Direction of RF-CMOS tuner technology

Akira Matsuzawa

Department of Physical Electronics
Tokyo Institute of Technology

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SoC for DVD systems

Before talking about RF-CMOS for tuners

Digital signal processing enables perfect cure for the damaged signals.

World first fully integrated mixed signal SoC for DVD systems has developed.

Digital read channel technology

0.13um CMOS, 24Mtr

Okamoto, et. al., ISSCC 2003.

7b, 400MHz, 40mW ADC has been developed

My last work in Panasonic
Power of SoC

SoC has enabled performance increase and cost decrease. Many components and ICs have been kicked out from the PC board.

Panasonic DVD recorder

Contents

• Conventional AM/FM tuner
• Analog-centric CMOS tuner
• Digital-centric CMOS tuner
• Feature of CMOS technology
• Conclusion

E-mail: matsu@ssc.pe.titech.ac.jp
URL: http://www.ssc.pe.titech.ac.jp/

Courtesy Niigata-Seimitsu Co., Ltd.
Current AM/FM tuner system

Current AM/FM tuner uses 3 ICs and large # of external components. Furthermore 12 adjustment points are needed.

Large # of products, but not expensive product. More efforts for the cost reduction are still needed.

Bipolar IC = 1 (RF)  
CMOS IC = 2 (PLL, RDS)  
External Components=187

AM/FM Tuner for home use

12 adjustment points
Large # of external components. They should be integrated on a chip.
Large # of external components are needed due to analog signal processing.

<table>
<thead>
<tr>
<th>External Parts</th>
<th>Blocks to be used</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>FM: Single conversion super heterodyne. IF=10.7MHz</td>
</tr>
<tr>
<td></td>
<td>AM: Single or Double conversion super heterodyne  IF=450KHz or 10.7MHz + 450KHz</td>
</tr>
<tr>
<td>Resistor</td>
<td>AGC, bias, LPF for PLL</td>
</tr>
<tr>
<td>Semi-fixed and Variable resistor</td>
<td>RSSI level alignment, volume control</td>
</tr>
<tr>
<td>Ceramic capacitor</td>
<td>RF bypass, coupling, de-coupling</td>
</tr>
<tr>
<td>Small value capacitor</td>
<td></td>
</tr>
<tr>
<td>Electrolytic capacitor</td>
<td>AGC smoother, power-ground decoupling</td>
</tr>
<tr>
<td>Inductor</td>
<td>RF tuning, local oscillator, IF transformer, FM detector</td>
</tr>
<tr>
<td>Variable capacitance</td>
<td>RF tuning, Local oscillator</td>
</tr>
<tr>
<td>Analog filter</td>
<td>Noise canceller, LPF</td>
</tr>
<tr>
<td>Ceramic filter</td>
<td>FM and AM IF BPF for channel filter</td>
</tr>
<tr>
<td>Xtal Osc. element</td>
<td>System clock, Reference for PLL synthesizer</td>
</tr>
<tr>
<td><strong>Total number of external parts</strong></td>
<td><strong>Home tuner and radio cassette tuner : around 165pcs</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Car tuner : 80 to 130pcs</strong></td>
</tr>
</tbody>
</table>
Issues and conventional solutions of AM/FM tuner

Application of CMOS technology to AM/FM tuner looks very difficult, due to lower frequency and high dynamic range.

**Lower frequency**
- AM: 522 KHz to 1710 KHz
- SW: 2.3MHz to 26MHz
- FM: 87.5 to 108 MHz

**Larger Inductance and capacitance** → **External components**

**Serious 1/f noise** → **Bipolar**

**High dynamic range**
- AM: 14 dBuV to 126 dBuV
- FM: 0 dBuV to 126 dBuV

**Sharp and fine filter** → **External filters (Ceramic)**

**High linearity ckt.** → **Bipolar**
1\textsuperscript{st} trial by CMOS technology

1\textsuperscript{st} trial to realize AM/FM tuner by CMOS technology, many external components should be reduced.
Result of analog-centric CMOS tuner

Characteristics is affected by process variation easily. Element mismatch causes DC offset, noise, distortion, and low filter performance. The reduction of # of external components is not attractive for users.

External components 187→69
1st trial was analog-centric CMOS tuner technology.

Circuits have been replaced by CMOS, however still use analog technology. Thus it had many issues and many external components were still needed.

<table>
<thead>
<tr>
<th>Parts</th>
<th>Methods for on-chip</th>
<th>Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM/FM IF BPF</td>
<td>1. Low IF( a few hundred KHz) 2. Gm-C BPF with auto alignment, SCF</td>
<td>1. poor selectivity(-45dB), 2. SCF Switch noise 3. Center frequency shift by DC offset 4. Poor image rejection ratio (25 to 35dB)</td>
</tr>
<tr>
<td>FM Demodulator</td>
<td>Pulse count FM detector</td>
<td>Poor THD (0.5%)</td>
</tr>
<tr>
<td>Stereo Decoder</td>
<td>Multi-vibrator VCO, SCF filter</td>
<td>Large variation of free-run frequency Still need external LPF for PLL</td>
</tr>
<tr>
<td>RSSI Level adj.</td>
<td>Signal detector with DC compensation</td>
<td>Can’t cover all process corner</td>
</tr>
<tr>
<td>Varactor</td>
<td>MOS varactor</td>
<td>Too much sharp C-V curve, distorted signal</td>
</tr>
<tr>
<td>AGC smoother</td>
<td>Time division charge and discharge</td>
<td>Needs large capacitor for low audio frequency</td>
</tr>
<tr>
<td>Capacitors</td>
<td>Stages Direct connection, use small value coupling capacitor</td>
<td>High impedance required, Difficult for low frequency</td>
</tr>
</tbody>
</table>
Issues and advanced solutions of AM/FM tuner

Lower frequency
- AM: 522 KHz to 1710 KHz
- SW: 2.3MHz to 26MHz
- FM: 87.5 to 108 MHz

Larger Inductance and capacitance
- Digital filter, Mixer, PLL
- GHz OSC with divider

Serious 1/f noise
- PMOS

Larger signal dynamic range
- AM: 14 dBuV to 126 dBuV
- FM: 0 dBuV to 126 dBuV

Sharp and fine filter
- Digital Signal processing
- With high resolution ADC
- IF Freq. changed from 10.7 MHz to several 100 KHz

High linearity ckt.
- High resolution ADC
- Switch mixer
- Watching desired and undesired signals
Digital-centric CMOS tuner has been developed.
Digital-centric CMOS tuner

One-chip CMOS tuner has been successfully developed. It can attain high tuner performance and can reduce the # of external components. Furthermore it can realize no adjustment points.

Full CMOS one-chip solution
- # of external components are 11
- No adjustment points
- Sensitivity: FM: 9dBuV, AM: 16dBuV
- Selectivity: FM/AM >65dB
- SNR: FM: 63dB, AM: 53dB
- Stereo sep: 55dB
- Image ratio: FM: 65dB, AM: Infinity
- Distortion: FM: 0.09%, AM=0.25%
Digital-centric CMOS tuner technology

Main signal processing is done by DSP.

1. AM/FM demodulations
2. Stereo decoder
3. AM mixer
4. Channel select filter
5. Support for image reject
6. Watch the signal reveal and control gain of each stage
7. Parameter control and adjustment with MCU

Diagram:

- FM
- AM
- LNA → MIXER → VGA + Filter → ADC → DSP
- DSP processes include:
  - AM/FM demodulations
  - Stereo decoder
  - AM mixer
  - Channel select filter
  - Support for image reject
  - Watch the signal reveal and control gain of each stage
  - Parameter control and adjustment with MCU
Demodulation of AM/FM signal

AM/ FM signals can be demodulated by simple arithmetic operations

1) AM demodulation

\[ [1 + S(t)] \cdot \exp(j\omega_c t) \times \exp(-j\omega_c t) = 1 + S(t) \]

2) FM demodulation

\[ R(t) \exp(\Delta j\omega t + jK_d \int m(\tau)d\tau) \]

\( \Delta \omega : \) Frequency offset

\( R(t) : \) Amplitude variation

\( m(\tau) : \) Baseband signal to be recovered

\[ \theta = \Delta \omega t + K_d \int m(\tau)d\tau \]

\[ \frac{d\theta}{dt} = \Delta \omega + K_d m(t) \]

m(t) can be demodulated
Stereo decoder

The stereo signal can be reconstructed by numerical PLL, mixer, and filter.

\[ S(t) = (L + R) + (L - R) \cos \omega_s t + K \cos \omega_p t \]

\( \omega_s : \text{Sub-carrier} = 38\text{KHz} \)

\( \omega_p : \text{Pilot tone} = 19\text{KHz} \)

PLL locks the pilot tone and generates 38KHz for sub-carrier.
Image rejection

The dummy image signal is generated by IMO and the controller controls signal delay and amplitude on Q path to minimize the I/Q imbalance.

Image frequency oscillator

From ADCs

 IMO

 Controller

 Deci. LPF

 Vari. Delay

 Vari. Gain

 BPF

 DSP

 BPF

 IM detect

Image Rejection Ratio >60dB
### Impact of components reduction

<table>
<thead>
<tr>
<th>Reduced components</th>
<th>Reduction ratio</th>
<th>Impact on the Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip resistor</td>
<td>1/10 pcs or less</td>
<td>Components # will be reduced by more than 7 billion pcs per year.</td>
</tr>
<tr>
<td>Ceramic capacitor</td>
<td>1/10 pcs or less</td>
<td>Components # will be reduced by more than 15 billion pcs per year.</td>
</tr>
<tr>
<td>Electrolytic capacitor</td>
<td>1/10 ~ 1/20 pcs</td>
<td>In AV area estimated 3 billion pcs per year will decrease to less than 500 mil. pcs. Aluminum consumption is expected to decrease by 2 thousand ton per year.</td>
</tr>
<tr>
<td>Chip inductor</td>
<td>1/2 pcs or less</td>
<td>Components # will be less than half the # of existing pcs, but still some remain.</td>
</tr>
<tr>
<td></td>
<td>(0~4pcs)</td>
<td></td>
</tr>
<tr>
<td>FM/AM Ceramic filter</td>
<td>0</td>
<td>Estimated 600 mil. pcs per year will be reduced to 0.</td>
</tr>
<tr>
<td>Varactor diode</td>
<td>0</td>
<td>In AV area, about 1.5 billion pcs per year will be reduced to 0.</td>
</tr>
<tr>
<td>PIN diode</td>
<td>0</td>
<td>In AV area, about 50 mil. pcs per year will be reduced to 0.</td>
</tr>
<tr>
<td>Intermediate-frequency transformer</td>
<td>0</td>
<td>About 1 billion pcs per year will be reduced to tens of millions pcs.</td>
</tr>
<tr>
<td>Bipolar IC for tuner</td>
<td>Incorporated into Full CMOS</td>
<td>Bipolar IC exclusive for RF is not necessary any more.</td>
</tr>
<tr>
<td>Printed board</td>
<td>1/6 pcs or less</td>
<td></td>
</tr>
<tr>
<td>Tuner module</td>
<td>Unit manufacturers fix IC directly onto unit base</td>
<td>Tuner makers are not necessary any more.</td>
</tr>
</tbody>
</table>

*Assuming that units manufactured per year are: 100 mil. units for car radios, 80 mil. units for home radios.*
Feature of CMOS technology

• Digital:
  By Scaling theory
  – Cost/transistor: 0.5x
  – Speed/ transistor: 1.4x
  – Power: 0.5x

  For one technology generation advance

• Analog:
  – $f_T$ increase: 1.4x
  – Large mismatch, large PVT fluctuations
  – Low gm (1/3 vs. Bipolar)
  – Affected by digital noise seriously
Integration and power dissipation trend

Integration level increases and power dissipation decreases with scaling

![Graph showing gate density and power dissipation trends with technology generation.](image)
Feature of Analog CMOS technology

• Pros
  – Can use switch and voltage controlled conductance
  – Smaller distortion
  – No carrier accumulation
  – Can use switched capacitor circuits
  – Can increase $f_T$ by scaling
  – Easy use of complementally circuits
  – Easy integration with digital circuits

• Cons
  – Low $g_m/I_{ds}$
  – Larger mismatch voltage and 1/f noise
  – Lower operating voltage with scaling
  – Difficult to enable impedance matching
  – Easily affected by substrate

1/f noise of MOS is much larger than that of bipolar. For the lower 1/f noise, the larger gate area is needed.

\[ V_{nf}^2 = \frac{S_{vf} \Delta f}{LW f}, \quad S_{vf} \propto T_{ox}^2 \]

- For the lower 1/f noise, the larger gate area is needed.
Why CMOS?

- Low cost
  - Must be biggest motivation
  - CMOS is 30-40% lower than Bi-CMOS

- High level system integration
  - CMOS is one or two generation advanced
  - CMOS can realize full system integration

- Stable supplyment and multi-foundries
  - Fabs for SiGe-BiCMOS are very limited.
    → Slow price decrease and limited product capability

- Easy to use
  - Universities and start-up companies can use CMOS with low usage fee, but SiGe is difficult to use such programs.
Is CMOS cheaper?

Wafer cost of SiGe BiCMOS is 30-40% higher than CMOS at the same generation, however almost same as one generation advanced CMOS.
Cost up issue by analog parts

Cost of mixed A/D LSI will increase when using deep sub-micron device, due to the increase of cost of non-scalable analog parts.

Large analog may be unacceptable. Some analog circuits should be replaced by digital circuits.

Technology trend in RF-CMOS LSI

Analog-centric RF CMOS will be replaced by digital-centric RF CMOS. High performance, low cost, stable and robust circuits, no or less external components, no adjustment points, and high testability are the keys. DSP and ADC will play important role.

### Technology Trends

<table>
<thead>
<tr>
<th>Analog-centric</th>
<th>Digital-centric</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal processing</strong></td>
<td><strong>Digital processing</strong></td>
</tr>
<tr>
<td>Analog circuits</td>
<td>DSP+ADC + Small and robust analog ckts.</td>
</tr>
<tr>
<td>Analog processing +External component</td>
<td></td>
</tr>
<tr>
<td><strong>Adjustment</strong></td>
<td><strong>Digital on chip, no external</strong></td>
</tr>
<tr>
<td>External</td>
<td></td>
</tr>
<tr>
<td><strong>External components</strong></td>
<td><strong>No or less</strong></td>
</tr>
<tr>
<td>Large #</td>
<td></td>
</tr>
</tbody>
</table>
Analog centric RF CMOS will be replaced by digital centric RF CMOS.

- Wireless LAN, 802.11 a/b/g
  0.25um, 2.5V, 23mm², 5GHz

- Discrete-time Bluetooth
  0.13um, 1.5V, 2.4GHz
Wide-band delta-sigma ADC

Wide band and high dynamic range delta-sigma ADC is the key for digital centric systems

90nm CMOS, BW=20MHz, DR(=SNR)=77dB, 50mmW, FoM=200fJ/conv.

L. J. Breems, et., al.
“A 56mW CT Quadrature Cascaded SD Modulator with 77dB in a Near aero-IF 20MHz Band.
ISSCC 2007, pp. 238-239.

<table>
<thead>
<tr>
<th>Technology</th>
<th>90nm CMOS, 1P6M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>1.2V</td>
</tr>
<tr>
<td>Architecture</td>
<td>CT quadrature cascaded $\Sigma\Delta$ modulator (2-2, 4b)</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>340MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20MHz @ 10.5MHz IF</td>
</tr>
<tr>
<td>Max. input voltage</td>
<td>1Vp (differential)</td>
</tr>
<tr>
<td>Dynamic range*</td>
<td>77dB (97dB @ 200kHz, 115dB @ 3kHz)</td>
</tr>
<tr>
<td>Peak SNR / SNDR*</td>
<td>71dB / 69dB</td>
</tr>
<tr>
<td>Image rejection</td>
<td>&gt;55dB (for -1MHz input tone)</td>
</tr>
<tr>
<td>Active chip area</td>
<td>0.5mm$^2$</td>
</tr>
<tr>
<td>Power consumption</td>
<td>50mW (analog), 6mW (digital)</td>
</tr>
<tr>
<td>Figure-of-merit (FOM)</td>
<td>0.2pJ/conv. (FOM=P/(2$^\text{enob}$<em>2</em>BW))</td>
</tr>
</tbody>
</table>

(*1MHz input signal, signal bandwidth is 20MHz)
The bandwidth of sigma-delta ADCs has been increased up to 20MHz with effective resolution of about 12 bit.

Nyquist ADC:

\[ SNR \propto CV_{sig}^2 \]

Delta-sigma ADC:

\[ SNR \propto CV_{sig}^2 \cdot M^\alpha \]
Conclusion

- Radio tuners have not been replaced by CMOS technology in contrast to many other wireless systems; cellular phones and wireless LANs have been replaced by CMOS.
  - Low frequency:
    - External large L and C, Filters
    - 1/f noise
  - High dynamic range:
    - External sharp and fine tuning filters

- Analog-centric CMOS technology is not effective
  - No attractive performance and affected by PVT fluctuation seriously.
  - Cost increase for further technology scaling
  - Still need large # of external components and adjusting points

- Digital-centric CMOS technology must be right way
  - High performance and very robust against PVT fluctuations
  - Further performance increase and cost reduction are expected by using more scaled technology
  - No or less external components and no adjustment points