Digital-Centric RF-CMOS technology

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Courtesy Niigata-Seimitsu Co., Ltd.

Digital-centric CMOS tuner technology

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– **Conventional AM/FM tuner**
– **Analog-centric CMOS tuner**
– **Digital-centric CMOS tuner**

Cost up issue by analog parts

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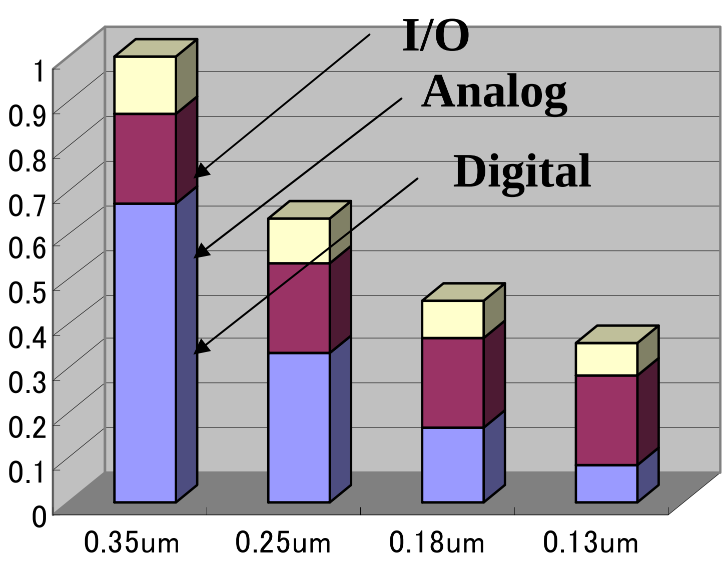
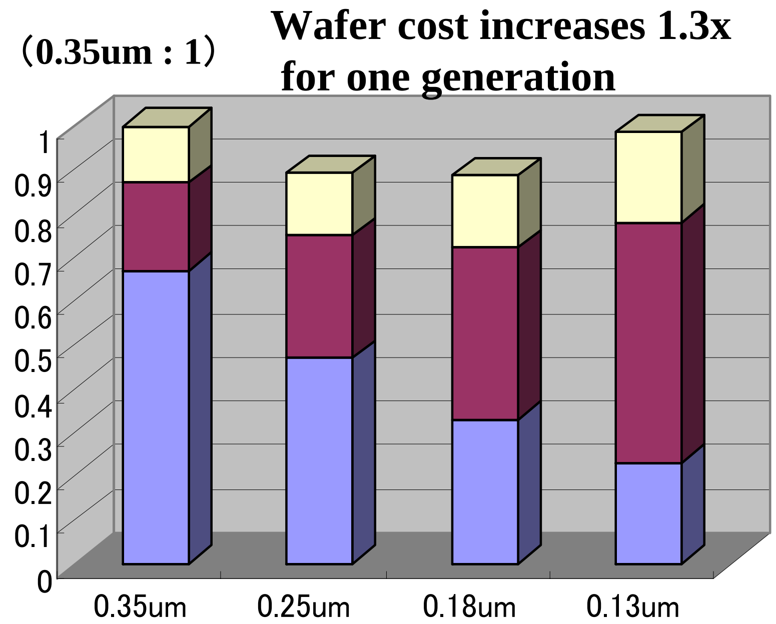
Cost of mixed A/D LSI will increase when using deep sub-micron device, due to the increase of cost in non-scalable analog parts.

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



Chip area



Chip cost

Akira Matsuzawa, "RF-SoC- Expectations and Required Conditions," IEEE Tran. On Microwave Theory and Techniques, Vol. 50, No. 1, pp. 245-253, Jan. 2002

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 roles.

Analog-centric → **Digital-centric**

	Analog-centric	Digital-centric
Signal processing	Analog circuits Analog processing +External component	DSP+ADC + Small and robust analog ckts.
Adjustment	External	Digital on chip, no external
External components	Large #	No or less

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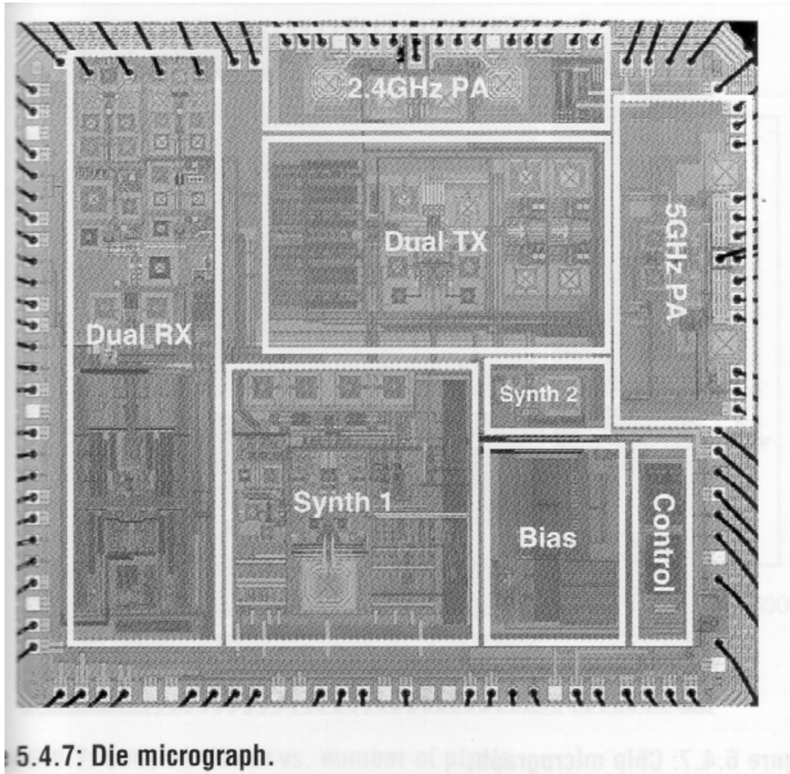
Technology trend in RF CMOS LSI

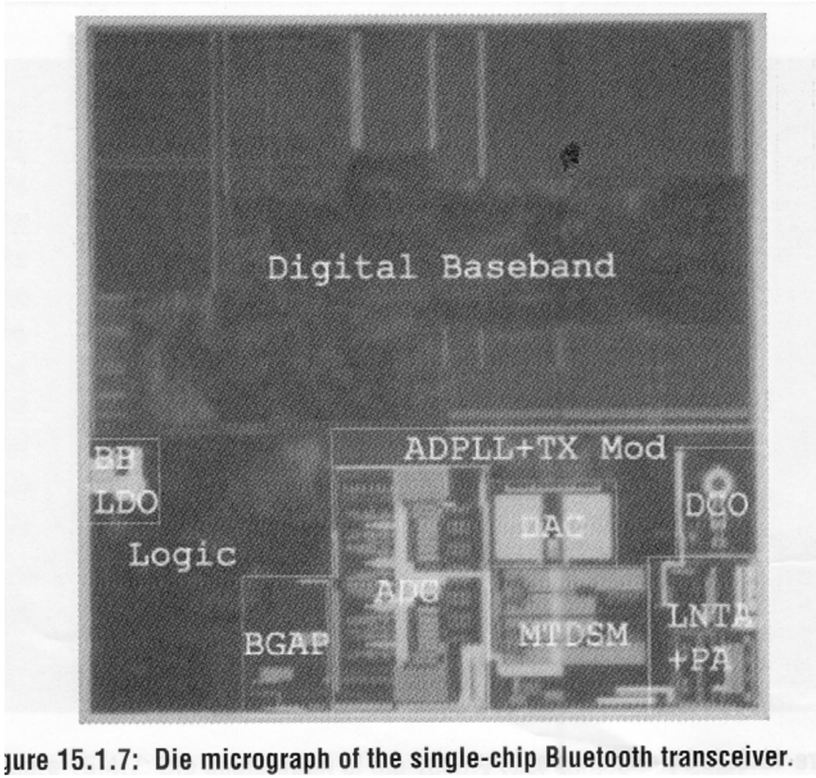
Analog-centric RF CMOS will be replaced by digital-centric RF CMOS.

Wireless LAN, 802.11 a/b/g
0.25um, 2.5V, 23mm^2, 5GHz



M. Zargari (Atheros), et al., ISSCC 2004, pp.96

Discrete-time Bluetooth
0.13um, 1.5V, 2.4GHz



K. Muhammad (TI), et al., ISSCC2004, pp.268

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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 to reduce the cost are still required.

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

AM/FM Tuner for home use

12 adjustment points

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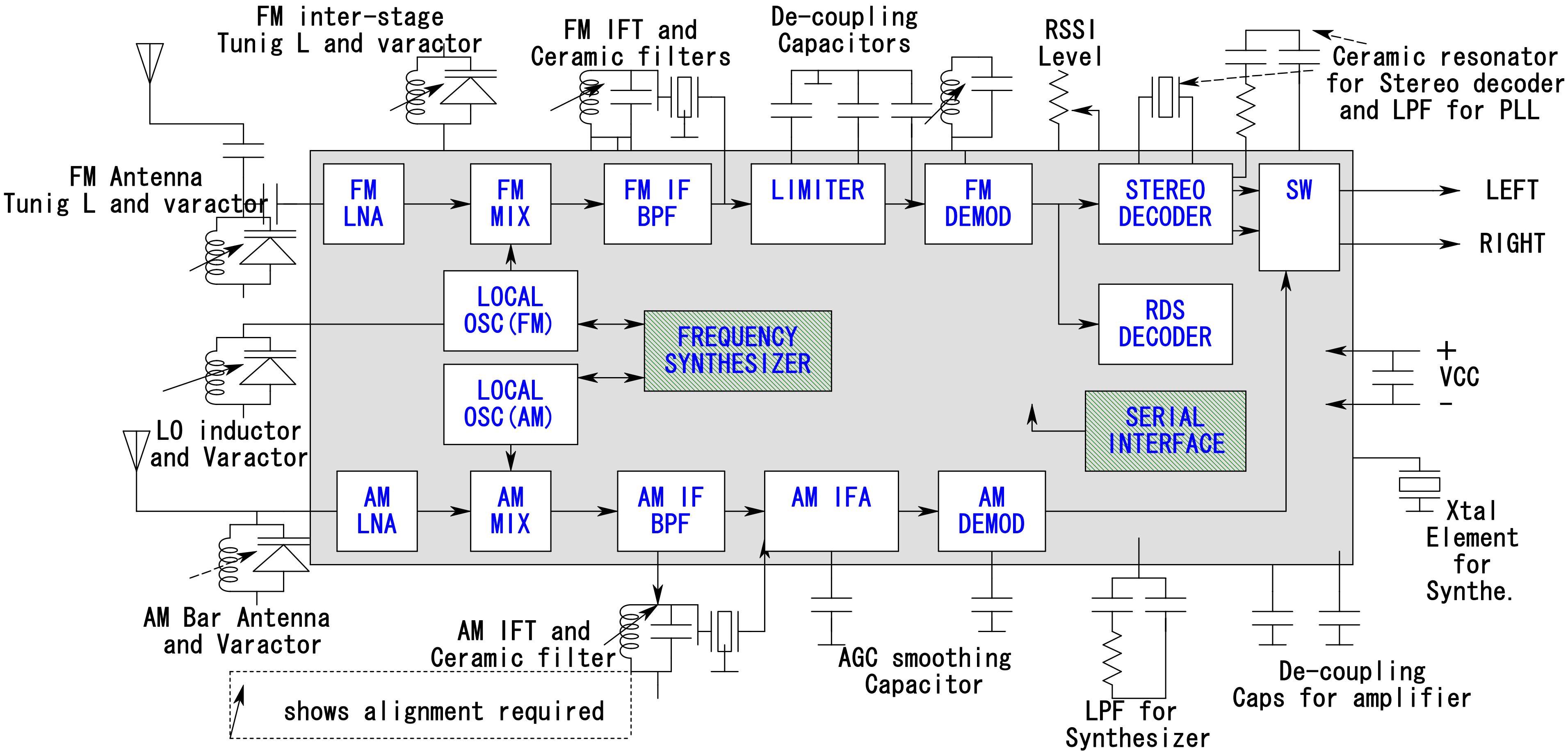
Block Diagram of Current FM/AM tuner

Large # of external components. They should be integrated on a chip.



External parts used in existing IC

Large # of external components are required due to analog signal processing.

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

Issues and conventional solutions for 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

Higher dynamic range

AM: 14 dBuV to 126 dBuV
FM: 0 dBuV to 126 dBuV

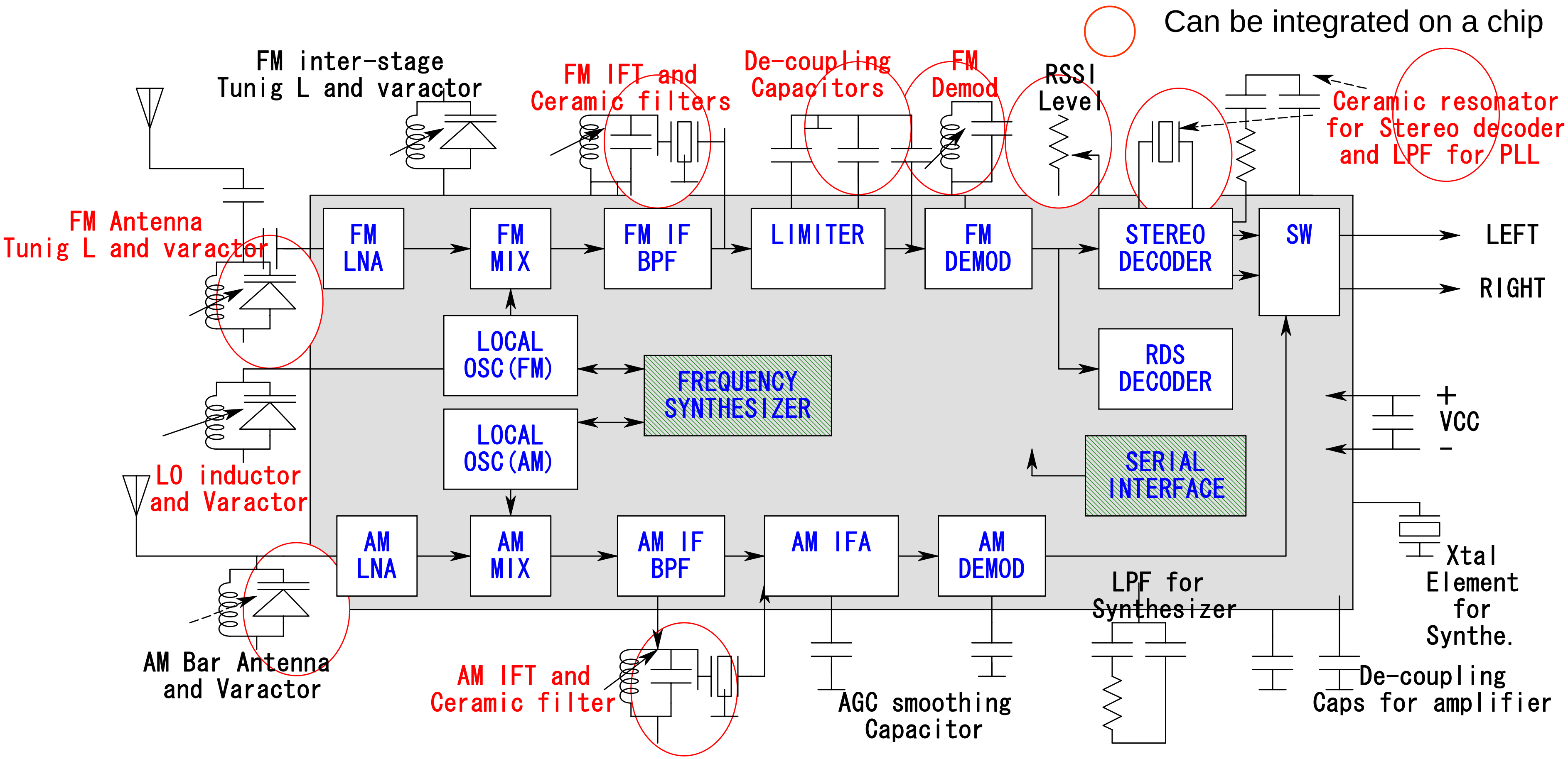
Sharp and fine filter → External filters (Ceramic)

External varactors

High linearity ckt. → Bipolar

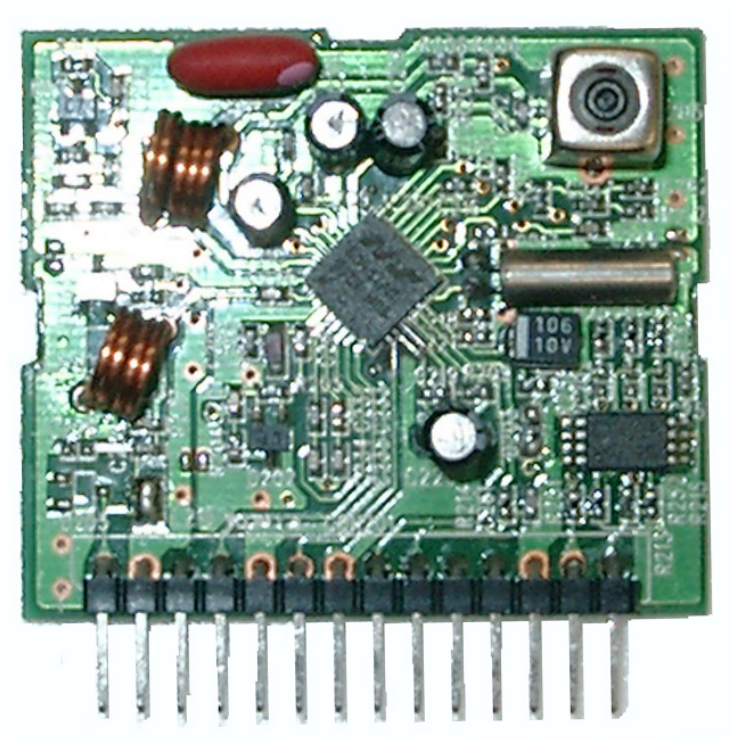
1st trial by CMOS technology

1st 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

Analog-centric CMOS tuner technology

1st trial used 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.

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

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

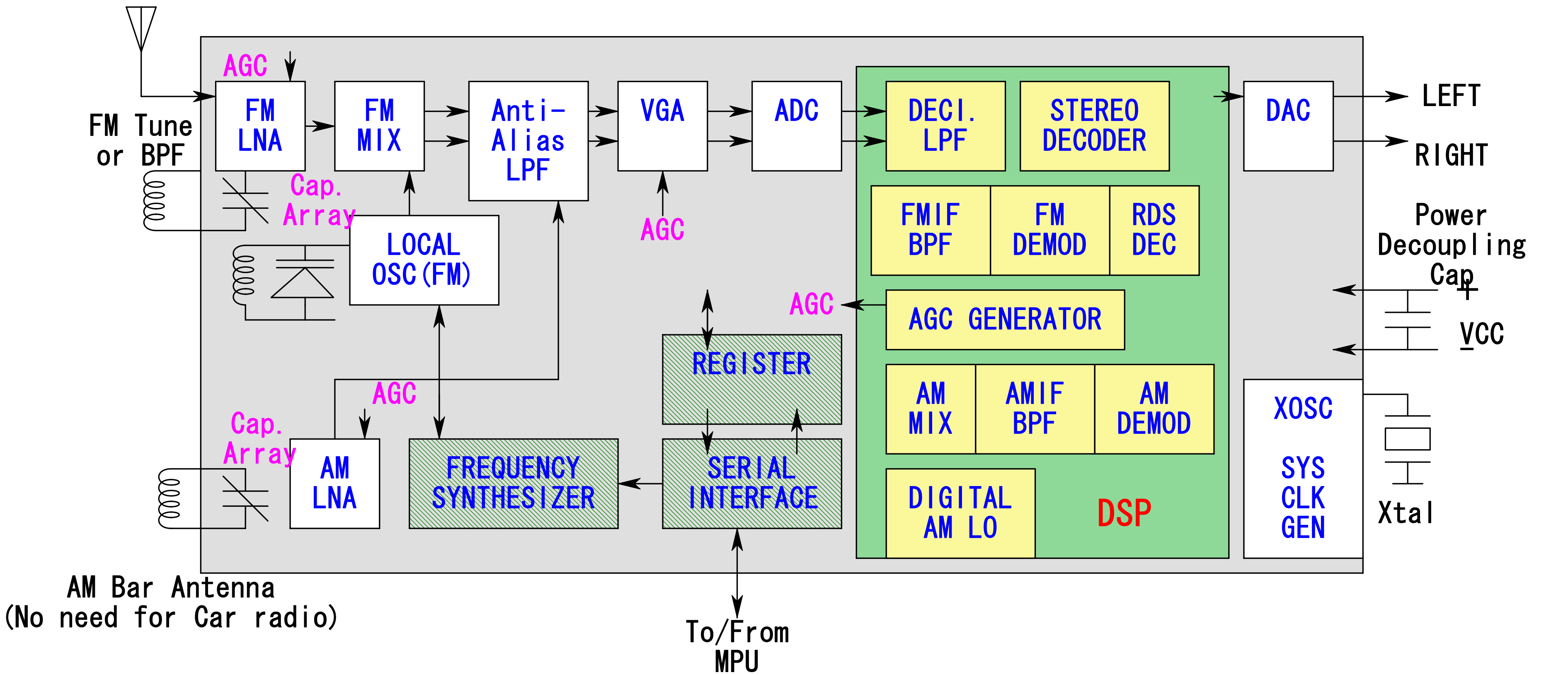
Higher signal dynamic range

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

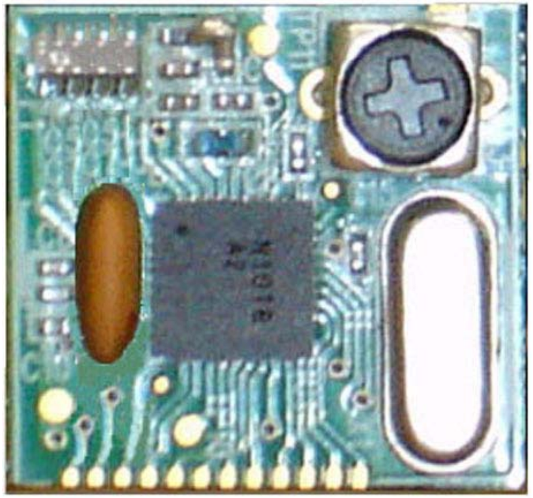
Advanced CMOS tuner

Digital-centric CMOS tuner has been developed.



Digital-centric CMOS tuner

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



Full CMOS one-chip solution

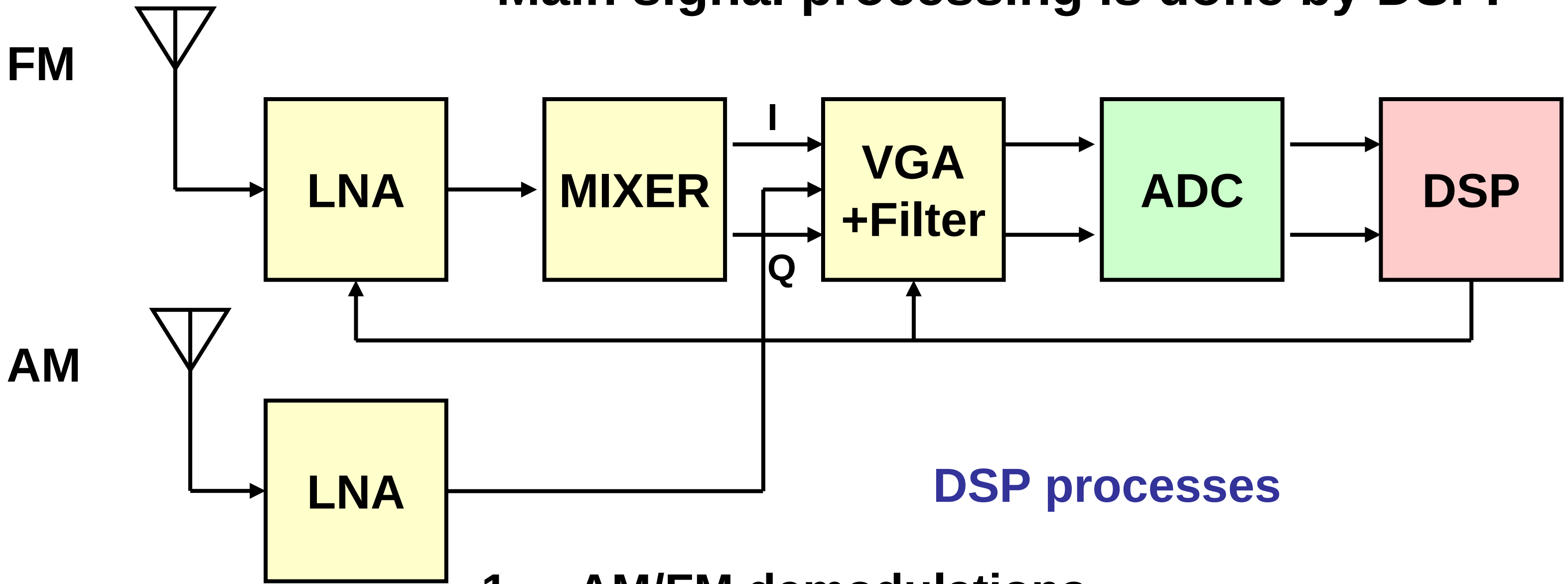
# of external components are 11

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.



DSP processes

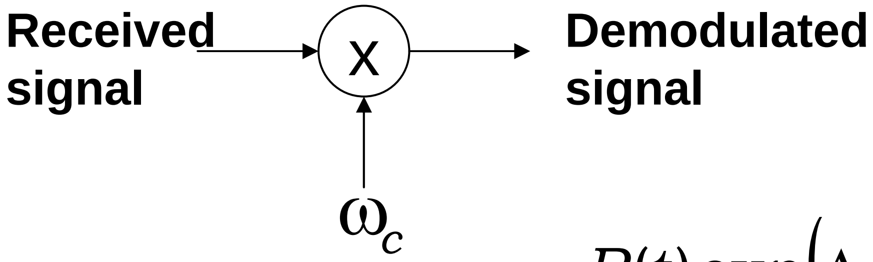
1. AM/FM demodulations
2. Stereo decoder
3. AM mixer
4. Channel select filter
5. Support for image reject
6. Watch the signal revel and control gain of each stage
7. Parameter control and adjustment with MCU

Demodulation of AM/FM signal

AM/ FM signals can be demodulated by simple arithmetic operations

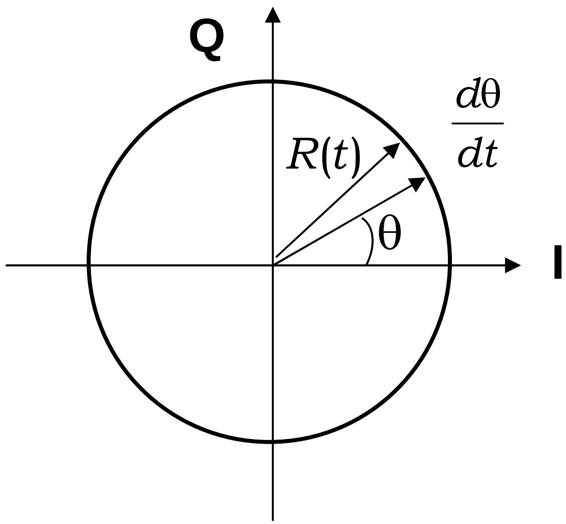
1) AM demodulation

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



2) FM demodulation

$$R(t)\exp\left(\Delta j\omega t+jK_d\int m(\tau)d\tau\right)$$



$\Delta\omega$: *Frequency offset*

$R(t)$: *Amplitude variation*

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

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

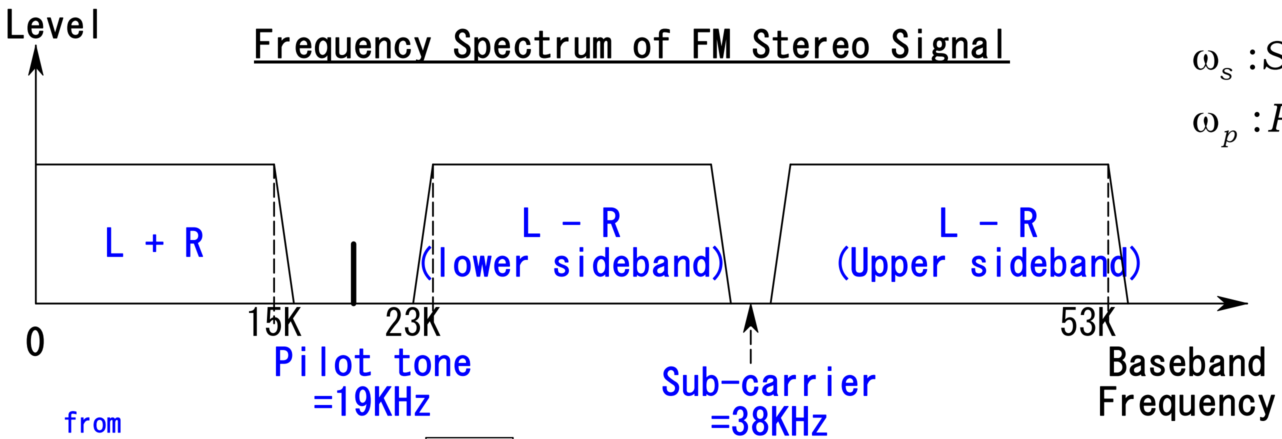
$$\frac{d\theta}{dt}=\Delta\omega+K_d m(t)$$

m(t) can be demodulated

Stereo decoder

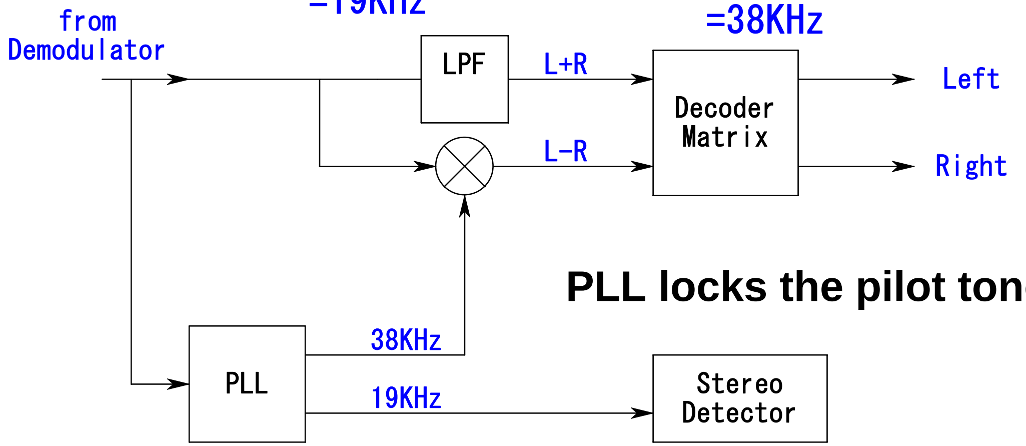
Te stereo signal can be reconstructed by numerical PLL, mixer, and filter.

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



$\omega_s : Sub-carrier = 38KHz$

$\omega_p : Pilot\ tone = 19KHz$



$$(L+R)+(L-R)=2L$$
$$(L+R)-(L-R)=2R$$

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

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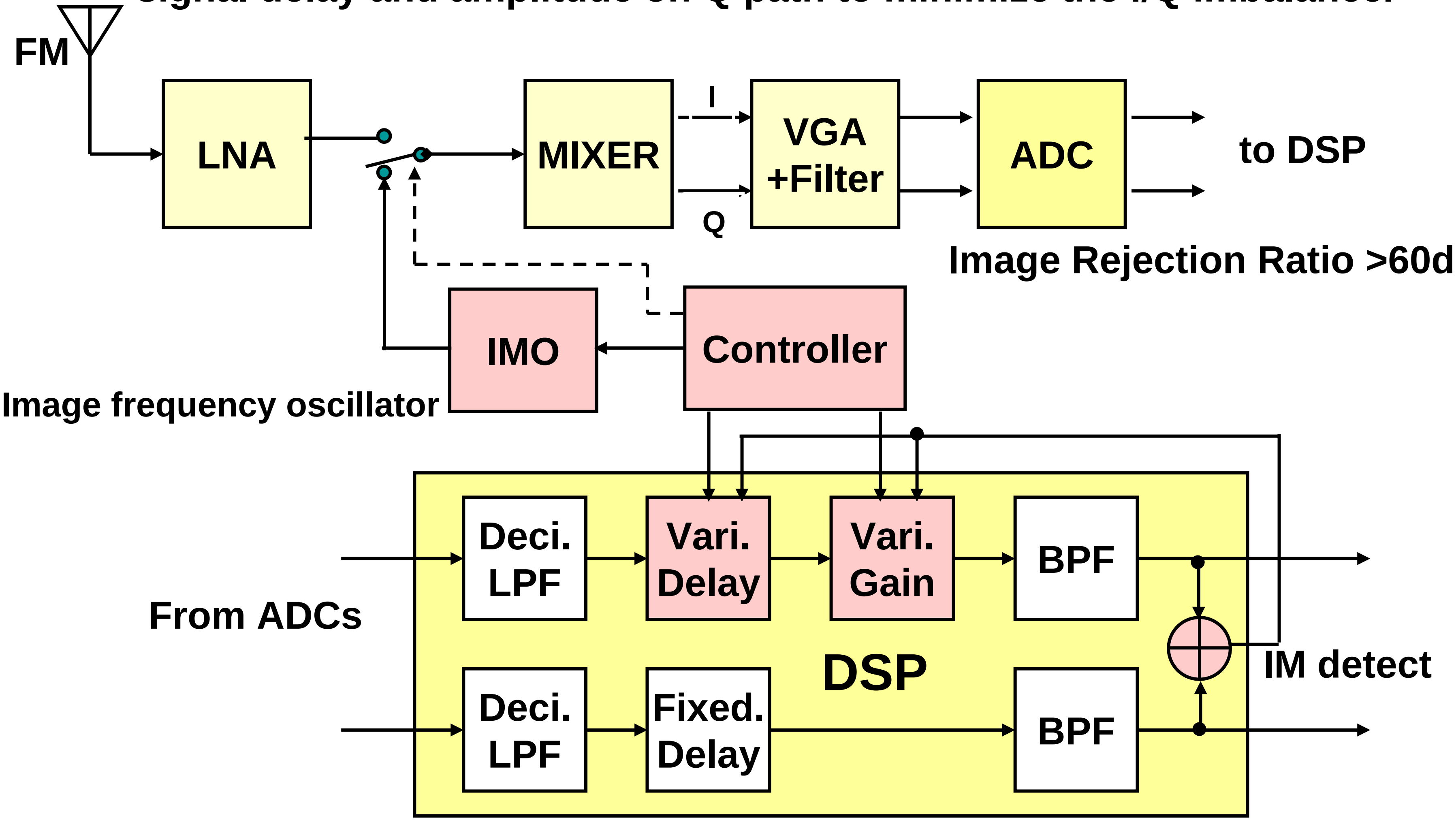
Image rejection

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.



Impact of components reduction

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

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

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Digital-RF technology

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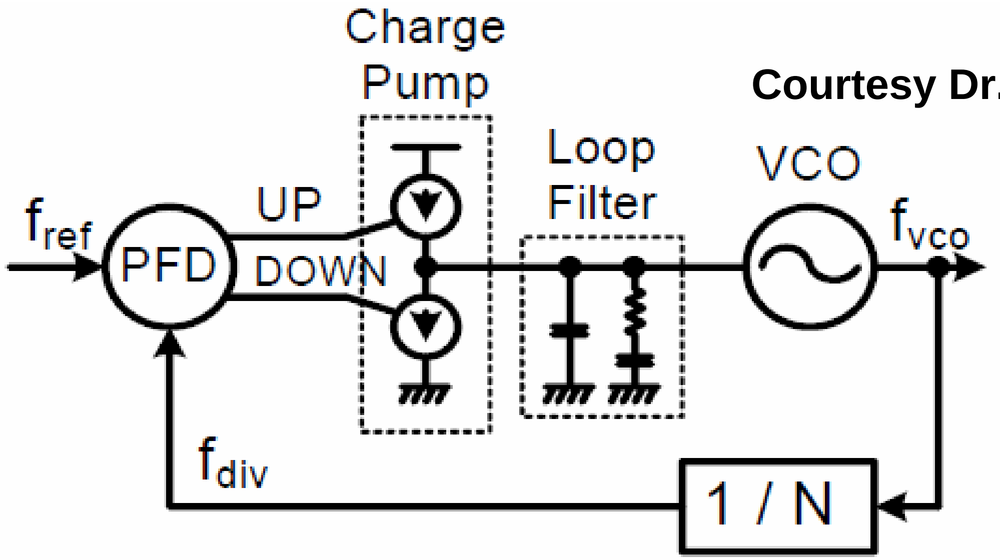
– **All Digital PLL**
– **Sampling mixer**

Issues of conventional PLL

Performance of conventional PLL will degrade along with technology scaling. Functions are not sufficient for future systems.

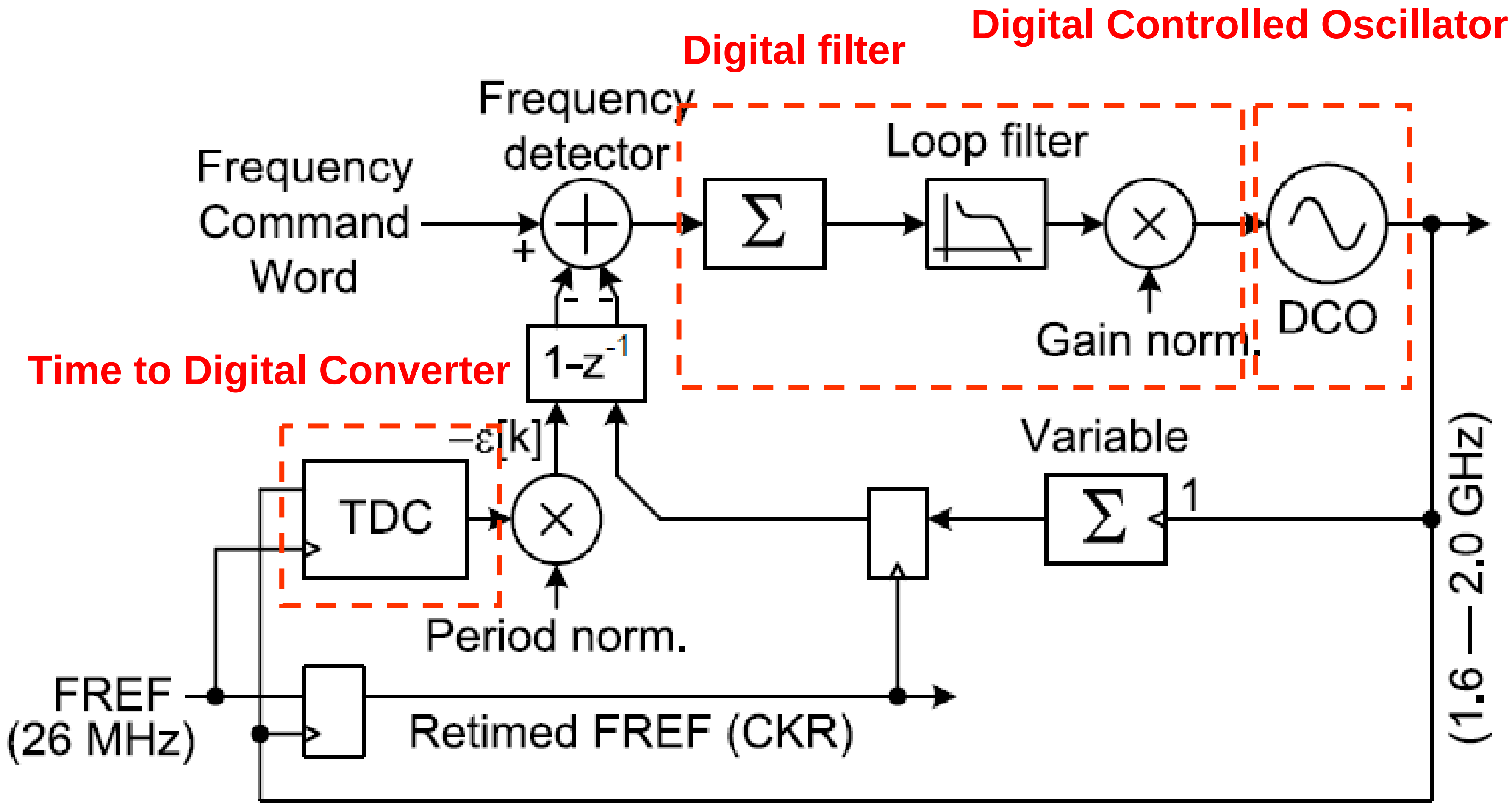
Courtesy Dr. R.B. Staszewski, TI



- Many analog functions = multiple noise sources
- Varactors in VCO are sensitive (high tuning factor, i.e. KVCO)
- Loop filter may be large, leaky capacitors (for open loop "freeze"), variances in passives…
- Hard to calibrate
- Lock times can be long (>100μsec)

All-Digital PLL

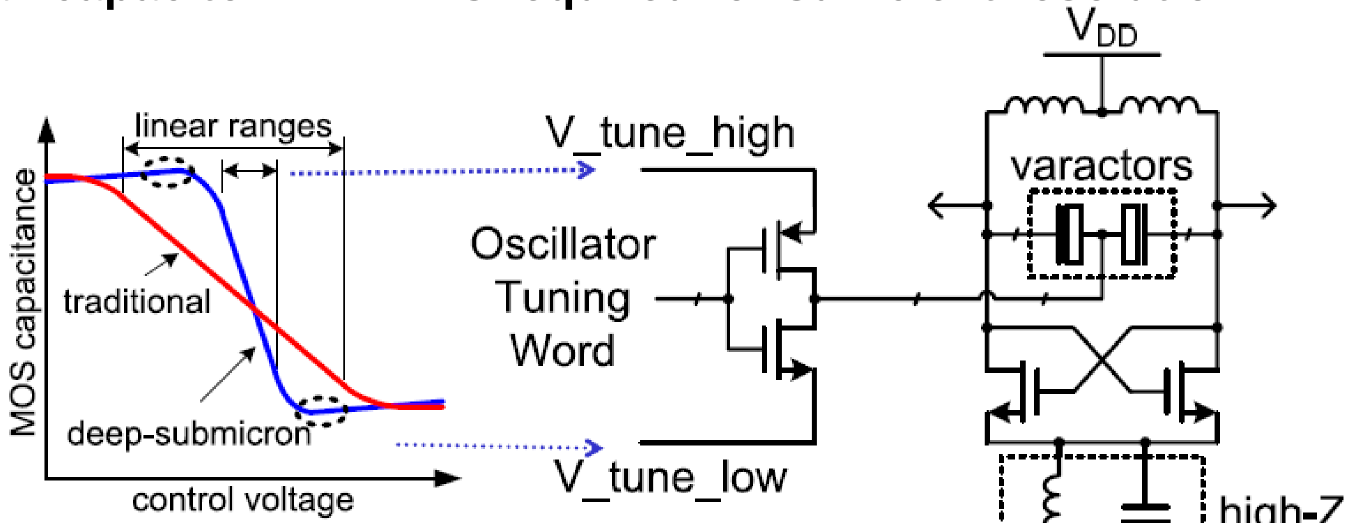
ALL-Digital PLL has been proposed.

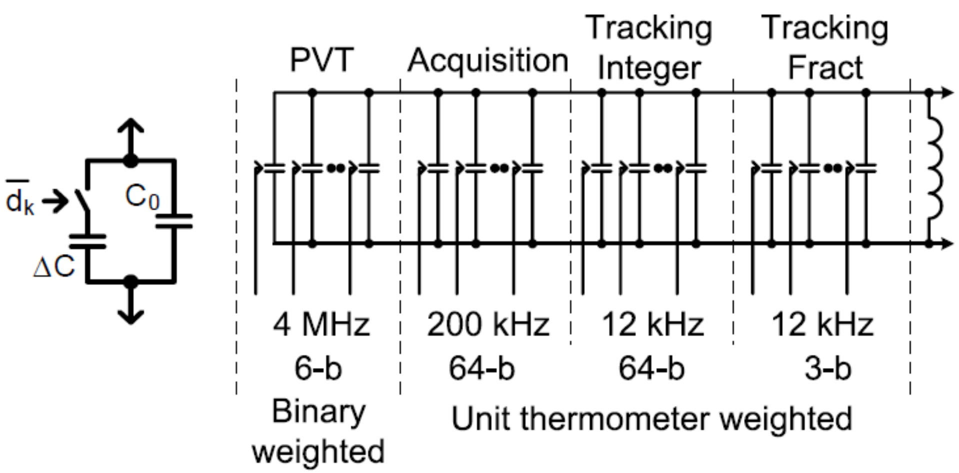


Courtesy Dr. R.B. Staszewski, TI

Digitally-controlled oscillator

Pros: Small effect to AM/PM conversion and noise on control voltage.
Cons: Extremely small capacitor L.T 1fF is required for sufficient resolution.



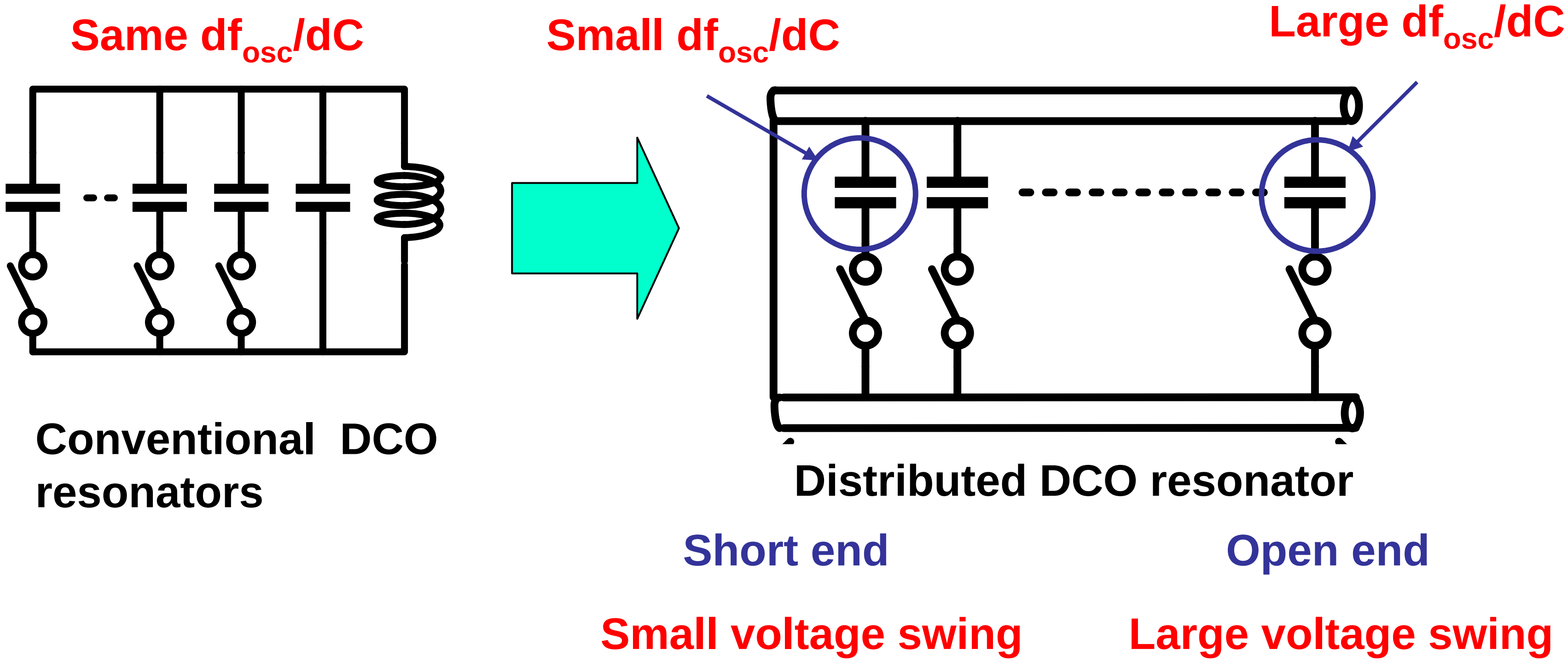


Courtesy Dr. R. B. Staszewski, TI

High-speed dithering and dynamic element matching are used to achieve high resolution (LSB = ~1.5Hz).

Proposed DCO

We proposed distributed DCO to realize fine frequency tuning with conventional capacitors



Win Chaivipas, Takeshi Ito, Takashi Kurashina, Kenichi Okada, and Akira Matsuzawa
"Fine and Wide Frequency Tuning Digital Controlled Oscillators
Utilizing Capacitance Position Sensitivity in Distributed Resonators"
A-SSCC, 16-1, pp 424-427, korea, jeju, Nov, 2007

Measured C to F_{osc} sensitivity

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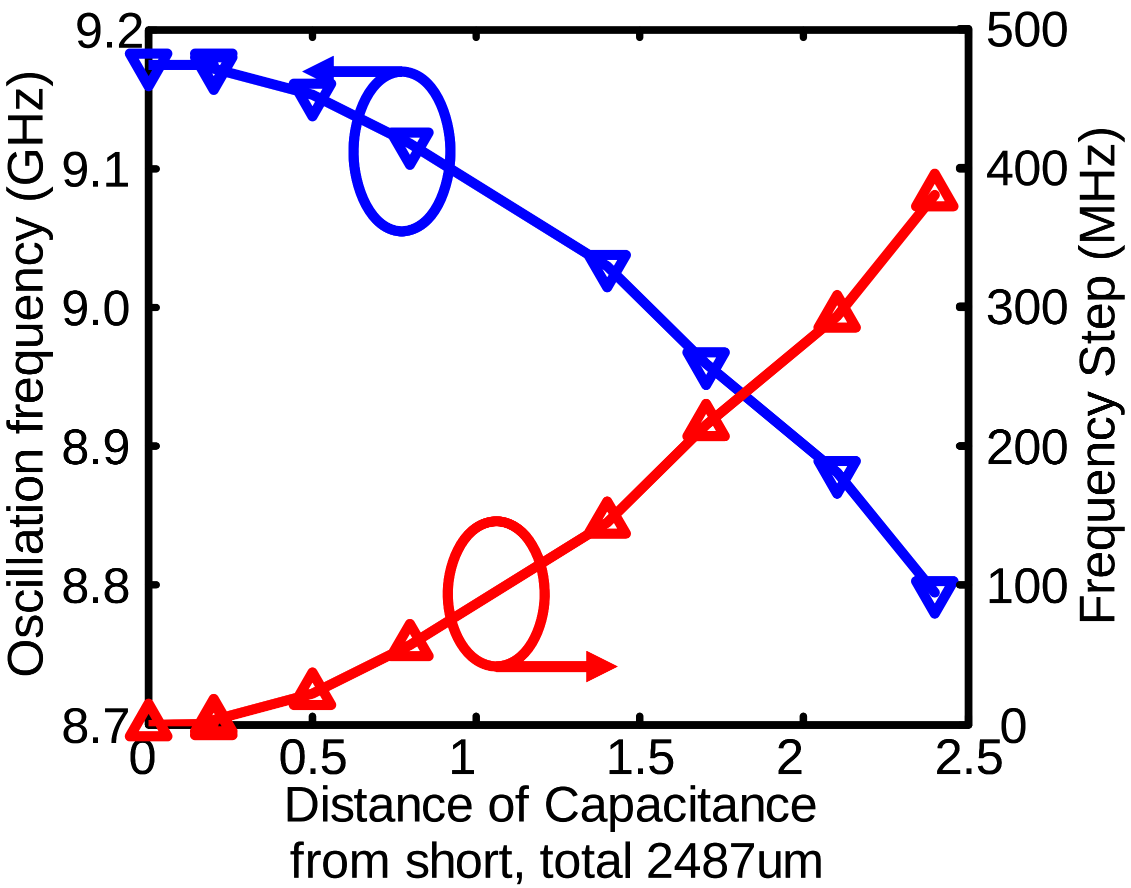
Over 100x capacitance to frequency sensitivity has been observed.



Outer Step C0
376 MHz

Inner Step C6
3.45 MHz

Min Step C7
<100kHz

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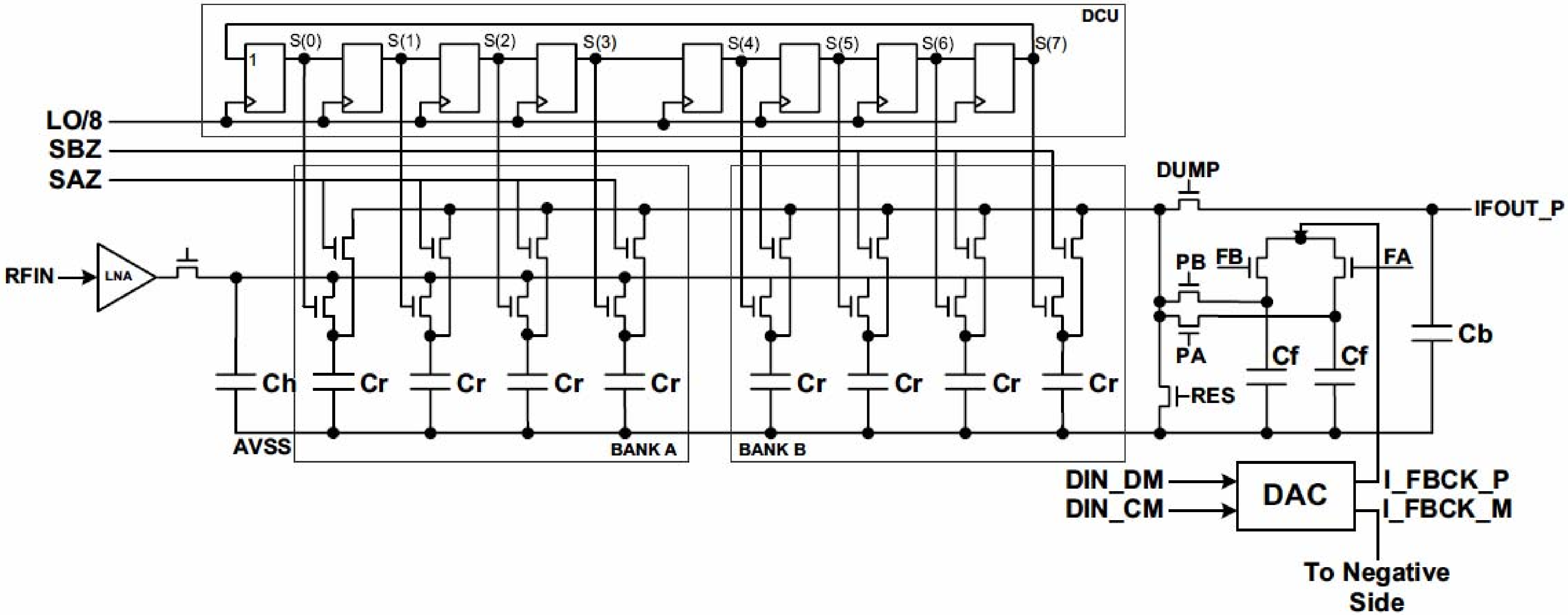
Sampling mixer

Sampling mixer has been proposed to form the filter with passive components.

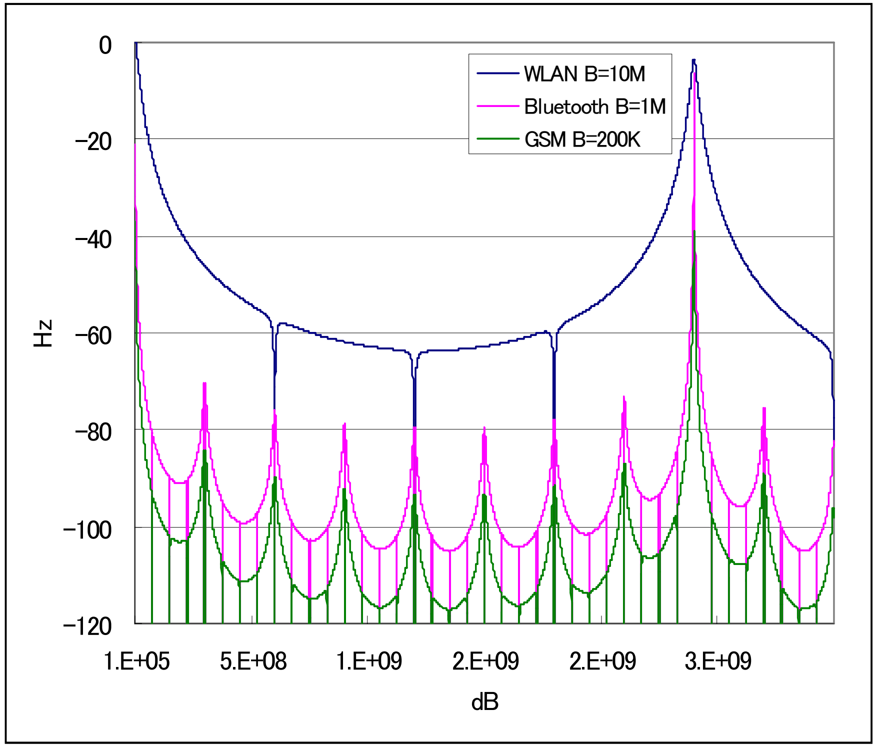


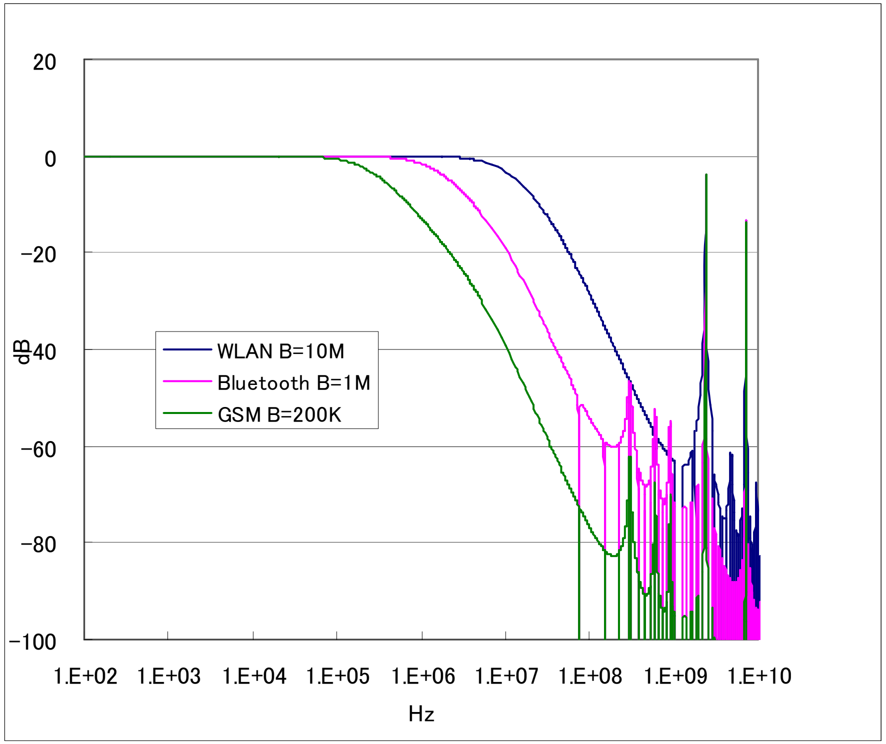
K. Muhanmad (TI) et al.
"All-Digital TX Frequency Synthesizer and Discrete-Time Receiver for Bluetooth Radio in 130-nm CMOS"
(JSSC Vol.39, No.12, pp. 2278-2291, Dec. 2004)

Filter function

Sampling mixer can realize filter function,
However not attractive so much .

Low filter order
Alias issue

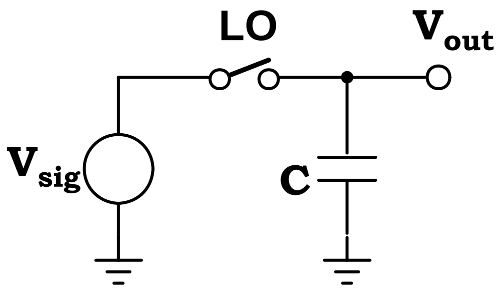




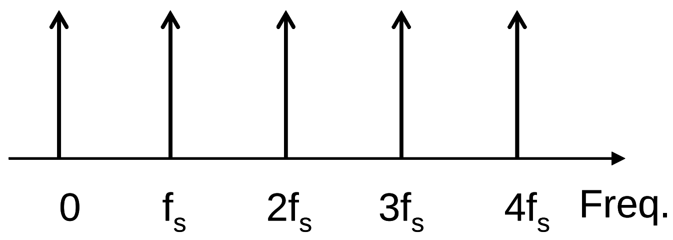
Sampling mixer vs. switch mixer

Switch mixer has almost same frequency characteristics as sampling mixer.

Voltage sampling

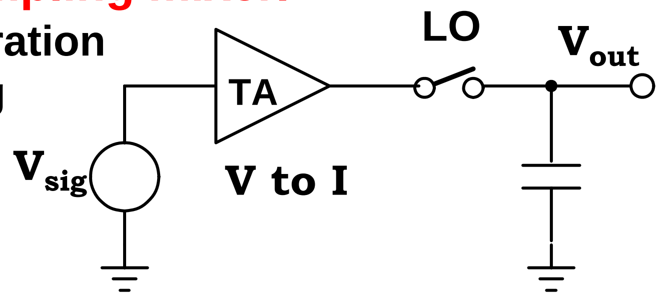


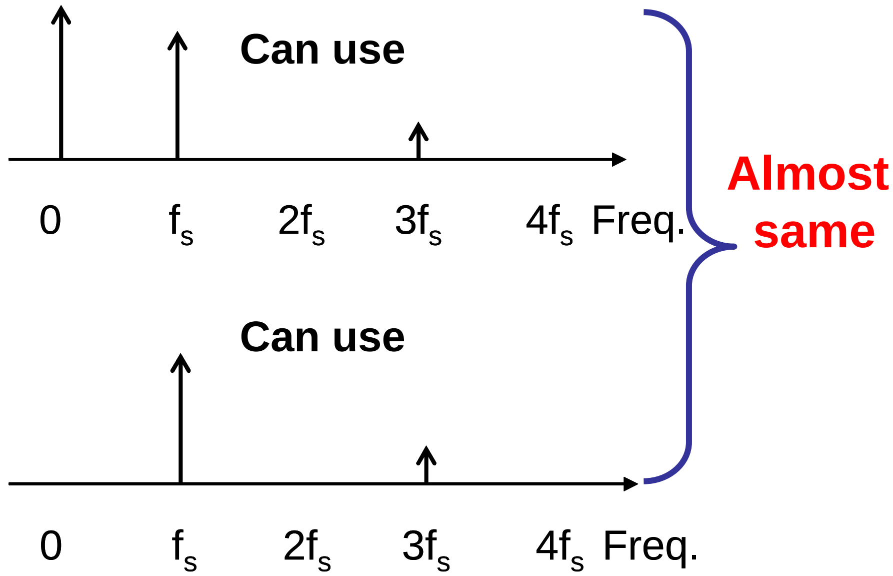
Can't use, because of large aliases



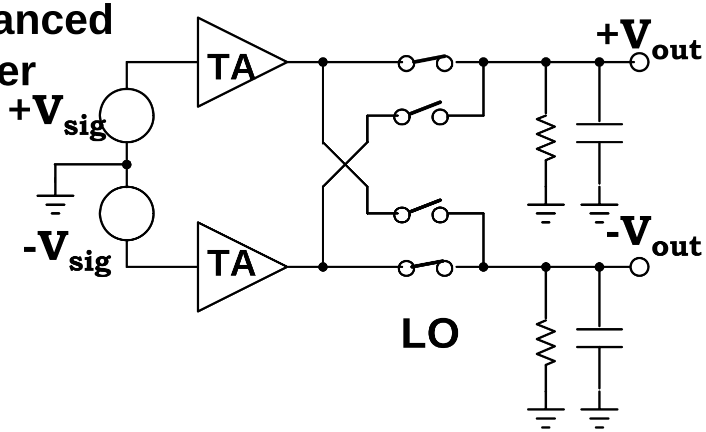
This is a sampling mixer.

Current integration and sampling





Double balanced Switch mixer



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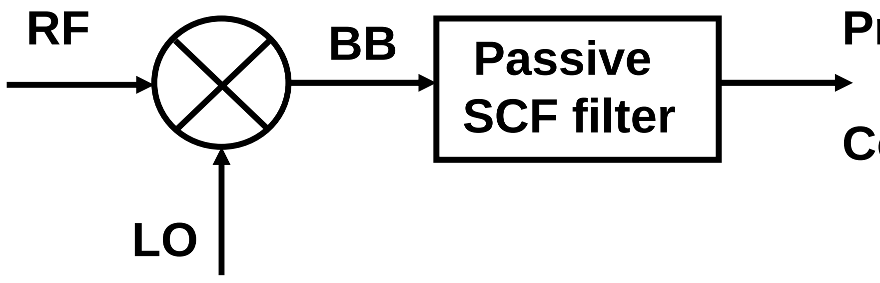
Passive SCF filter vs. CT filter

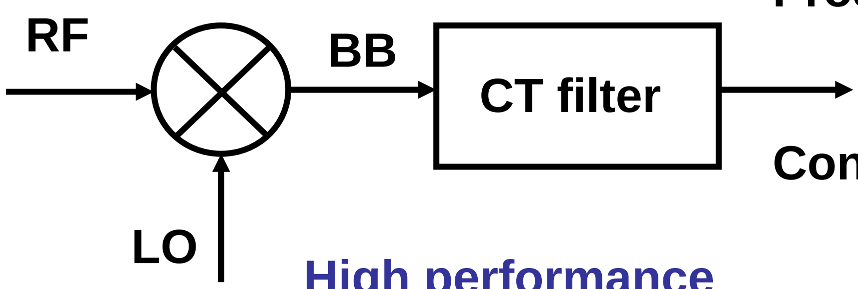
Passive SCF filter looks less attractive, so far.



Pros: Low power

Cons: Still needs an anti-alias filter
Narrow band and low filter order
Restricted operating frequency

Poor performance
Not suitable for reconfigurability



Pros: No needs an anti-alias filter
Wider band and higher order

Cons: consumes power

High performance
Suitable for reconfigurability

Conclusion

- **Analog-centric CMOS technology will go away**
  - 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
- **Digital-RF technology sounds interesting, however not matured yet.**
  - Performance is not attractive