

Cavity Field Control

- RF Signal Detection and Actuation

LLRF Lecture Part 3.4

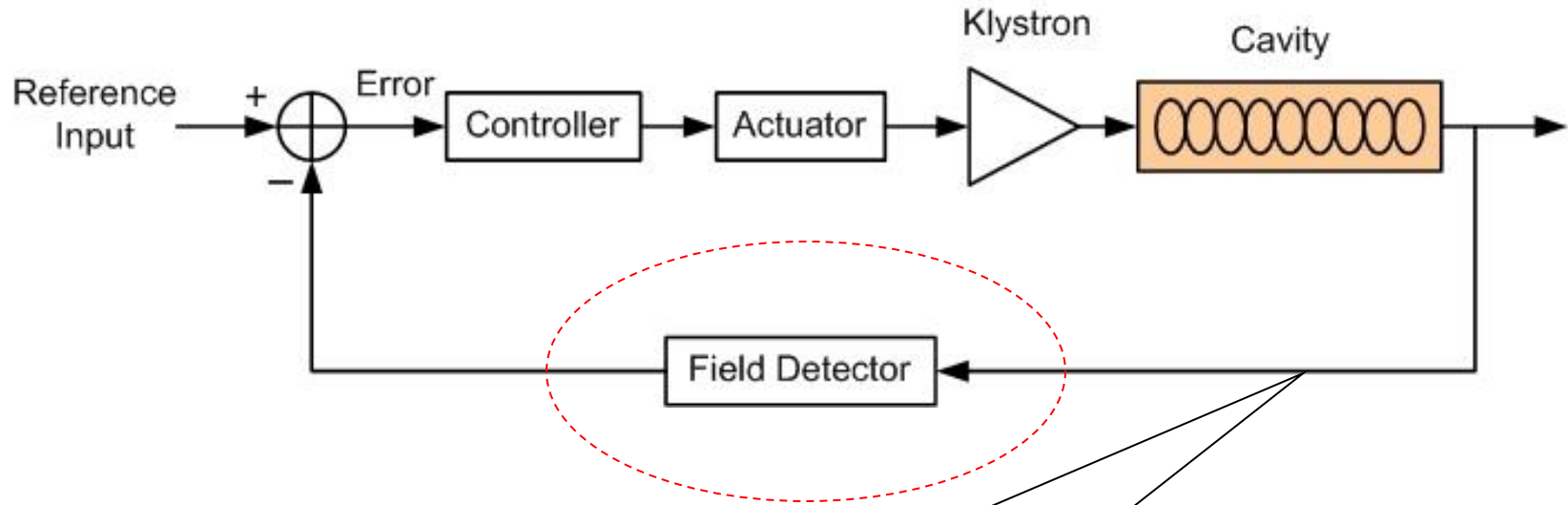
S. Simrock, Z. Geng

ITER / PSI

- 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

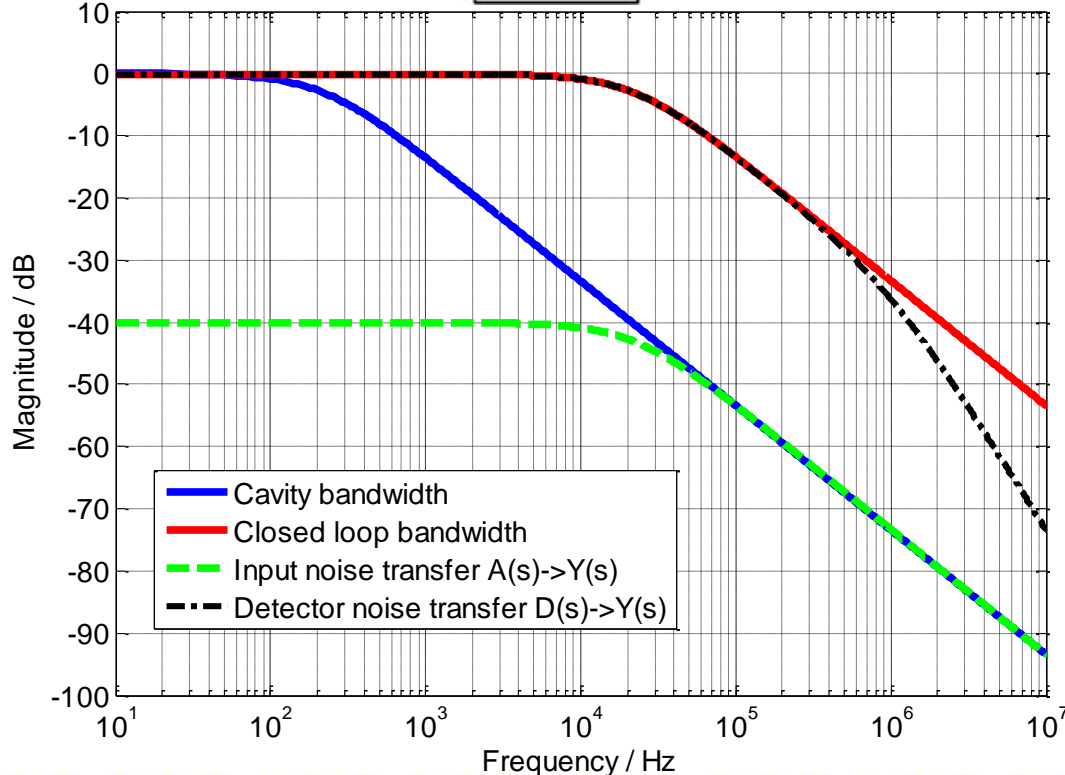
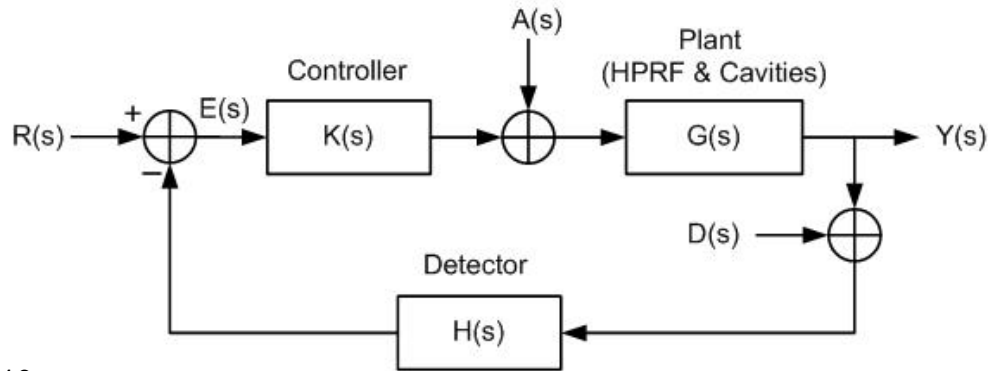
Context of the RF Field Detector



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



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!



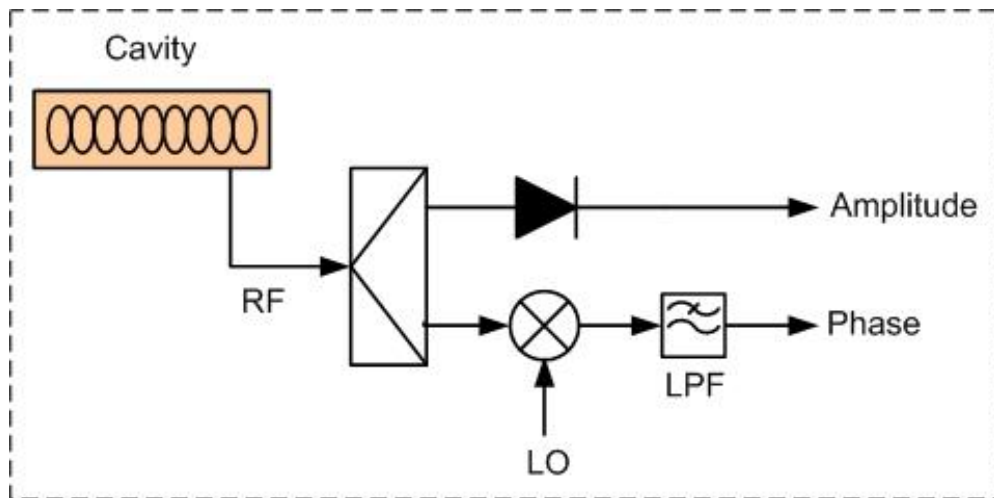
Requirements to the RF Field Detector

- 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



Mixer input:

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

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

Mixer output:

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

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

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

Inputs:

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

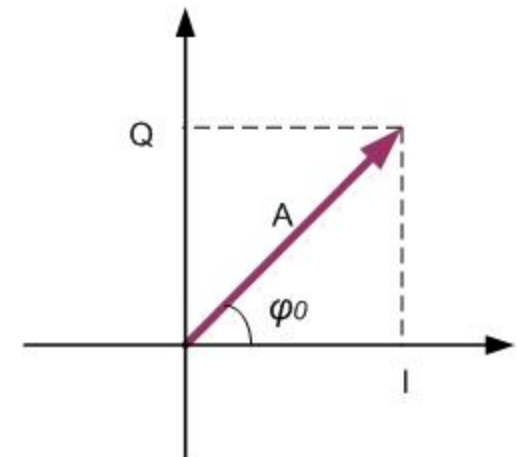
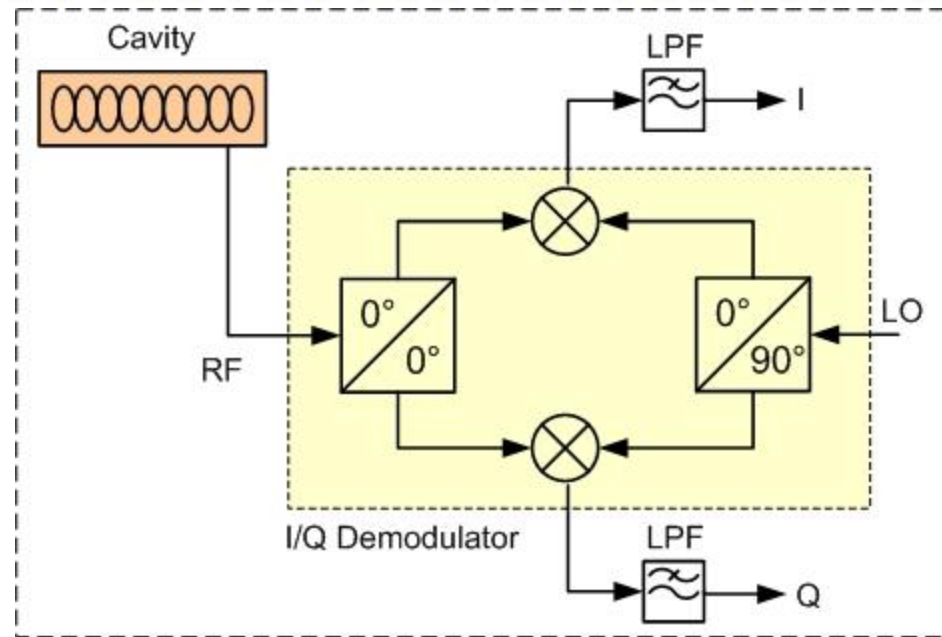
$$V_{LO}(t) = A_{LO} \cos(\omega t)$$

Outputs:

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

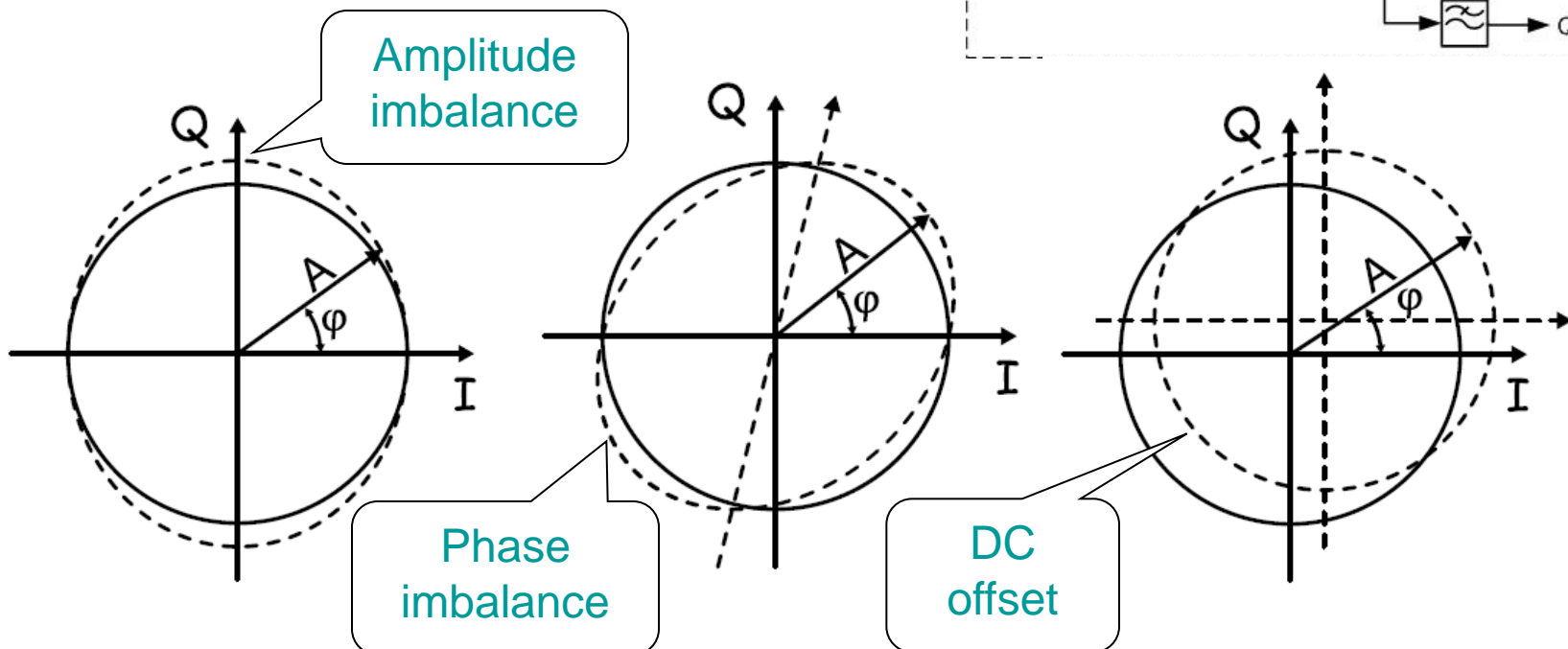
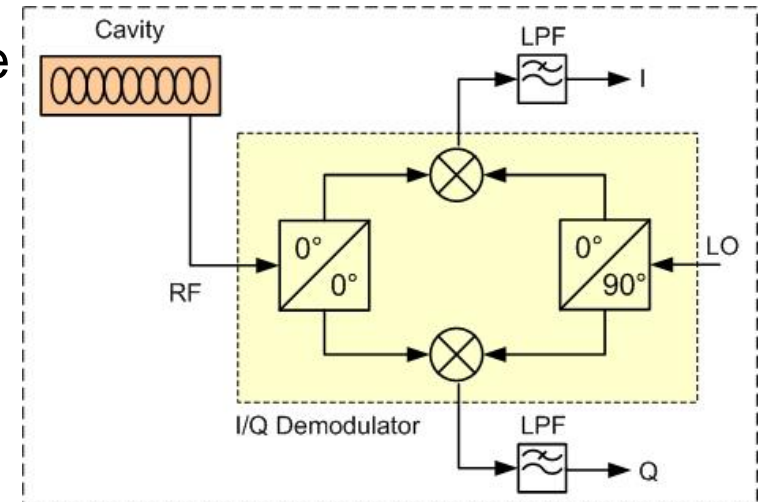
$$Q = LPF \left\{ -\frac{A_{RF}}{\sqrt{2}} \cos(\omega t + \varphi_0) \cdot \frac{A_{LO}}{\sqrt{2}} \sin(\omega t) \right\} = \frac{A_{RF} A_{LO}}{4} \sin \varphi_0$$

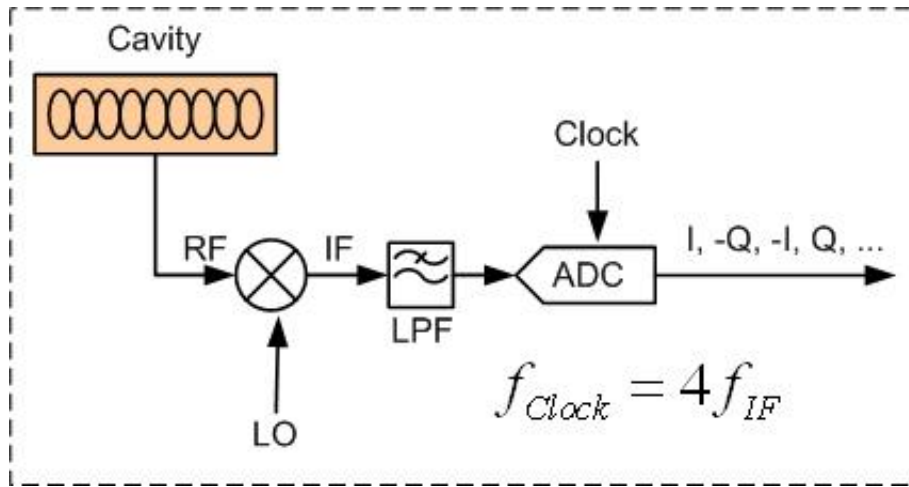
$$\varphi_0 = \tan^{-1} \left(\frac{Q}{I} \right) \quad A = \sqrt{I^2 + Q^2}$$



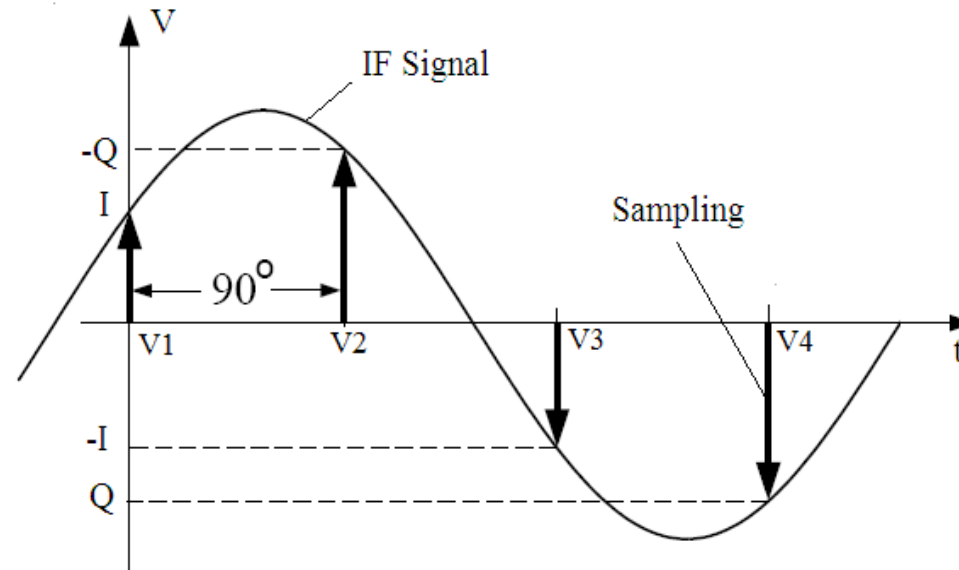
Analog I/Q Detection

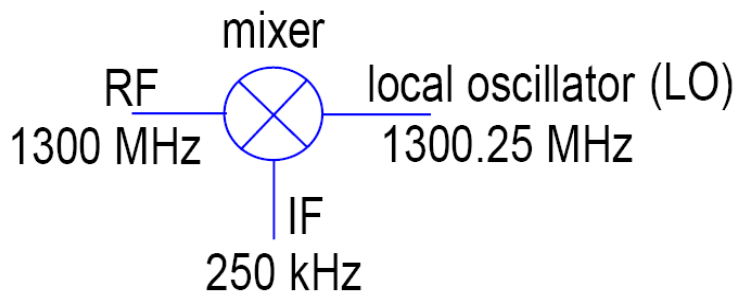
- Phase measurement is linear for the whole range of 360°
- Low efforts of digital processing
- Disadvantages:
 - Phase and amplitude imbalance
 - DC offset



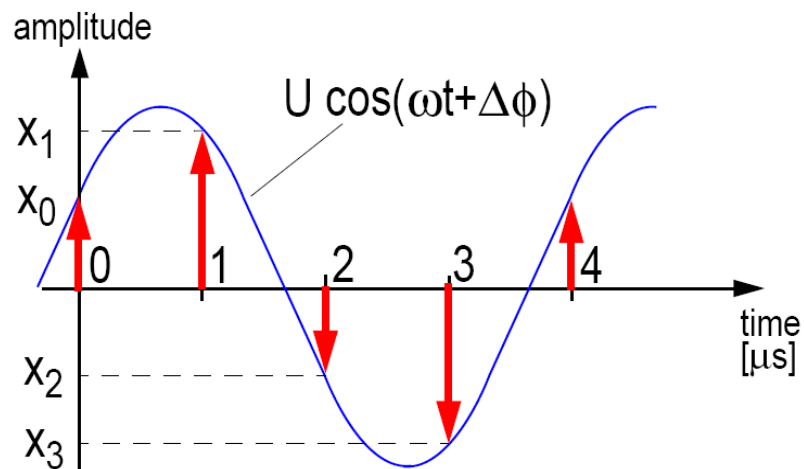


- Digital I/Q detection
- IF and clock signal should be synchronized
- Alternating samples give I and Q components of the cavity field





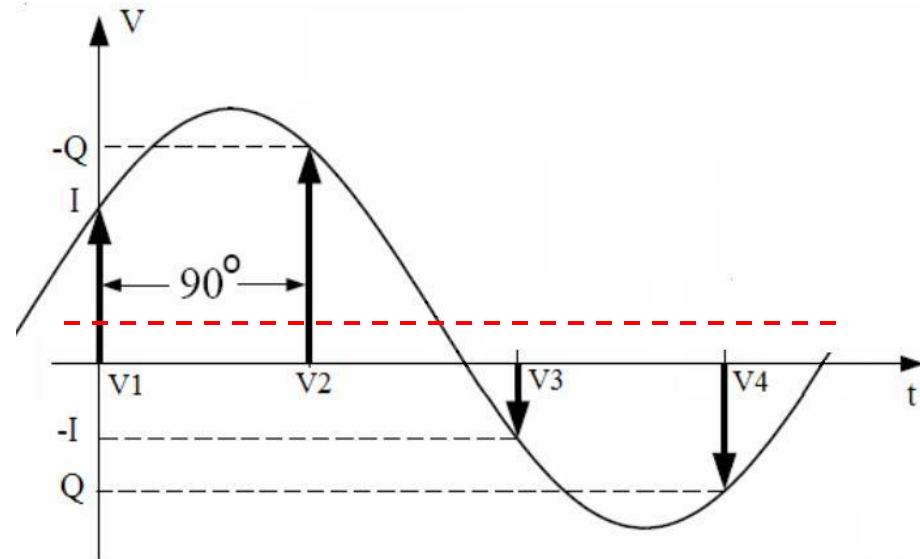
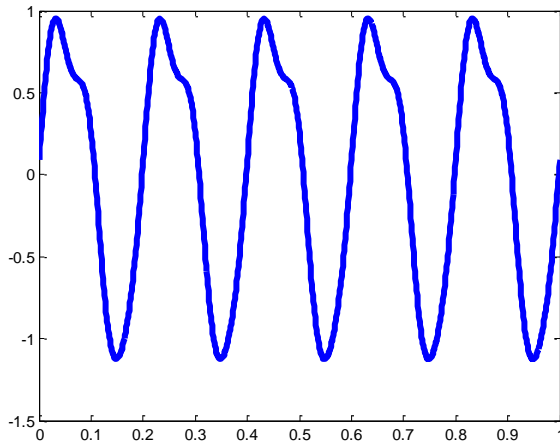
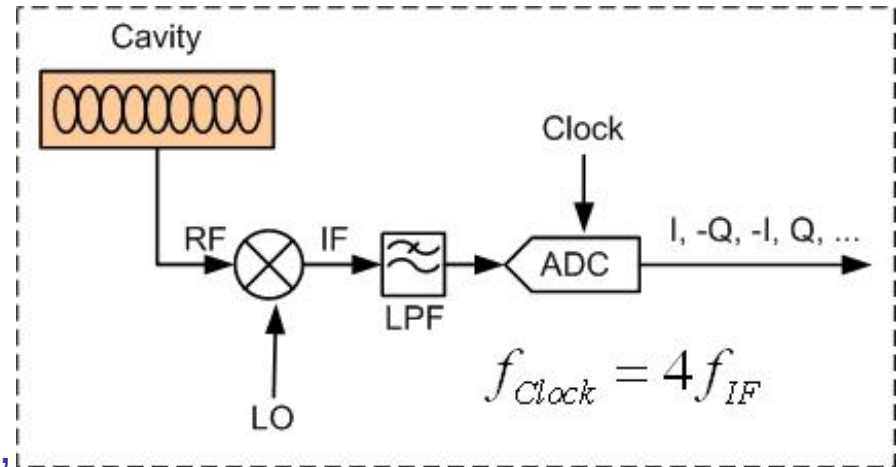
- downconversion of cavity field to IF frequency at 250 kHz
- complete phase and amplitude information of the accelerating field is preserved.

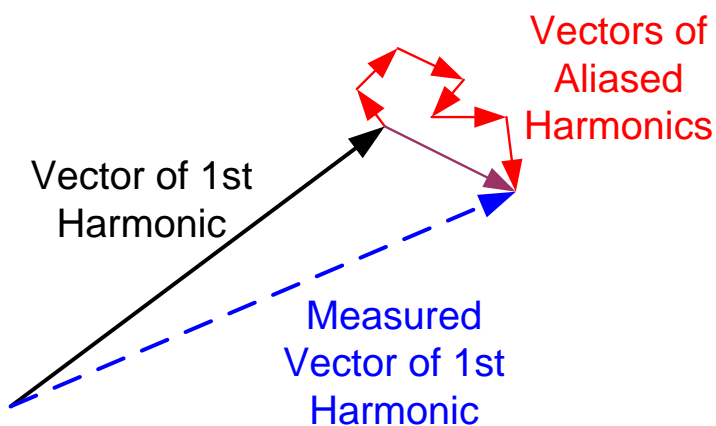
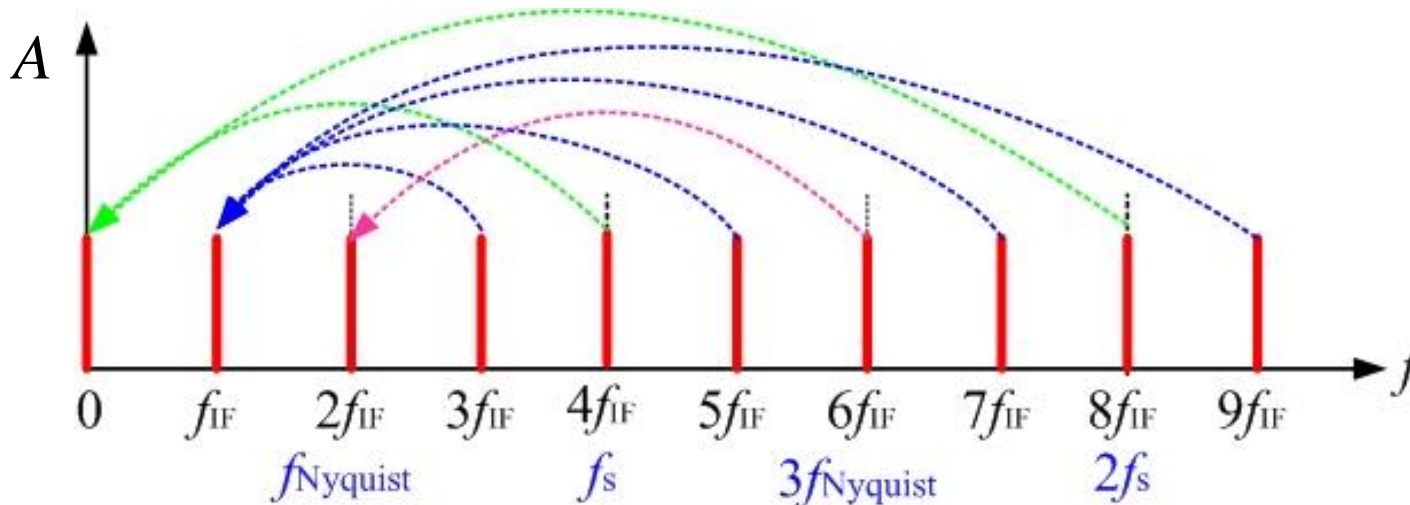


- sample IF signal at 1MHz rate
- subsequent samples describe real and imaginary component of the cavity field.

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

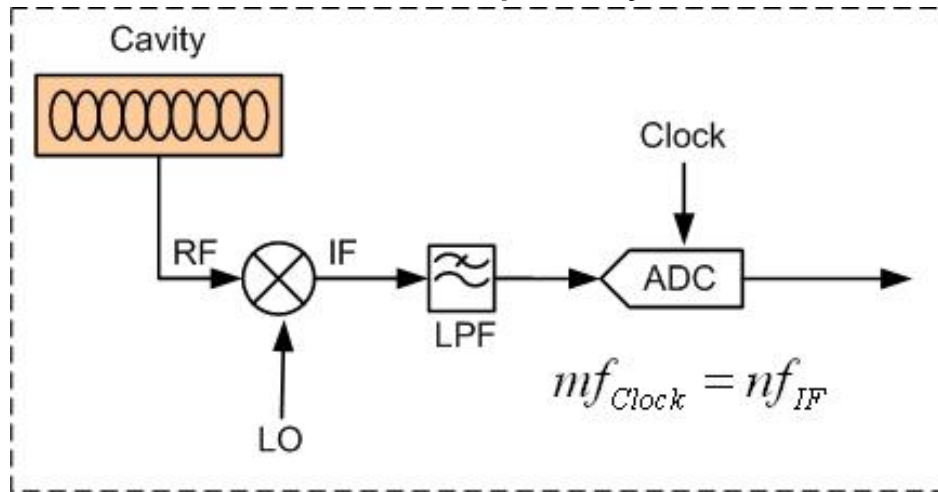




- The phase of n th harmonic changes n times faster than the fundamental phase
- Phase shifts in the cavity due to microphonics and Lorenz force detuning will lead to a time dependent error

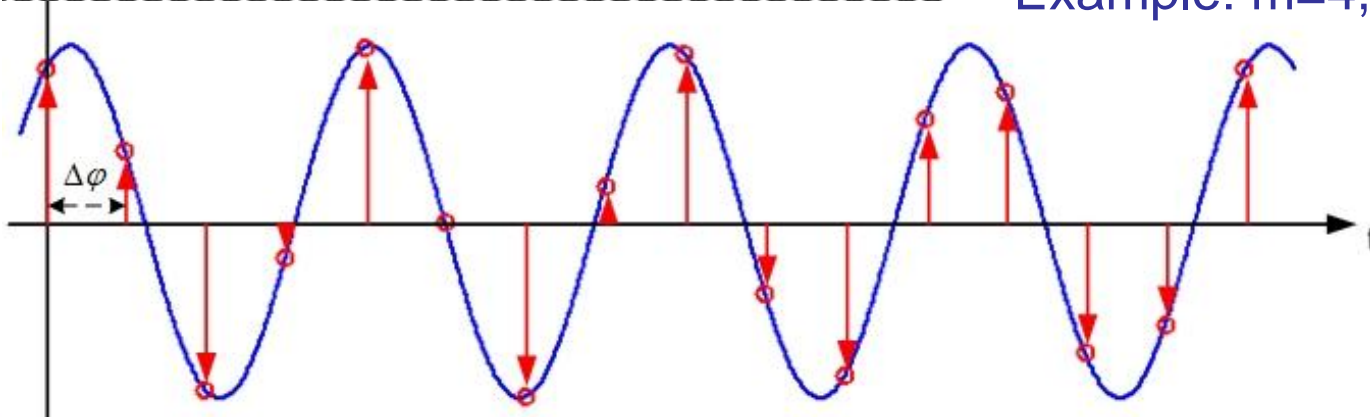
Non-IQ Sampling

- 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



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

Example: $m=4, n=15$



- Fourier series decomposition of the RF signal

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

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

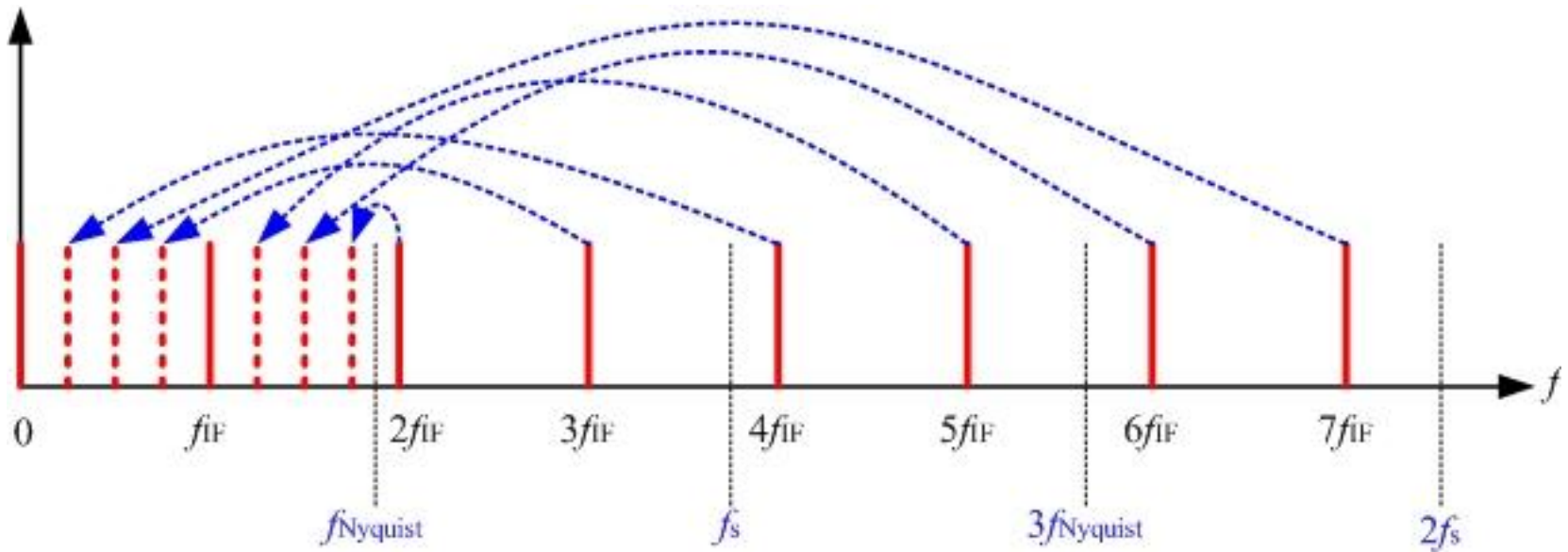
$$\begin{cases} a_k = \frac{2}{T} \int_0^T s(t) \cos(k 2\pi f_{IF} t) dt \\ b_k = \frac{2}{T} \int_0^T s(t) \sin(k 2\pi f_{IF} t) dt \end{cases}, \quad k = 1, 2, \dots$$

- Demodulation algorithm:

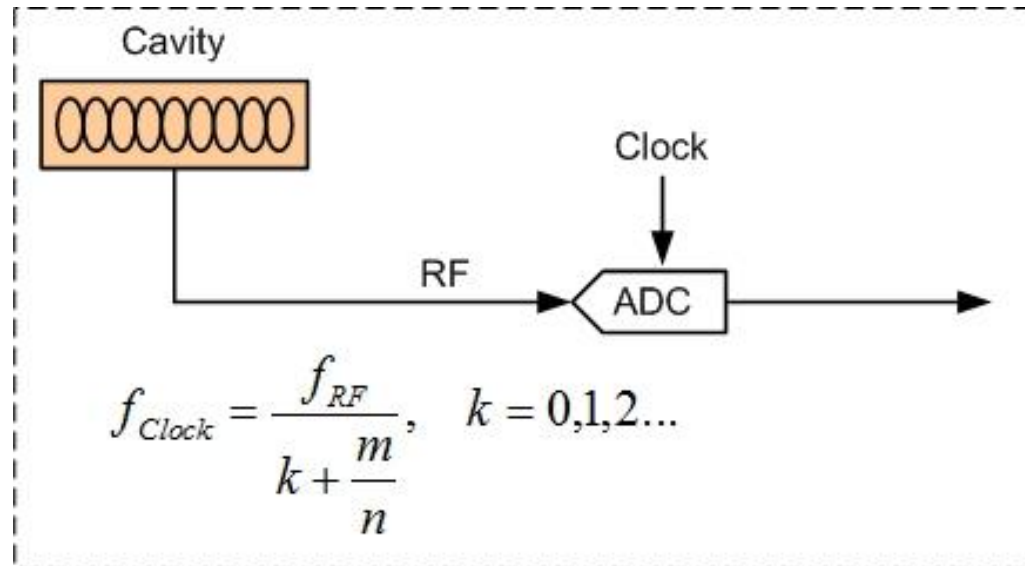
$$I = \frac{2}{n} \sum_{i=0}^{n-1} x_i \cos(i\Delta\varphi), \quad Q = \frac{2}{n} \sum_{i=0}^{n-1} x_i \sin(i\Delta\varphi)$$

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

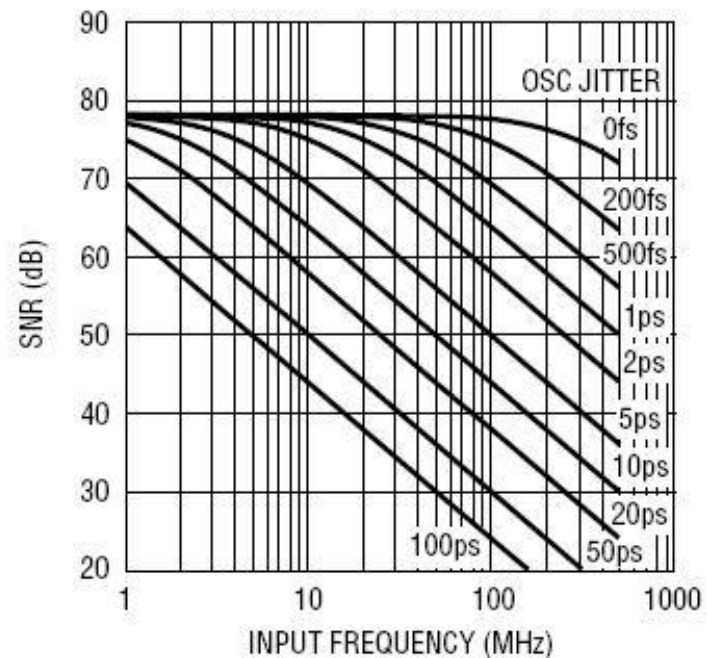
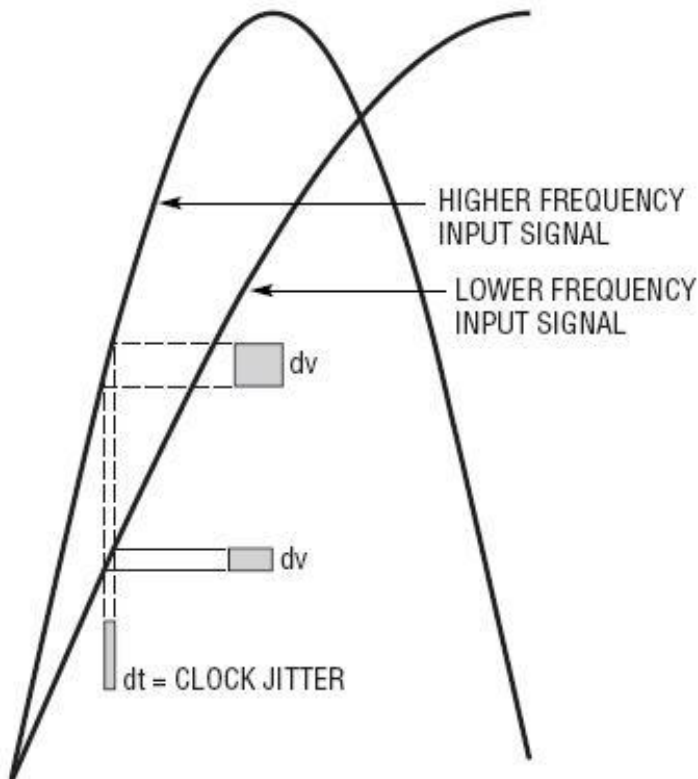


- Example for available ADC: ADS5474, 14 bits, 400MSPS, 1.4GHz bandwidth
- Under-sampling
- Non-IQ sampling (m,n have the same meaning as the discussion of non-IQ sampling)

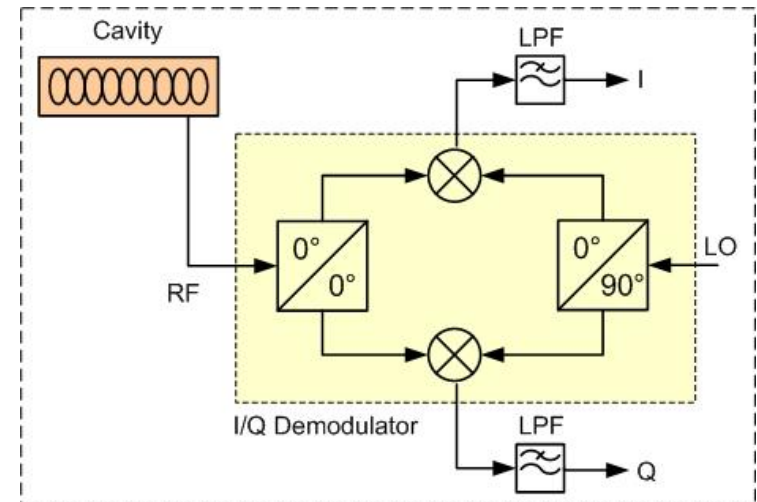
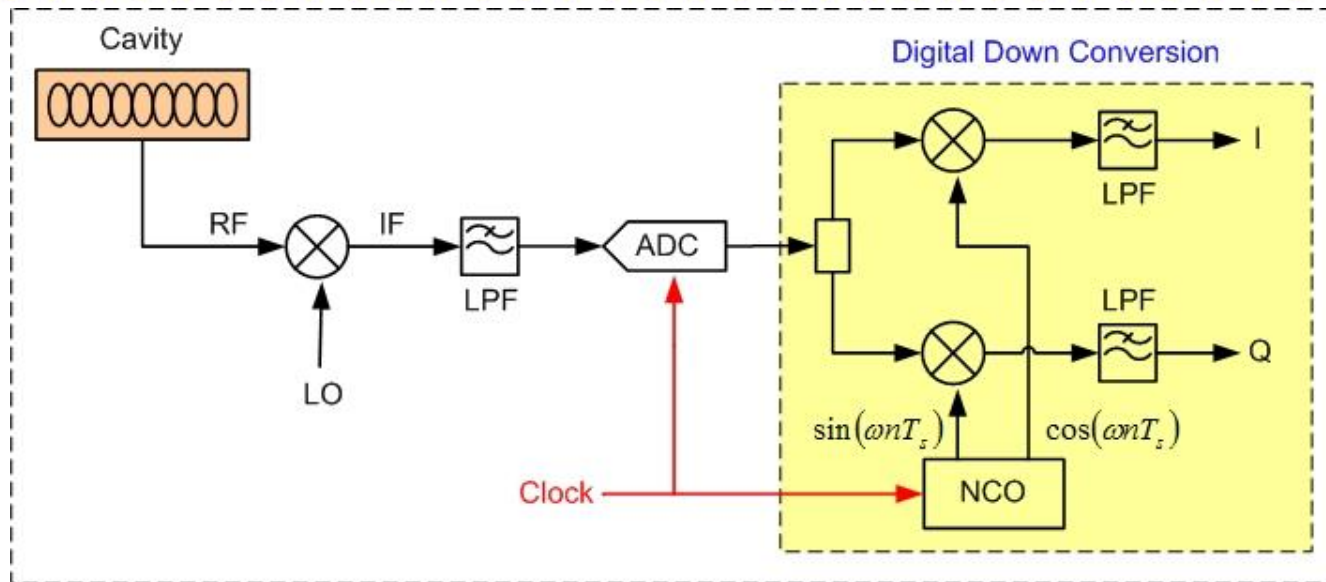
Direct Sampling

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

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

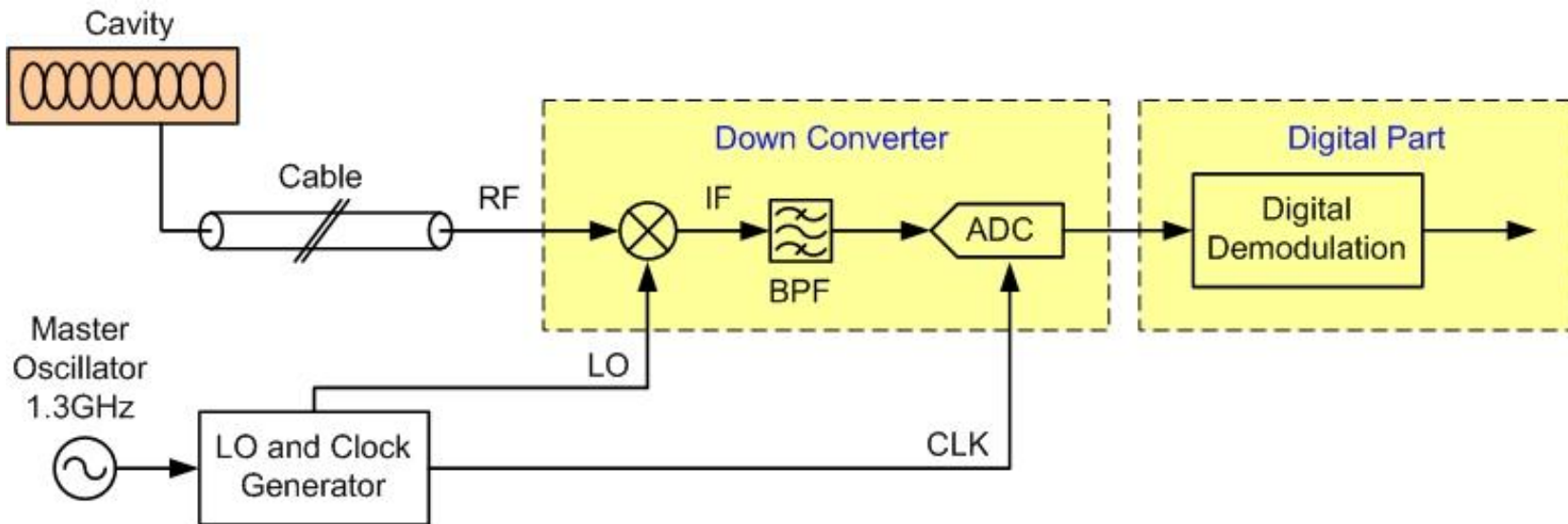


Digital Down Conversion



- 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

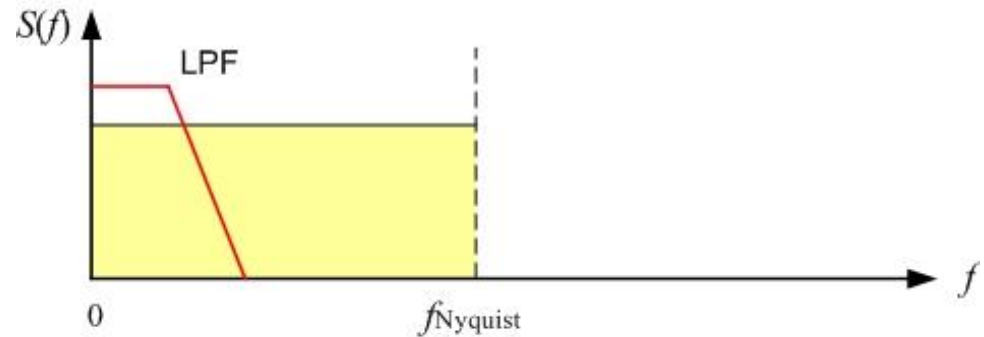
Reduce the Noises and Compensate the Drifts in RF Field Detection



- 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

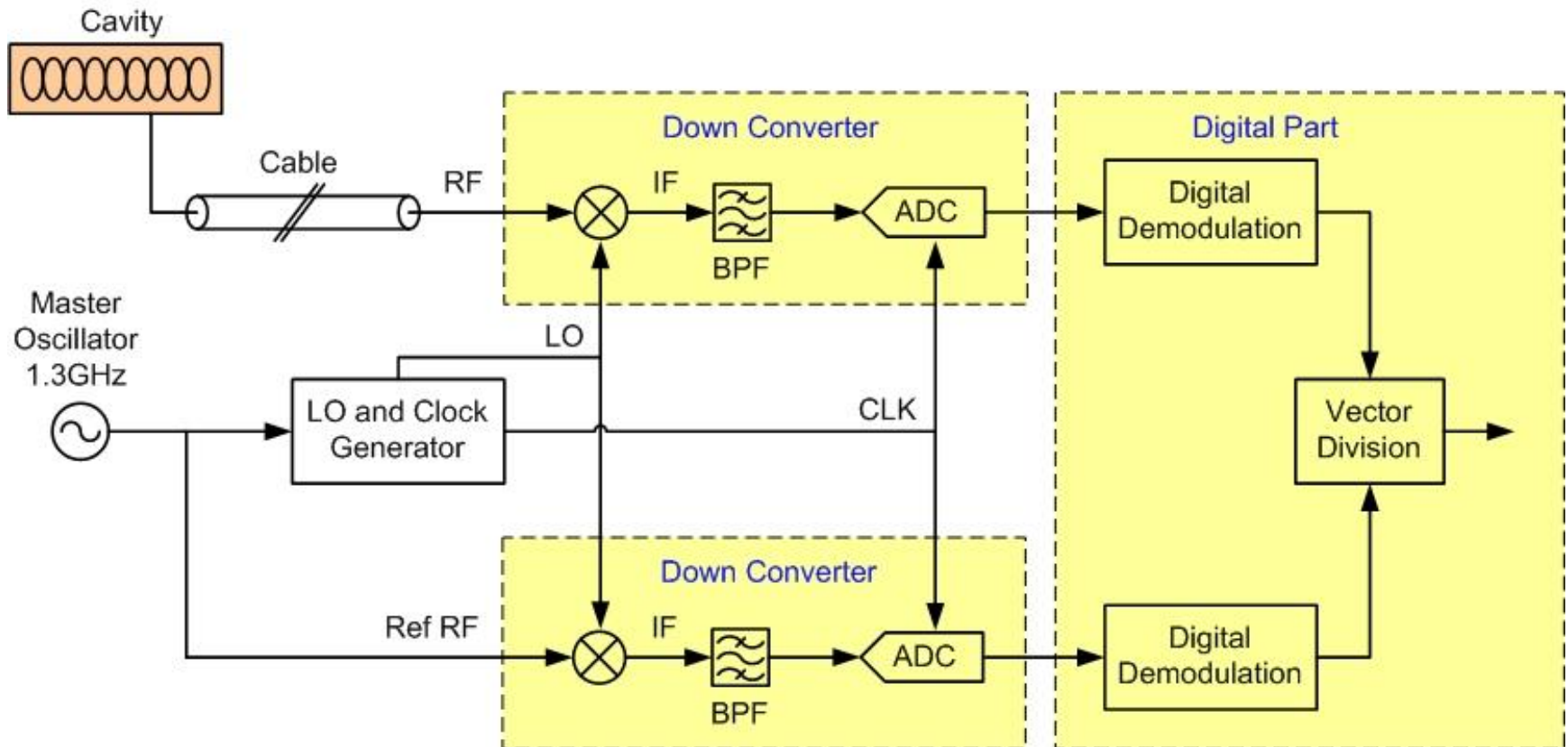
- Select components of down converter with low noise level
- Filtering in RF side
- ADC oversampling



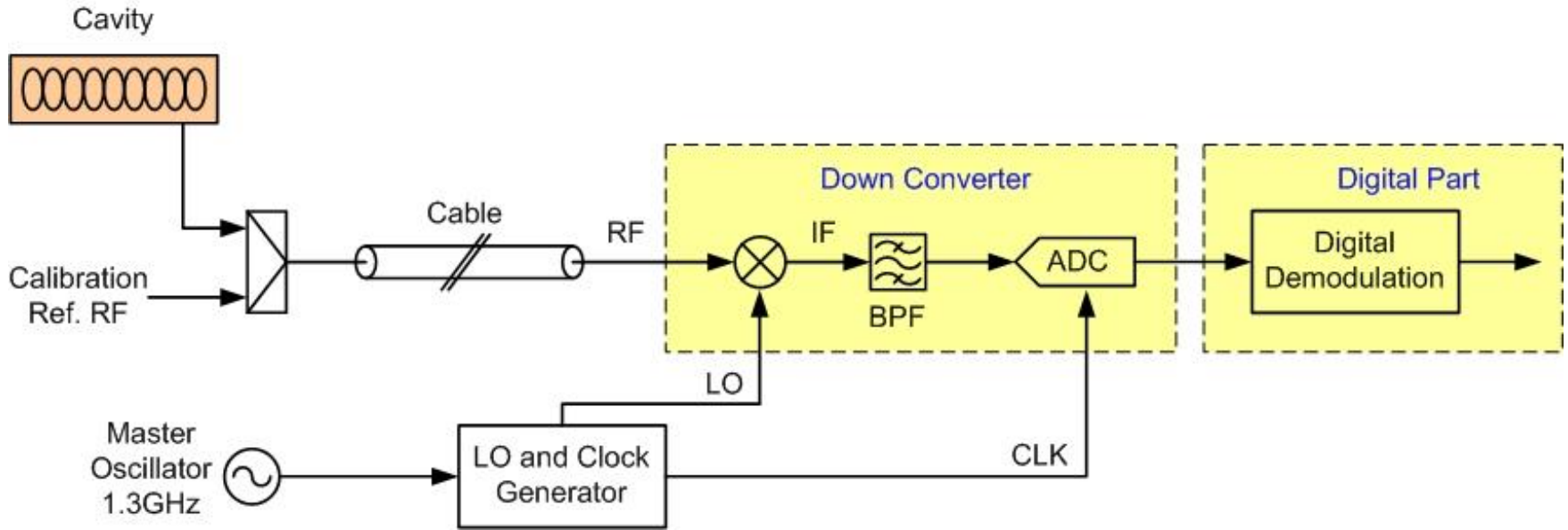
↓ (double the sampling frequency)



Reference tracking



Measurement chain drift calibration



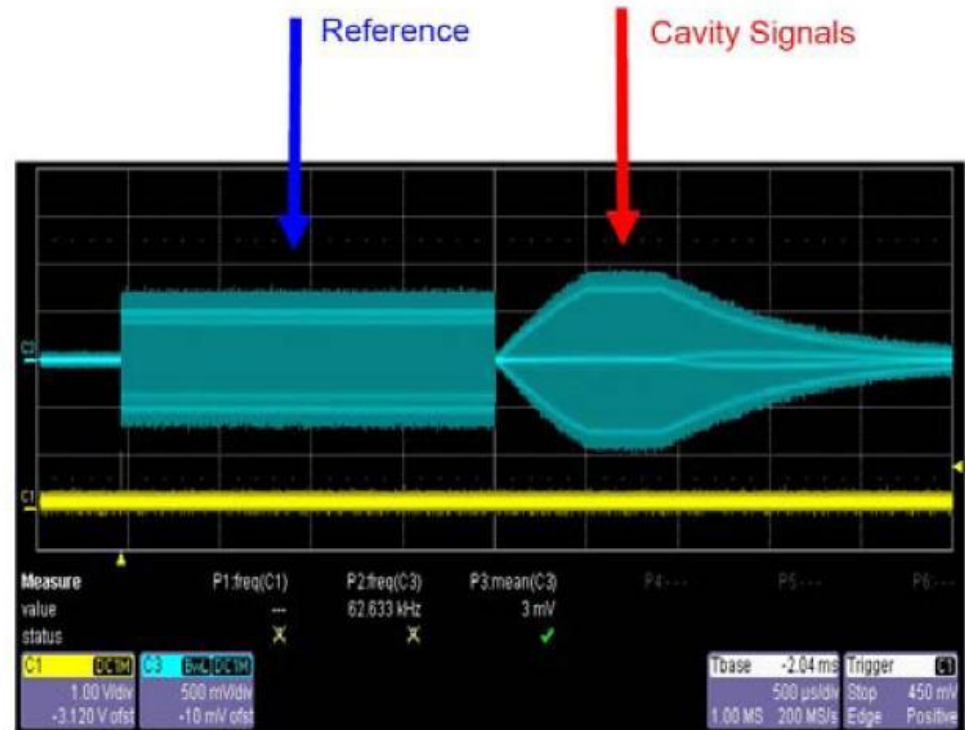
- **Pulsed RF Station:** Calibration Ref. RF can have the same frequency but be injected at different time slot compared to the RF pulse
- **CW RF Station:** Calibration Ref. RF should have different frequency to the cavity RF

Measurement chain drift calibration: test setup

- Setup DEV System :



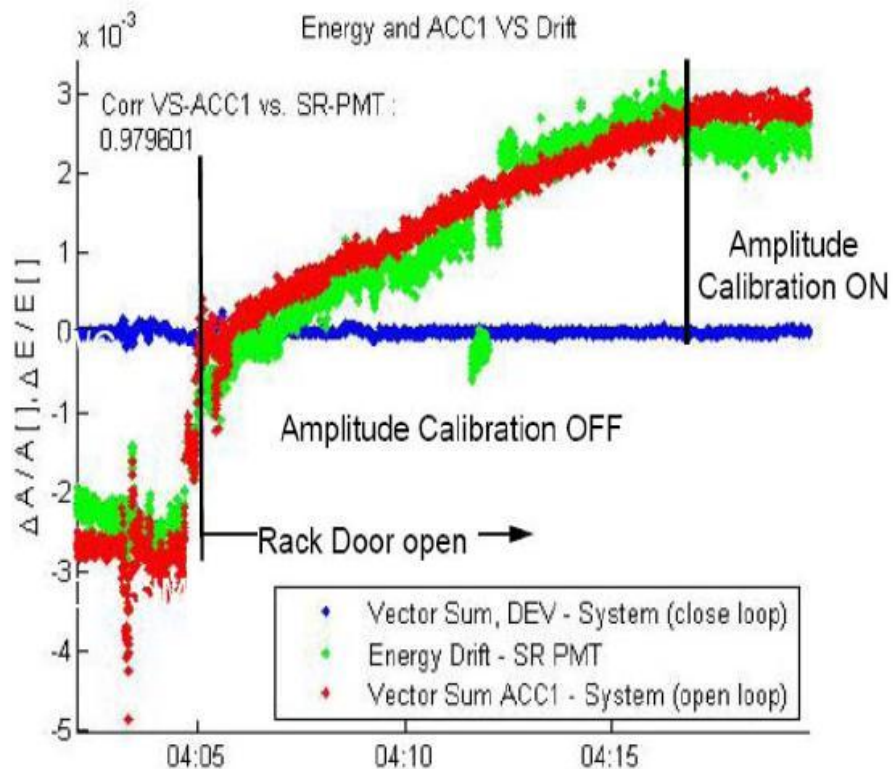
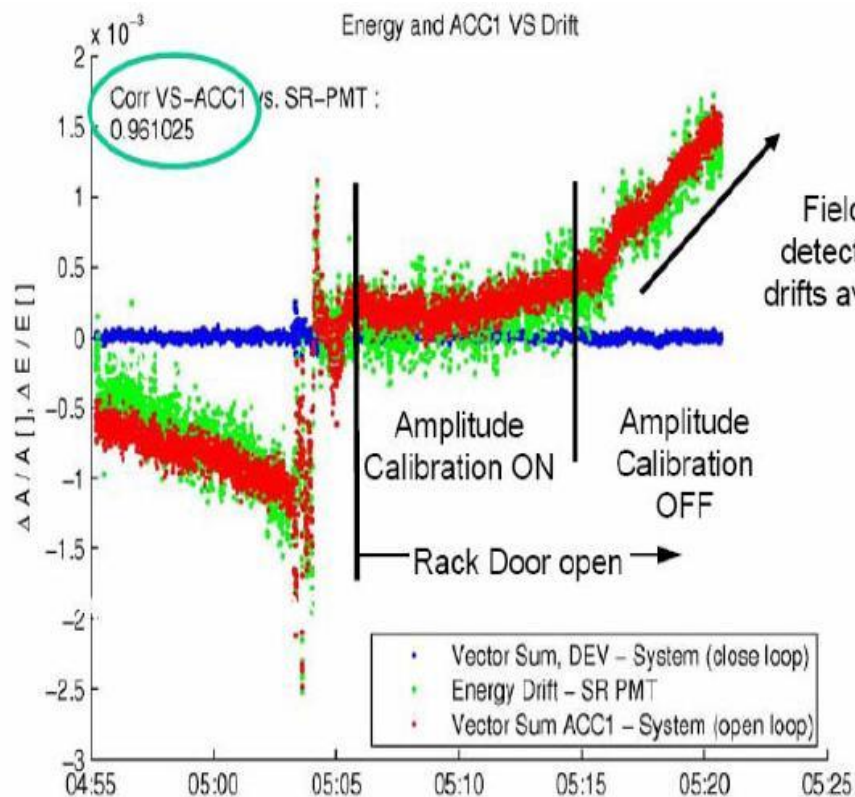
- Calibration / Cavity Phase :





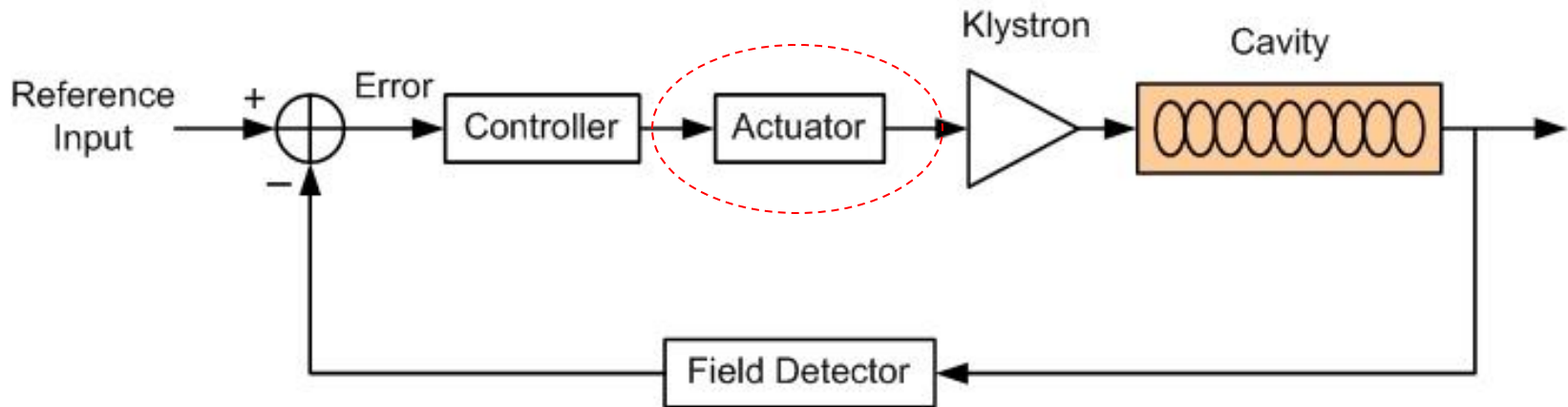
Drift and Fluctuation Correction

Measurement chain drift calibration: test result at ACC1 of FLASH

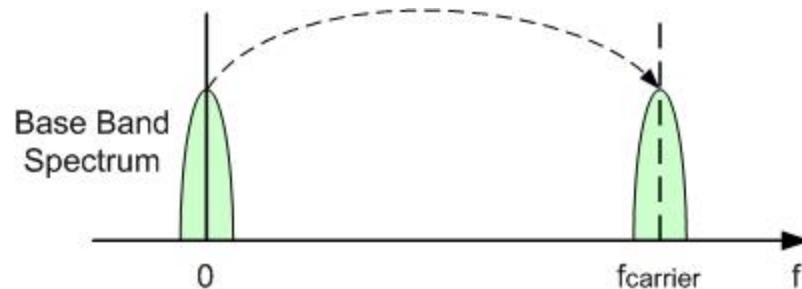
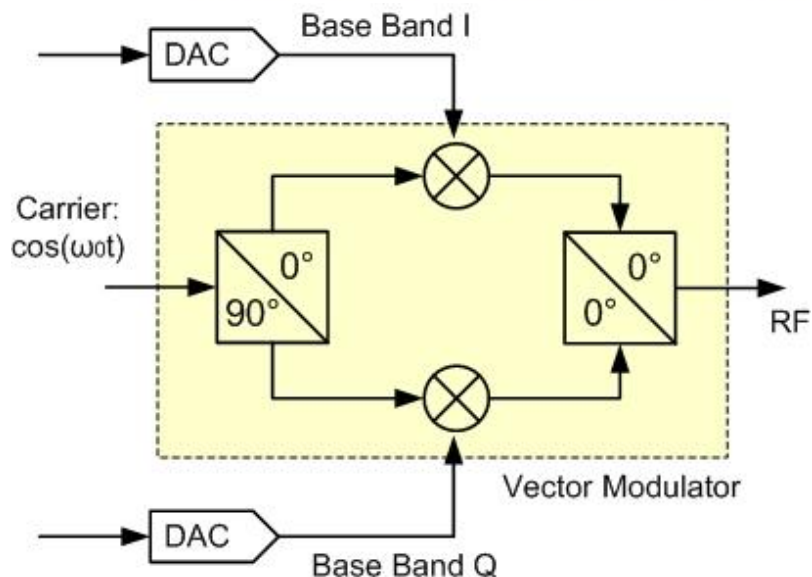


RF Actuation

- 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

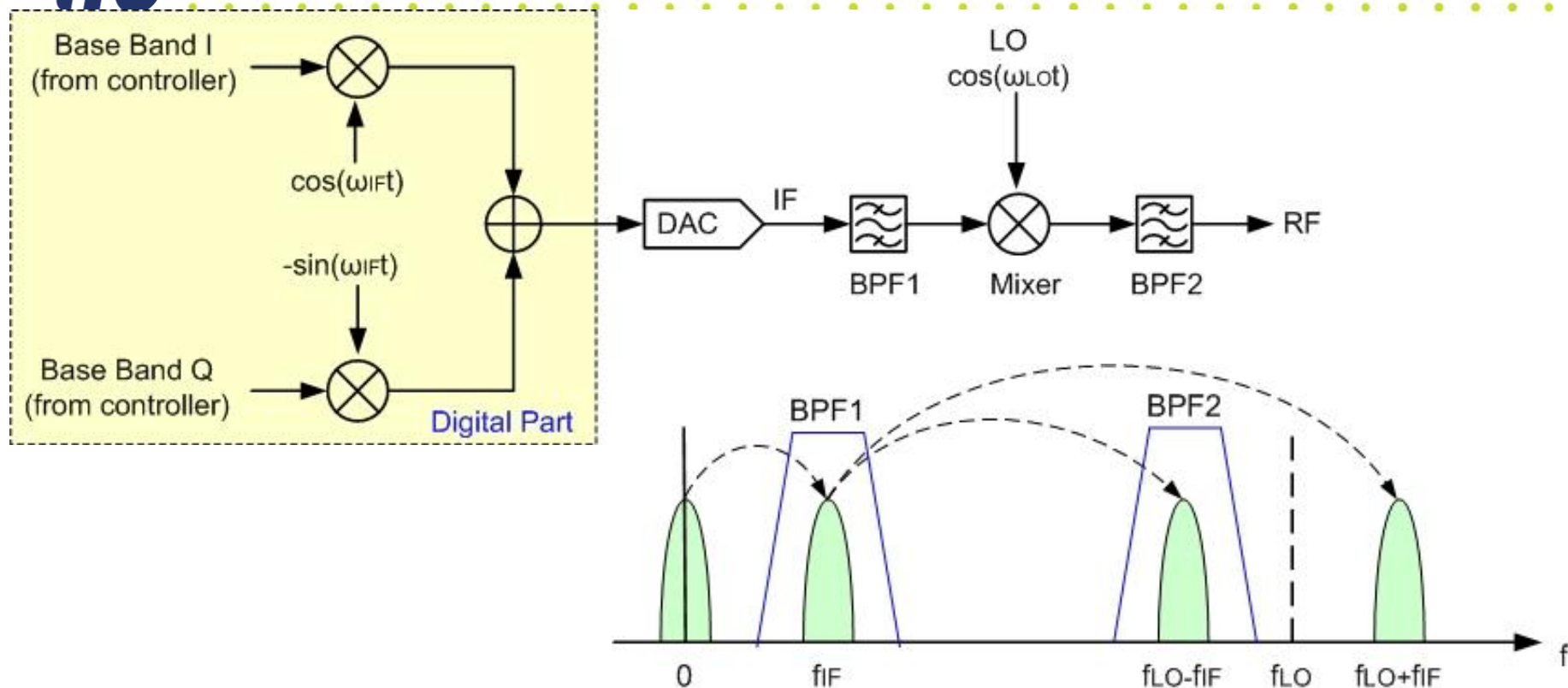


$$RF = I \cos(\omega_0 t) - Q \sin(\omega_0 t) = A \cos(\omega_0 t + \varphi)$$

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

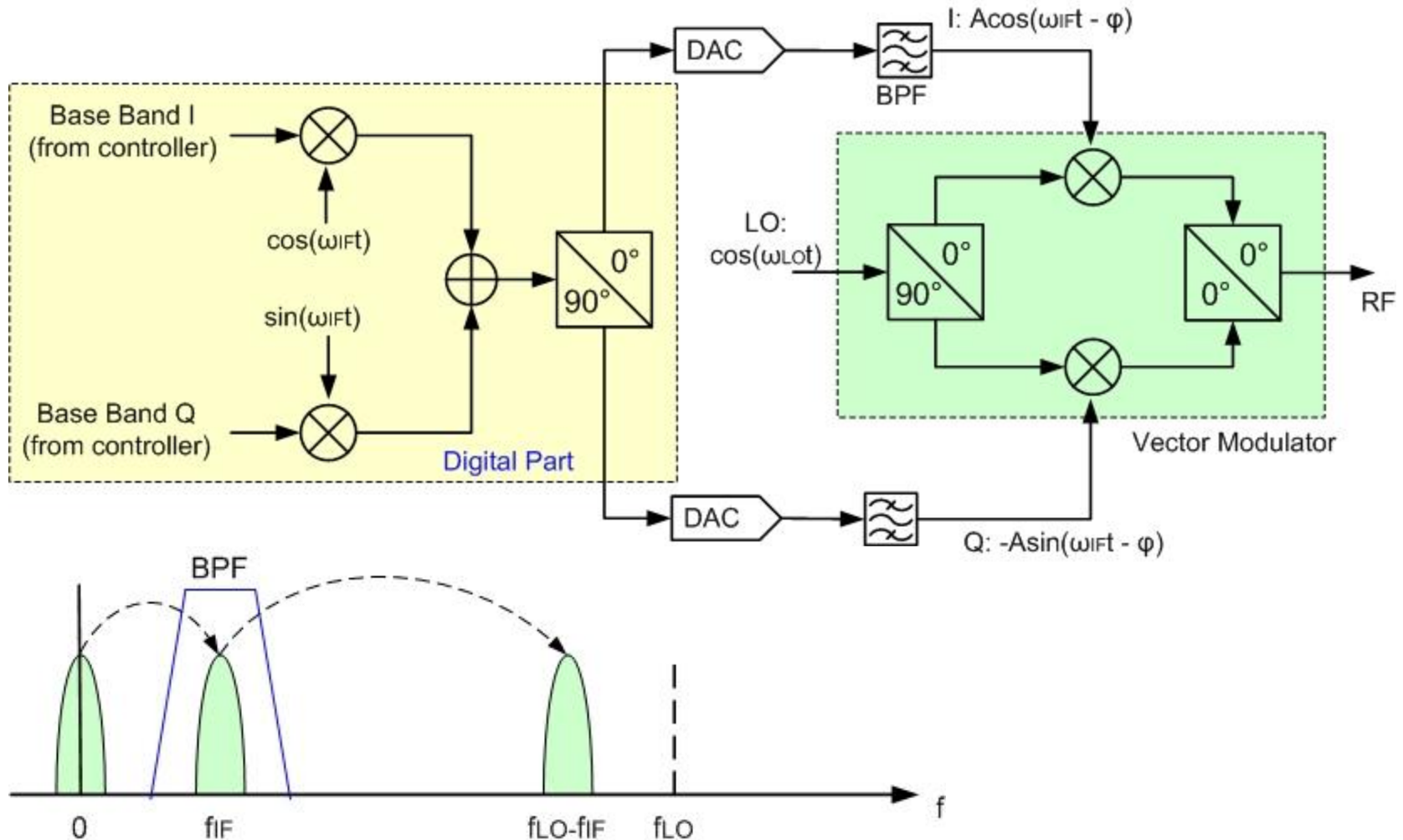
- Easy to implement
- Requirements to DAC clock jitter is low
- Suffers from the DC offset in I/Q base band signals and the phase and amplitude imbalance of the vector modulator

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
- Requires high quality DACs and low DAC clock jitter

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

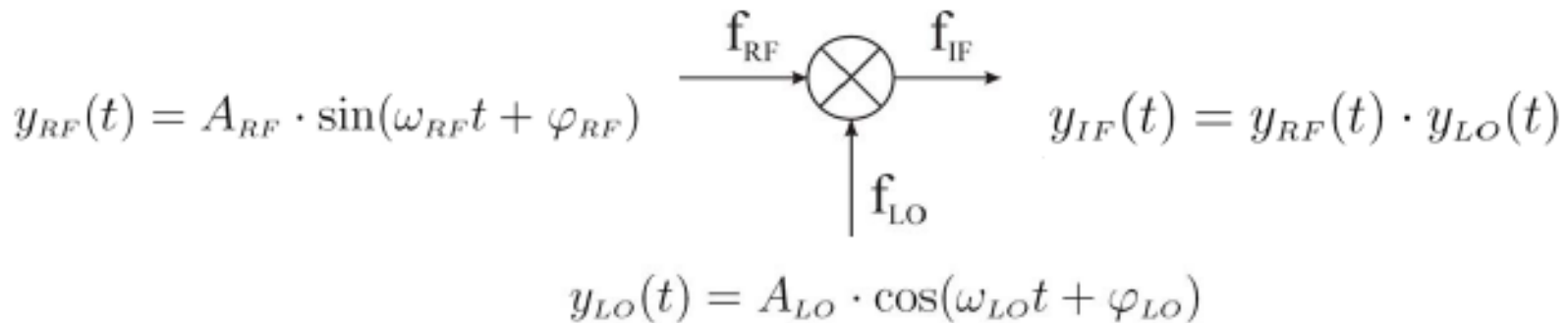
In this part, we have learnt:

- 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

- [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



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

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

lower sideband
upper sideband

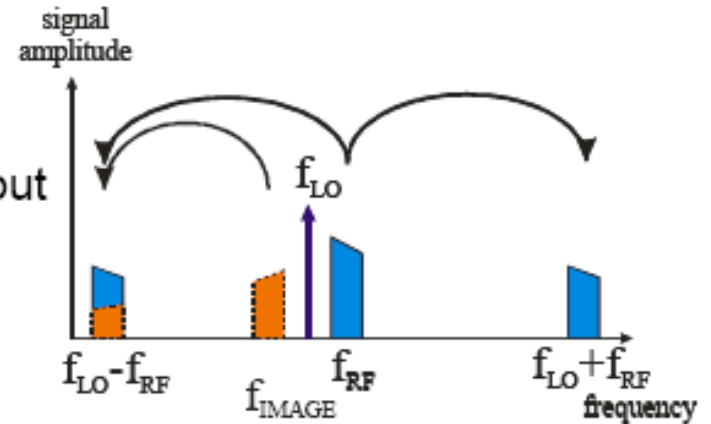
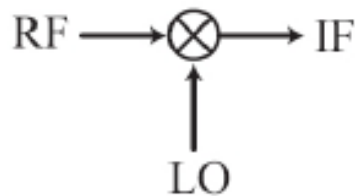
➔ even ideal mixers produce two sidebands

➔ ideal mixer: output is the multiplication of the two input signals

➔ down conversion:

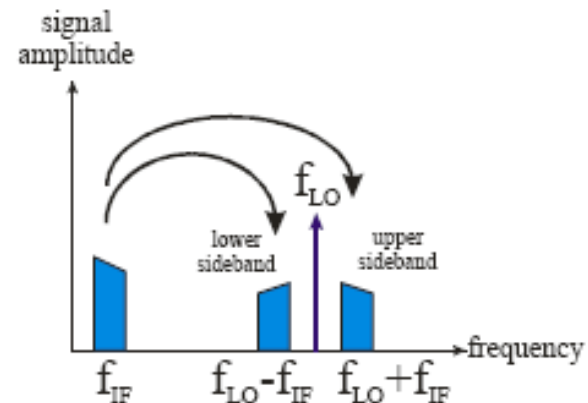
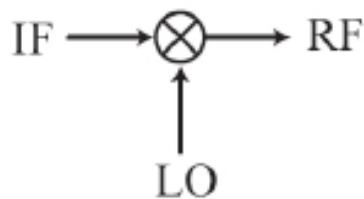
RF, LO are high frequency inputs

IF: lower intermediate frequency output



➔ up conversion:

IF is input, RF is output



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:

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

$$\omega_{IF} = \omega_{RF} - \omega_{LO}$$

$$A_{IF} = \frac{1}{2} A_{LO} A_{RF} \sim A_{RF} \quad \text{with constant } A_{LO}$$

$$\varphi_{IF} = \varphi_{RF} - \varphi_{LO} \sim \varphi_{RF} \quad \text{with constant } \varphi_{LO}$$

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

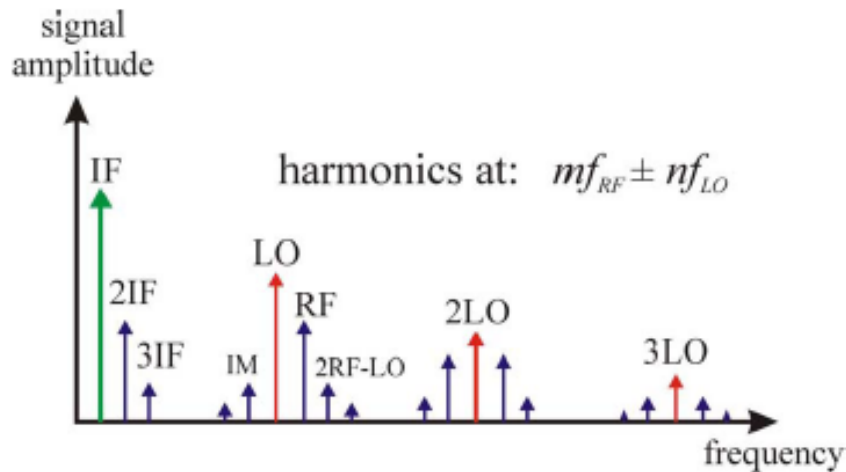
important properties:

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

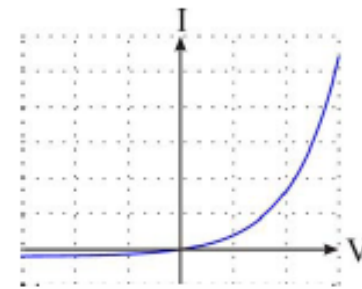
➔ tougher requirements for direct RF sampling !

real mixers = non linear devices

- ➡ many undesired harmonics in frequency spectrum
- ➡ non-linearities in IF signal



I-V curve of a diode

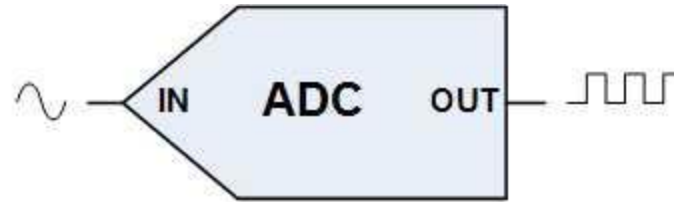


$$I = I_0(e^{V/V_T} - 1)$$

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

- ➡ 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)

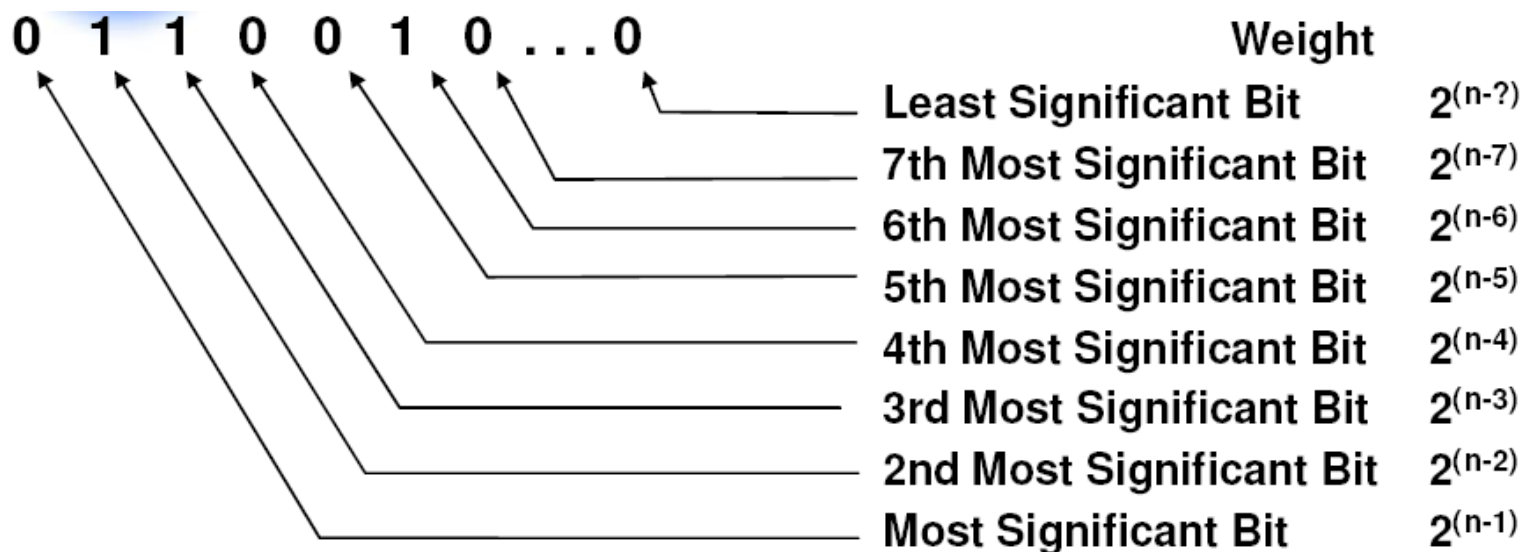
What is an ADC?

- **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)



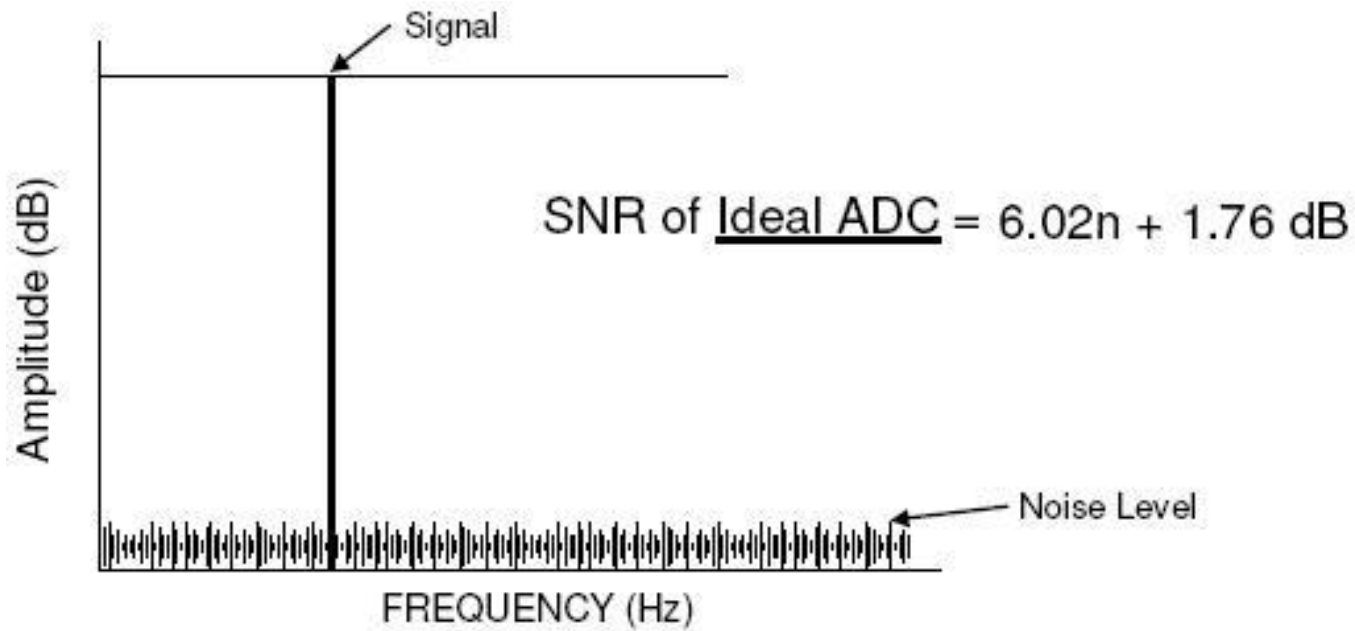
Analog to Digital Converter

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



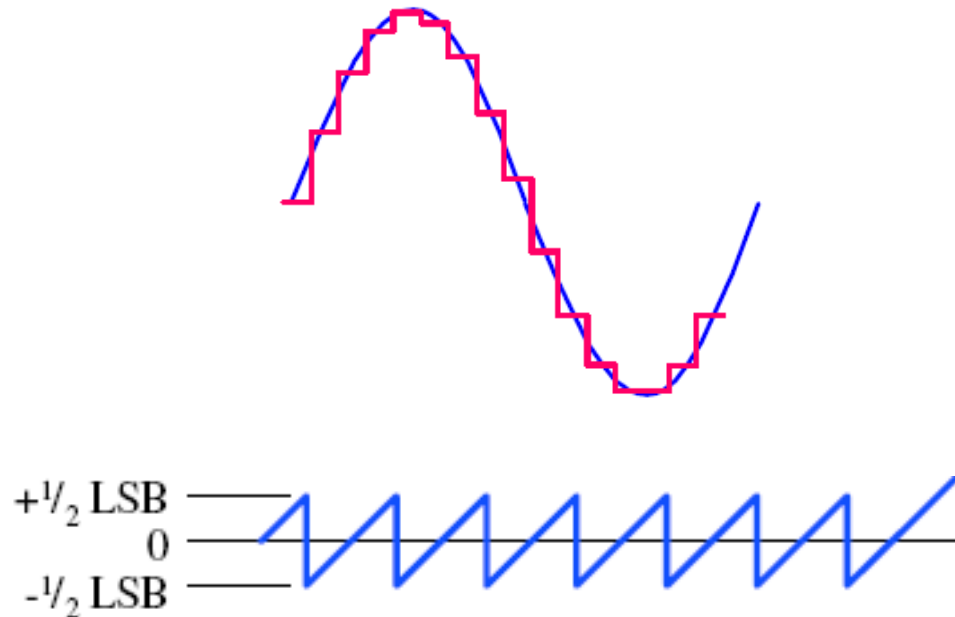
Bit Weights of an 8-Bit Word

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



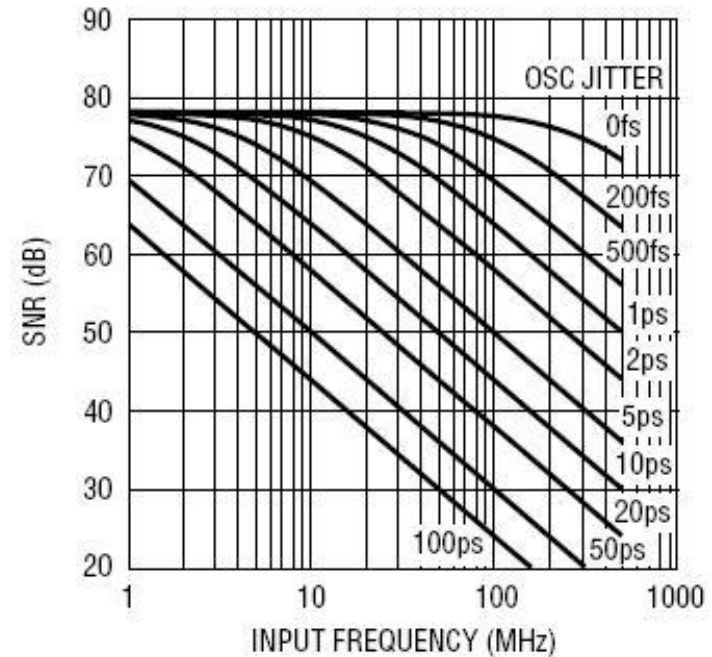
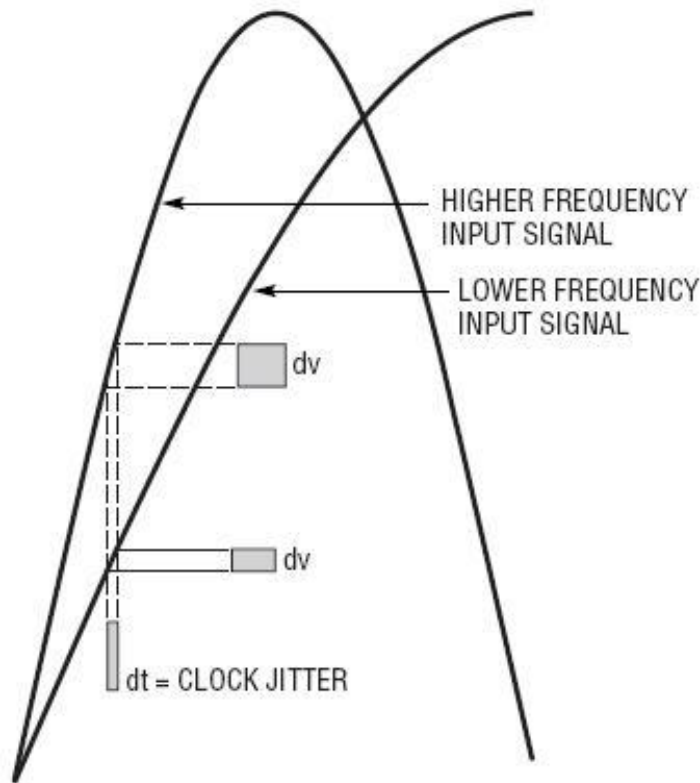
ADC noise source: Quantization noise

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



ADC noise source: Clock jitter

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





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

Signal to Noise Ratio (SNR) of ADC:

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

f_a : input frequency [Hz]

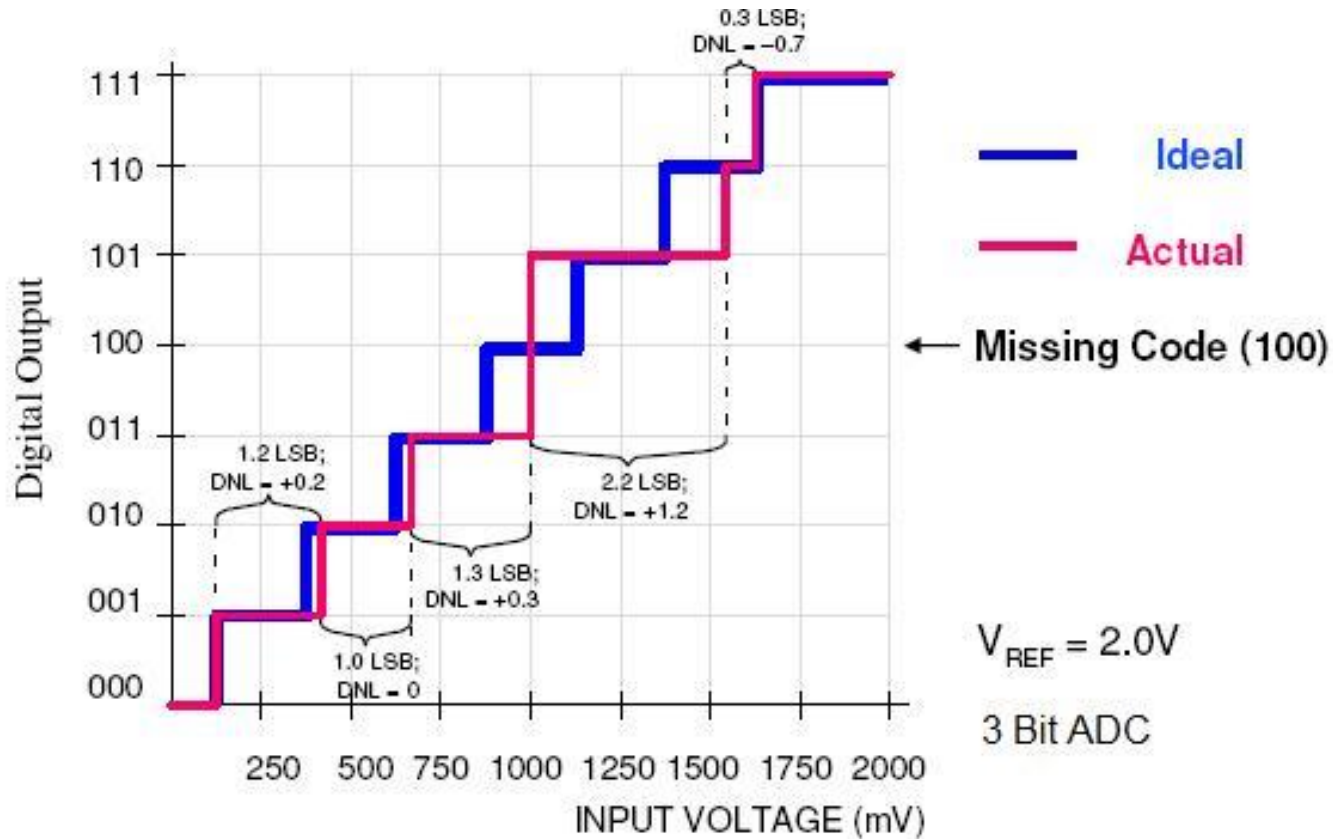
t_j : rms clock timing jitter [s]

ϵ : differential nonlinearity, DNL [LSB]

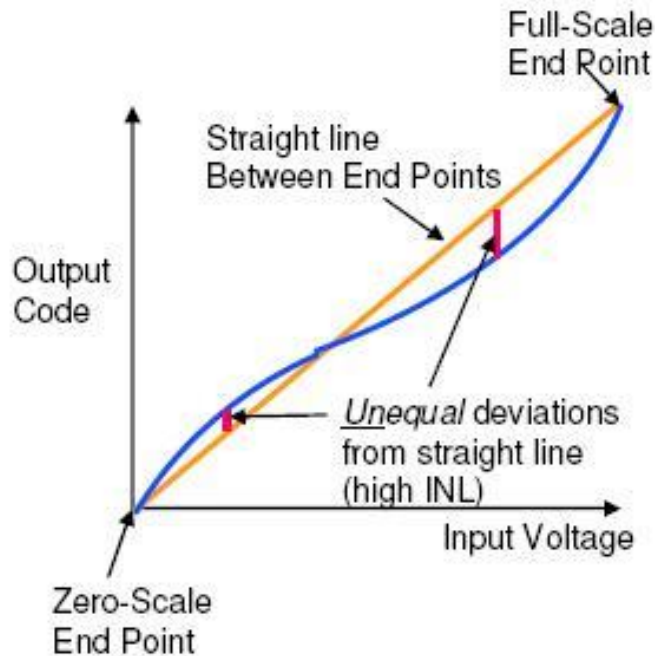
N : number of bits

V_n : equivalent input noise [LSB].

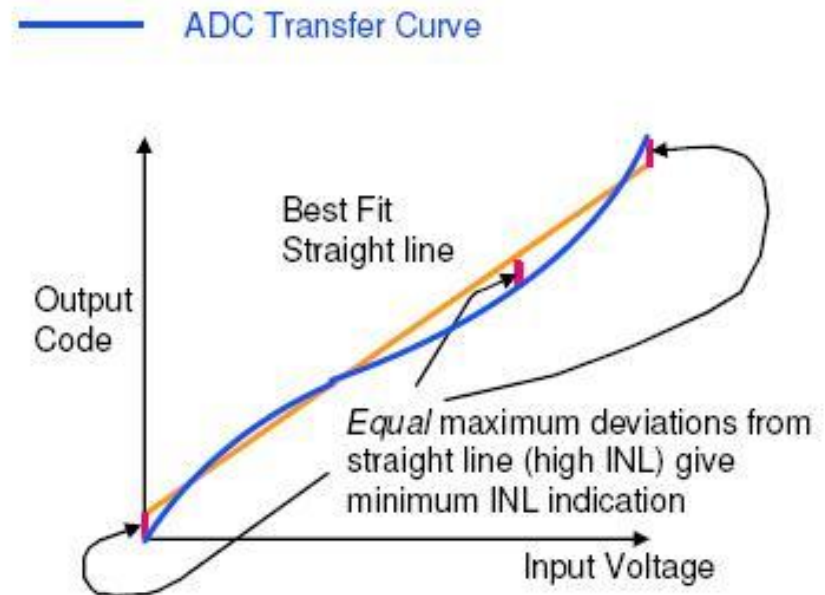
Differential Non-Linearity (DNL): “small scale” code to code errors



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