LLRF for SC Heavy Ion Linear Accelerators

Paper study at USPAS17
Qi Chen
IMPCAS and LBNL

DEVELOPMENT OF LOW LEVEL RF CONTROL SYSTEMS FOR SUPERCONDUCTING HEAVY ION LINEAR ACCELERATORS, ELECTRON SYNCHROTRONS AND STORAGE RINGS *

M. Pekeler, C. Piel Accel GmbH, Bergisch Gladbach, Germany.
B. Aminov, A. Borisov, S. Kolesov, H. Piel, Cryoelectra GmbH, Wuppertal, Germany

Abstract

Since 2001 ACCEL Instruments is supplying low level RF control systems together with turn key cavity systems. The early LLRF systems used the established technology based on discrete analogue amplitude and phase detectors and modulators. Today analogue LLRF systems can make use of advanced vector demodulators and modulators combined with a fast computer controlled analogue feed back loop. Feed forward control is implemented to operate the RF cavity in an open loop mode or to compensate for predictable perturbations. The paper will introduce the general design philosophy and show how this can be adapted to different tasks as controlling a synchrotron booster nc RF system at 500 MHz, or a sc storage ring rf, as well as a the superconducting 176 MHz accelerating cavities of a linear accelerator at 176 MHz with multiple cavities individual driven and controlled.

INTRODUCTION

In the following chapters we describe in detail and as an example the architecture of a computer controlled fast analogue low level RF control system for the injector and pre accelerator section of a superconducting linear

programmed according to the various operation modes of the linear accelerator, so that the excitation of each rf structure (HWR or RFQ) can be controlled separately. Table 1 and Table 2 summarise the technical data for the LLRF system for HWR and RFQ.
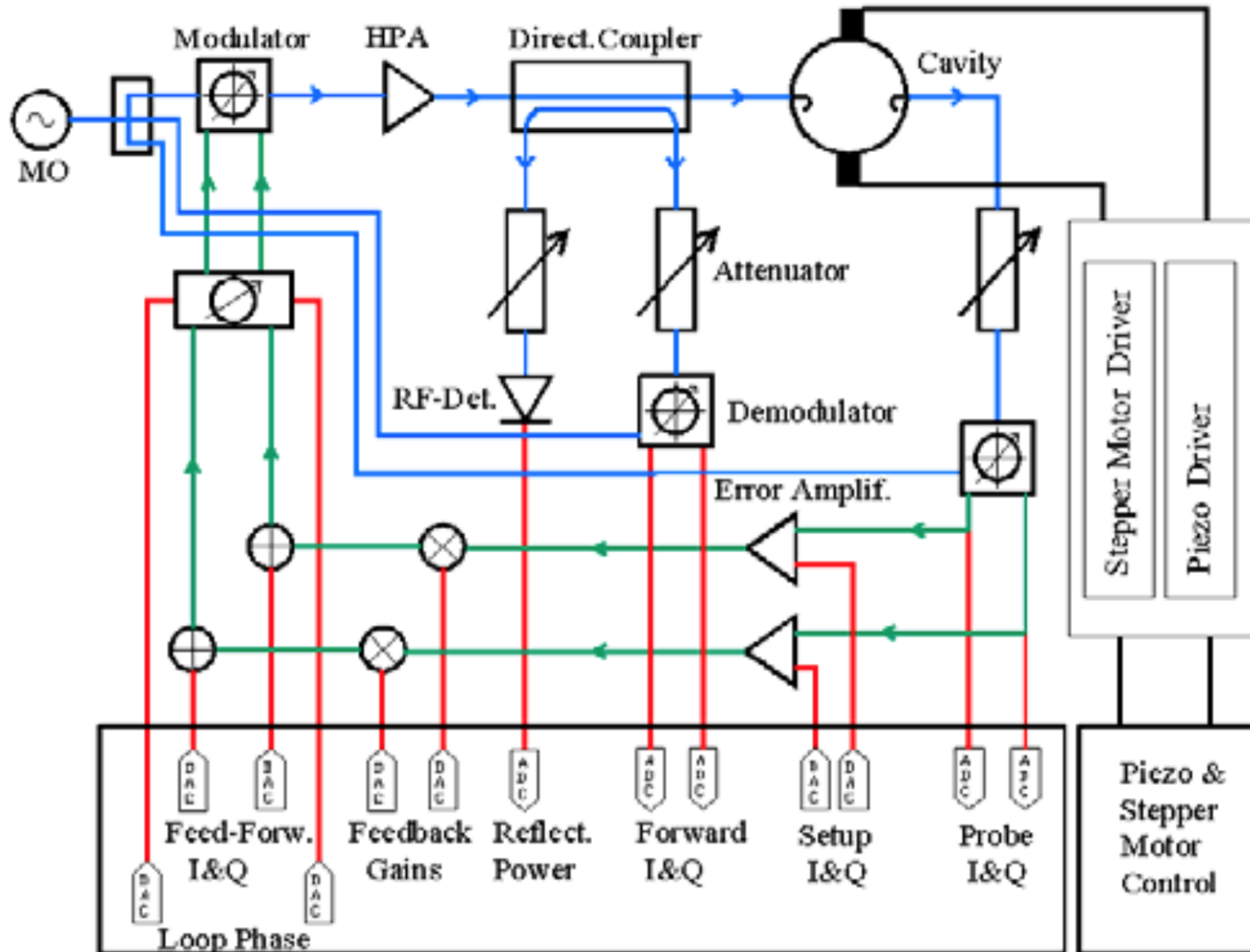
Table 2: Technical Specification of the LLRF for the Radio Frequency Quadrupole.

RFQ Parameters	Unit	Value
RFQ centre frequency	MHz	176
RFQ bandwidth	kHz	21
Output energy	MeV	1.5
LLRF loop gain	dB	40
Phase stability	degree	± 0.5
Amplitude stability	%	± 0.5
Setability of mechanical tuner	Hz	± 75

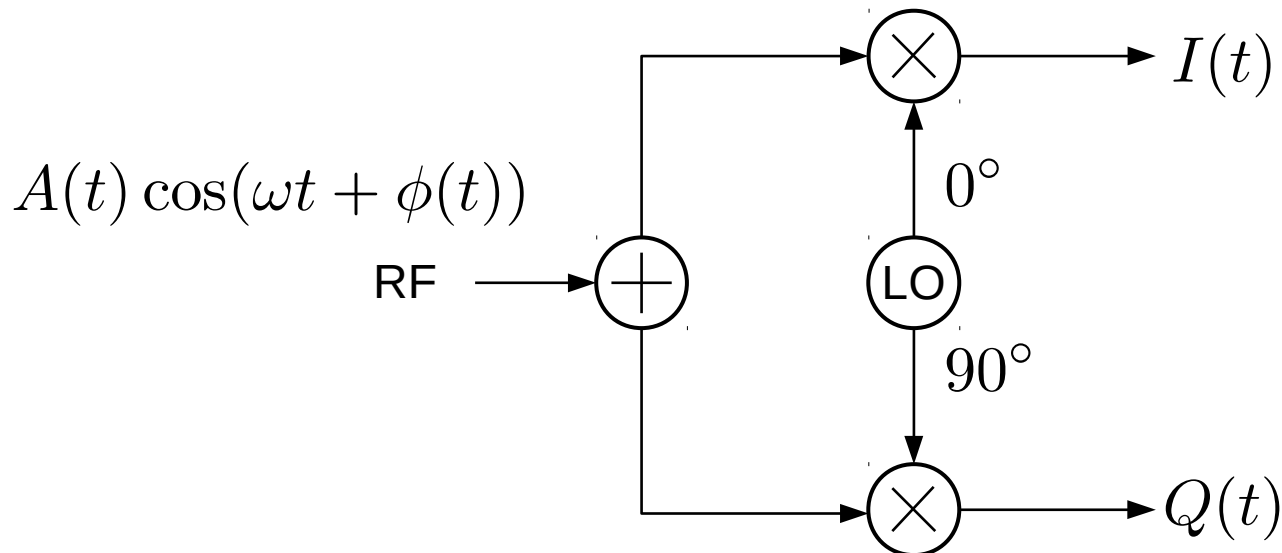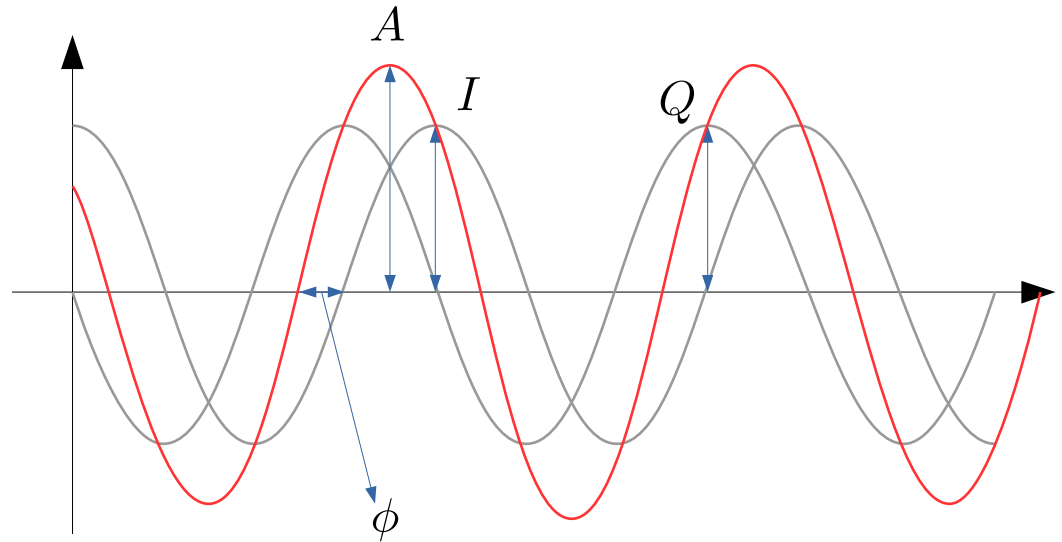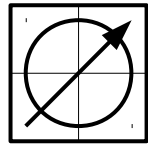## Low Level RF Fast Analogue Section

The block-diagram of the Low Level RF system is

Low Level RF block-diagram

Phase / Amplitude Detecting

- I & Q Demodulator

$A(t)\cos(\omega t + \phi(t))$

RF

LO

$0°$

$90°$

$I(t)$

$Q(t)$

Some trigonometric equations

$$\cos[\omega t + \phi(t)] \equiv \cos(\omega t) \cdot I(t) + \underbrace{\cos\left(\omega t + \tfrac{\pi}{2}\right)}_{-\sin(\omega t)} \cdot Q(t)$$
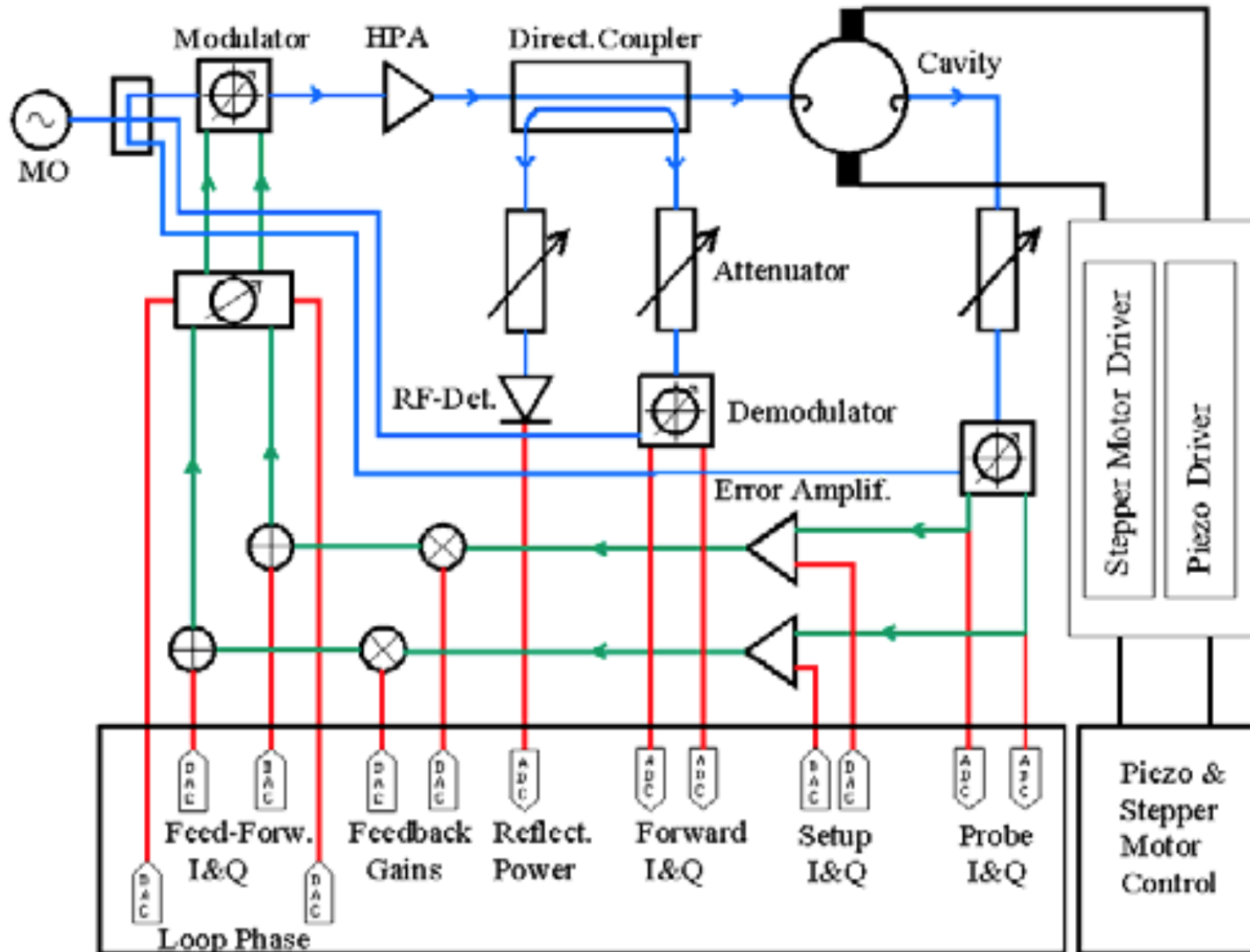
$$\sin[\omega t + \phi(t)] \equiv \sin(\omega t) \cdot I(t) + \underbrace{\sin\left(\omega t + \tfrac{\pi}{2}\right)}_{\cos(\omega t)} \cdot Q(t)$$

$$\sin[\omega t + \phi(t)] = \underbrace{\sin(\omega t) \cdot \cos[\phi(t)]}_{\text{in-phase}} + \underbrace{\overbrace{\sin\left(\omega t + \tfrac{\pi}{2}\right)}^{\cos(\omega t)} \cdot \sin[\phi(t)]}_{\text{quadrature}}.$$

$$\phi(t) \overset{\text{def}}{=} \tan^{-1}\left(Q(t)/I(t)\right)$$
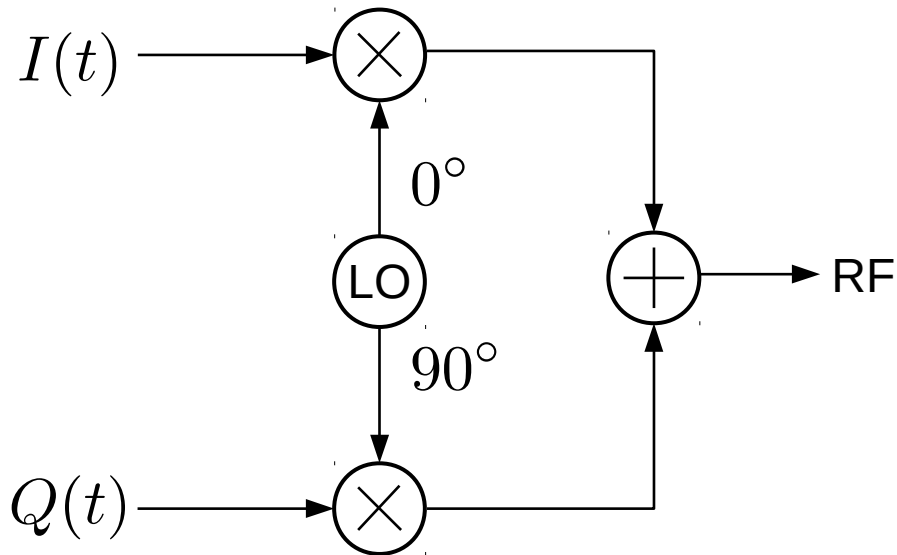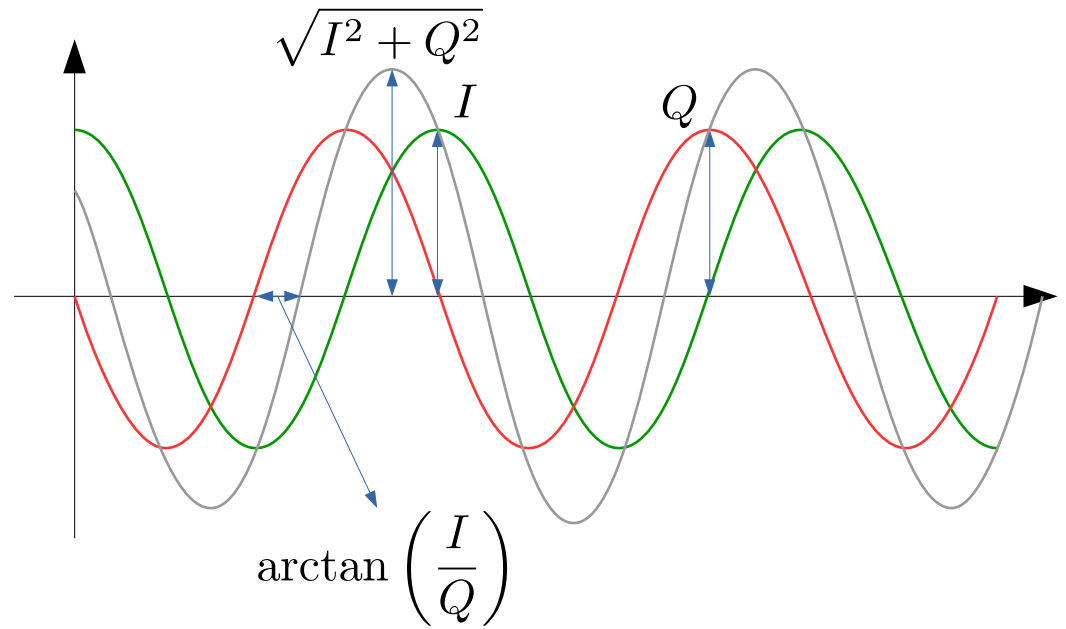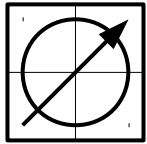
Low Level RF block-diagram

Phase / Amplitude Modulation

- I & Q Modulator

Some trigonometric equations

$$\cos[\omega t + \phi(t)] \equiv \cos(\omega t) \cdot I(t) + \underbrace{\cos\left(\omega t + \tfrac{\pi}{2}\right)}_{-\sin(\omega t)} \cdot Q(t)$$

$$\sin[\omega t + \phi(t)] \equiv \sin(\omega t) \cdot I(t) + \underbrace{\sin\left(\omega t + \tfrac{\pi}{2}\right)}_{\cos(\omega t)} \cdot Q(t)$$
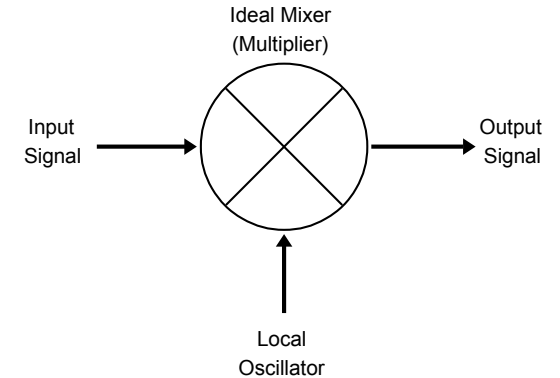
$$\sin[\omega t + \phi(t)] = \underbrace{\sin(\omega t) \cdot \cos[\phi(t)]}_{\text{in-phase}} + \underbrace{\overbrace{\sin\left(\omega t + \tfrac{\pi}{2}\right)}^{\cos(\omega t)} \cdot \sin[\phi(t)]}_{\text{quadrature}}.$$

$$\phi(t) \overset{\text{def}}{=} \tan^{-1}\left(Q(t)/I(t)\right)$$

How mixer works

- We need new frequency

Ideal Mixer (Multiplier)

Input Signal → Output Signal

Local Oscillator

Suppose that two input sinusoids of different frequencies are fed into the diode, such that $v_1 = \sin at$ and $v_2 = \sin bt$. The signal V_0 becomes:

$$v_o = (\sin at + \sin bt) + \frac{1}{2}(\sin at + \sin bt)^2 + \ldots$$

Expanding the square term yields:

$$v_o = (\sin at + \sin bt) + \frac{1}{2}(\sin^2 at + 2\sin at \sin bt + \sin^2 bt) + \ldots$$

Ignoring all terms except for the $\sin at \sin bt$ term and utilizing the prosthaphaeresis (product to sum) identity,
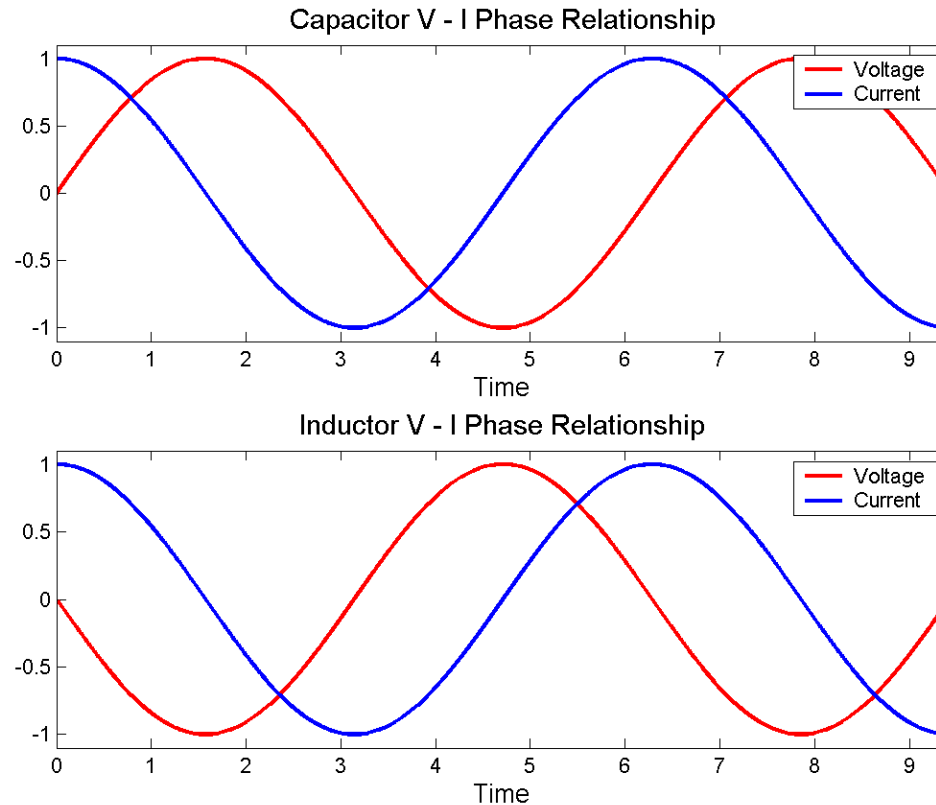
$$\sin a \sin b = \frac{\cos(a - b) - \cos(a + b)}{2}$$

yields,

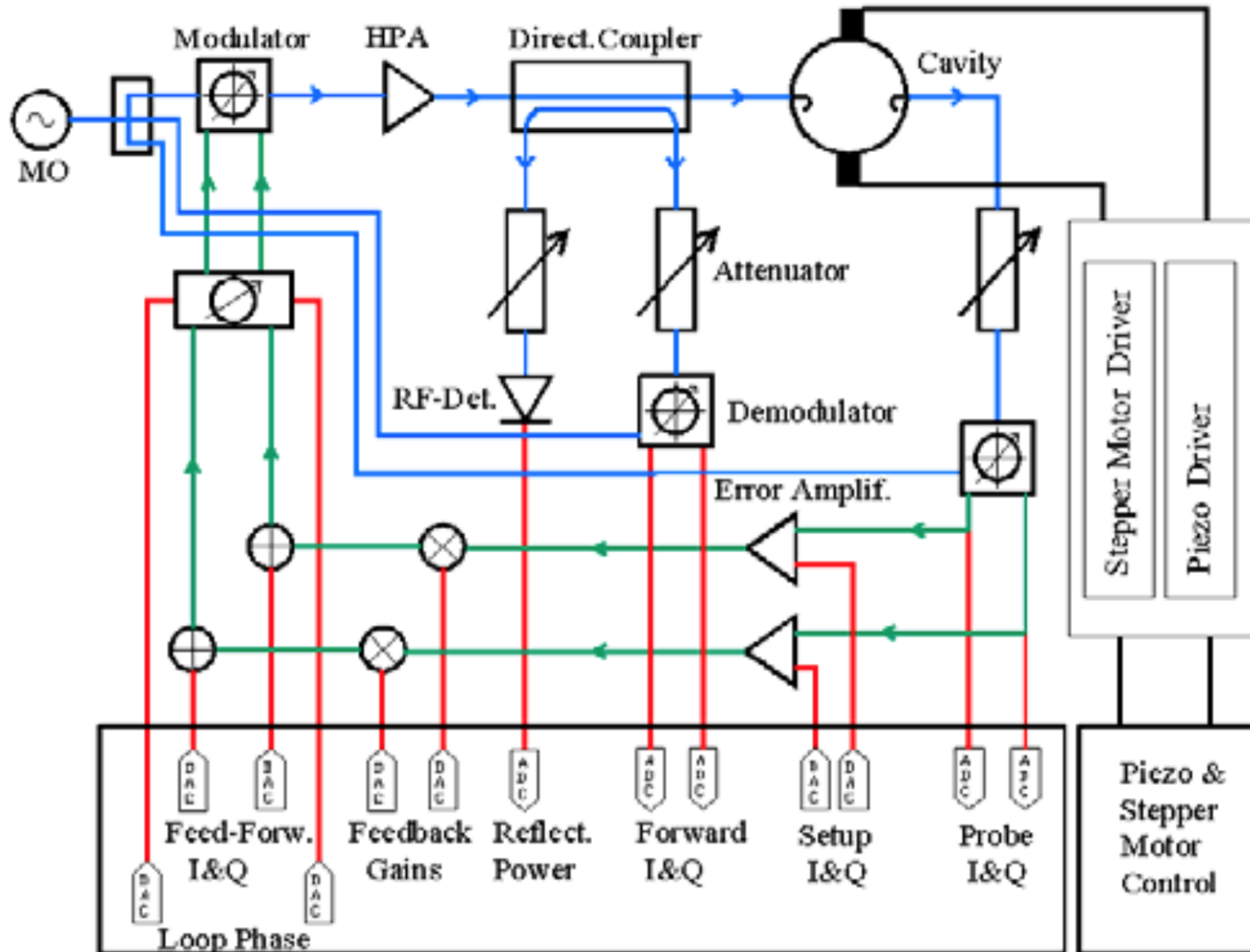$$v_o = \cos((a - b)t) - \cos((a + b)t) + \ldots$$

demonstrating how new frequencies are created from the mixer.
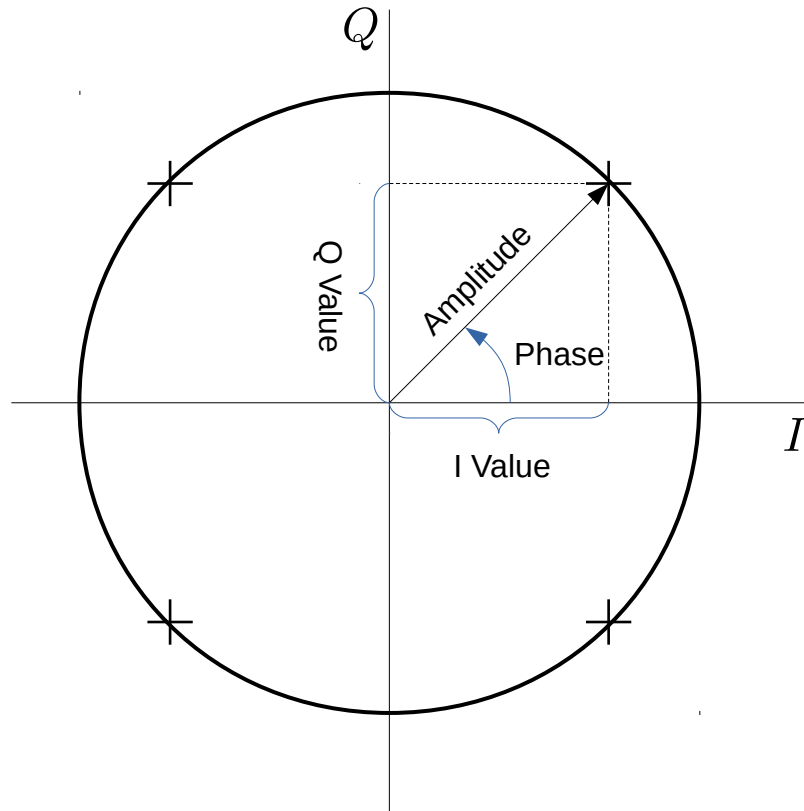
How to get 90° phase shift

- When a sinusoidal voltage is applied to either a simple capacitor or inductor, the resultant current that flows is "in quadrature" with the voltage.
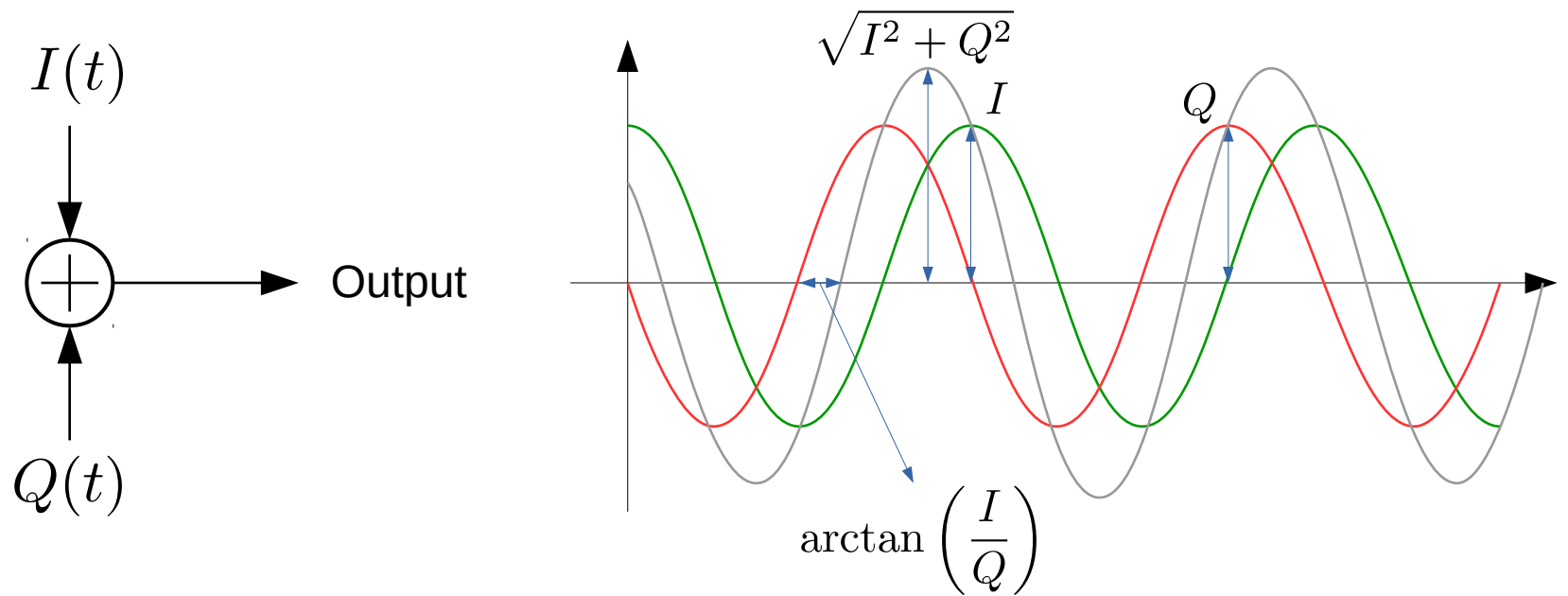
Low Level RF block-diagram

Phase Diagram

I & Q Modulation

- I & Q Modulator

Low Level RF block-diagram