MIM}} \cdot C_{\text{OFF}}}{C_{\text{MIM}} + C_{\text{OFF}}} \]

\[ C_{\text{max}} = \left(2^{\text{bits}} - 1\right) C_{\text{MIM}} \]

Tuning ratio \[ \frac{C_{\text{max}}}{C_{\text{min}}} = 1 + \frac{C_{\text{MIM}}}{C_{\text{OFF}}} \]

\[ Q_{\text{min}} = \frac{1}{\omega C_{\text{MIM}} R_{\text{ON}}} = \frac{1}{\omega \cdot \left(\frac{C_{\text{max}}}{C_{\text{min}}} - 1\right) \cdot R_{\text{ON}} \cdot C_{\text{OFF}}} \]

• Demonstrates choice of Q vs Tuning Ratio For different FOM’s

RF Front-End Tunability for LTE Handset Applications

Richard Whatley, Tero Ranta, and Dylan Kelly

Figure 4: DTC Q vs. Tuning Ratio for several \( R_{\text{on}} C_{\text{off}} \) values
RFMD Antenna Tuner products RFSOI

- Versatile single chip SOI CMOS based antenna tuner
- Single chain tuner covering 0.7 – 2.2 GHz
- WLCSP for low parasitics and small size
- MIPI RFFE controlled
- Die size 2.4 x 2.6 mm

Application board photo showing surface mount inductors
Inductor Q

- Critical Inductors needed for Impedance Tuners to minimize loss of tuning network
- Q’s ~ 50-70 typical at 1GHz
- Critical design choice for tuner networks
- Essentially it becomes the limiting factor of a tuner network and not capacitor Q’s
- On-going research for Q optimization could yield values >100 near term
Tornado 2 shunt PAC characterization results

PAC = Programable Array of Capacitors

- **Cs (pF)** versus state at different frequencies:
  - f = 1000 MHz
  - f = 2000 MHz

- **Q** versus state at different frequencies:
  - f = 1000 MHz
  - f = 2000 MHz

- **Rs (Ω)** versus state at different frequencies:
  - f = 1000 MHz
  - f = 2000 MHz

Total extracted series inductance = 0.131nH (above data is deembedded for this); Shunt capacitance range = 0.51 to 4.65 pF.
Tornado 2: Tuner gain vs load impedance; 895 MHz

Green break even circle @ $G_{\text{TUNER}} = 0$ dB. Where losses and improvement by tuning balances

Tuner PAC states optimized to give maximum $G_{\text{TUNER}}$

Red circles represent load VSWR of 2, 3, and 5.

$G_{\text{TUNER}} = -0.56$ dB @ 50 Ω
Tornado 2: Tuner gain vs load impedance; 1940 MHz

Green break even circle @ $G_{\text{TUNER}} = 0$ dB. Where losses and improvement by tuning balances

Tuner PAC states optimized to give maximum $G_{\text{TUNER}}$

$G_{\text{TUNER}} = -0.63$ dB @ 50 Ω

Red circles represent load VSWR of 2, 3, and 5
Other Tunable Notches in RFSOI

- Options for component implementation
  - Laminates/Ceramics for high density integration
  - SOI for tunable components/RFFE Control
  - SMD for high performance
Tunable Networks with RFSOI

- Full EM Modeling of entire stack
- Large Scale manufacturing with high yields
- Low cost and small profile
- Very exciting product family to follow!
Conclusion

- 4G Cellular standards with carrier aggregation will require unparalleled levels of linearity in key switch and tuner components where TX bands co-exist with problematic dual/quad RX bands.

- Techniques for mitigation of substrate induced harmonics need to continue to minimize induced distortion to reach IP3 requirements for 4G CA standards.

- RFSOI and MEMS solutions will compete in the RF Front End space for tuning solutions. MEMS technologies may need to migrate to substrates with similar level of harmonic treatments to accomplish such distortion requirements.