Cavity Field Control

- RF Signal Detection and Actuation

LLRF Lecture Part 3.4

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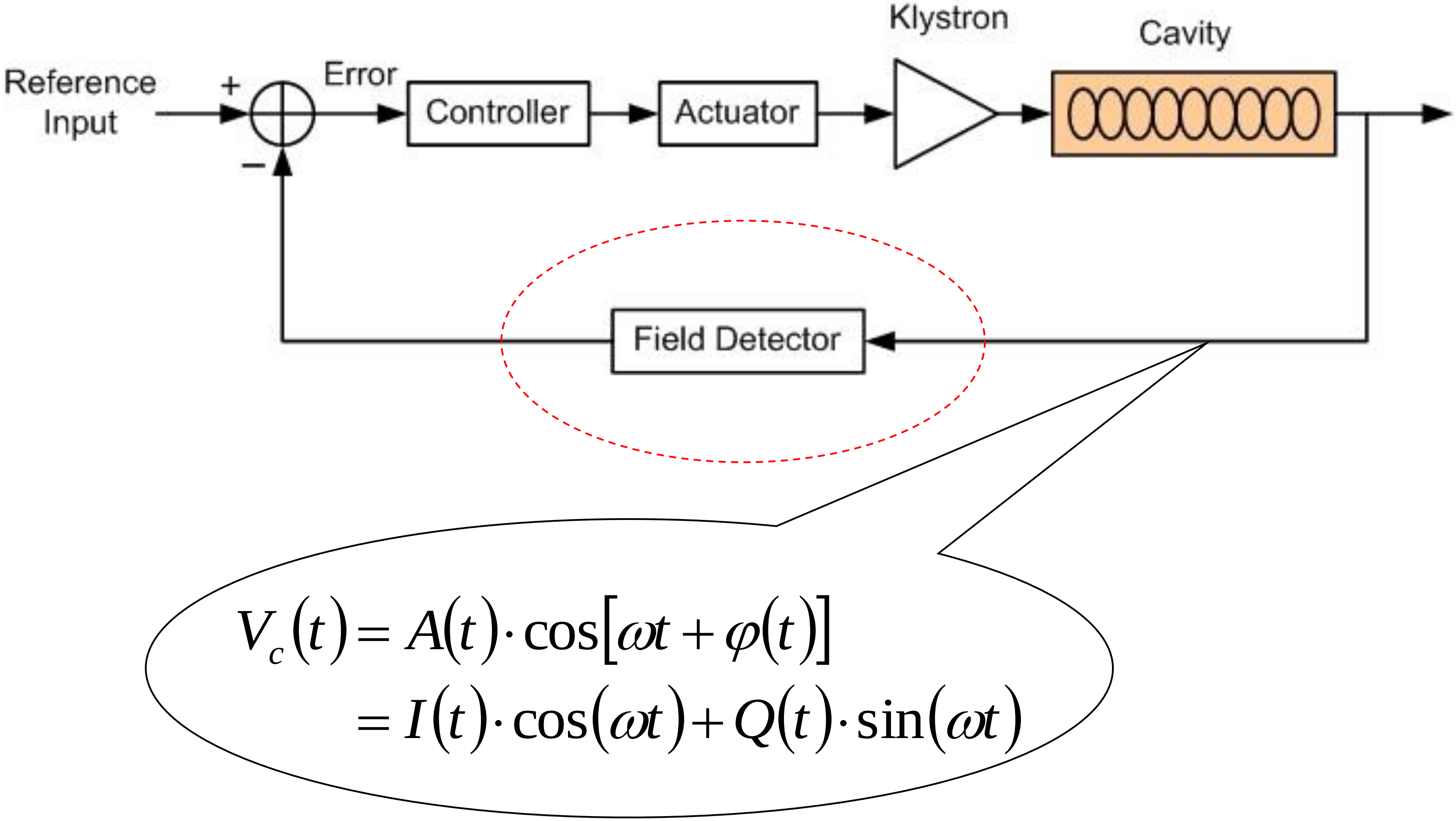
ITER / SLAC

Outline

- Requirements to RF field detector
- RF field detection methodology
- Reduce the noises and compensate the drifts in RF field detection
- RF actuation
- Appendix
  - – Typical hardware for RF field detection
    - Mixer
    - Analog to Digital Converter (ADC)

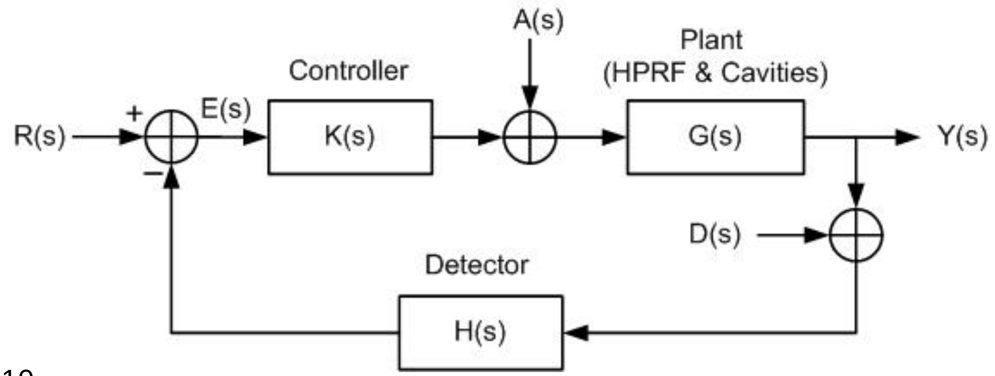
Requirements to RF Field Detector

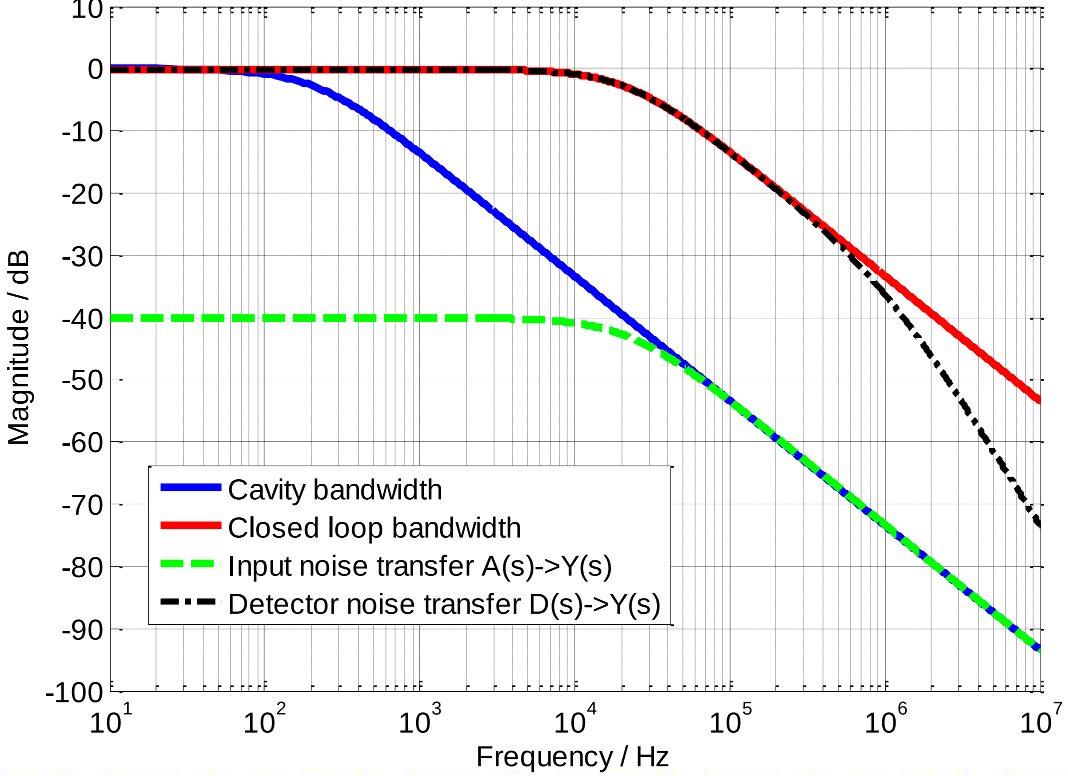
Context of the RF Field Detector



$$
\begin{aligned}
V_c(t) &= A(t)\cdot\cos\left[\omega t+\varphi(t)\right]\\
&= I(t)\cdot\cos(\omega t)+Q(t)\cdot\sin(\omega t)
\end{aligned}
$$

Recall: Transfer Function from Detector Noise to Cavity Field





- Low frequency noise of detector is transferred directly to the cavity output; high frequency noise is filtered by closed loop bandwidth and detector bandwidth
- Reducing the detector noise will be essential to get highly stable cavity field!

Requirements to the RF Field Detector

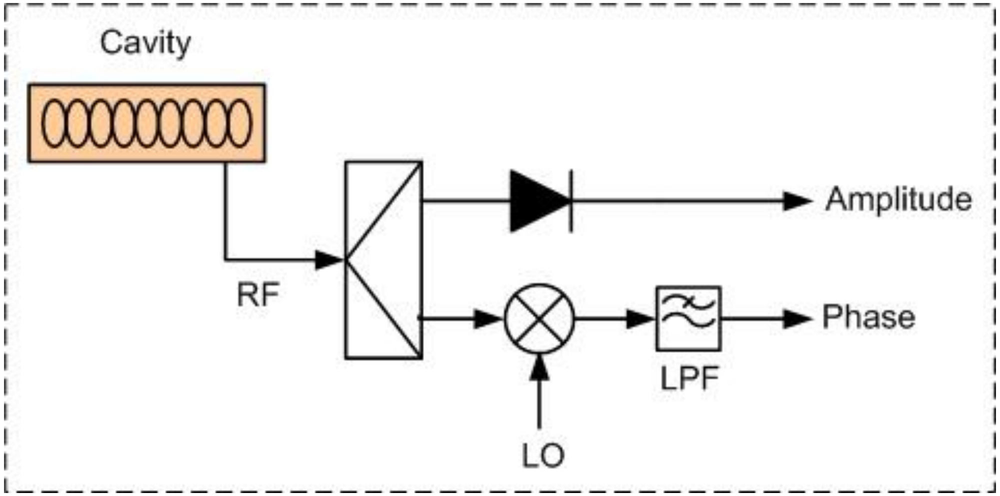
- The requirements of the RF field detector should be derived from the overall requirements to LLRF system
- Functional requirements: detect the amplitude and phase of RF field for each cavity in real time
- Quality requirements:
  - Field detection bandwidth
  - Amplitude and phase error
  - Non-linearity

Example for FLASH:

- Field detection bandwidth: 10 MHz
- Amplitude and phase error: < 10^-4
- Non-linearity: at full scale of the measurement, the amplitude compression should be less than 1% and phase shift should be less than 0.5 degree

RF Field Detection Methodology

Direct Amplitude and Phase Detection



Mixer input:

$$V_{RF}(t) = A_{RF}\sin(\omega t + \varphi_0)$$

$$V_{LO}(t) = A_{LO}\cos(\omega t)$$

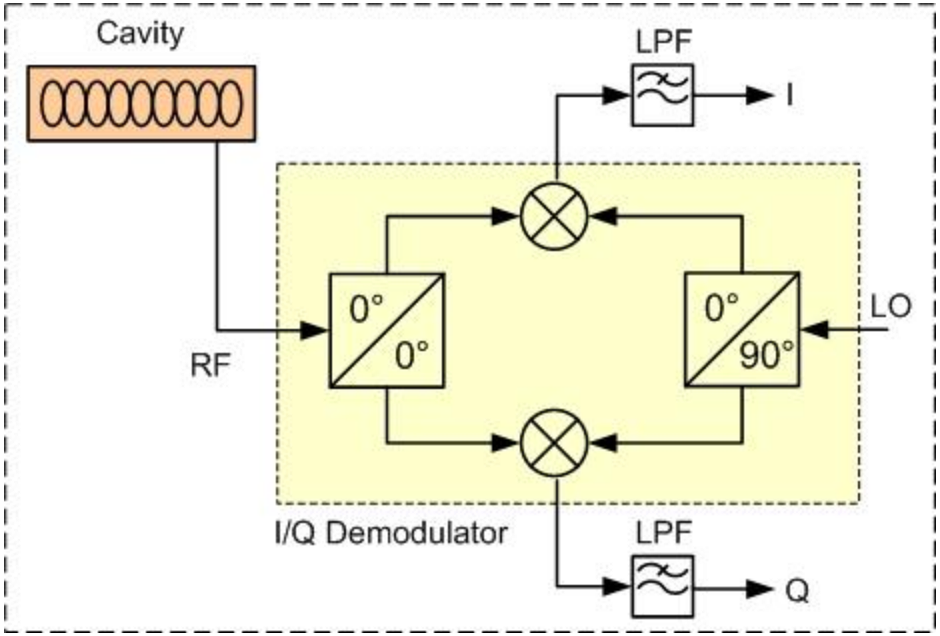
Mixer output:

$$V_{mixer} = A_{RF}\sin(\omega t + \varphi_0)\cdot A_{LO}\cos(\omega t) = \frac{A_{RF}A_{LO}}{2}\left[\sin\varphi_0 + \sin(2\omega t + \varphi_0)\right]$$

$$LPF\{V_{mixer}\} = \frac{A_{RF}A_{LO}}{2}\sin\varphi_0 \approx \frac{A_{RF}A_{LO}}{2}\varphi_0 \quad (\text{for small } \varphi_0)$$

- Simple system structure
- Linear for small phase errors
- Phase measurement is influenced by the amplitude error of the RF or LO signal

Analog I/Q Detection



Inputs:

$$V_{RF}(t) = A_{RF}\cos(\omega t + \varphi_0)$$

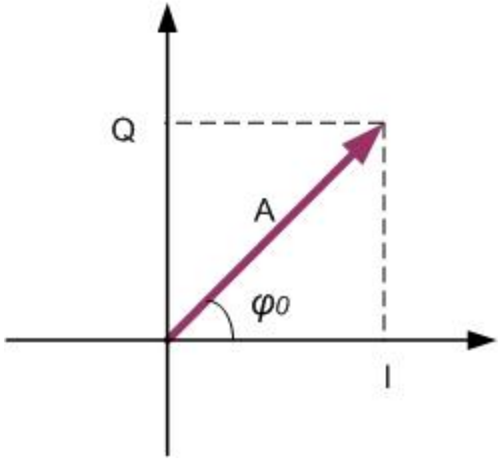
$$V_{LO}(t) = A_{LO}\cos(\omega t)$$

Outputs:

$$I = LPF\left\{\frac{A_{RF}}{\sqrt{2}}\cos(\omega t + \varphi_0)\cdot\frac{A_{LO}}{\sqrt{2}}\cos(\omega t)\right\} = \frac{A_{RF}A_{LO}}{4}\cos\varphi_0$$

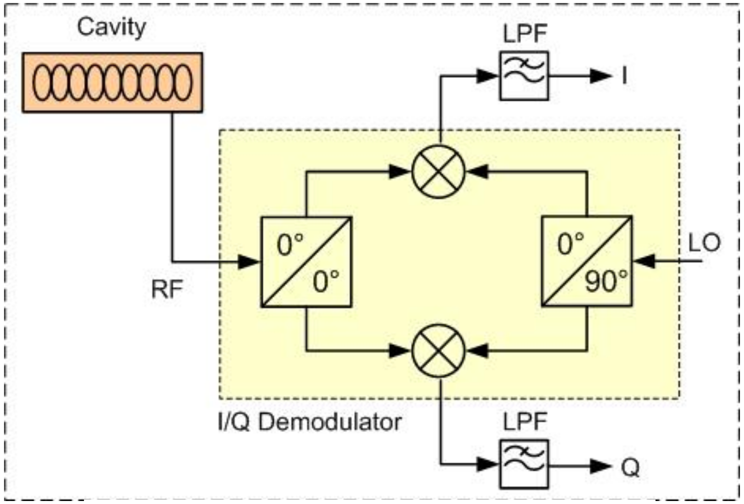
$$Q = LPF\left\{-\frac{A_{RF}}{\sqrt{2}}\cos(\omega t + \varphi_0)\cdot\frac{A_{LO}}{\sqrt{2}}\sin(\omega t)\right\} = \frac{A_{RF}A_{LO}}{4}\sin\varphi_0$$

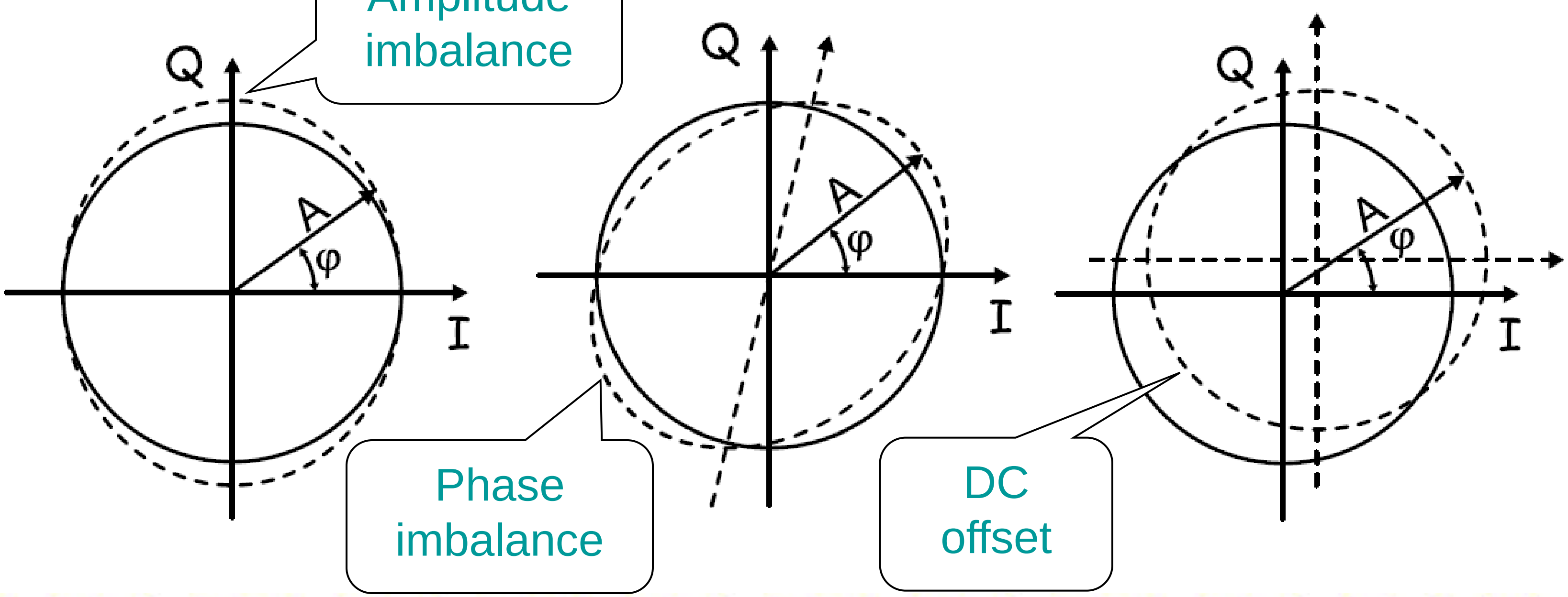
$$\varphi_0 = \tan^{-1}\left(\frac{Q}{I}\right) \qquad A = \sqrt{I^2 + Q^2}$$



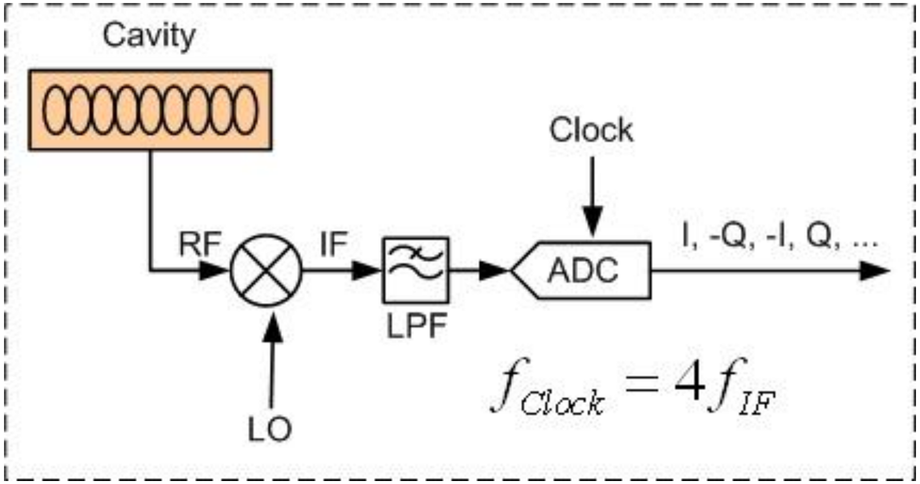
Analog I/Q Detection

- Phase measurement is linear for the whole range of 360º
- Low efforts of digital processing
- Disadvantages:
  - Phase and amplitude imbalance
  - DC offset



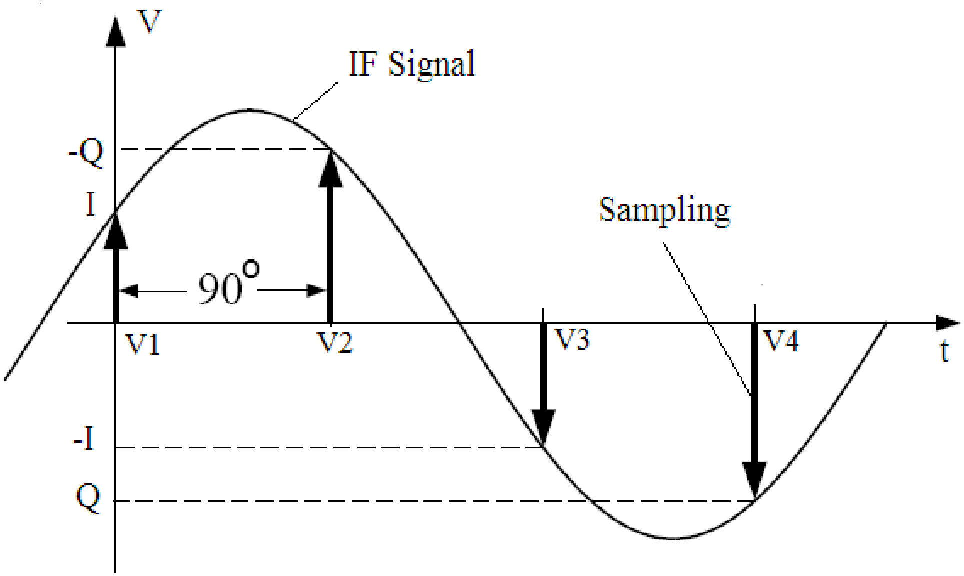


IQ Sampling

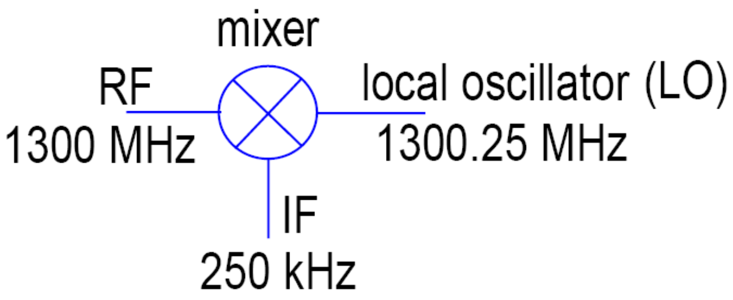


$$f_{Clock} = 4 f_{IF}$$

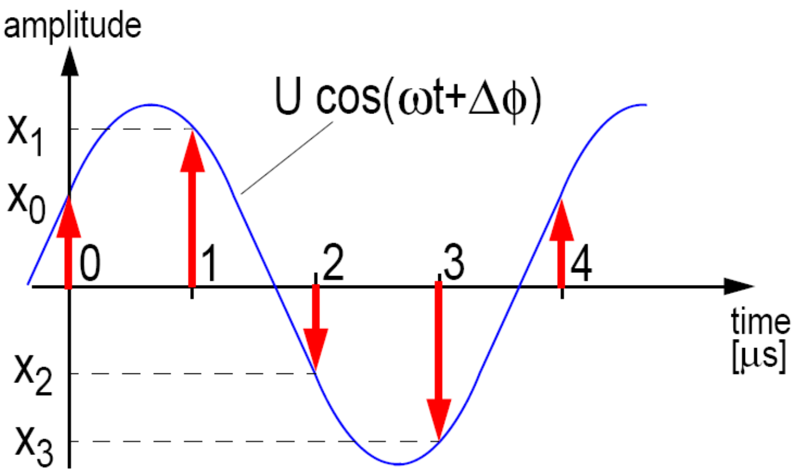
- Digital I/Q detection
- IF and clock signal should be synchronized
- Alternating sample give I and Q components of the cavity field



IQ Sampling at FLASH



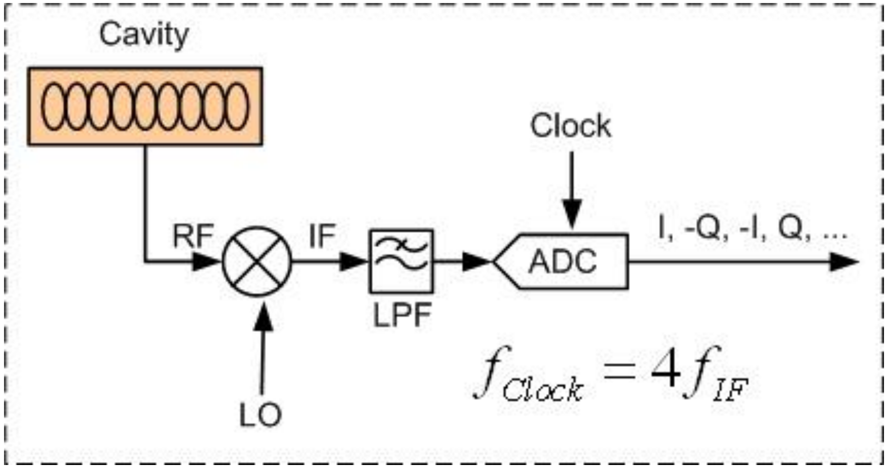
- downconversion of cavity field to IF frequency at 250 kHz
- complete phase and amplitude information of the accelerating field is preserved.

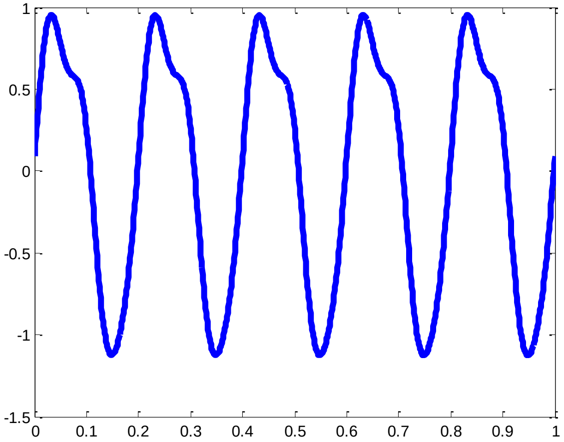


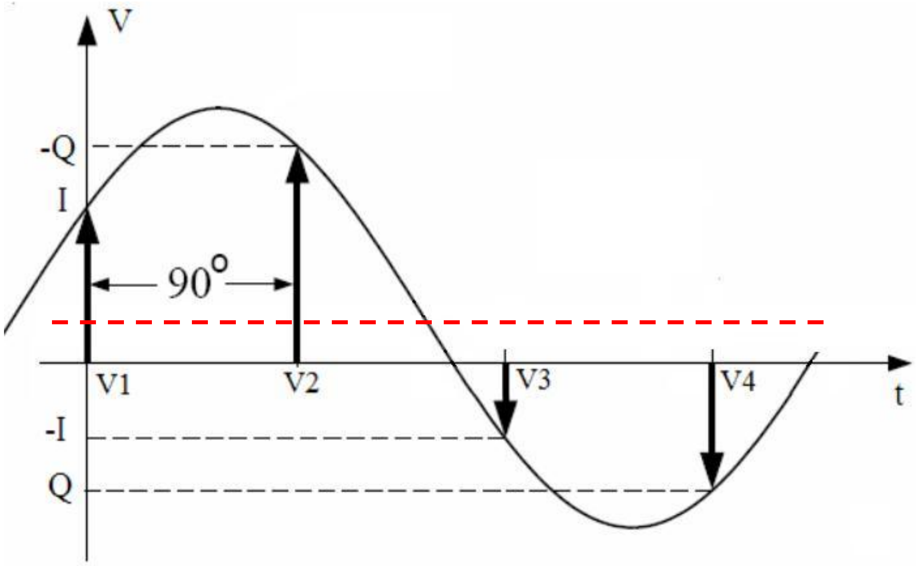
- sample IF signal at 1MHz rate
- subsequent samples describe real and imaginary component of the cavity field.

IQ Sampling

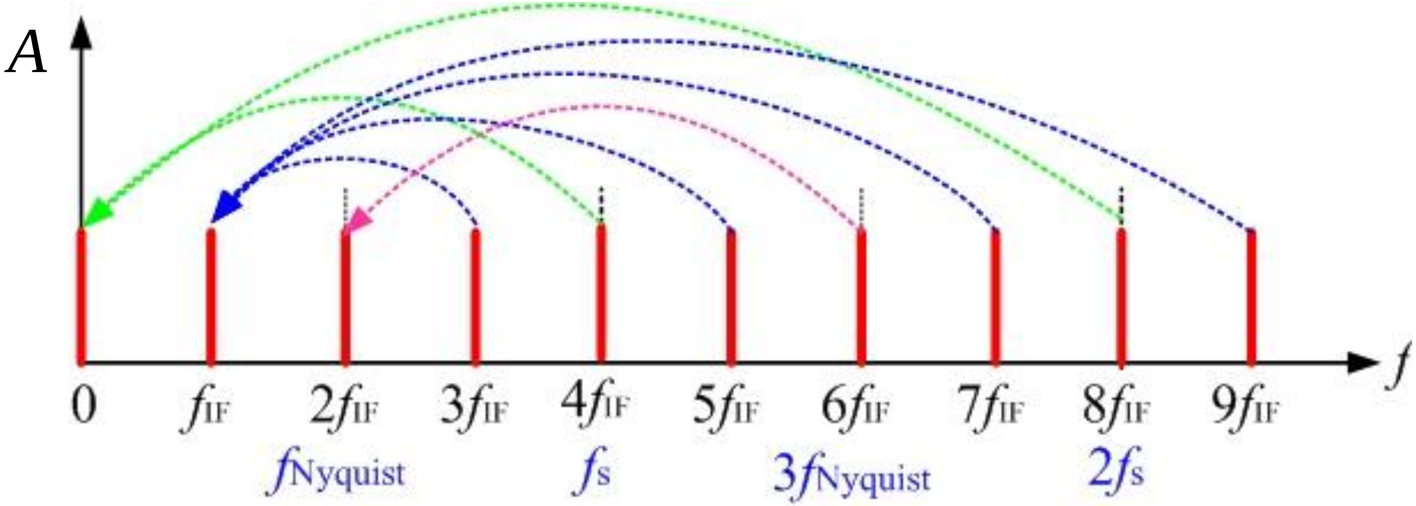
- Advantages
  - Get rid of the imbalance effect compared with the analog I/Q demodulator
- Problems
  - DC offset caused by the mixer
  - Nonlinearities in the analog front-end or the ADC generate harmonics, which will be aliased to the IF frequency

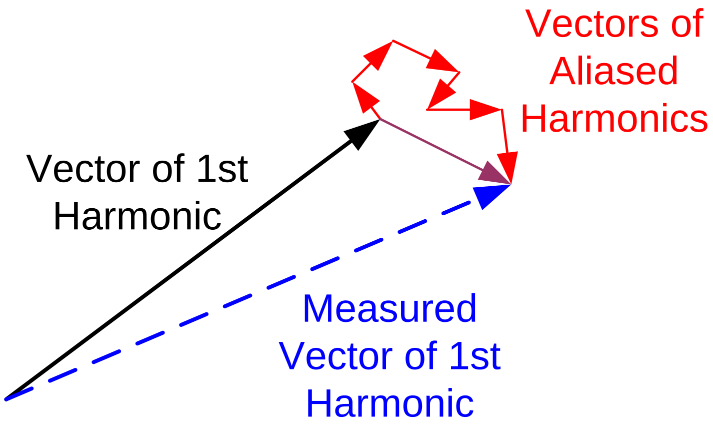






IQ Sampling

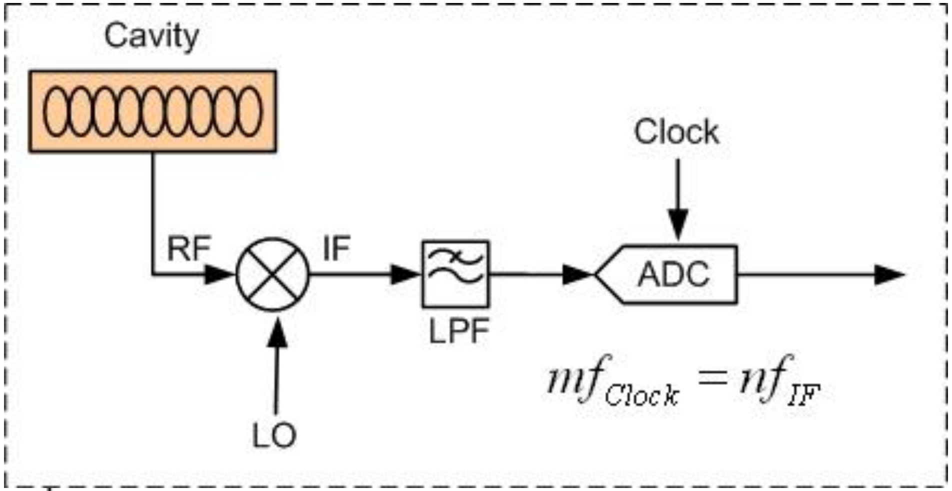




- The phase of nth harmonic changes n times faster than the fundamental phase
- Phase shifts in the cavity due to microphonics and Lorenz force detuning will lead to a time dependent error

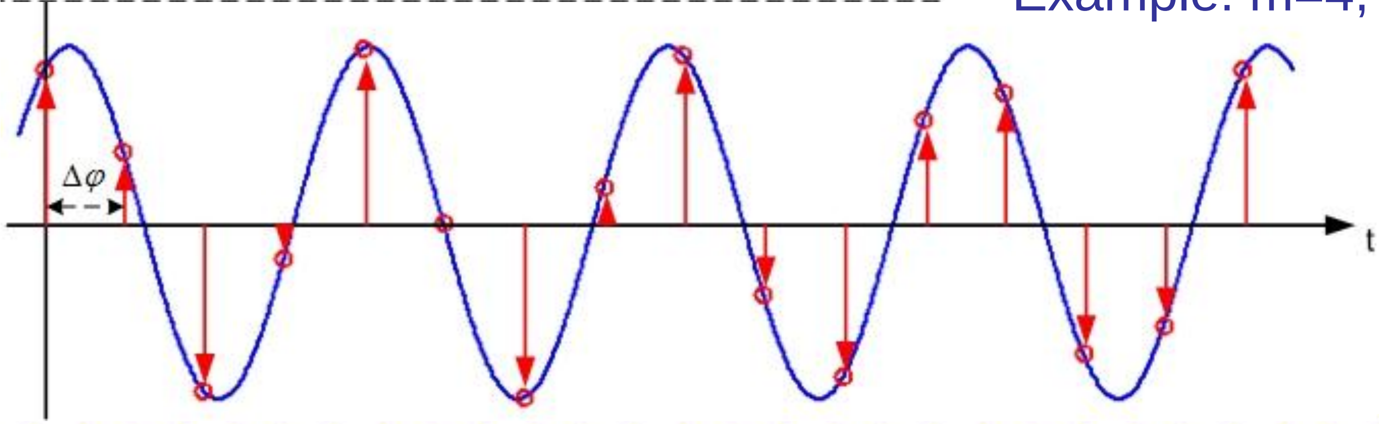
Non-IQ Sampling

- Compared with IQ sampling, non-IQ sampling is aimed to avoid the harmonics aliasing by shifting the sampling frequency slightly from 4 times of the IF frequency



$$\Delta\varphi = \frac{m}{n} \cdot 2\pi$$

Example: m=4, n=15



Non-IQ Sampling

- Fourier series decomposition of the RF signal

$$s(t) = A\sin(2\pi f_{IF}t + \varphi) = I\cos(2\pi f_{IF}t) + Q\sin(2\pi f_{IF}t)$$

$$s(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty}\left[a_k\cos(k2\pi f_{IF}t) + b_k\sin(k2\pi f_{IF}t)\right]$$

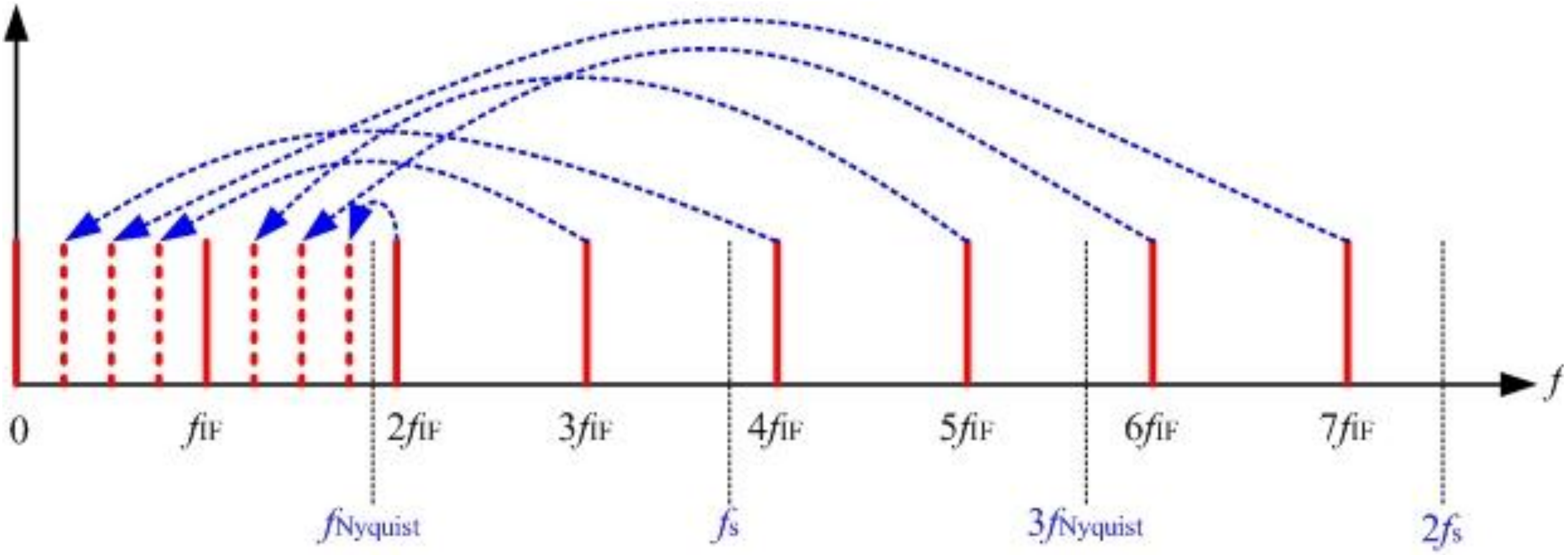
$$\begin{cases} a_k = \frac{2}{T}\int_0^T s(t)\cos(k2\pi f_{IF}t)dt \\ b_k = \frac{2}{T}\int_0^T s(t)\sin(k2\pi f_{IF}t)dt \end{cases}, \quad k = 1,2,\ldots$$

- Demodulation algorithm:

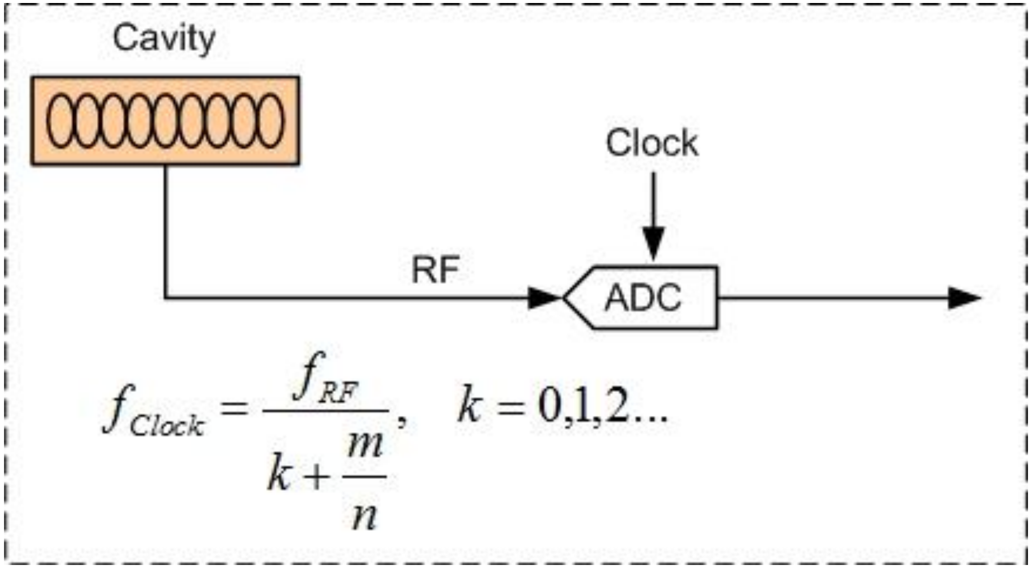
$$I = \frac{2}{n}\sum_{i=0}^{n-1} x_i\cos(i\Delta\varphi), \quad Q = \frac{2}{n}\sum_{i=0}^{n-1} x_i\sin(i\Delta\varphi)$$

Non-IQ Sampling

- Most harmonics no longer line up with IF frequency. Influence due to the higher order harmonics and DC offset can be reduced with band pass filter.
- The algorithm for demodulation need more computation power and will cause larger latency



Direct Sampling



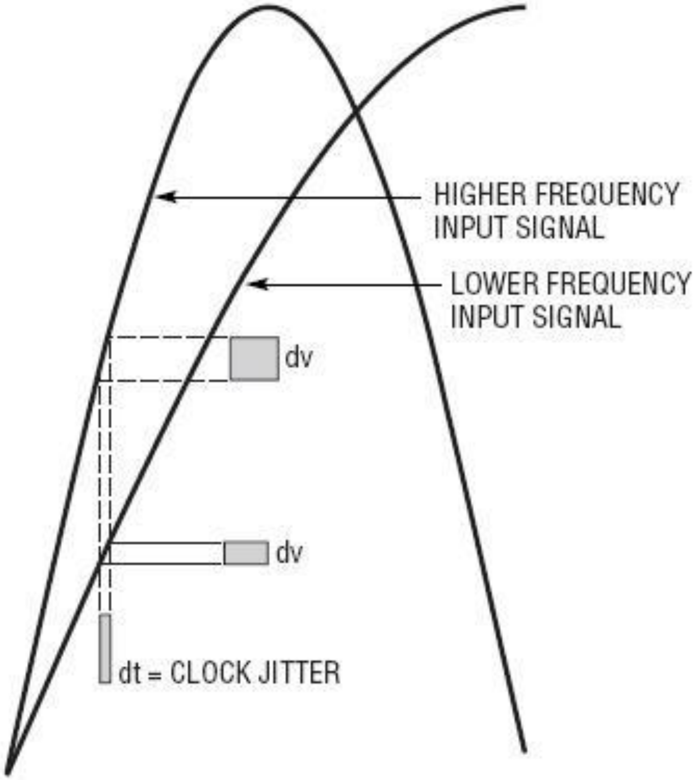
$$f_{Clock} = \frac{f_{RF}}{k + \frac{m}{n}}, \quad k = 0,1,2\ldots$$

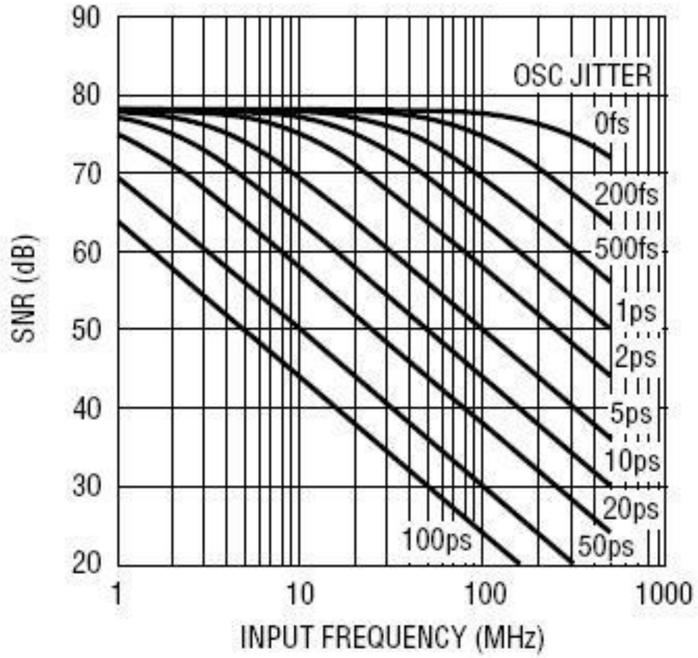
- Example for available ADC: ADS5474, 14 bits, 400MSPS, 1.4GHz bandwidth
- Under-sampling
- Non-IQ sampling (m,n have the same meaning as the discussion of non-IQ sampling)

Direct Sampling

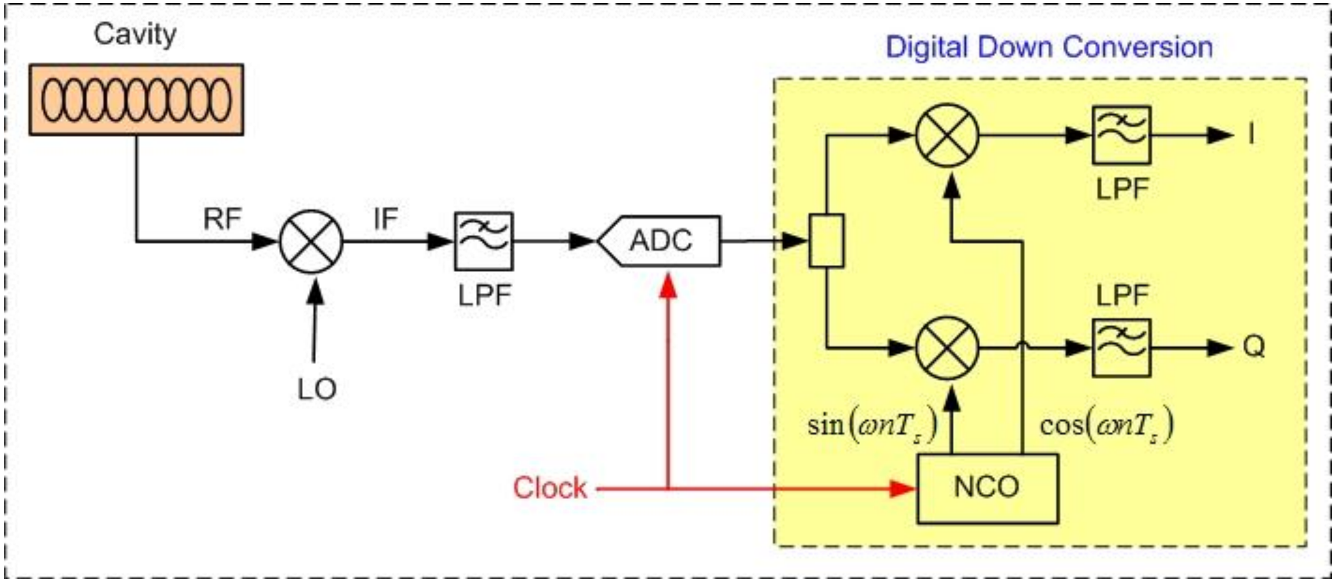
- Advantage: no down converter needed
- Essential problems: ADC measurement noise is sensitive to the clock jitter due to the high input RF frequency

$$SNR_{jitter} = -20\log_{10}\left(2\pi f_{RF} t_{jitter\_rms}\right)$$

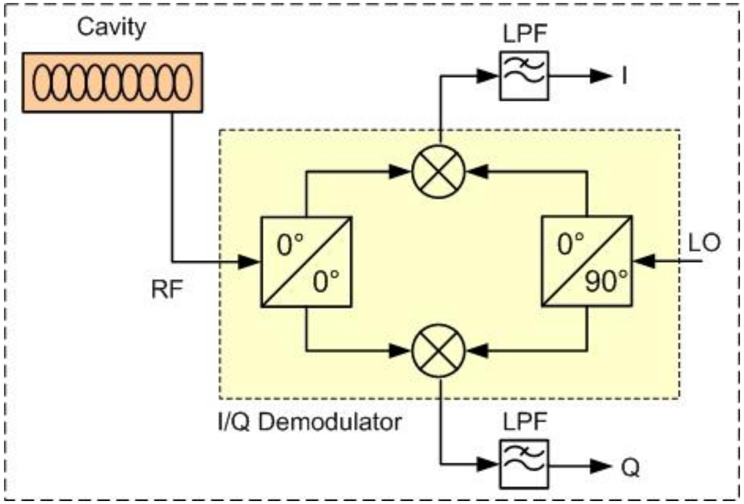




Digital Down Conversion

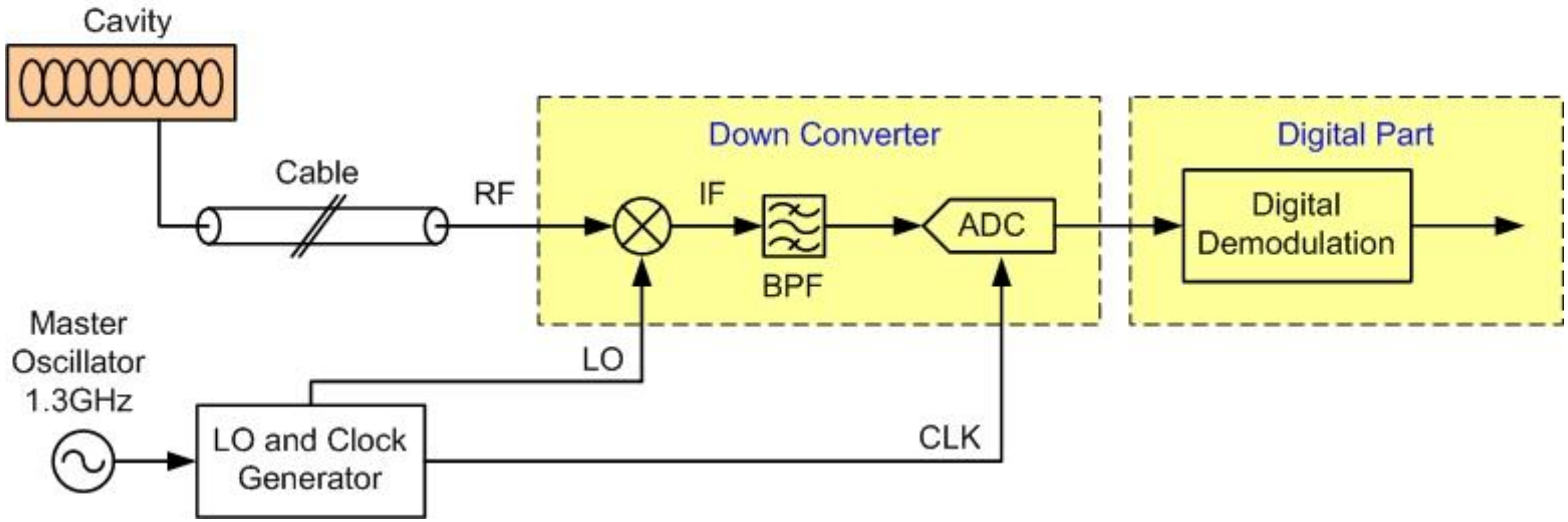


- Principle same as analog I/Q demodulator
- NCO: Numerical Controlled Oscillator
- Digital mixer: multiplication operation in processors (in FPGA can be multiplier cores)
- Digital low pass filter, can be IIR, FIR or CIC filter



Reduce the Noises and Compensate the Drifts in RF Field Detection

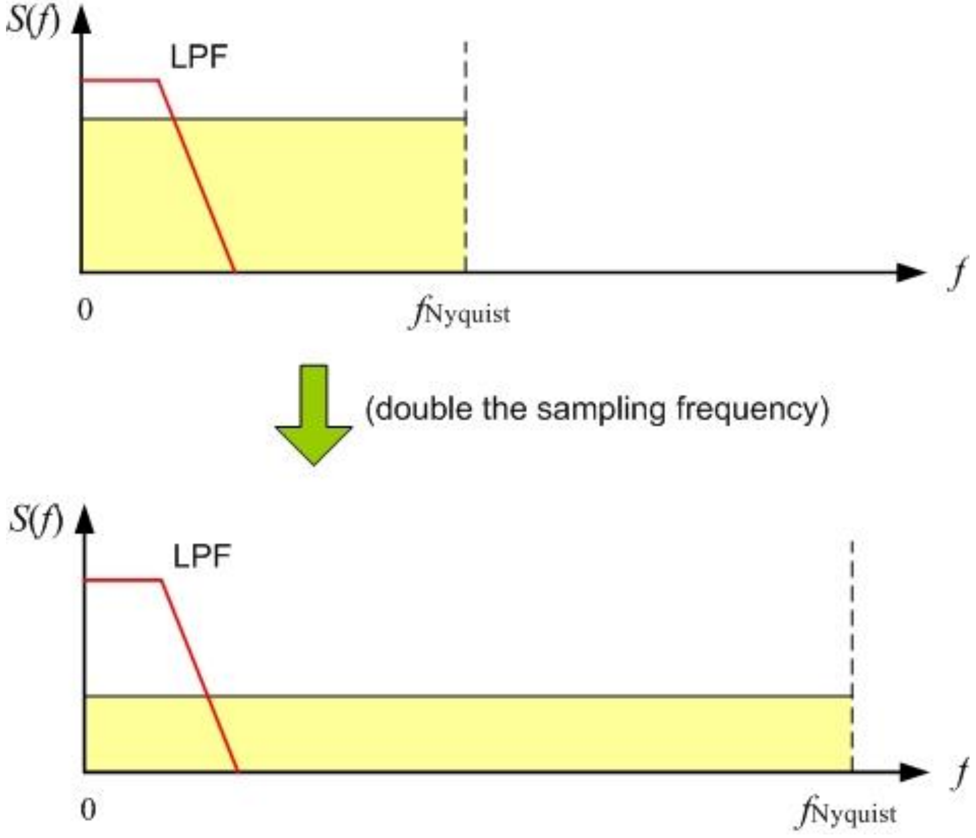
Noise and Drift Sources for RF Detection



- Slow phase and amplitude drifts:
  - Cavity pick up cables
  - Down converter
  - LO low frequency phase noise
- Fast phase and amplitude jitters:
  - Thermal noise
  - LO high frequency phase noise
  - ADC noise

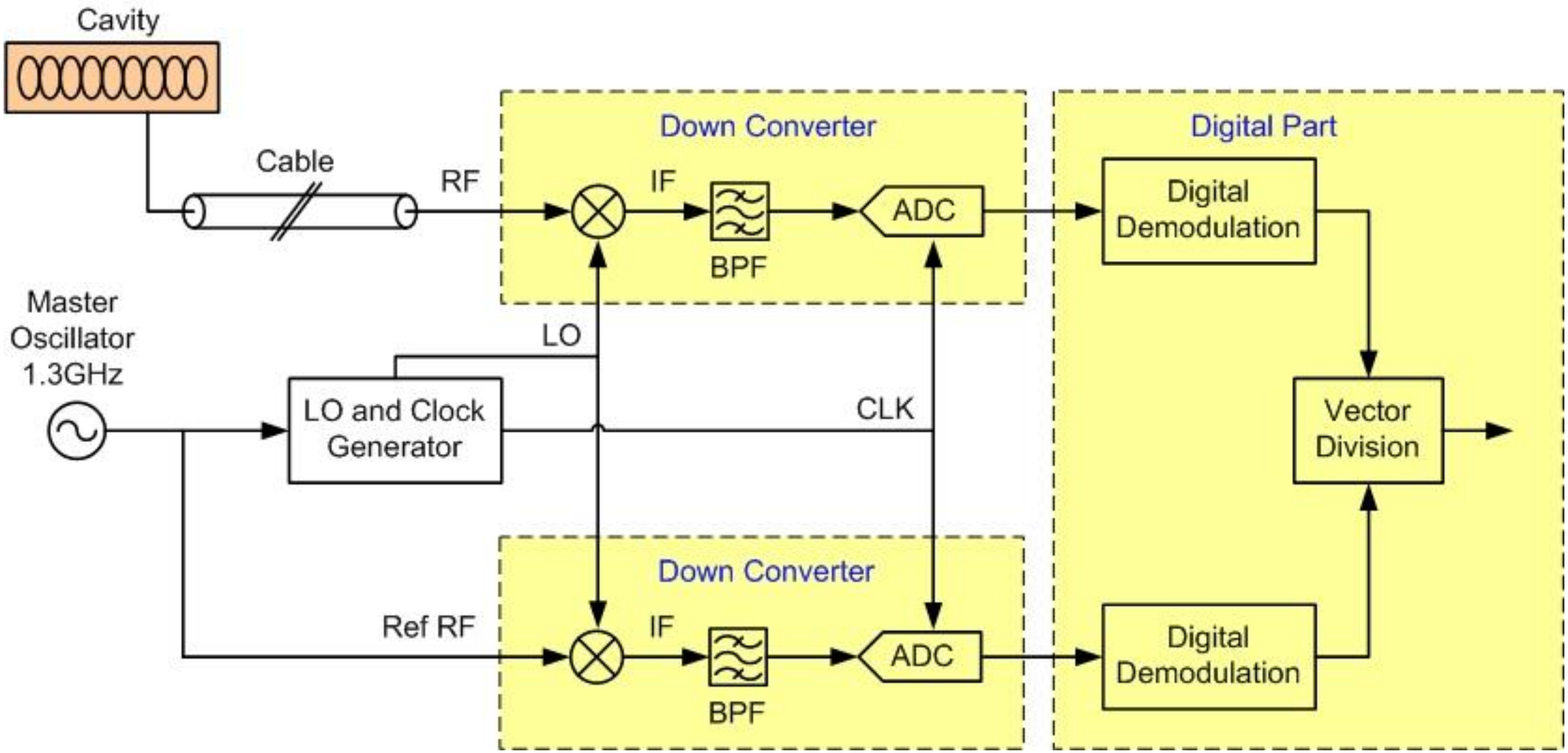
Reduce the High Frequency Noise

- Select components of down converter with low noise level
- Filtering in RF side
- ADC oversampling



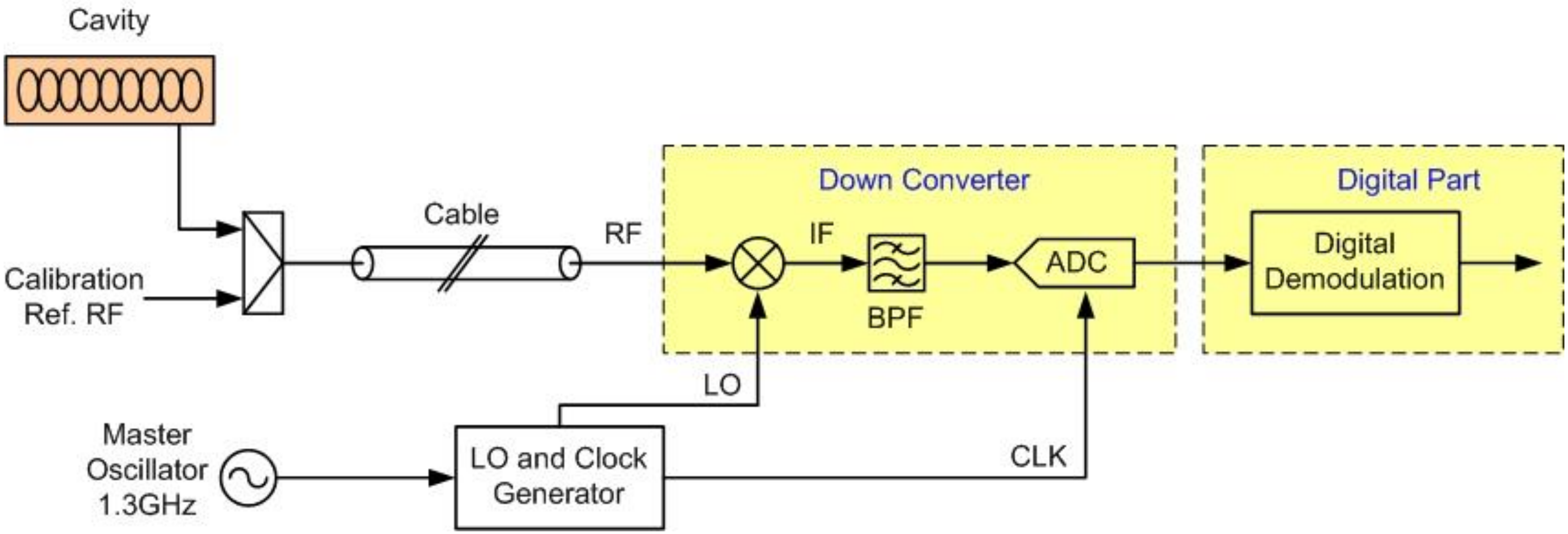
Drift and Fluctuation Correction

Reference tracking



Drift and Fluctuation Correction

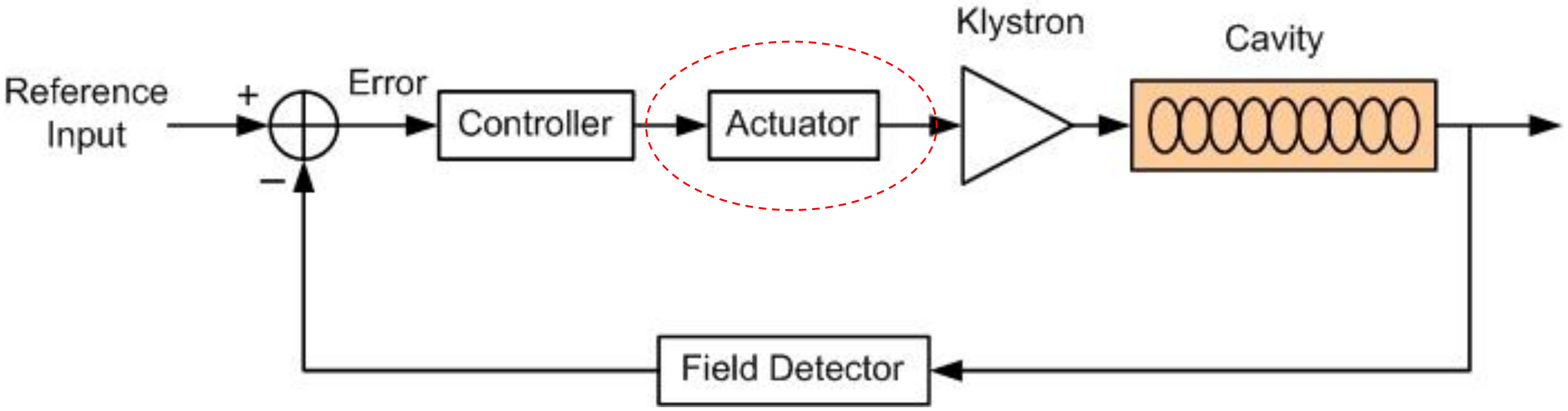
Measurement chain drift calibration



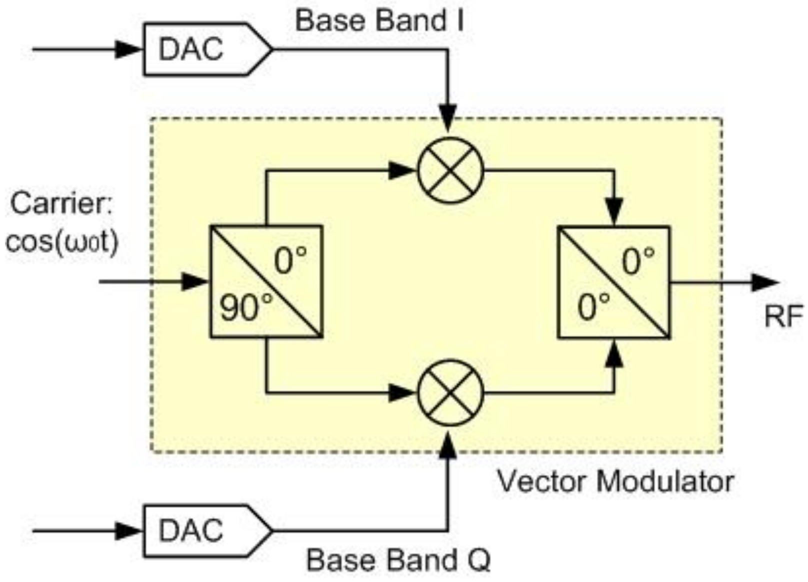
RF Actuation

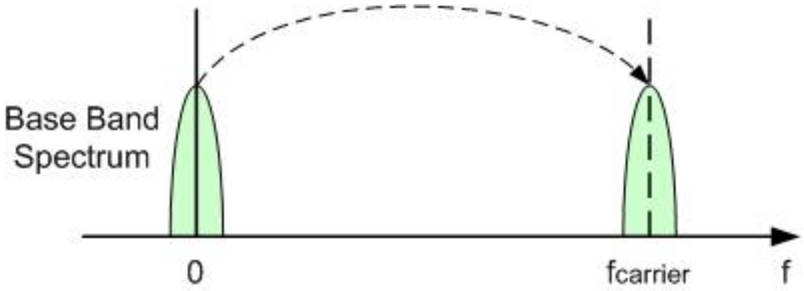
RF Actuator

- Change the amplitude and phase of RF driving signal and perform frequency up-conversion
- Widely used solutions:
  - Direct up-conversion
  - IF up-conversion
  - Single sideband up-conversion



Direct Up-conversion



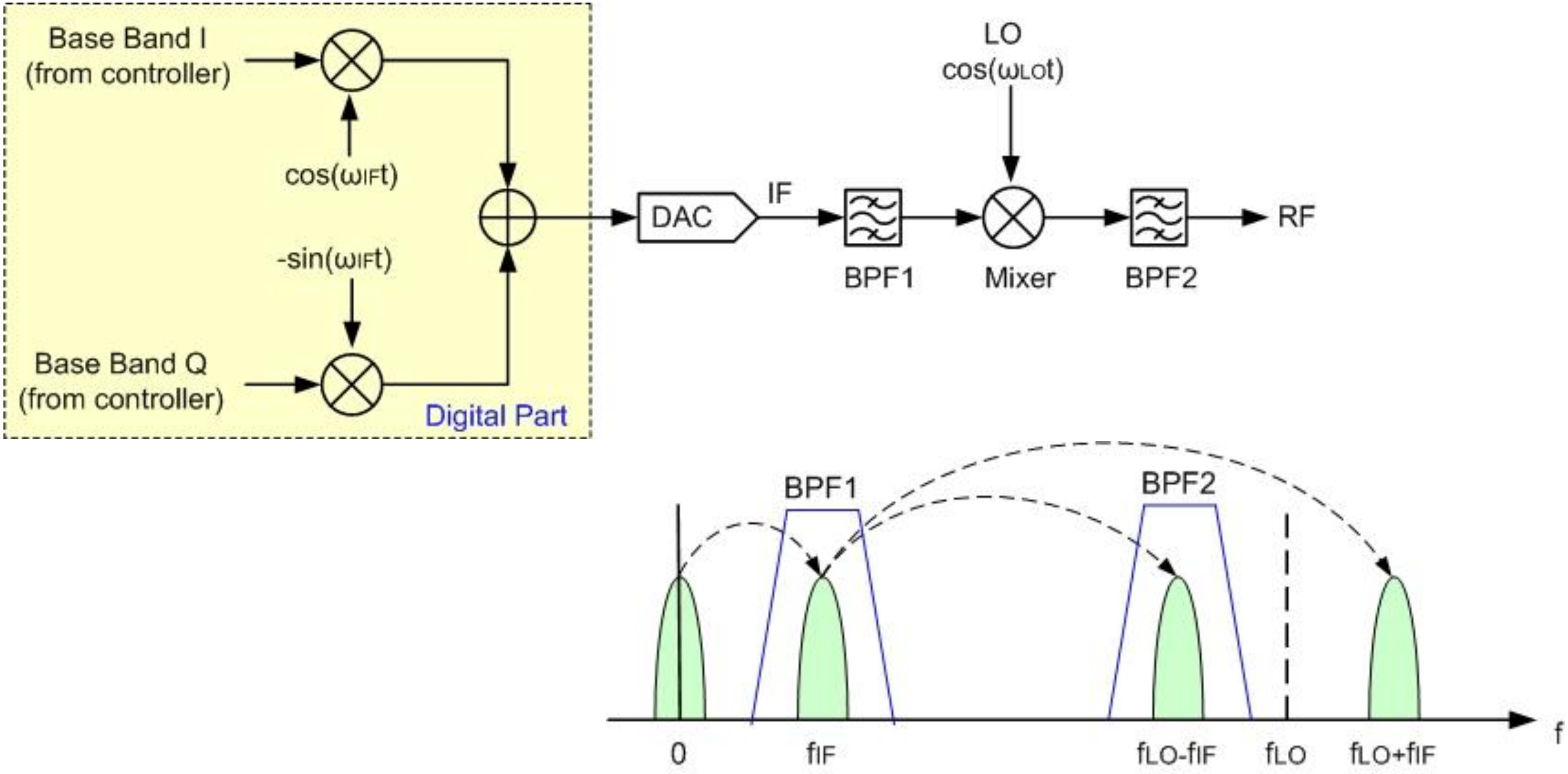


$$RF = I\cos(\omega_0 t) - Q\sin(\omega_0 t) = A\cos(\omega_0 t + \varphi)$$

$$A = \sqrt{I^2 + Q^2}, \quad \varphi = \tan^{-1}\left(\frac{Q}{I}\right)$$

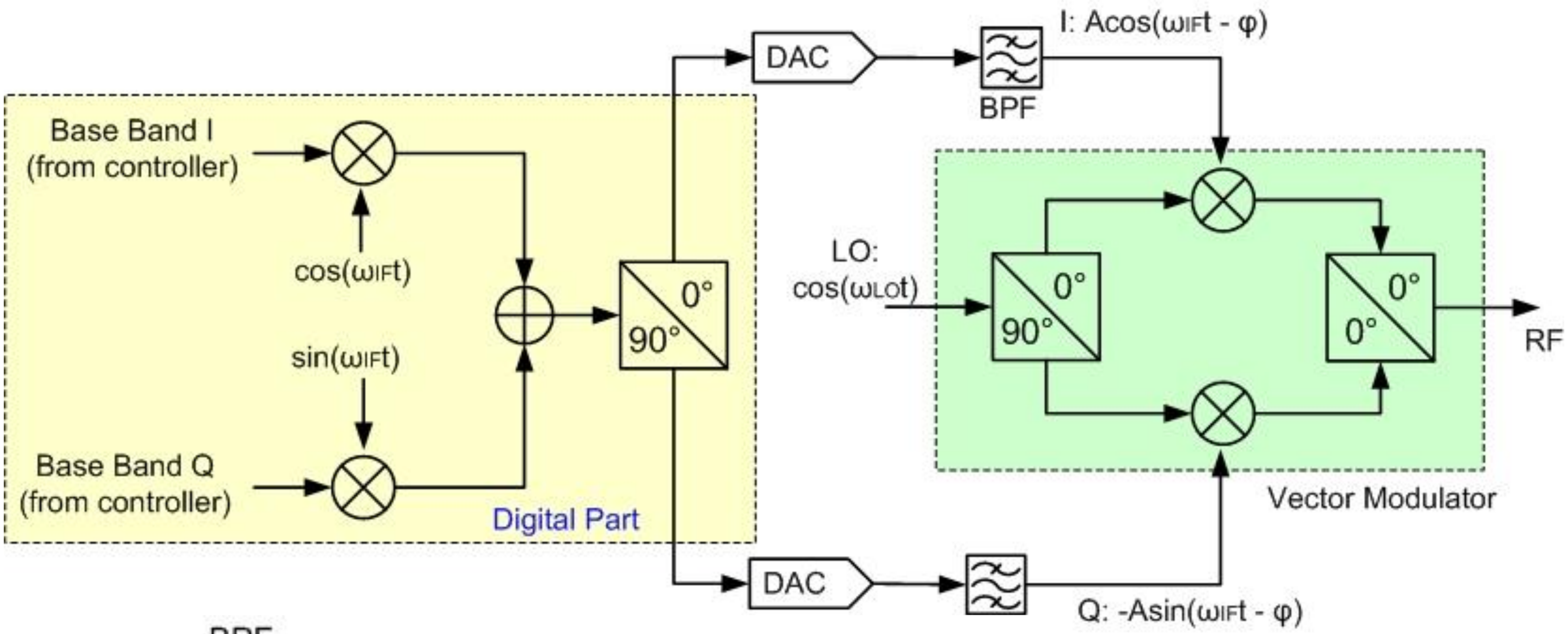
- Easy to implement
- Suffer from the DC offset in I/Q base band signals and the phase and amplitude imbalance of the vector modulator

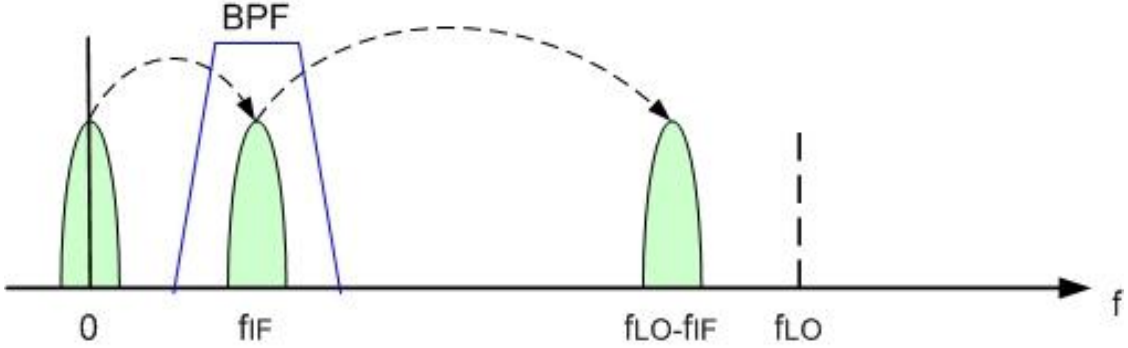
IF Up-conversion



- Band pass filter after the DAC can remove the DC offset
- Band pass filter after the mixer is necessary
- If IF is small, filter design will be critical

Single Sideband Up-conversion





$$RF = A\cos(\omega_{LO}t)\cos(\omega_{IF}t-\varphi)+A\sin(\omega_{LO}t)\sin(\omega_{IF}t-\varphi)=A\cos[(\omega_{LO}-\omega_{IF})t+\varphi]$$

Summary

In this part, we have learnt:

- Principles and characteristics of several RF field detection methods
- Ideas to correct the noise and drift of the RF field detector
- Principles for several RF actuation (up-conversion) methods

Reference

[1] Z. Geng. Design and Construction of the Phasing System for BEPCII Linac. Ph.D. thesis of Chinese Academy of Sciences, 2007

[2] T. Schilcher. Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities. Ph. D. Thesis of DESY, 1998

[3] M. Hoffmann. Development of A Multichannel RF Field Detector for the Low-Level RF Control of the Free-Electron Laser at Hamburg. Ph.D. Thesis of DESY, 2008

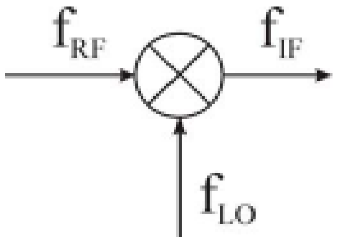
[4] L. Doolittle. Digital Low-Level RF Control Using Non-IQ Sampling. LINAC2006, Knoxville, Tennessee USA

[5] Z. Geng, S. Simrock. Evaluation of Fast ADCs for Direct Sampling RF Field Detector for the European XFEL and ILC. LINAC2008, Victoria, BC, Canada

Appendix:
Typical Hardware for RF Field Detection

Mixer

$$y_{RF}(t) = A_{RF} \cdot \sin(\omega_{RF} t + \varphi_{RF})$$



$$y_{IF}(t) = y_{RF}(t) \cdot y_{LO}(t)$$

$$y_{LO}(t) = A_{LO} \cdot \cos(\omega_{LO} t + \varphi_{LO})$$

mixer: linear time varying circuit, non-linear circuit (diodes…)

$$\Rightarrow y_{IF}(t) = \frac{1}{2} A_{LO} A_{RF} \cdot \left(\boxed{\sin[(\omega_{RF} - \omega_{LO})t + (\varphi_{RF} - \varphi_{LO})]} \right. \\ \left. + \boxed{\sin[(\omega_{RF} + \omega_{LO})t + (\varphi_{RF} + \varphi_{LO})]} \right)$$

lower sideband

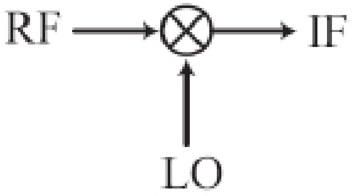
upper sideband

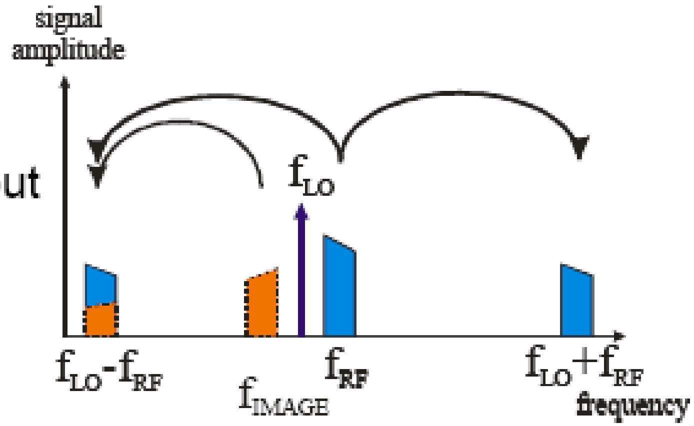
➡ even ideal mixers produce two sidebands

Mixer

- ideal mixer: output is the multiplication of the two input signals
- down conversion:

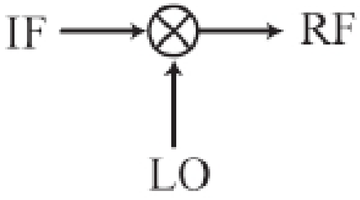
  RF, LO are high frequency inputs
  IF: lower intermediate frequency output

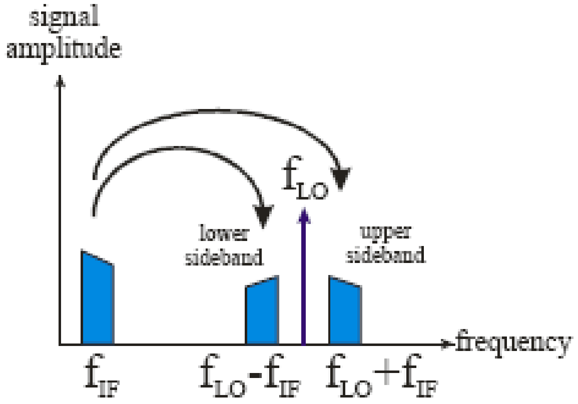




- up conversion:

  IF is input, RF is output





Mixer

down conversion:

$$y_{IF}(t) = \frac{1}{2} A_{LO} A_{RF} \cdot \left(\sin[(\omega_{RF} - \omega_{LO})t + (\varphi_{RF} - \varphi_{LO})] + \sin[(\omega_{RF} + \omega_{LO})t + (\varphi_{RF} + \varphi_{LO})] \right)$$

low pass filtering the upper sideband:

$$\boxed{\Rightarrow y_{IF}(t) = A_{IF} \cdot \sin\left(\omega_{IF} t + \varphi_{IF} \right)}$$

$$\begin{aligned} \omega_{IF} &= \omega_{RF} - \omega_{LO} & & & \\ A_{IF} &= \tfrac{1}{2} A_{LO} A_{RF} & \sim & \quad A_{RF} & \quad \text{with constant } A_{LO} \\ \varphi_{IF} &= \varphi_{RF} - \varphi_{LO} & \sim & \quad \varphi_{RF} & \quad \text{with constant } \varphi_{LO} \end{aligned} \Bigg\}$$

basic properties of RF signal are conserved (ampl./phase)

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important properties:

- phase changes/jitter are conserved during down conversion,
  e.g. 1° @ f_{RF}=1.5 GHz ↔ 1° @ f_{IF}=50 MHz
- comparison: sampling IF or RF (direct sampling)?
  timing jitter results in different phases!
  (e.g. 10 ps @ 500 MHz → 1.8°; 10 ps @ 50 MHz → 0.18°)

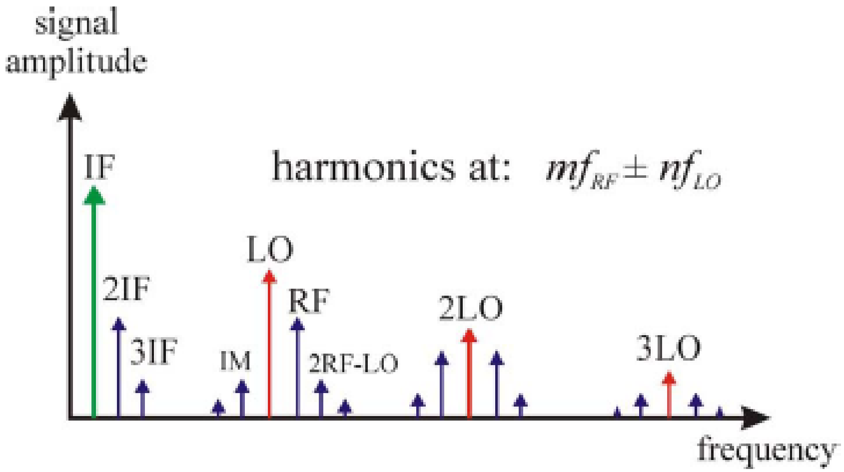
⇒ **tougher requirements for direct RF sampling !**

Mixer

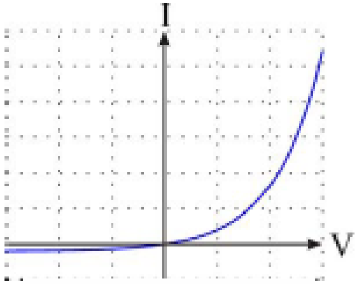
real mixers = non linear devices

➡ many undesired harmonics in frequency spectrum

➡ non-linearities in IF signal



I-V curve of a diode



$$I = I_0(e^{V/V_T} - 1)$$

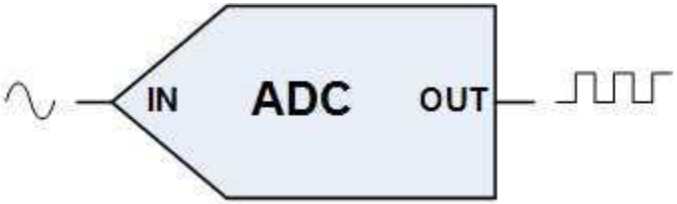
$$\Delta I = I_0 e^{V/V_T}\left(\frac{\Delta V}{V_T} + \frac{1}{2}\left(\frac{\Delta V}{V_T}\right)^2 + \frac{1}{6}\left(\frac{\Delta V}{V_T}\right)^3 + \ldots\right)$$

➡ filtering the output of a mixer might be necessary

➡ take care about the introduced group delay by the filter

} trade off!

Analog to Digital Converter



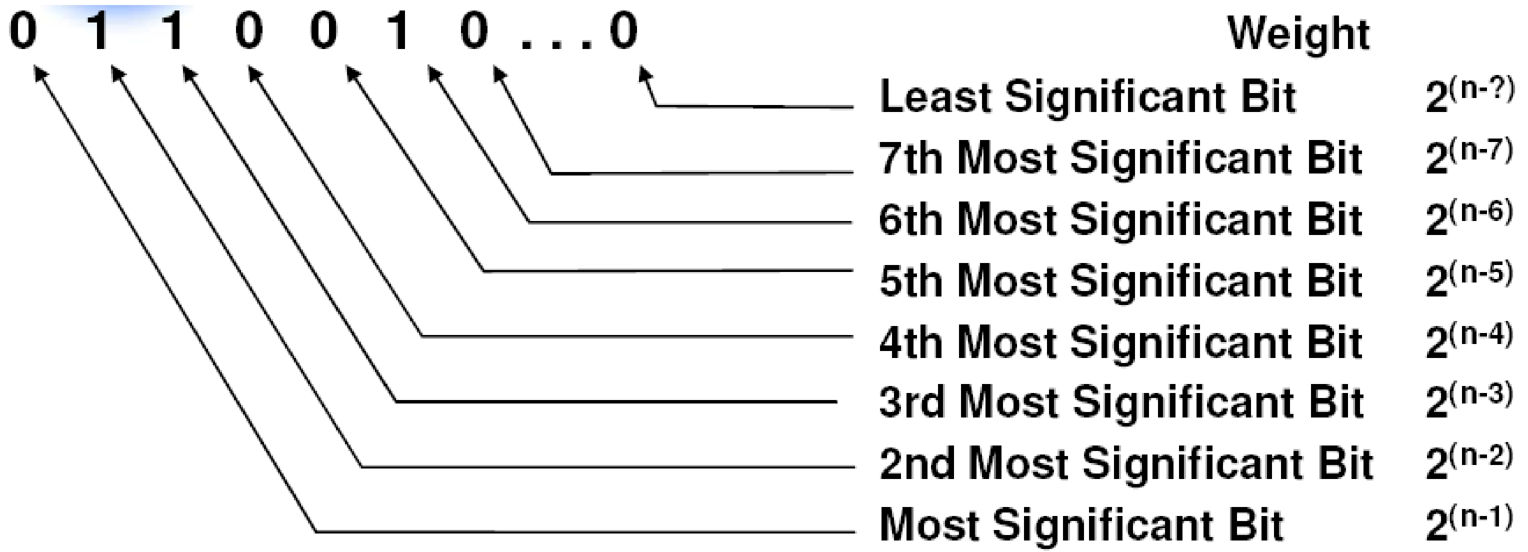
ELECTRICAL SYMBOL FOR ANALOG TO DIGITAL CONVERTER (ADC)

What is an ADC?

- **Mixed-Signal Device**
  - Analog Input
  - Digital Output
- **May be Considered to be a Divider**
  - Output says: Input is What Fraction of V_{REF}?
  - ➡ Output = $2^n \times G \times A_{IN} / V_{REF}$
    - n = # of Output Bits (Resolution)
    - G = Gain Factor (usually "1")
    - A_{IN} = Analog Input Voltage (or Current)
    - V_{REF} (I_{REF})= Reference Voltage (or Current)

Analog to Digital Converter

Least Significant Bit (LSB) and Most Significant Bit (MSB)



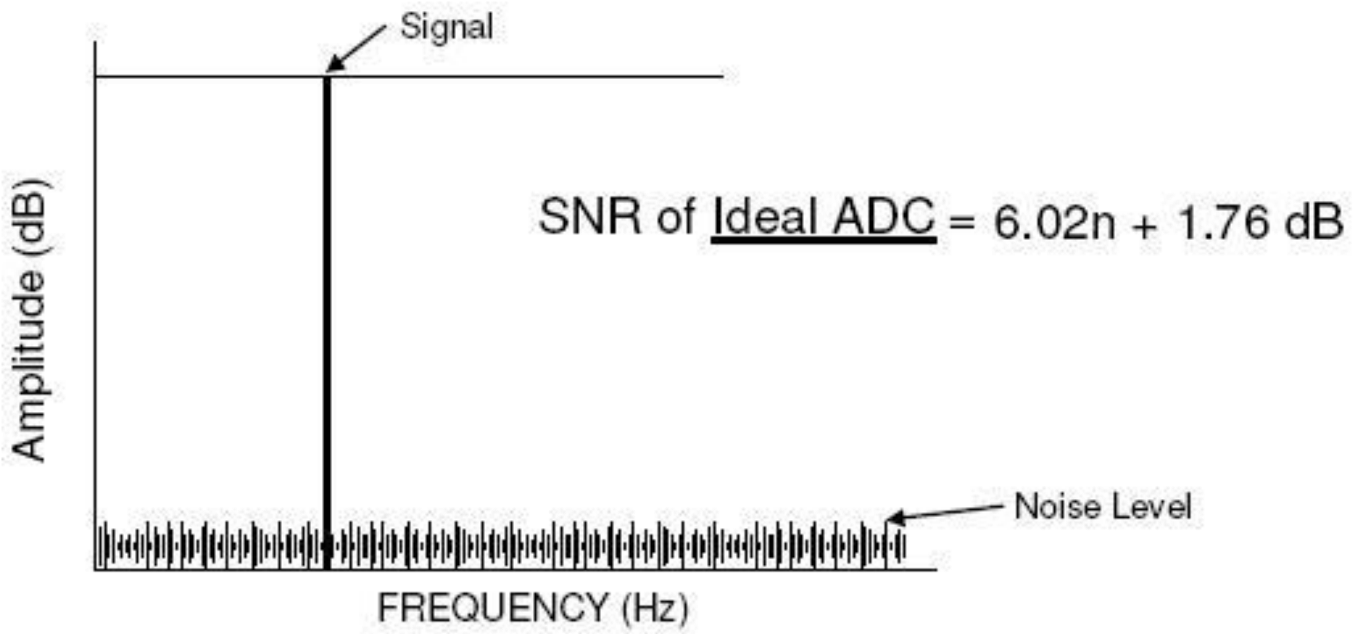
0 1 1 0 0 1 0 . . . 0

	Weight
Least Significant Bit	$2^{(n-?)}$
7th Most Significant Bit	$2^{(n-7)}$
6th Most Significant Bit	$2^{(n-6)}$
5th Most Significant Bit	$2^{(n-5)}$
4th Most Significant Bit	$2^{(n-4)}$
3rd Most Significant Bit	$2^{(n-3)}$
2nd Most Significant Bit	$2^{(n-2)}$
Most Significant Bit	$2^{(n-1)}$

Bit Weights of an 8-Bit Word

MSB B7	B6	B5	B4	B3	B2	B1	LSB B0
128	64	32	16	8	4	2	1

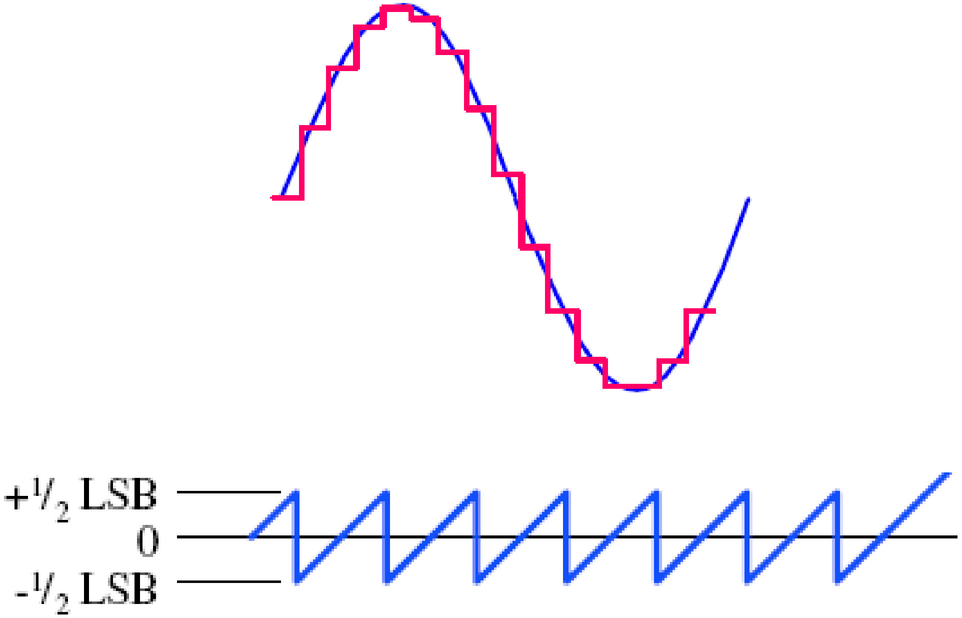
Analog to Digital Converter



Analog to Digital Converter

ADC noise source: Quantization noise

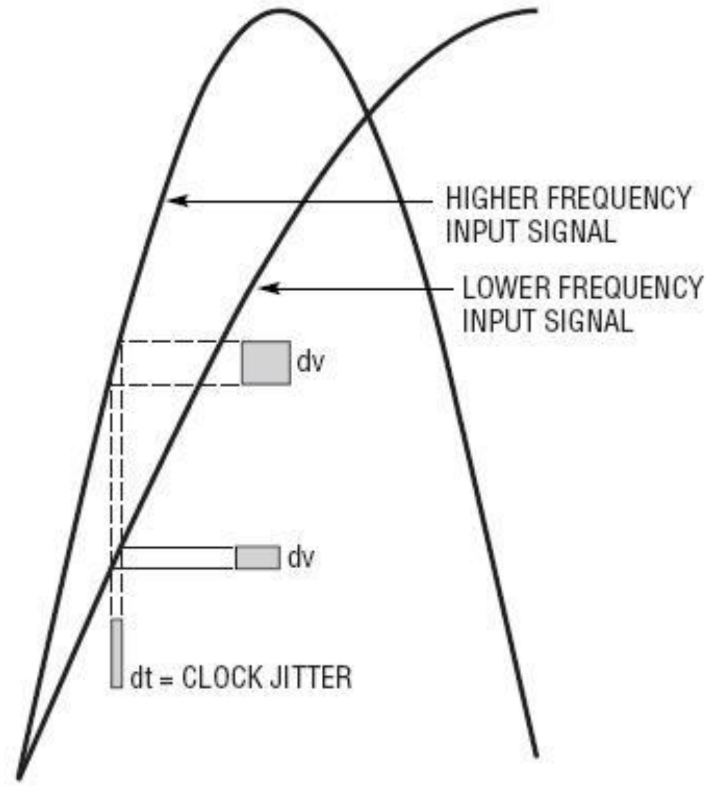
- **Quantization Produces Noise**
- **Quantization Noise Is Inversely**
- **Inversely Proportional to ADC Resolution**

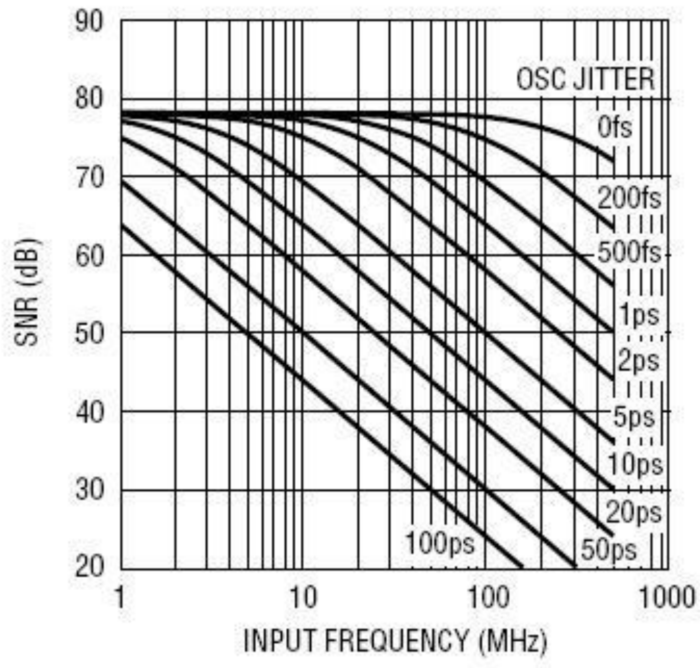


Analog to Digital Converter

ADC noise source: Clock jitter

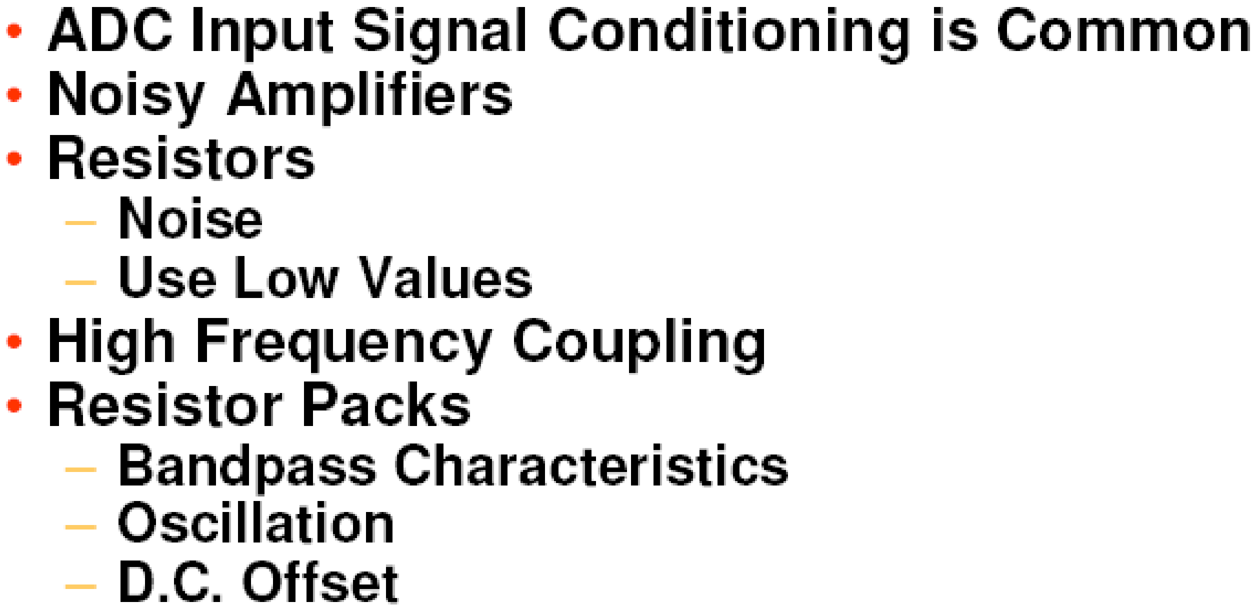
$$SNR_{jitter} = -20\log_{10}\left(2\pi f_{RF}\, t_{jitter\_rms}\right)$$





Analog to Digital Converter

ADC noise source: Noisy components or circuitry



- ADC Input Signal Conditioning is Common
- Noisy Amplifiers
- Resistors
  - Noise
  - Use Low Values
- High Frequency Coupling
- Resistor Packs
  - Bandpass Characteristics
  - Oscillation
  - D.C. Offset

Analog to Digital Converter

Signal to Noise Ratio (SNR) of ADC:

$$\mathrm{SNR_{dB}} = -20\log_{10}\left[(2\pi f_a t_j)^2 + \frac{2}{3}\left(\frac{1+\epsilon}{2^N}\right)^2 + \left(\frac{2\sqrt{2}V_n}{2^N}\right)^2\right]^{\frac{1}{2}}$$

f_a : input frequency [Hz]

t_j : rms clock timing jitter [s]

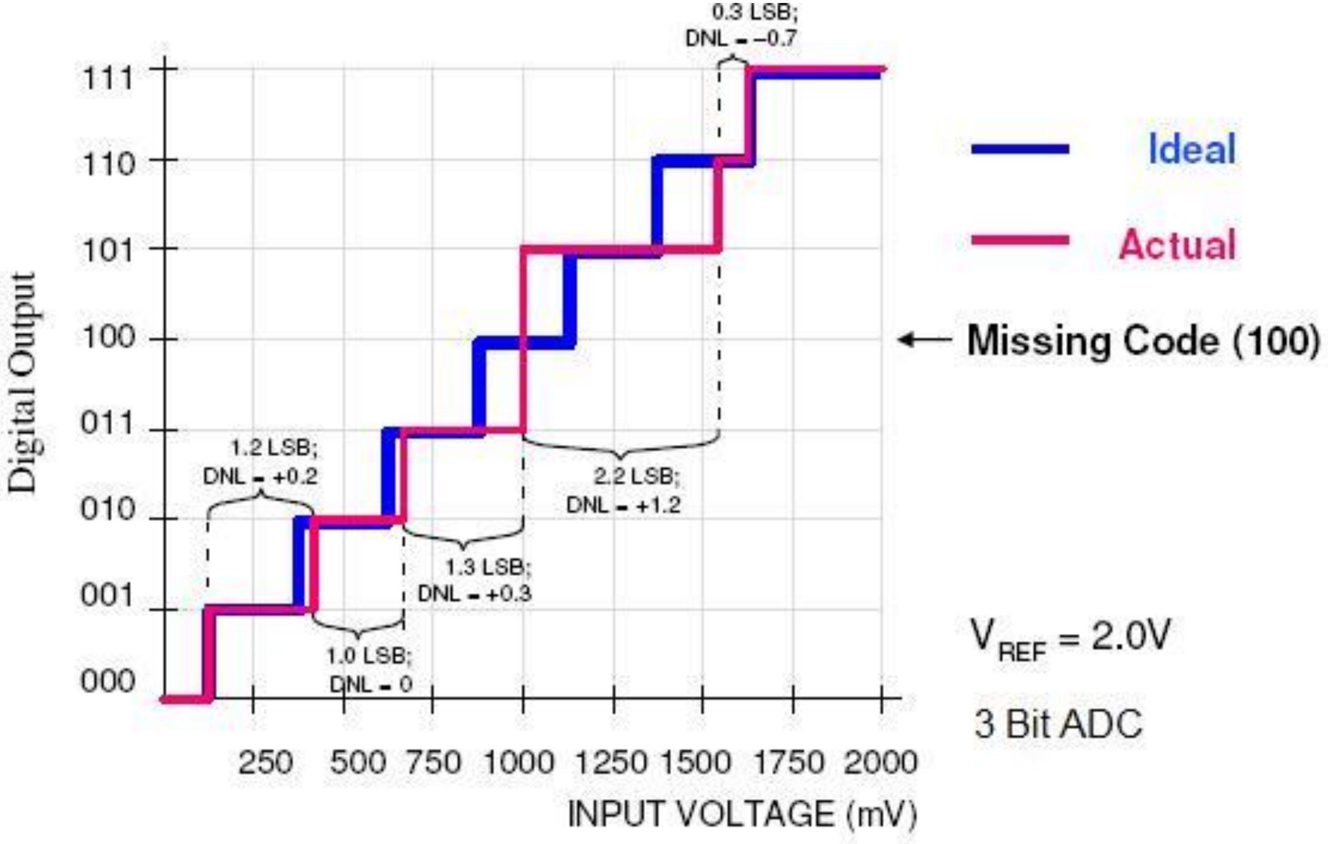
ϵ : differential nonlinearity, DNL [LSB]

N : number of bits

V_n : equivalent input noise [LSB].

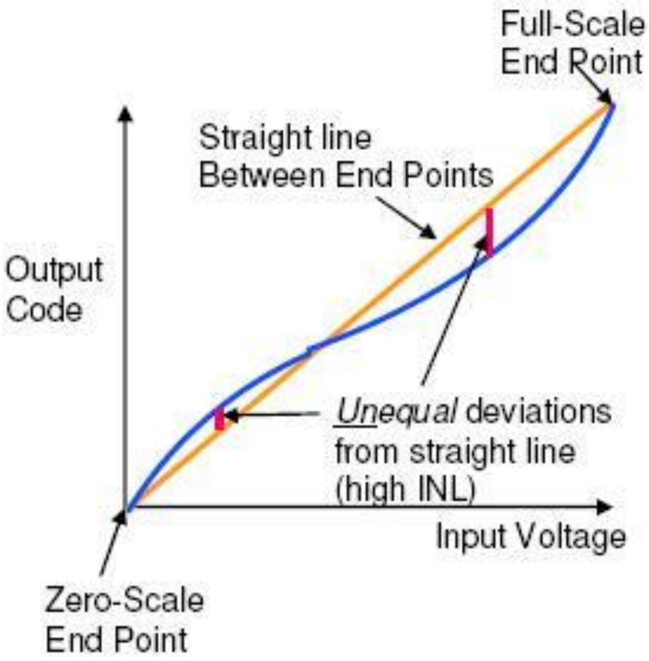
Analog to Digital Converter

Differential Non-Linearity (DNL): “small scale” code to code errors

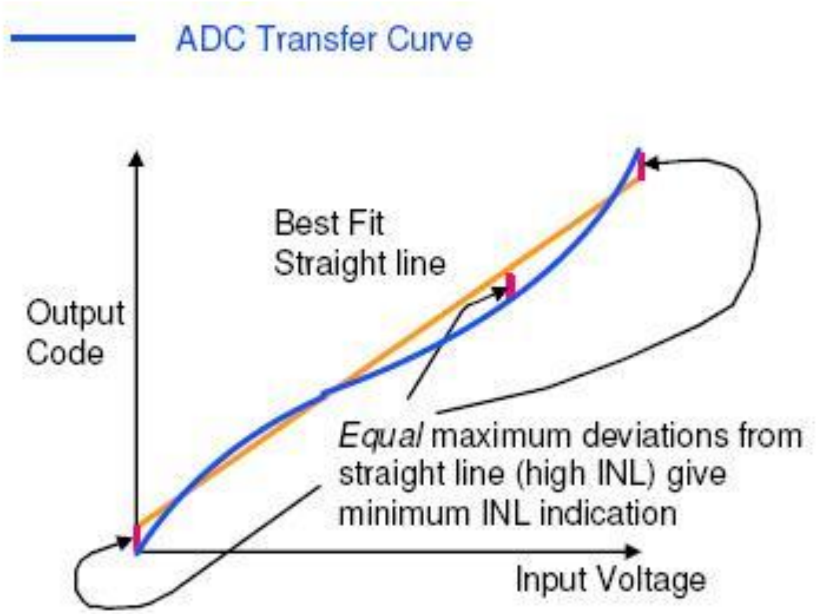


Analog to Digital Converter

Integral Non-Linearity (INL): “large scale” overall transfer function error



“End-Point” INL Measurement Indicates Worst Case INL



“Best-Fit” INL Measurement Provides Best Possible INL Specification