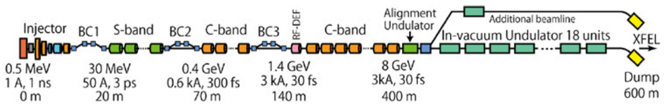
Error correction of IQ demodulator used at XFEL/SPRING-8 "SACLA"

T. Ohshima, H. Maesaka, S. Matsubara and Y. Otake
RIKEN, XFEL project/SPring-8, 1-1-1 Kouto, Sayo, Hyogo, 679-5148, Japan

Requirements

Stable operation of XFEL requires stabilization of rf voltage with
- amplitude : < 1E-4 rms
- phase : < 100fs rms

as a first stage operation



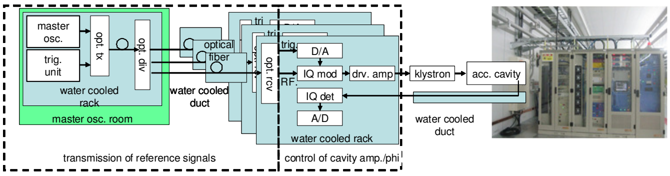
Configuration of LLRF system at SACLA

Reference rf signal is delivered to each unit using optical link.

Pulse modulation and phase / amplitude control is done with In-phase Quadrature (IQ) modulator.

Modulated signal is amplified and fed to cavity.

Cavity rf voltage is measured by using IQ demodulator.



Setting / measurement error at IQ modulator / demodulator such as cross talk between phase and amplitude degrades the performance of feedback control, and should be corrected.

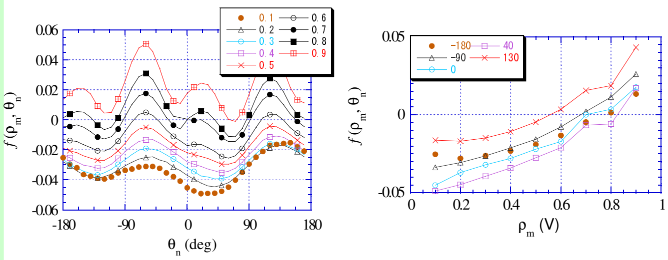
[error sources]
- offset, gain err of DAC / ADC
- offset, gain error, tilt of orthogonal axis at IQ mixer
- etc.

Measurement of phase dependent amplitude variation of IQ demodulator

Set value of IQ modulator (DAC out) is swept
- from 0.1V to 0.9V with 0.1V step (number of data points M=9),
- from 0deg to 350deg with 10deg step. (number of data points N=36)

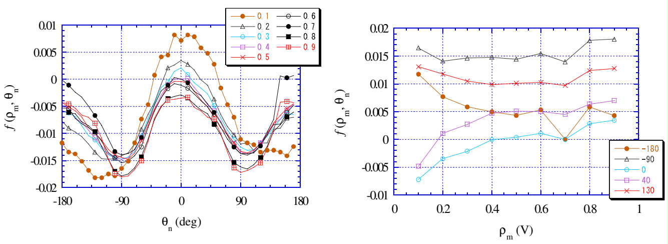
Amplitude error of IQ modulator at set amplitude ρ_m and phase θ_n is calculated from measured data using network analyzer

$f(\rho_m, \theta_n)$ = [measured amp. of Network Analyzer] / [set value] - 1



Amplitude error of 238MHz IQ modulator measured by using N. A.

Error of IQ demodulator is obtained by using calibrated IQ modulator.



Amplitude error of 238MHz IQ demodulator measured by using calibrated IQ modulator.

Error correction

Correction should be made at any amplitude ρ and phase θ.
One method of correction is linear interpolation using the table of measured error, which has large number of parameters.
Another method is approximation using Discrete Fourier Transform.
The error as a function of phase has a periodicity of $f(\theta_n)= f(\theta_n+2\pi)$, and DFT coefficient of F(ν) can be expressed as

$$F(\nu)=\frac{1}{N}\sum_{n=0}^{N} f(\theta_n)\, e^{j\frac{n}{N}\theta_n},$$

where N is the number of data points. Inverse DFT coefficient, which is the error correction value at θ, can be expressed as,

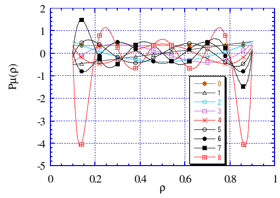
$$f(\theta) = F(\nu)e^{-j\frac{n}{N}\theta}.$$

Expanding this approach in amplitude, we introduce calculation of two dimensional DFT coefficient. The dependence of the error in the amplitude has not periodicity as the case in phase. So we use a polynomial function as a base function of DFT. The μ^{th} order orthonormal function of polynomial $P\mu(\rho_m)$ is obtained by Gram-Schmidt orthonormalization. 2D-DFT coefficient is expressed as

$$F(\mu,\nu) = \frac{1}{MN}\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} f(\rho_m,\theta_n)P_\mu(\rho_m)e^{j\nu\theta_n}$$

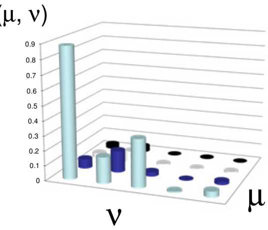
Inverse DFT coefficient at amplitude ρ and phase θ is expressed as

$$f(\rho,\theta) = \sum_{\mu=0}^{M-1}\sum_{\nu=0}^{N-1} F(\mu,\nu)P_\mu(\rho)e^{-j\nu\theta}$$

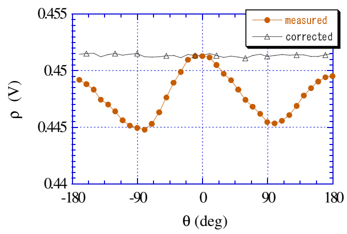


Orhonormal polynomial function
$P\mu(\rho_m)$ $0.1< \rho_m<0.9$ 0^{th} to 8^{th}

Results



The DFT coefficient of 238MHz IQ demodulator



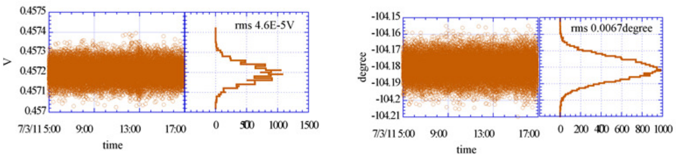
Measured and corrected amplitude of IQ demodulator

Main components are within 5^{th} order in both axis; amplitude μ and phase ν. So the error correction is done up to this order. At the case of 238MHz IQ demodulator, the error was reduced from 1% to 0.1%.
In actual application there existed some additional error sources, such as reflection from coaxial cables and performance of the error suppression was degraded; from 1.2% to 0.2% .

Feedback control process using the data with the error correction is running on a VME cpu to stabilize the phase of the cavity.
The achieved stabilities are

238MHz	0.006deg (80fs) std	and 1E-4 std.
C-band cavity CB01-1	0.03deg (20fs) std	and 6E-4 std,

which almost satisfy the requirement.



Stability of the cavity amplitude and phase at 238MHz cavity

Summary

The error of the IQ detector is corrected by using two dimensional Fourier transform. The basis of the orthonormal functions, exponential and polynomials are used for phase and amplitude, respectively. By using the correction up to 5^{th} , the measured amplitude error were reduced from 1.2% to 0.2%, respectively.
This results demonstrate the effectiveness of the approximation of 2D FFT approximation with small number of coefficients compared with the usage of look-up table which has large number of parameters. The phase stability of less than 100fs was achieved by feedback control with this correction.