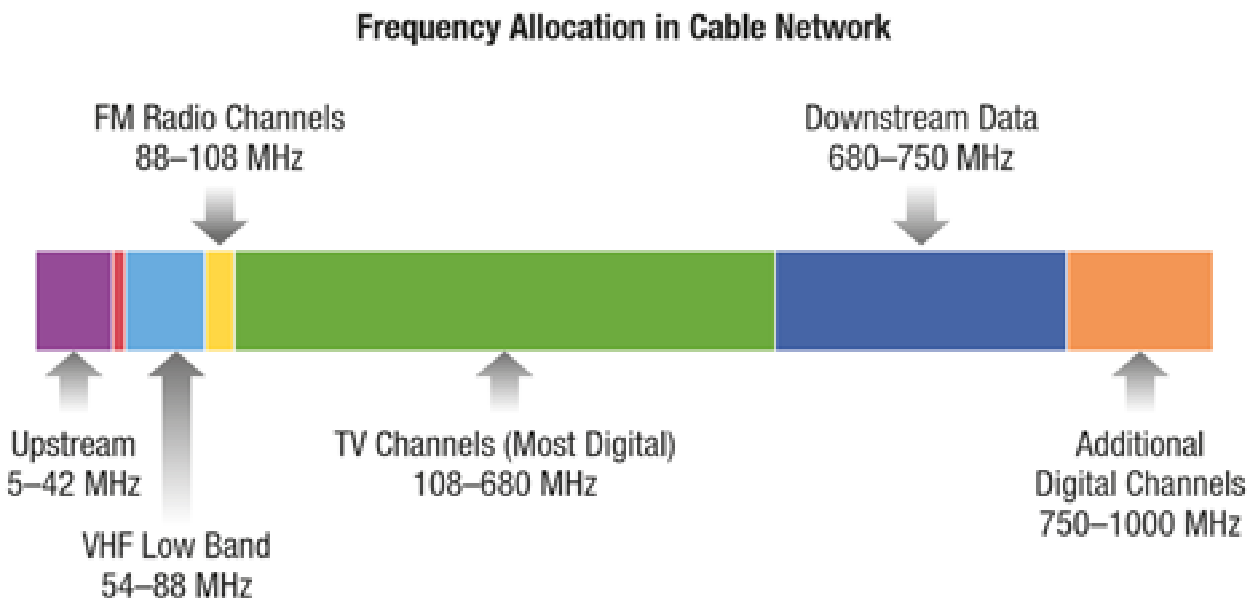
broad-band Receiver Radio Architectures

- **The up-down radio architecture**
- **The direct-conversion harmonic-rejection architecture**
- **The spectrum-capture architecture**
- **References**

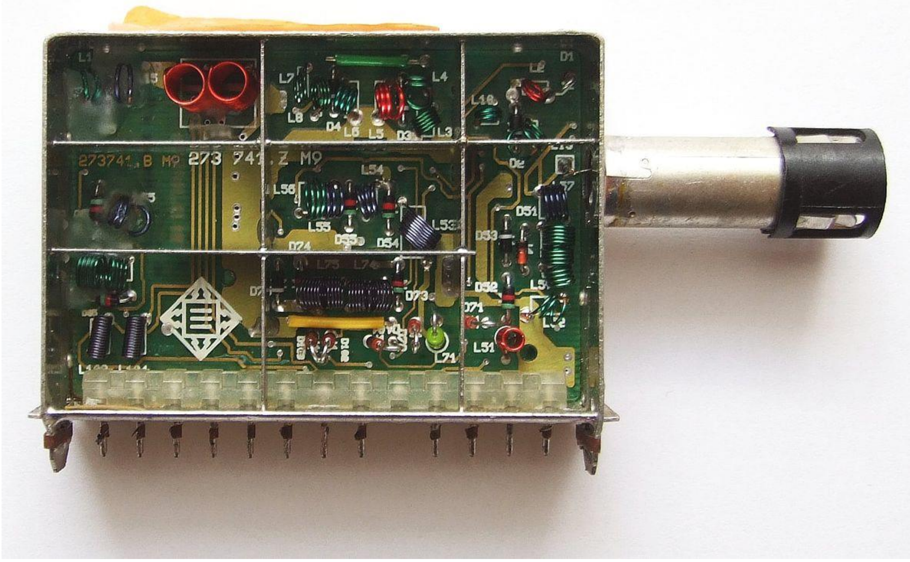
Example of broadband system is TV tuners:



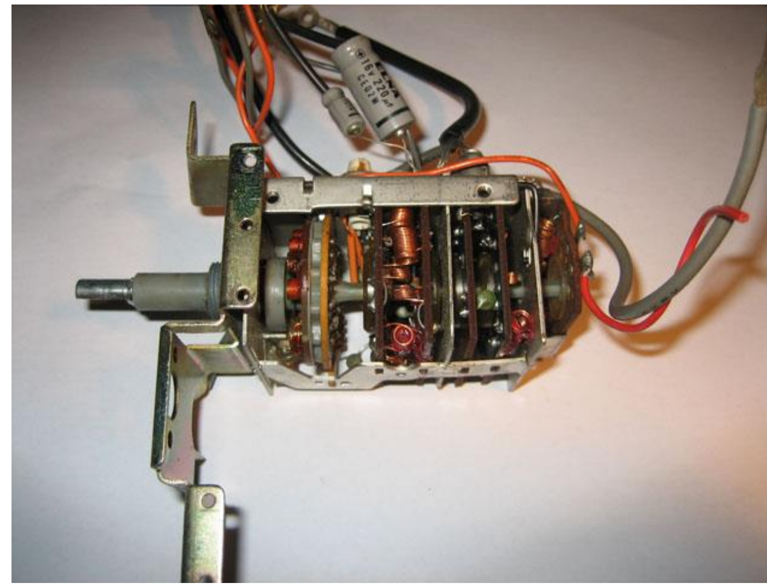
- Need to receive any TV or FM channel in 50MHz to 1GHz band.
- TV Band/CH-BW varies country to country but to build a universal tuner you need to support the super-set of channels
- Tuners that support terrestrial, cable and various digital channels are called “Universal Tuners”.

The old way of building TV tuners (can-tuners):

Relatively new model

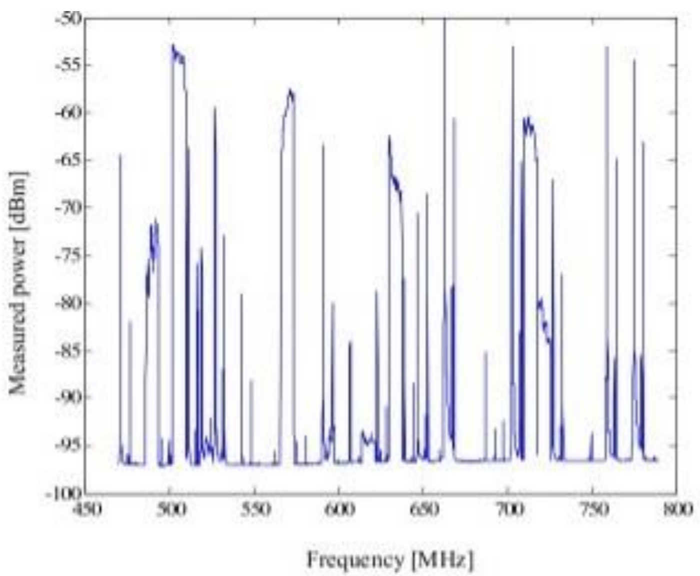


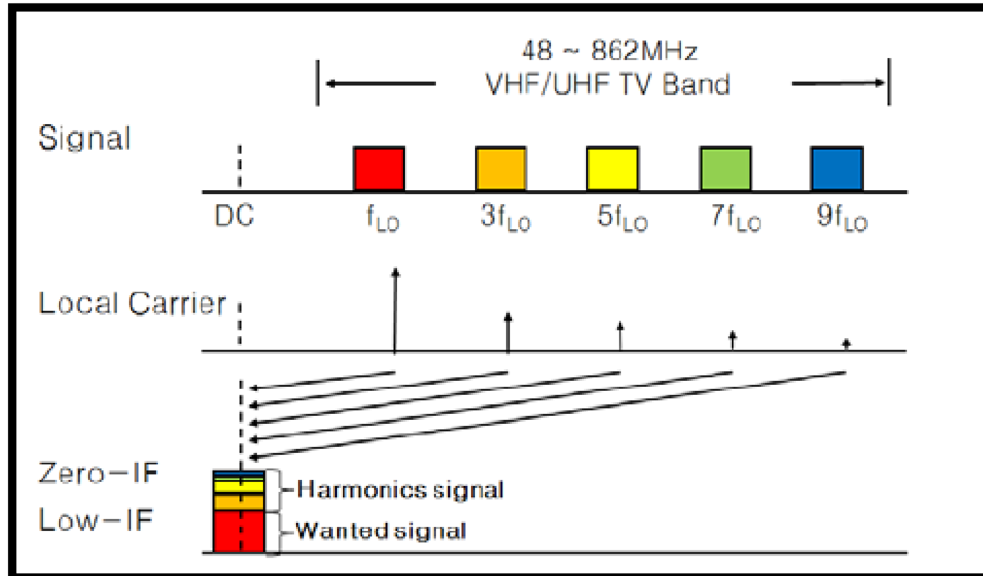
Relatively older model



- Tuner is pretty much made of high-Q passive filter banks for different TV channels that can be selected by a “clunk” rotator
- Assembly line is made of intensive human labor calibration flow
- Very cheap (the whole thing sells for <$3)

Why people were not able to build a solid-state tuner?:



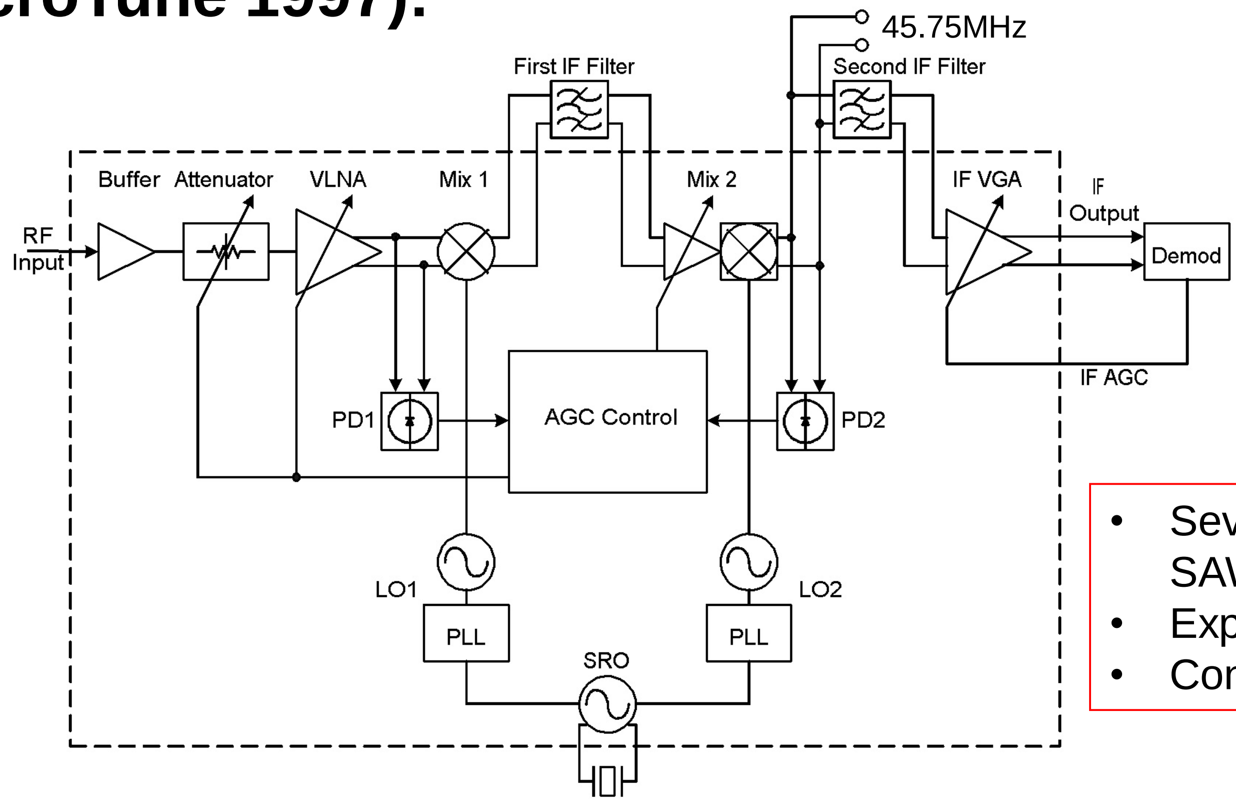


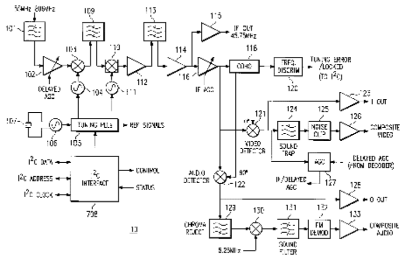
The issue of LO-harmonic mixing:

• TV signals can have 50~60dB variation in power relative to each other for terrestrial TV (~15dB for cable TV)

• if you try to use direct-conversion to say receive the 100MHz channel, the LO harmonics (3^{rd}, 5^{th}, 7^{th}, 9^{th}, etc.) at 300MHz, 500MHz, 700MHz and 900MHz will mix also with TV channels at these frequencies (can be ~50dB higher in power) and down-convert them to baseband

1) The up-down SS tuner architecture (courtesy of MicroTune 1997):





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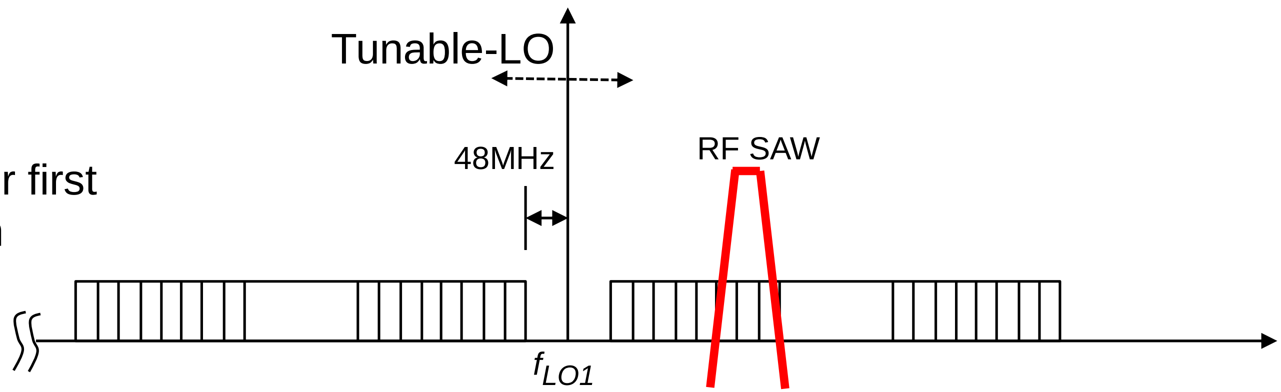
- Several off-chip bulky SAW filters are needed.
- Expensive
- Consumes ~1.5W

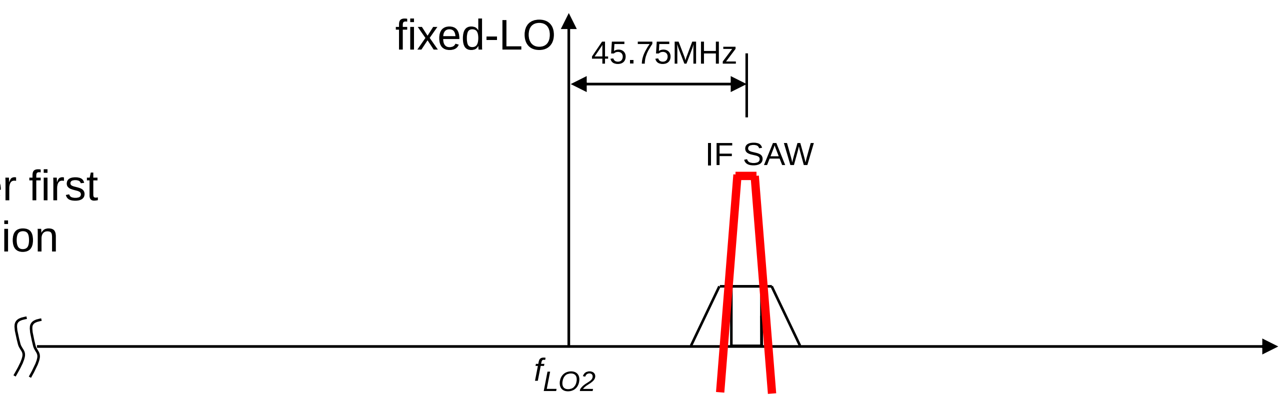
● firstly, up-convert the entire TV spectrum to very high-frequency (say 2GHz) using 2GHz tunable LO (LO 3rd harmonic falls outside TV band). A first channel-select SAW filter rejects most of unwanted TV channels. A second fixed LO down-converts desired TV cannel to 45.75MHz (to be compatible with CAN tuners). A second channel-select SAW filter at 45.75MHZ further rejects close-in TV channels. A final I/Q down-converter brings the 45.75MHz down to baseband for processing.

The up-down architecture pictorially:

Spectrum after first
up-conversion

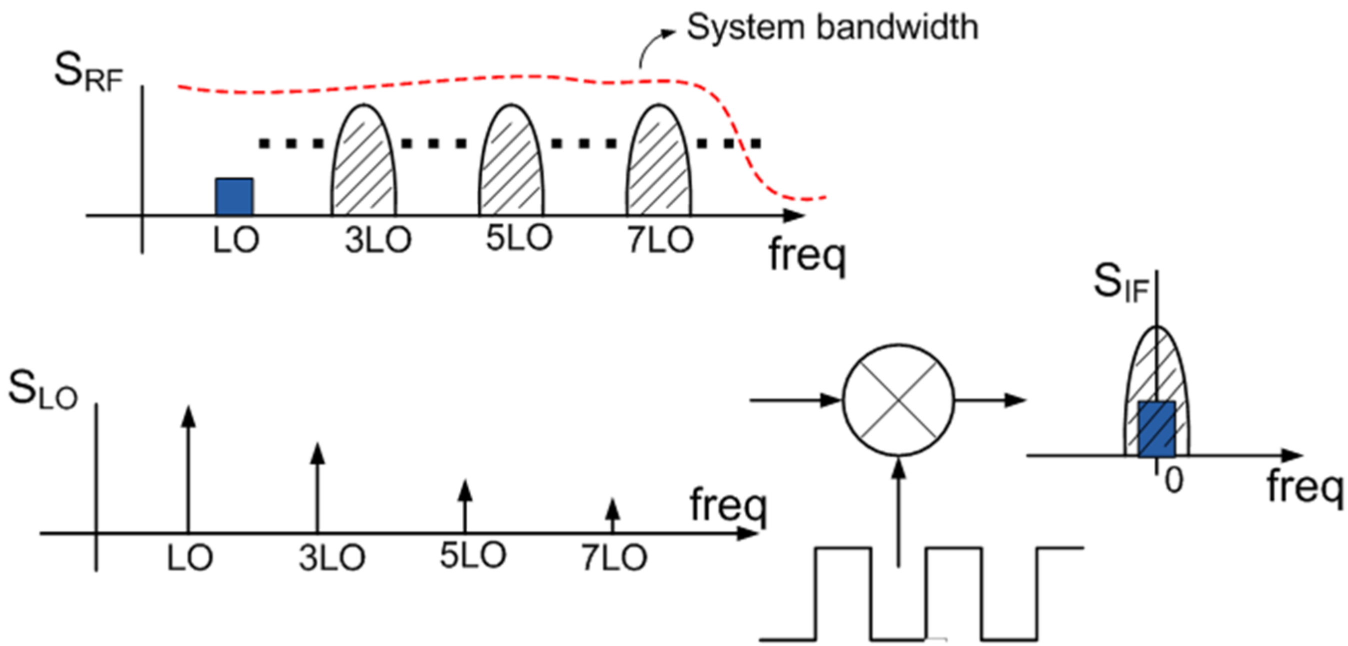


Spectrum after first
down-conversion



2) The harmonic-reject down-conversion

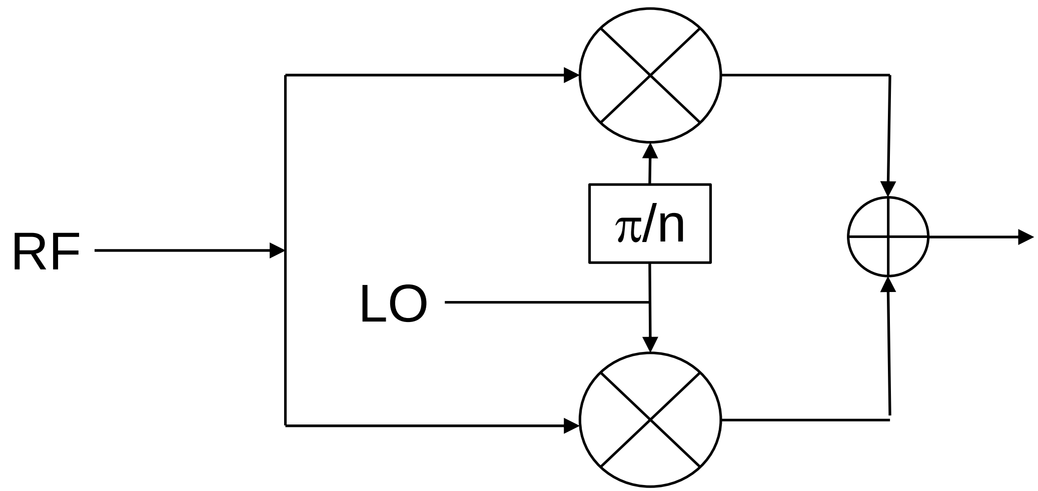
Harmonic mixing problem:



What if I can “somehow” generate an LO signal that is free of harmonics yet still need to be “square” wave in nature for best mixer performance?

2) How to reject one harmonic?

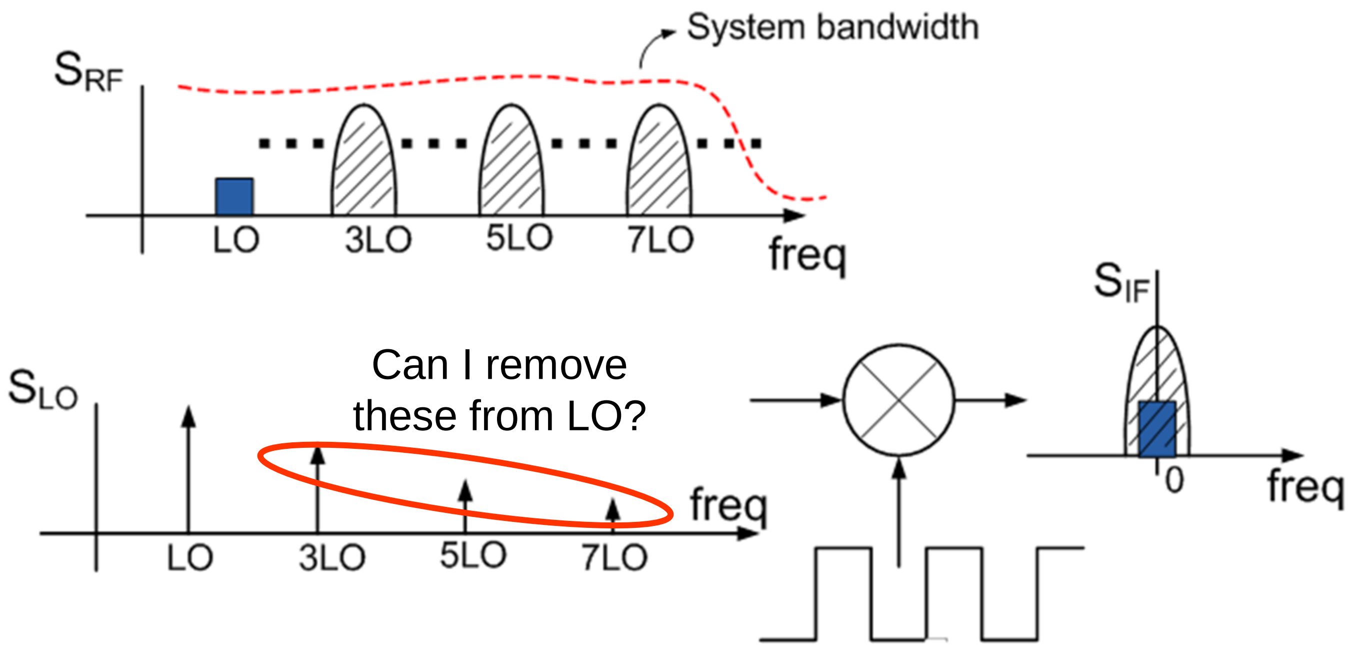
If I shift the LO by π/n, the nth harmonic of LO shifts by π. Therefore, if I add the two paths, I cancel the LO nth harmonic



- For example, for n =3, 3rd harmonic is rejected.
- desired signal level is affected slightly by few dB

2) The Weldon harmonic-reject scheme:

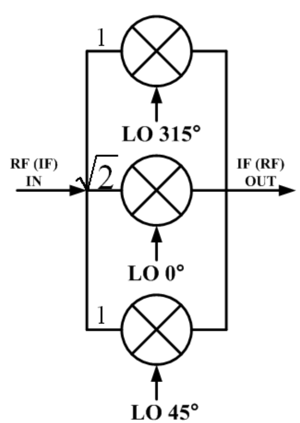
Harmonic mixing problem:

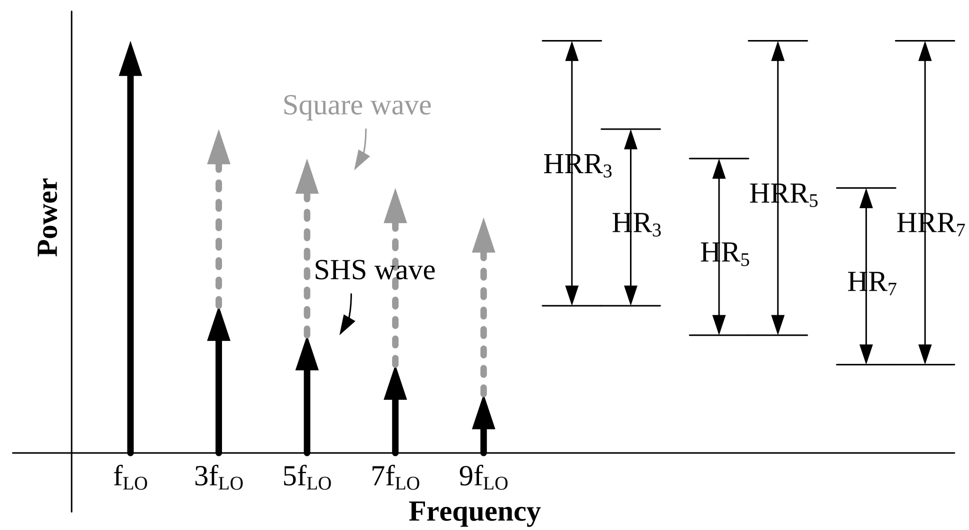


The Weldon HRM scheme relies on using different LO phases with different RF weight to cancel harmonic mixing

Harmonic Rejection Mixer – Principle

- Switching mixer principle
  - RF (IF) signal multiply with the square wave version of LO
- Square wave: $P0(t) = \frac{4}{\pi}[\cos(\omega t) - \frac{1}{3}\cos(3\omega t) + \frac{1}{5}\cos(5\omega t) - \frac{1}{7}\cos(7\omega t) + \frac{1}{9}\cos(9\omega t)\cdots]$
- Harmonic rejection
  - Generate square waves with opposite symbols for the coefficients of harmonics
  - Amplitude scaling
  - Add together
- Simplest HRM
  - 3 sub-mixers
  - Add together





Harmonic Rejection Mixer – Principle

- ±45° phase shift:

$$P_0(t) = \frac{4}{\pi}[\cos(\omega t) - \frac{1}{3}\cos(3\omega t) + \frac{1}{5}\cos(5\omega t) - \frac{1}{7}\cos(7\omega t) + \frac{1}{9}\cos(9\omega t)\cdots]$$

$$\underline{P_1(t) = P_0(t - T/8)}$$

$$= \frac{4}{\pi}[(\cos(\omega t) + \sin(\omega t)) + \frac{1}{3}(\cos(3\omega t) - \sin(3\omega t)) - \frac{1}{5}(\cos(5\omega t) + \sin(5\omega t)) - \frac{1}{7}(\cos(7\omega t) - \sin(7\omega t))\cdots]$$

$$\underline{P_2(t) = P_0(t + T/8)}$$

$$= \frac{4}{\pi}[(\cos(\omega t) - \sin(\omega t)) + \frac{1}{3}(\cos(3\omega t) + \sin(3\omega t)) - \frac{1}{5}(\cos(5\omega t) - \sin(5\omega t)) - \frac{1}{7}(\cos(7\omega t) + \sin(7\omega t))\cdots]$$

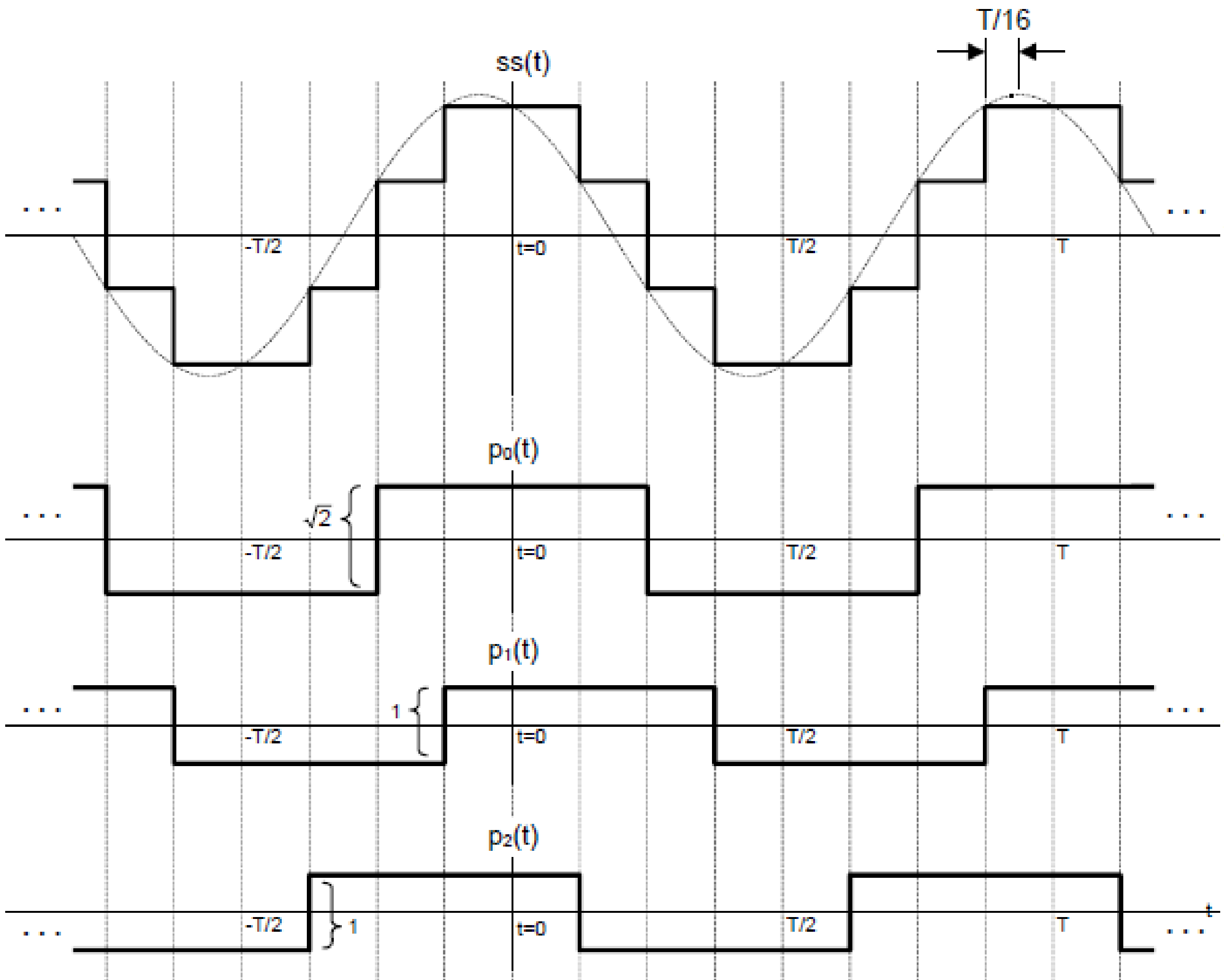
- Amplitude scale:

$$P_0'(t) = \sqrt{2}P_0(t) = \frac{4\sqrt{2}}{\pi}[\cos(\omega t) - \frac{1}{3}\cos(3\omega t) + \frac{1}{5}\cos(5\omega t) - \frac{1}{7}\cos(7\omega t)\cdots]$$

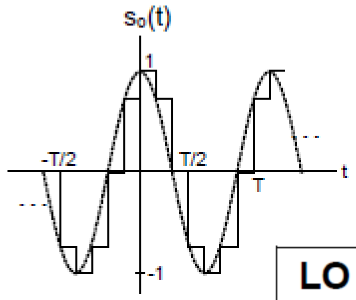
- Add together:

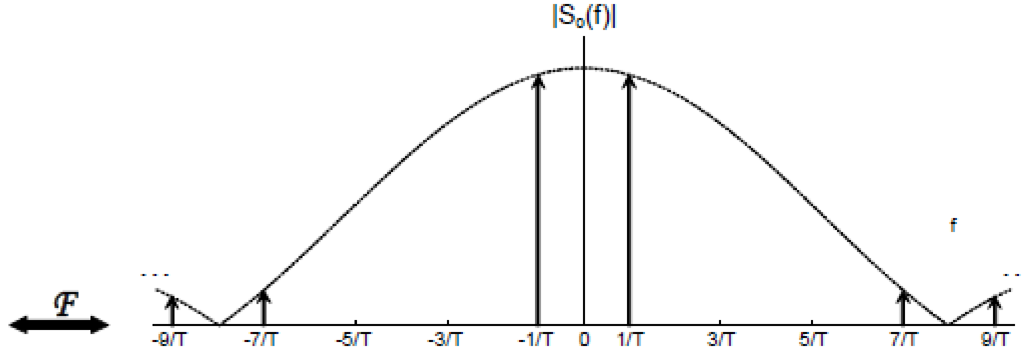
3rd and 5th LO harmonics are rejected!

$$P_0'(t) + P_1(t) + P_2(t) = \frac{8\sqrt{2}}{\pi}[\cos(\omega t) - \frac{1}{7}\cos(7\omega t)\cdots]$$


T/16
ss(t)
-T/2
t=0
T/2
T
t
p0(t)
√2
p1(t)
1
p2(t)
1

rejected-Harmonics vs # LO phases:





LO Phase Shift	No. of Square Waves	Square Waves	Harmonics Can be Cancelled
45°	3	$\sqrt{2}$ *P_0(t), P_0(t-π/4), P_0(t+π/4)	3^{rd} , 5^{th}
30°	5	2*P_0(t), $\sqrt{3}$ *P_0(t-π/6), $\sqrt{3}$ *P_0(t+π/6), P_0(t-π/3), P_0(t+π/3)	3^{rd} , 5^{th} , 7^{th} , 9^{th}
22.5°	7	$\sqrt{2}$ *P_0(t), $\sqrt{2}$ *cos(π/8)*P_0(t-π/8), $\sqrt{2}$ *cos(π/8)*P_0(t+π/8), P_0(t-π/4), P_0(t+π/4), $\sqrt{2}$ *sin(π/8)*P_0(t-3π/8), $\sqrt{2}$ *sin(π/8)*P_0(t+3π/8)	3^{rd} , 5^{th} , 7^{th} , 9^{th} , 11^{th} , 13^{th}

Performance Limitation of the Weldon HRM

- Ideal Case: HRR → infinite
- Real Case: Limited HRR ← amplitude mismatch (AM) and phase imbalance (PI)
- HRR equations (α, θ are the rms summation of AM, PI)

$$P_{0M}(t) = (1+\alpha)P_0(t+\theta\frac{T}{2\pi})$$

$$P_{1M}(t) = \frac{1}{\sqrt{2}}P_0(t-T/8)$$

$$P_{2M}(t) = \frac{1}{\sqrt{2}}P_0(t+T/8)$$

$$\Rightarrow$$

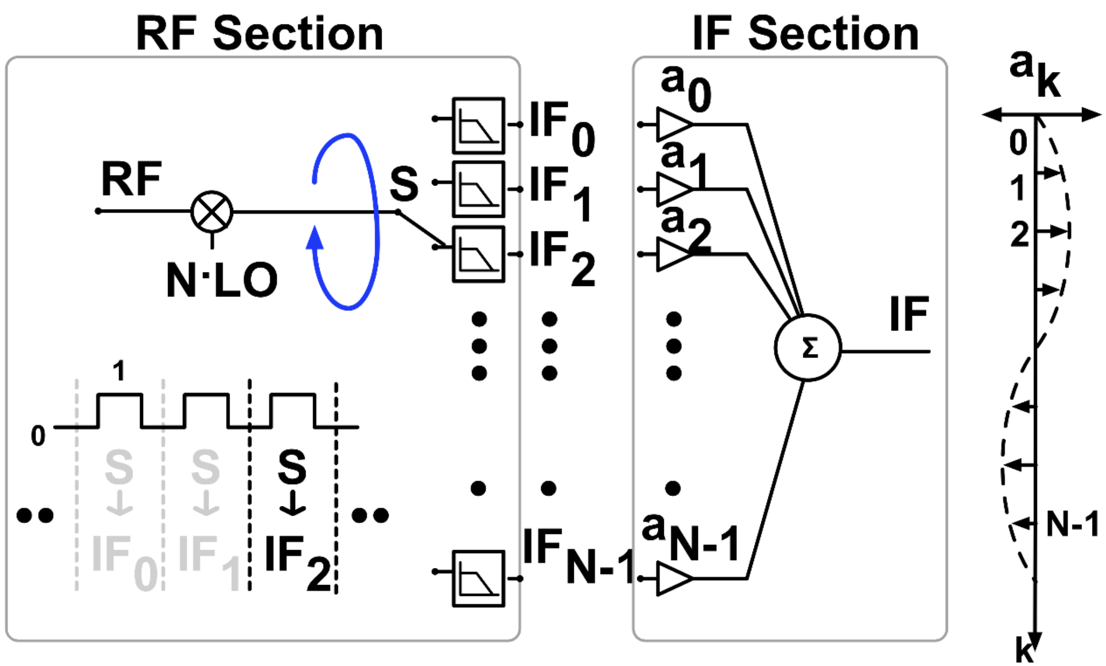
$$HRR_3 = 10\log\frac{9(1+(1+\alpha)\cos\theta)^2+9((1+\alpha)\sin\theta)^2}{(1-(1+\alpha)\cos 3\theta)^2+((1+\alpha)\sin 3\theta)^2}$$

$$HRR_5 = 10\log\frac{25(1+(1+\alpha)\cos\theta)^2+25((1+\alpha)\sin\theta)^2}{(1-(1+\alpha)\cos 5\theta)^2+((1+\alpha)\sin 5\theta)^2}$$

- HRR3 mostly limited to -35~-40dBc
- Here is the problem: how to achieve over -60dBc??

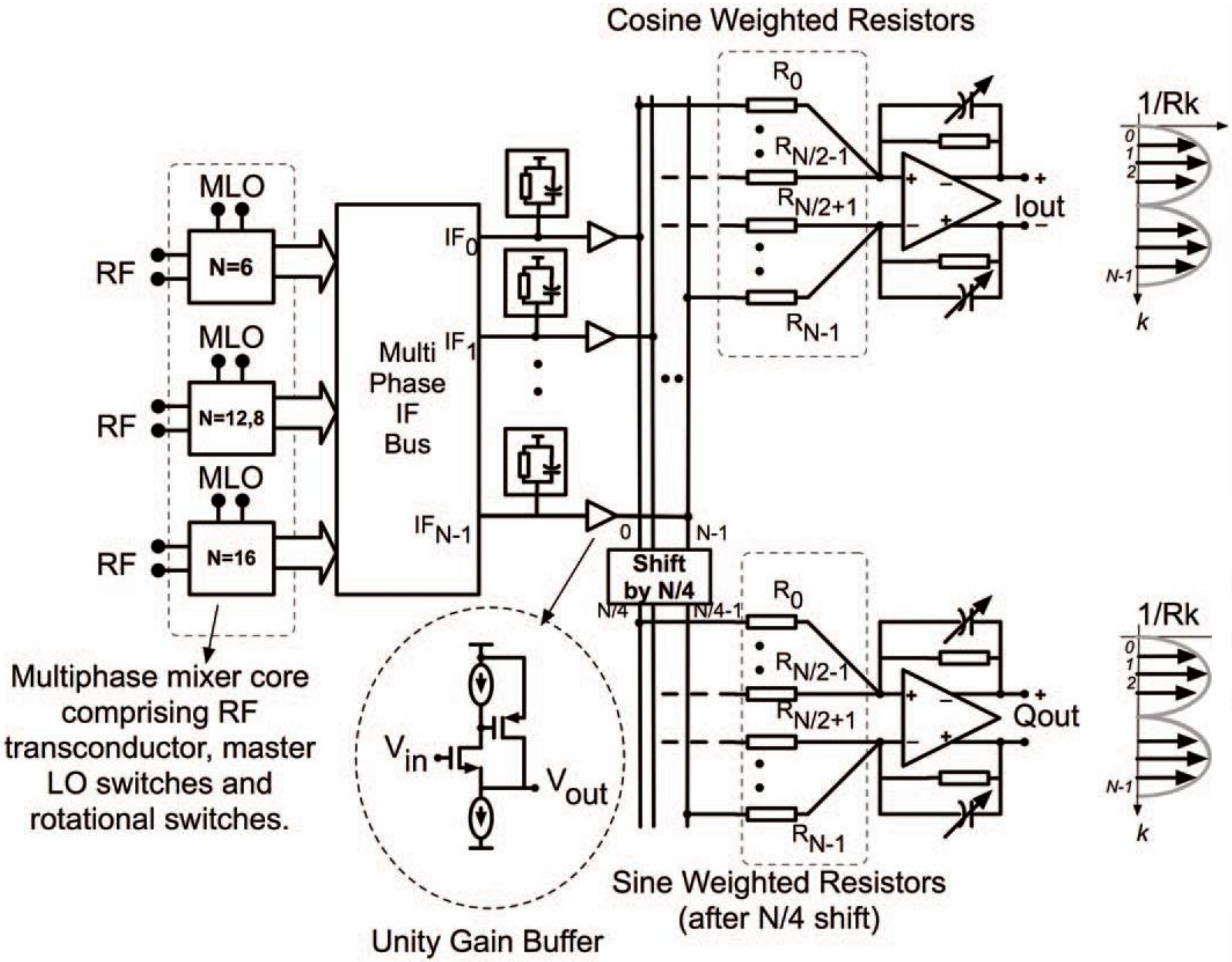
Do scaling at IF via resistors (Rafi ISSCC 2011)

S transitions when no signal through it

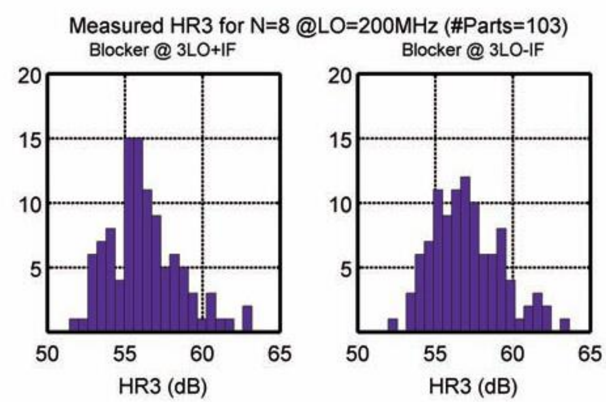


- Multiplication of RF with N·LO
- Rotation of S through *N* IF outputs, effectively multiplies RF with multi-phase LO

Do scaling at IF via resistors (Rafi ISSCC 2011)



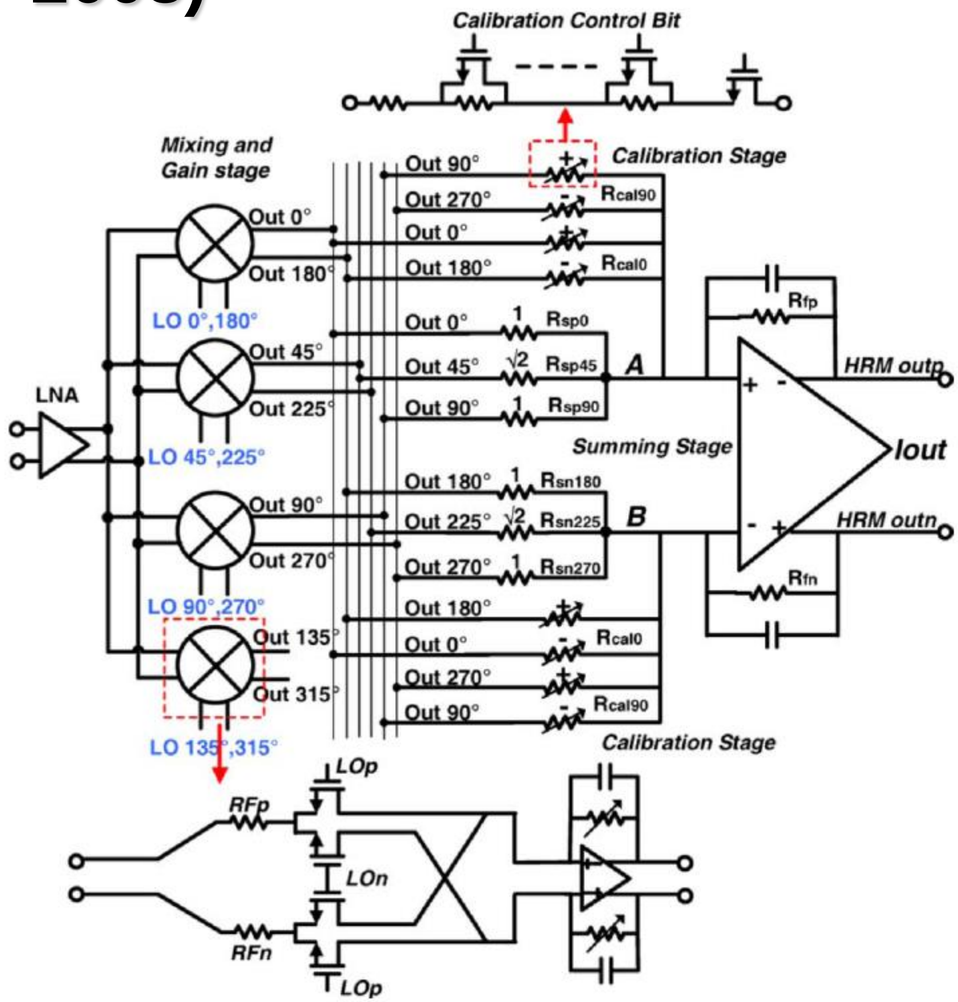
Resistors match better than transistors → good HRM



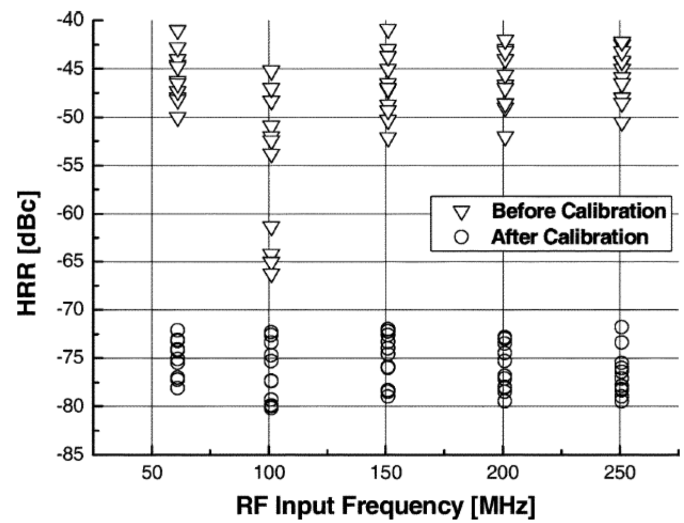
Disadvantage of IF R-scaling solution

- It adds a tremendous amount of circuit complexity
- The RC loadings and series resistors still introduce amplitude mismatch and phase imbalance
- It requires an LO 16 times the RF frequency which increases power

Adding Mismatch Calibration Path (Cha IMWCL 2008)



Main idea:
Utilize mismatch calibration to compensate both phase and gain mismatch.

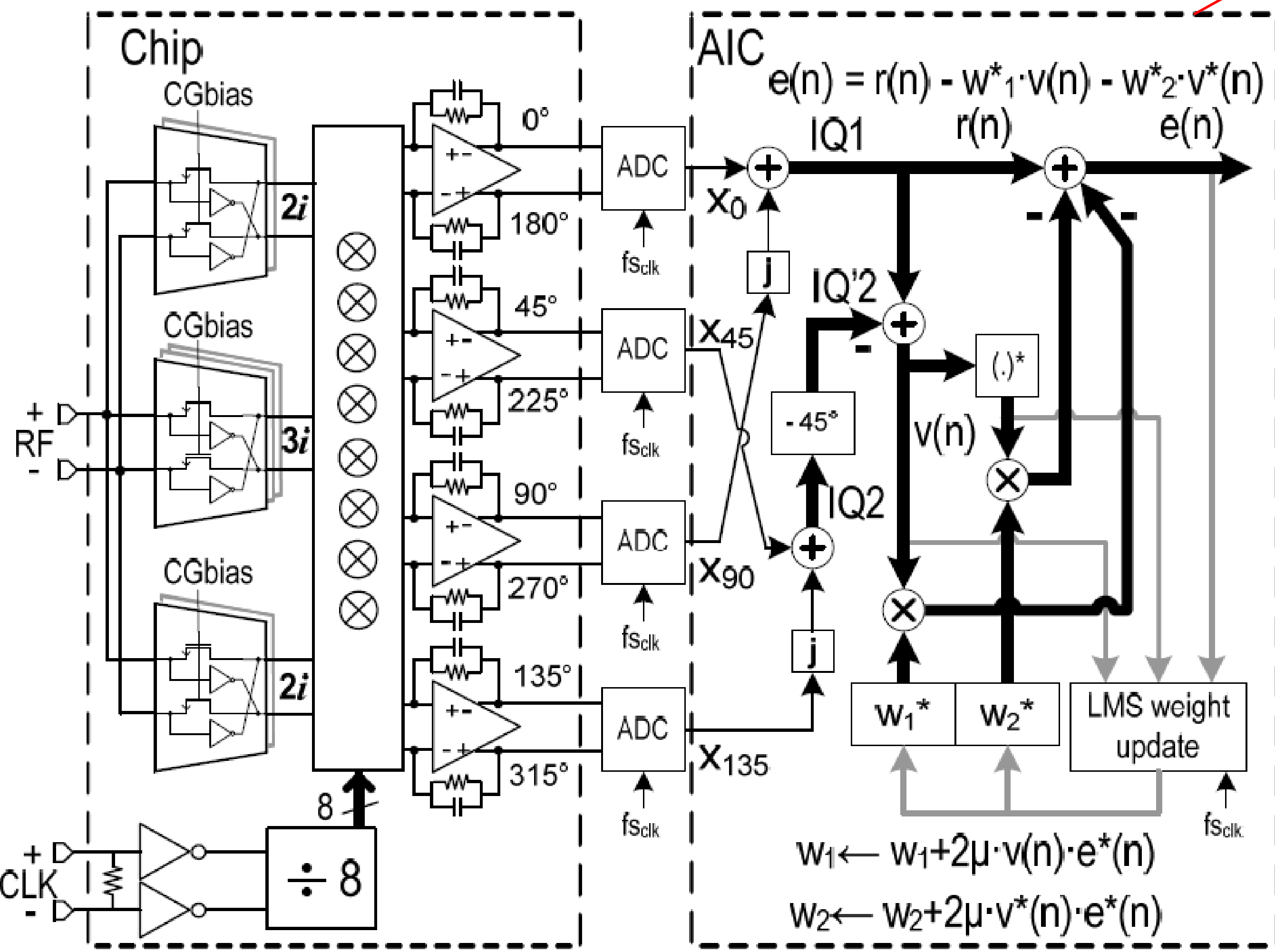


Disadvantage of MCP Solution

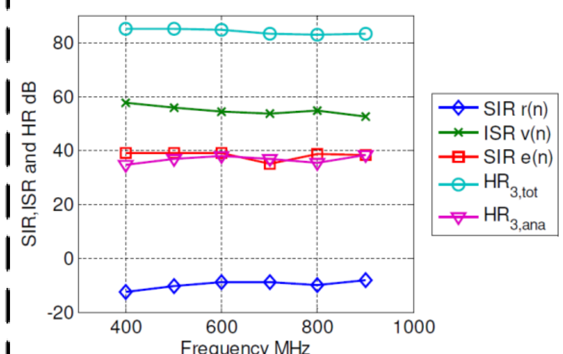
- Series resistors after switch quad increase gm loss thus degrading the gain
- The series resistors introduce extra amplitude mismatch
- Calibrated HRR depends on the resolution of the unit calibration resistor
- Manually set calibration control bits scheme reduces the flexibility of this technique (need automation somehow)

Adaptive Harmonic Interference Cancellation (Moseley ISSCC 2009)

Adaptive Interference Cancellation



Main idea:
Use AIC to remove interference caused by unwanted harmonics

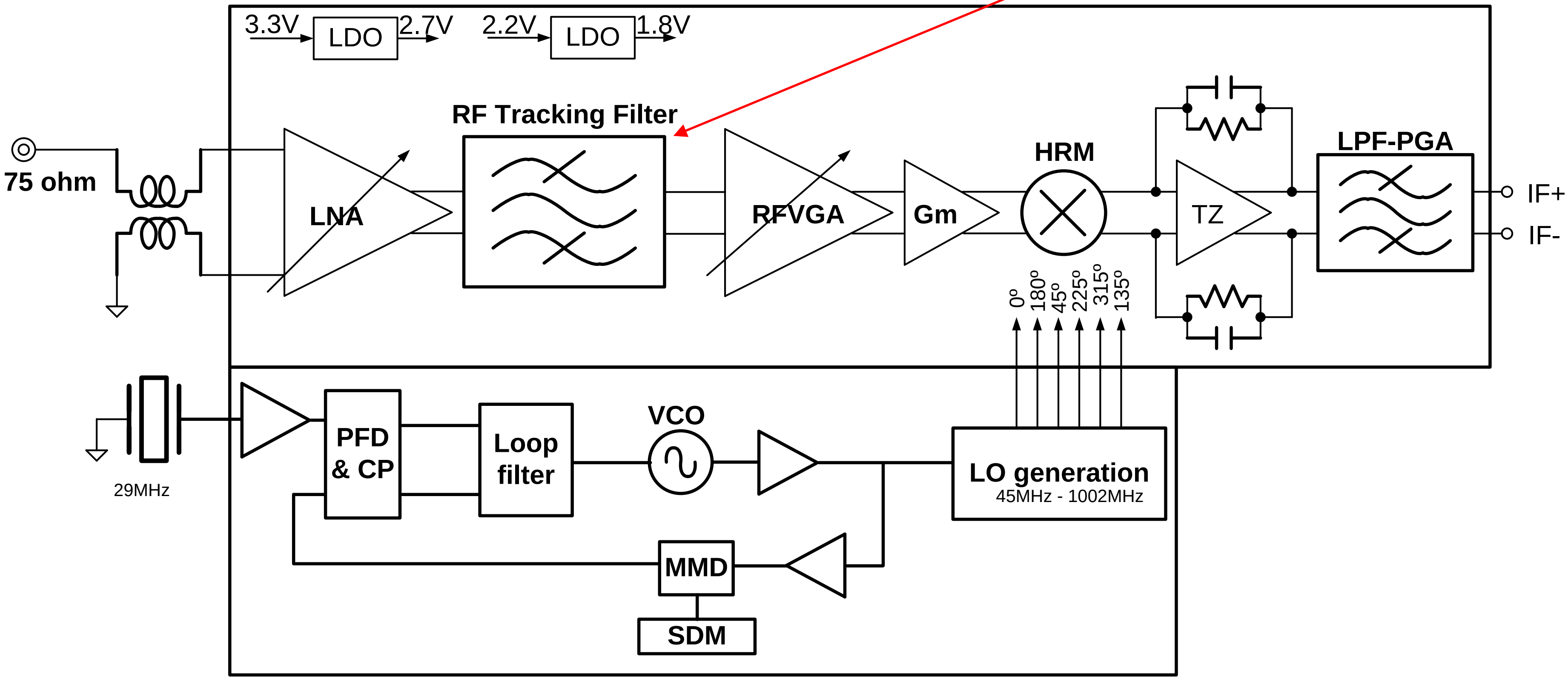


Disadvantage of AIC solution

- Two more analog baseband paths including LPF and ADCs increase power and area
- AIC technique increases design complexity and digital cost
- AIC performance depends on the quality of interference estimate v(n) which is still decided by amplitude and phase accuracy
- Signal path needs to handle large harmonic mixing components before they get canceled in digital baseband (high-dynamic-range requirement)

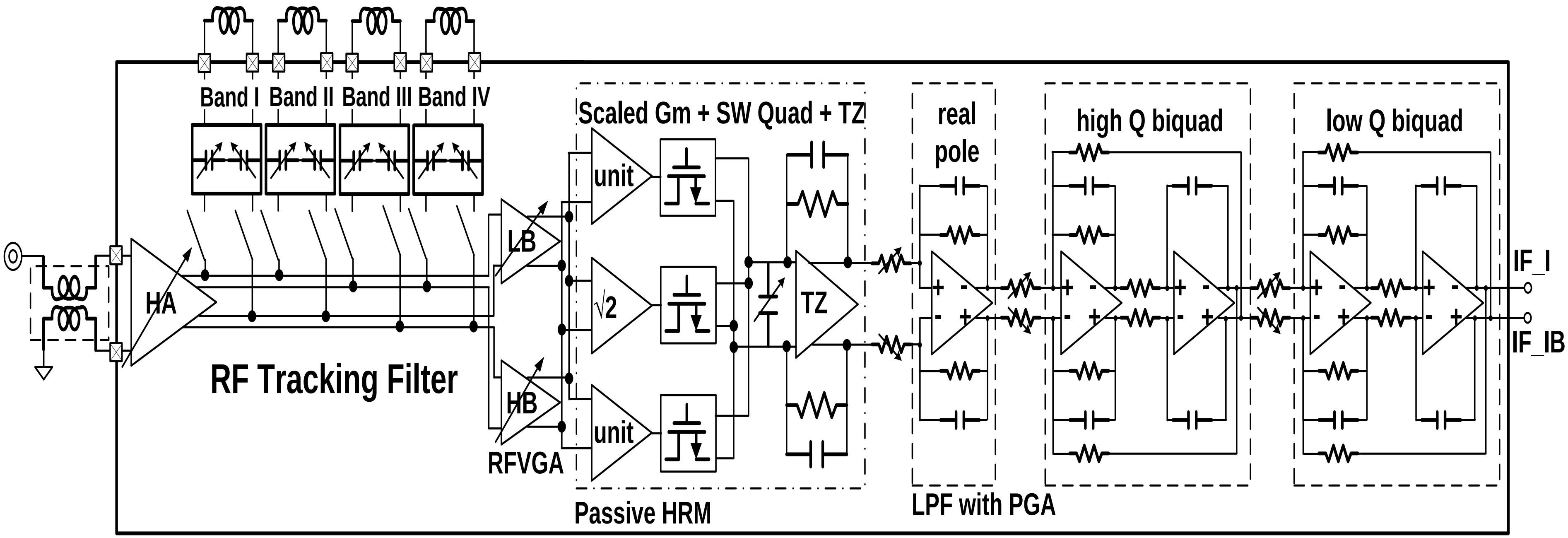
A full universal TV tuner using Weldon's HRM scheme (BengHwee ASSCC 2013):

Improves HRM and relaxes linearity requirement of subsequent stages



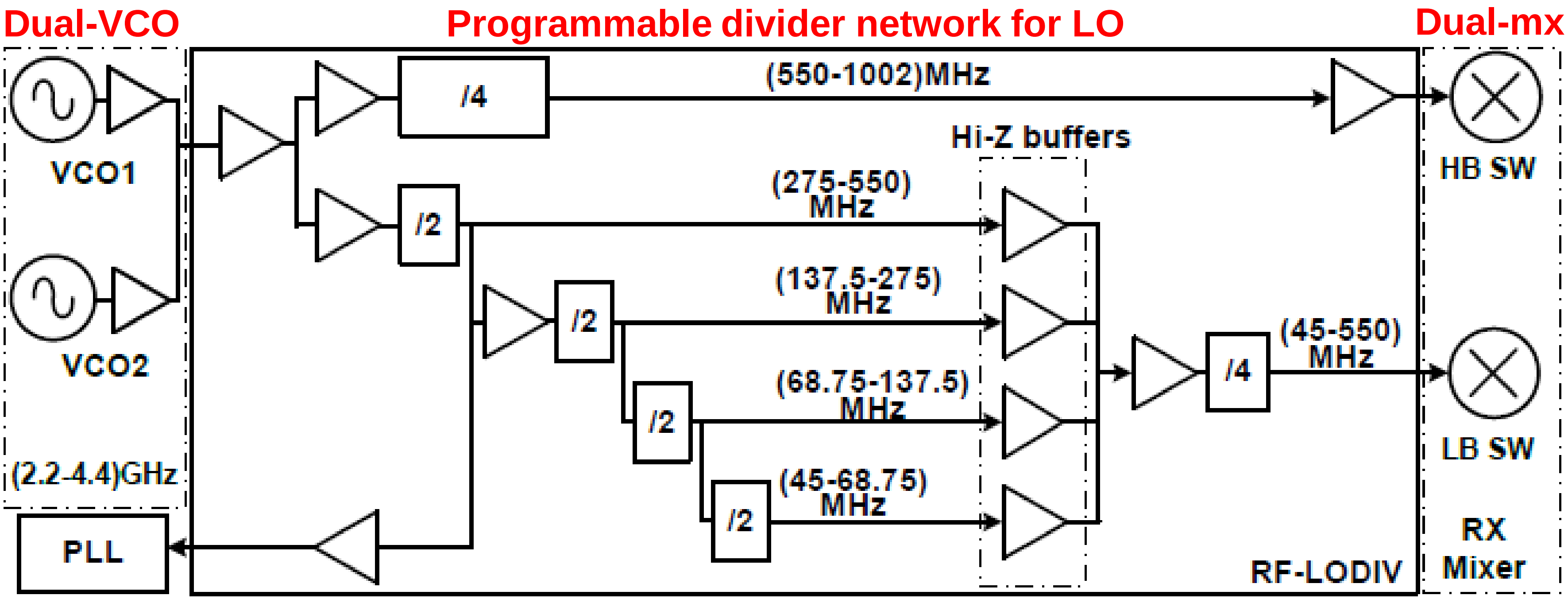
- **DCR receiver**
- **Wide frequency coverage Δ-Σ fractional-N synthesizer**

TV-tuner, DCR receiver 'cont



- LC passive TF with off-chip inductors
- Head Amplifier (HA) implemented as Gm stage to drive TF
- Weldon's HRM with passive mixers (current driven)
- Opam-based TIA amplifier and LPF

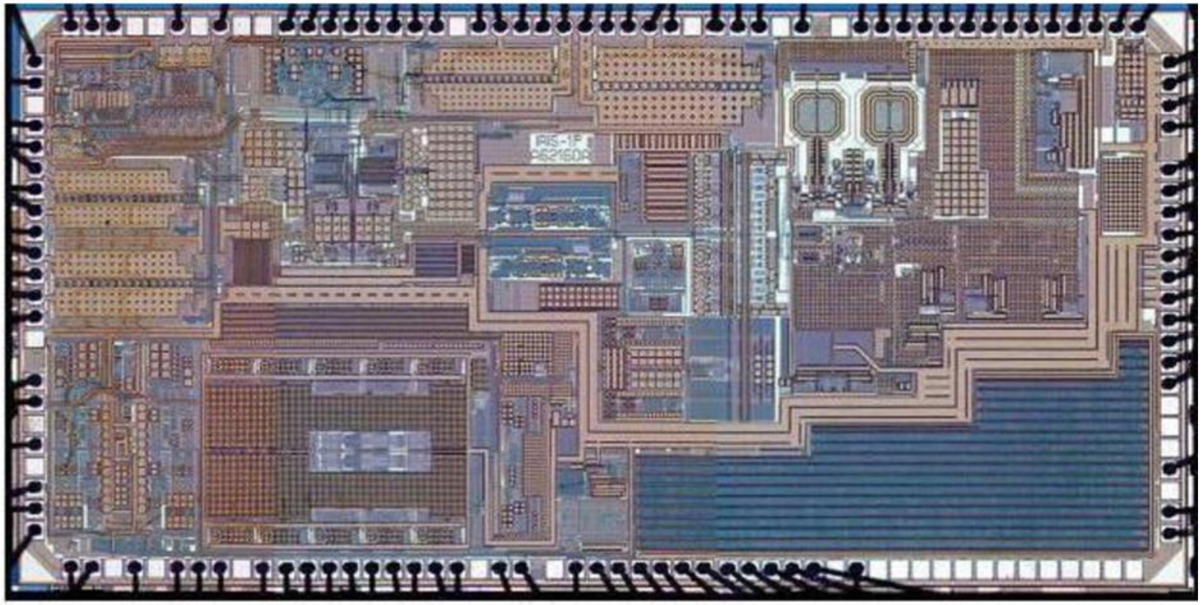
DC Tuner Synthesizer and LO generation:



	Dividing ratio	Corresponding frequency
VCO1 (2.2GHz ~ 3.1GHz)	/64	45M~48.4375M
	/32	68.75M~96.875M
	/16	137.5M~193.75M
	/8	275M~387.5M
	/4	550~775M

	Dividing ratio	Corresponding frequency
VCO2 (3.1GHz ~ 4.4GHz)	/64	48.4375M~68.75M
	/32	96.875M~137.5M
	/16	193.75M~275M
	/8	387.5M~550M
	/4	775~1002M

Tuner highlights:



- Digital calibration for image rejection to achieve >70dBc
- HRM and TF to achieve >65dBc
- Programmable blocks to accommodate various TV standards
- Needs <20 off-chip components (mainly Vdd bypass caps and TF inductors)
- $0.5 (still expensive!!)

Performance Summary:

Parameters	Condition	Unit	This work*
Technology			CMOS 0.18um
Die Size		mm^2	10
Power consumption		mW	659, 3.3V/2.2V
NF	max gain, typ	dB	<5.5dB
P1dB	AGC loop on	dBm	>16.5
IIP3	min gain, typ	dBm	30
IMRR	Image rejection	dBc	<-72
Phase noise	1kHz offset	dBc/Hz	-104
	10kHz offset	dBc/Hz	-105
	100kHz offset	dBc/Hz	-122

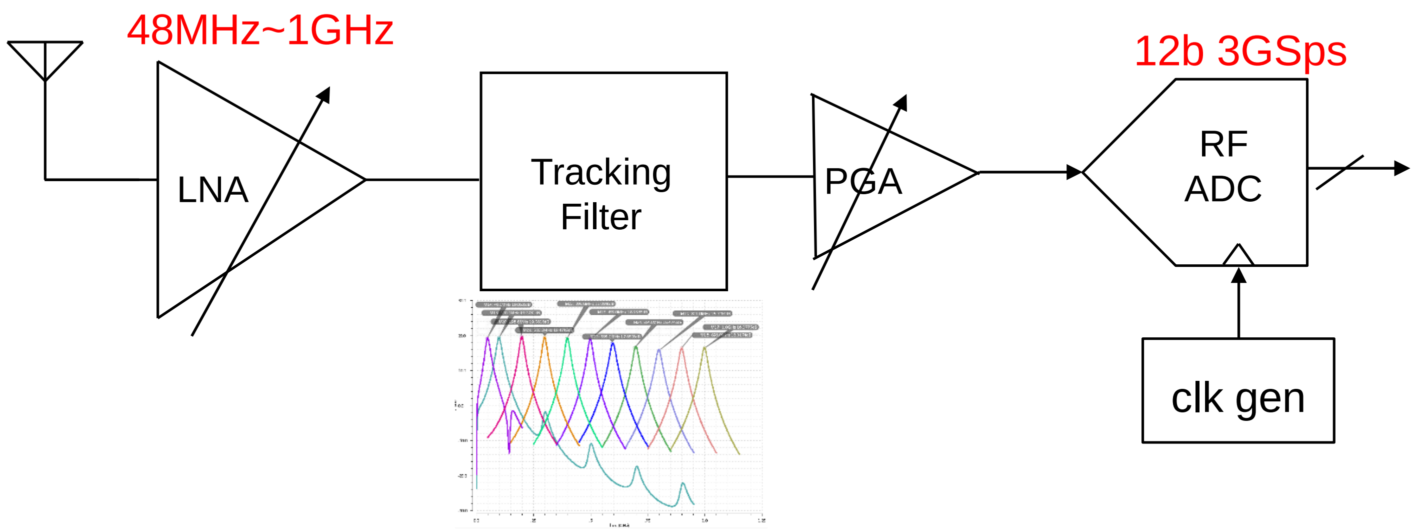
Parameters	Condition	Unit	This work
NF with N+1 blocker	NF, blocker N+1 =- 25dBm	dB	16.9dB@85.25MHz 16.3dB@181.25MHz 17.8dB@671.25MHz
NF with N+2 blocker	NF, blocker N+2 =- 25dBm	dB	13.3dB@85.25MHz 11.6dB@181.25MHz 11.7dB@671.25MHz
IIP2	max, typ	dBm	67
3rd HRR	VHF1	dBc	70
	VHF2	dBc	82
	UHF	dBc	82
IMRR	Image rejection ratio for ATV	dBc	<-72@85.25MHz <-72@181.25MHz <-72@671.25MHz
Spurious	Check Xtal harmonic CH @ V1/V2/UHF	dBc	64
CNR(BW=6MHz)	90dBuV in	dB	56(50+6)
	70dBuV in	dB	56(50+6)
	57dBuV in	dB	49(43+6)
	40dBuV in	dB	32
LO leakage	dBm	dBm	<-105

* B. Howee, BH Ong, ES Khoo, W Yang, MJ Wu, JQ Cui, SR Karri, JM Cao, M Kong, CH Leow, CL Heng and Osama Shana'a, "A Universal Silicon Tuner with A compact Synthesizer in 0.18um CMOS, " in conf proceedings of ASSCC 2011.

[4] M Gupta, S Lerstaveesin, D Kang and BS Song, "A 48MHz-to-860MHz CMOS Direct-Conversion TV Tuner, ISSCC 2007

[7] JM Stevenson, P Hisayasy, A Deiss, B Abesingha, K Beumer and J Esquivel, "A multi standard analog and digital TV tuner for cable and terrestrial application", ISSCC 2007

3. Spectrum-Capture wideband receiver architecture:



- **ADC-first architecture (no down-conversion mixers)**
- **High-resolution high-speed ADC (few GSps) is key block (entire tuner consumes <0.3W)**
- **Channel selection and filtering is done in digital baseband**
- **Tracking filter and PGA helps ADC dynamic range while LNA helps overall Rx NF**
- **Main stream TV tuner architecture (<$0.15!!)**

References:

- [1] Jan-Michael Stevenson, Phil Hisayasu, Armin Deiss, Buddhika Abesingha, Kim Beumer, Jose Esquivel., "A Multi-Standard Analog and Digital TV Tuner for Cable and Terrestrial Applications," in *ISSCC*, 2007, paper 11.3, p. 210-211.
- [2] J. Weldon *et al.*, "A 1.75-GHz highly integrated narrow-band CMOS transmitter with harmonic rejection mixers," *IEEE J. Solid-State Circuits*, vol. 36, pp. 2003–2015, Dec. 2001.
- [3] H. Cha, S. Song, H. Kim and K. Lee, "A CMOS harmonic rejection mixer with mismatch calibration circuitry for digital TV tuner applications," *IEEE Microwave and Wireless Components Letters*, vol. 18, pp. 617–619, Sep. 2008.
- [4] N. Moseley *et al.*, "A 400-to-900 MHz receiver with dual-domain harmonic rejection exploiting adaptive interference cancellation," in *ISSCC*, 2009, paper 12.9, p. 232.
- [5] A. Rafi, A. Piovaccari, P. Vancorenland and T. Tuttle, "A harmonic rejection mixer robust to RF device mismatches" in *ISSCC*, 2011, paper 3.8, p. 66-67.
- [6] Huajiang Zhang, Tian Bao Gao, Sam Tan, Osama Shana'a, "A Harmonic–Rejection Mixer with Improved Design Algorithm for Broadband TV Tuners," in RFIC2012, Montreal, Canada
- [7] BengHwee Ong, Wei Yang, MinJie Wu, JiQing Cui, Satyanarayana Reddy Karri, Junmin Cao, Ming Kong, ChinHeng Leow, CheeLee Heng and Osama Shana'a, "A Universal Silicon TV Tuner with a Compact Synthesizer in 0.18um CMOS," *in conf proceeding ASSCC 2013, pp*337-340