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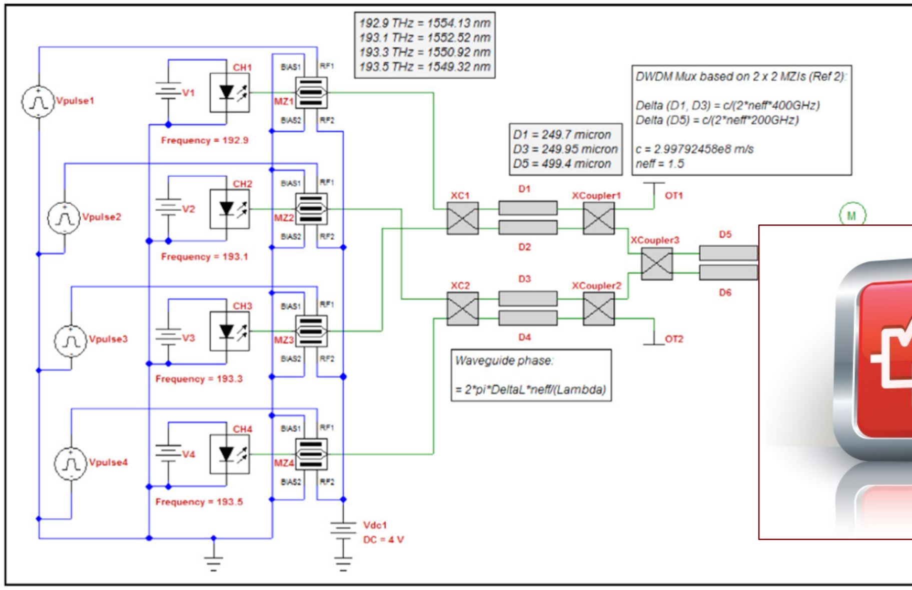
DESIGN SOFTWARE



OptiSPICE

Opto-Electronic Circuit Design Software

Optical PLL for homodyne detection

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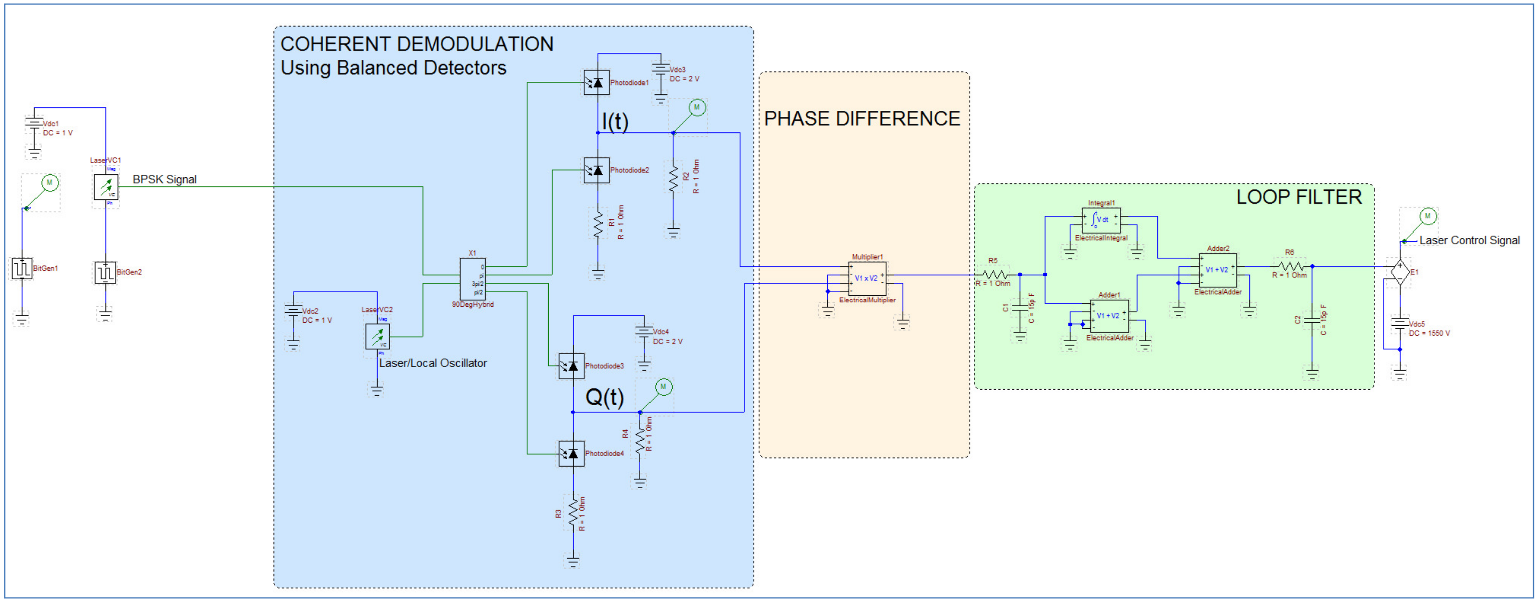
Optical BPSK PLL building blocks

OptiSPICE
Opto-Electronic Circuit Design Software

- Signal Generation and Detection
  - BPSK Signal Generator
  - Local Oscillator
  - 90 degree hybrid
  - Balanced detectors
- Phase Difference Calculation
  - Electrical multiplier
- Feedback: Generating the control signal
  - Loop Filter
  - DC Offset



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90 Degree Hybrid

The 90 Degree Hybrid mixes the incoming optical field with the local oscillator (LO) optical field and produces four outgoing signals with phase differences of 0, π, 3π/2 and π/2

The electric field amplitudes of the PSK and LO signals are represented by A and B, respectively

PSK signal $$In_1 = Ae^{j\omega_1 t+\phi_1(t)}$$

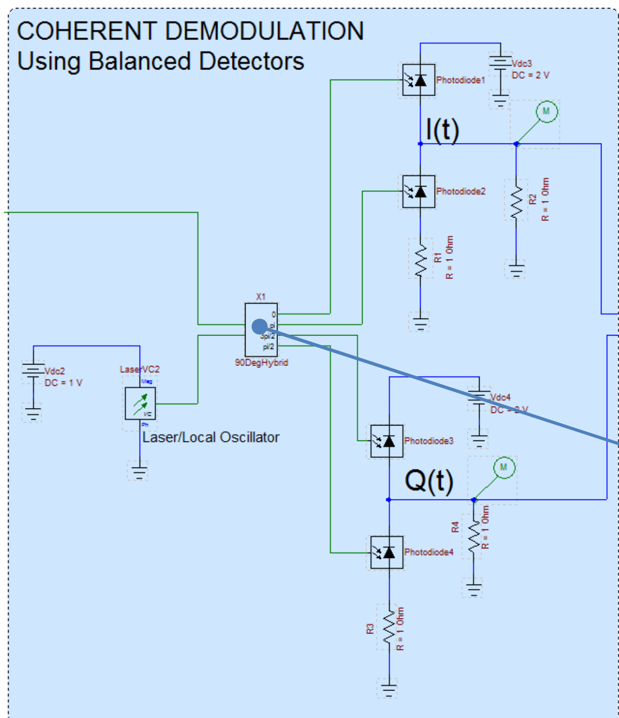
Local oscillator $$In_2 = Be^{j\omega_2 t+\phi_2(t)}$$

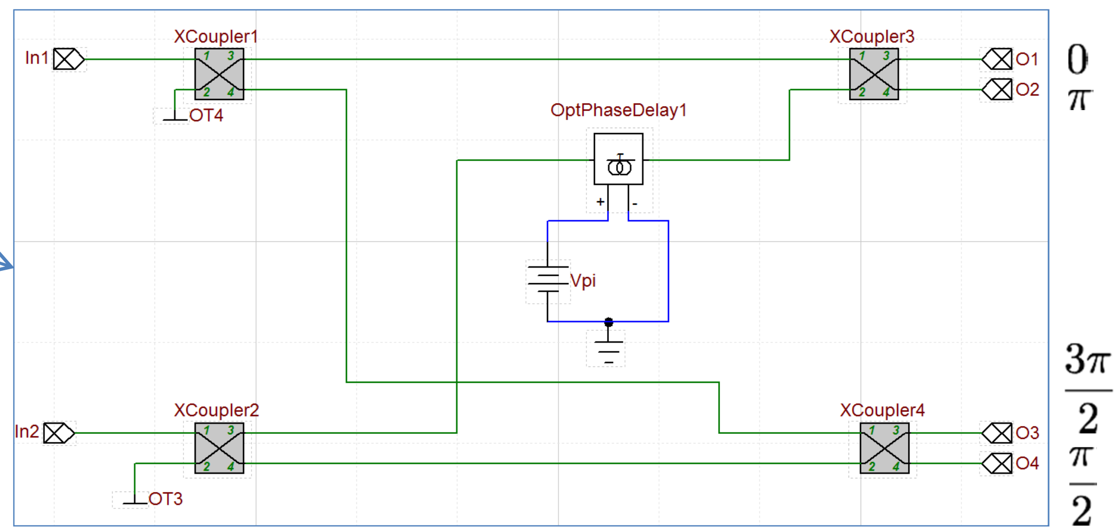
$$O_1 = Ae^{j\omega_1 t+\phi_1(t)} + Be^{j\omega_2 t+\phi_2(t)}$$

$$O_2 = Ae^{j\omega_1 t+\phi_1(t)+\frac{\pi}{2}} + Be^{j\omega_2 t+\phi_2(t)-\frac{\pi}{2}}$$

$$O_3 = Ae^{j\omega_1 t+\phi_1(t)+\frac{\pi}{2}} + Be^{j\omega_2 t+\phi_2(t)+\pi}$$

$$O_4 = Ae^{j\omega_1 t+\phi_1(t)+\pi} + Be^{j\omega_2 t+\phi_2(t)+\frac{\pi}{2}}$$





Coherent detection with balanced detectors

The instantaneous power incident on each photodiode can be calculated as follows

$$P_t = \frac{1}{2} O_n O_n^*$$

Therefore the instantaneous field intensity (power) in each arm is equal to,

LO field squared (DC term)

Sum and difference frequency terms (mixing)

$$P_{t_1} = \frac{1}{2}(A^2 + B^2 + 2ABcos(\Delta))$$

Signal field squared (DC term)

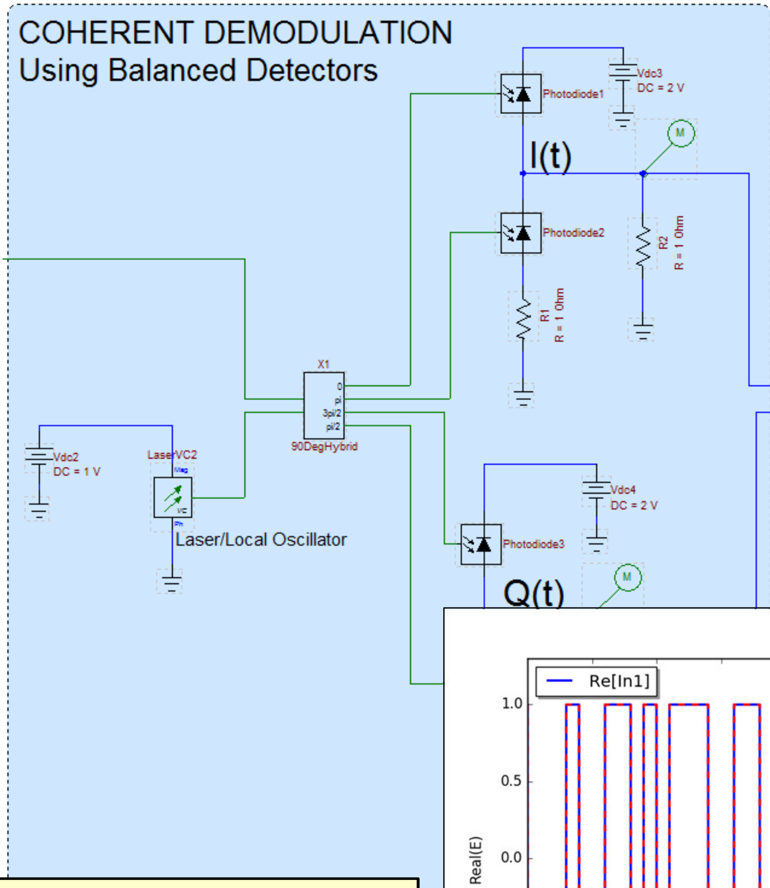
$$P_{t_2} = \frac{1}{2}(A^2 + B^2 + 2ABcos(\Delta + \frac{\pi}{2})) = \frac{1}{2}(A^2 + B^2 - 2ABcos(\Delta))$$

$$P_{t_3} = \frac{1}{2}(A^2 + B^2 + 2ABcos(\Delta + \frac{3\pi}{2})) = \frac{1}{2}(A^2 + B^2 + 2ABsin(\Delta))$$

$$P_{t_4} = \frac{1}{2}(A^2 + B^2 + 2ABcos(\Delta + \frac{\pi}{2})) = \frac{1}{2}(A^2 + B^2 - 2ABsin(\Delta))$$

$$\Delta = \omega_1 t - \omega_2 t + \phi_1(t) - \phi_2(t)$$

Homodyne balanced detection (ideal)



$$I(t) = P_{t_1} - P_{t_2} = ABcos(\Delta)$$

$$Q(t) = P_{t_3} - P_{t_4} = ABsin(\Delta)$$

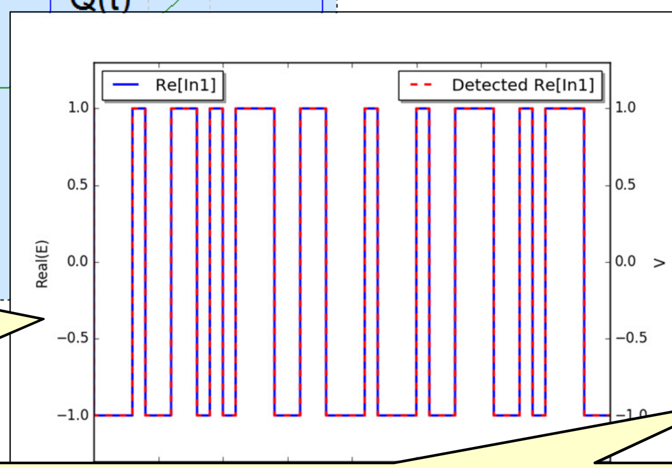
Perfect recovery in ideal conditions assuming ideal photodiode with Responsivity = 1

$\omega_1 = \omega_2$ and $\phi_2(t) = 0$

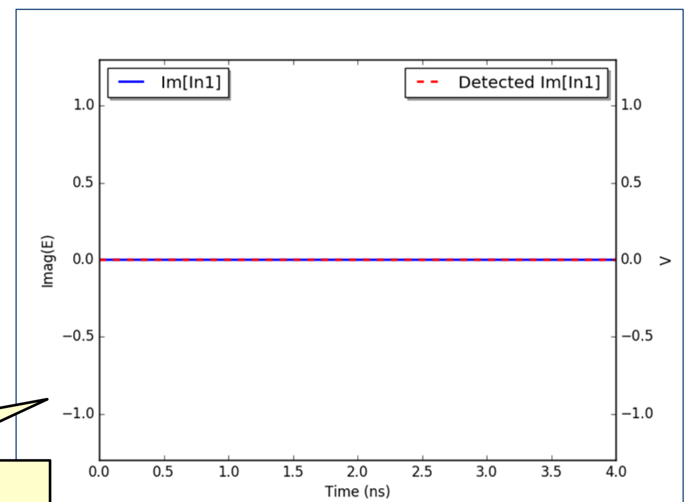
$$I(t) = ABcos(\phi_1(t)) \ \alpha \ Re[In_1]$$

$$Q(t) = ABsin(\phi_1(t)) \ \alpha \ Im[In_1]$$

$$\lambda_1 = 1550 \ nm, \lambda_2 = 1550 \ nm, \phi_2(t) = 0$$



*Represents the real part of the detected BPSK signal (Real(**In1**)) – measured from the upper branch of the balanced detector (**I(t)**)*



*Represents the imaginary part of the detected BPSK signal (Imag(**In1**)) – measured from the lower branch of the balanced detector (**Q(t)**). Under ideal conditions, this signal should be zero (the phase modulation occurs only along the **I** axis)*

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Homodyne balanced detection (non-ideal)

In non-ideal conditions phase correction is needed

$\omega 1 \neq \omega_2$ and/or $\phi_2(t) \neq 0$

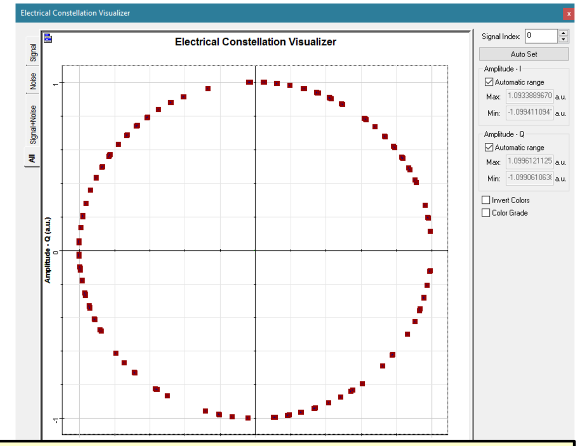
$$I(t) = ABcos(\phi_1(t) + \Delta\phi(t))$$

$$Q(t) = ABsin(\phi_1(t) + \Delta\phi(t))$$

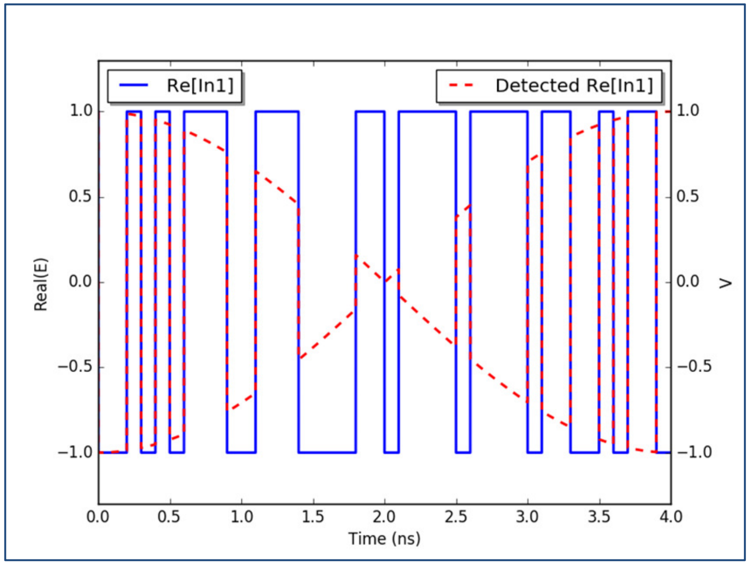
$$\Delta\phi(t) = \omega_1 t - \omega_2 t - \phi_2(t)$$

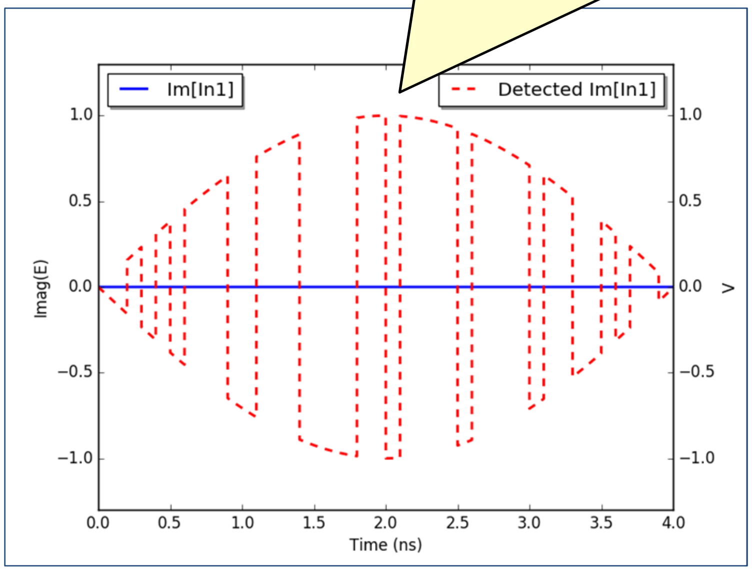
Rotation in the constellation diagram

$$\lambda_1 = 1550\ nm, \lambda_2 = 1550.001\ nm, \phi_2(t) = 0$$



Due to a frequency difference between the signal and LO, the detected BPSK signal constellation will have terms in both the I (real) and Q (imaginary) axes. This results in a rotation of the I-Q constellation





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Phase difference (Electrical multiplier) 1

Electrical multiplier estimates the phase
by multiplying I and Q

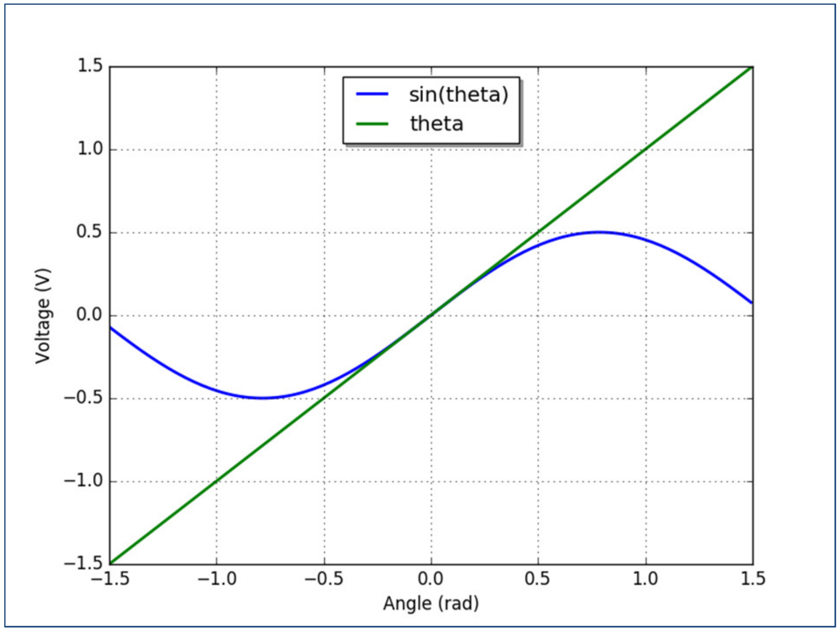
$$I(t) * Q(t) = (AB)^2 cos(\phi_1(t)) sin(\phi_1(t))$$

$$I(t) * Q(t) = \frac{(AB)^2}{2} sin(2\phi_1(t))$$

Using small angle approximation $sin(\theta) \approx \theta$

$$I(t) * Q(t) \approx (AB)^2 \phi_1(t)$$

The plot shows the sweep of the phase where
$\lambda_1 = 1550\ nm, \lambda_2 = 1550\ nm, \phi_1 = -\pi\ to\ \pi, \phi_2 = 0$

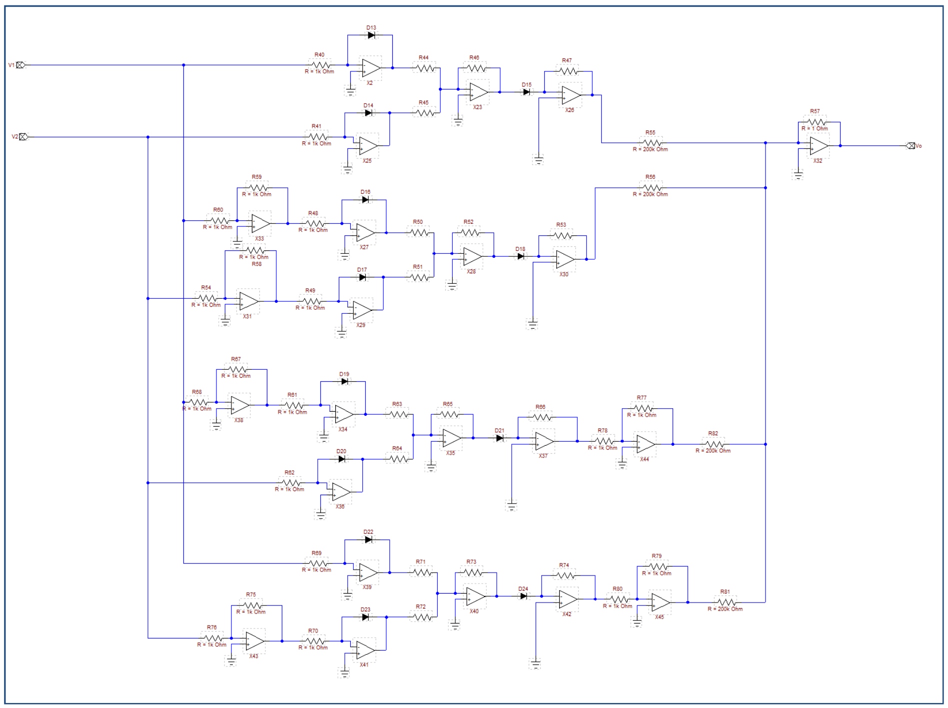


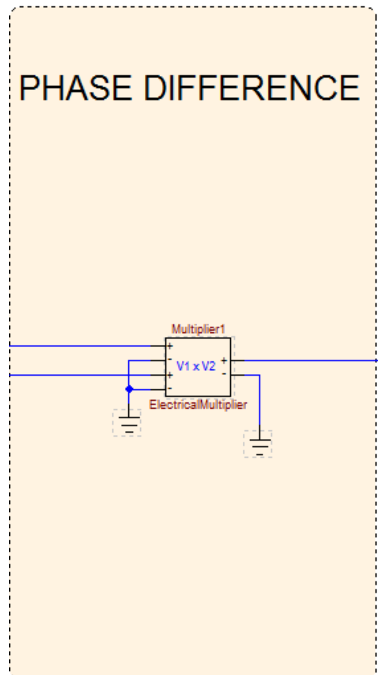
Phase difference (Electrical multiplier) 2

There is no straightforward circuit for analog multiplication (normally achieved by using log and inverse log)

$$AB = log^{-1}(log(A) + log(B))$$

This can be realized using operational amplifiers or transistors (see left diagram below). OptiSPICE also has an electrical multiplier element (see right diagram below) which can perform this operation mathematically.





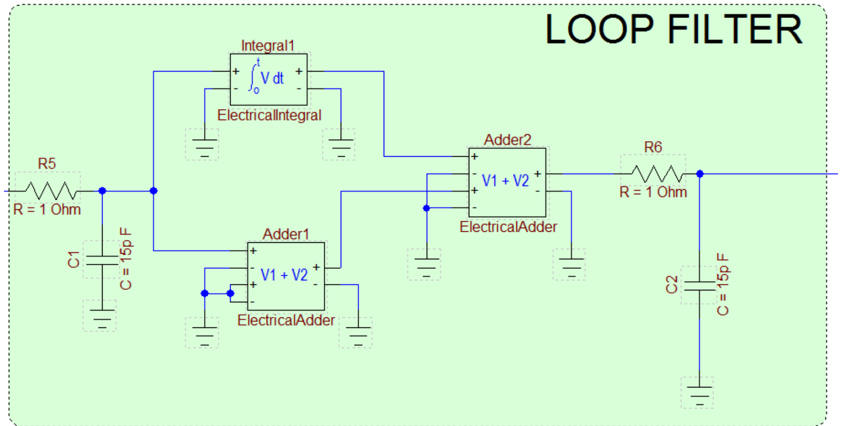
Loop Filter-PI Controller

A loop filter is used to generate the control signal for the tunable laser from the detected phase difference. It consists of a proportional integral controller and a low pass filter

$$V_{cont} = K_I \int \phi dt + K_p \phi$$

K_I & K_p are scaling factors

ϕ is the output of the electrical multiplier which is the detected phase difference (error signal)



- Adder and Integrator circuits can be created using operational amplifiers
- OptiSPICE has built-in voltage adder and integrator elements that can be used directly to perform these operations
- The controller works as long as the phase or frequency difference is not too large
- There is not any straight forward way to figure out the values for the scaling factors
- They can be adjusted manually or through an optimization routine to obtain a desired PLL response

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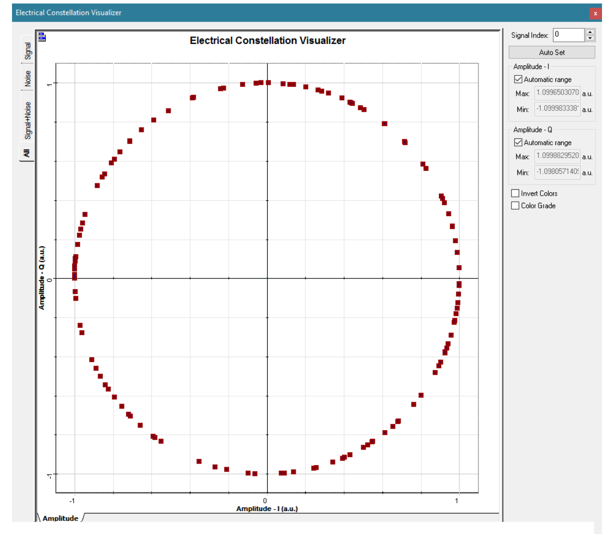
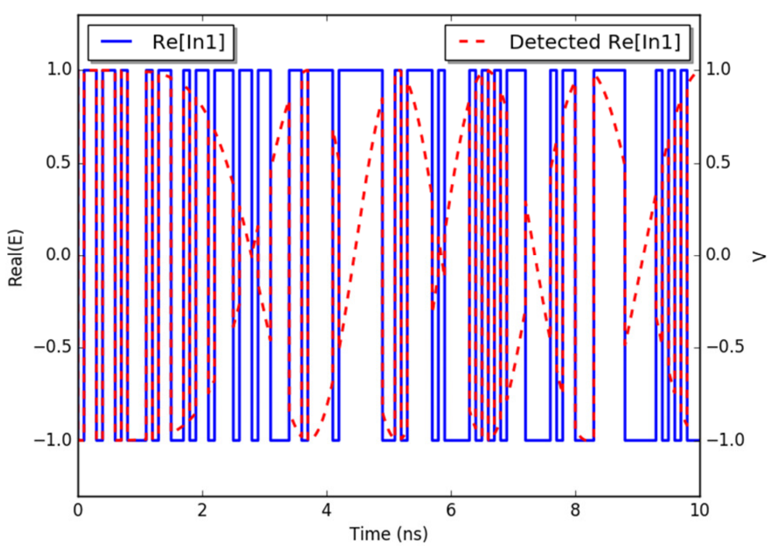
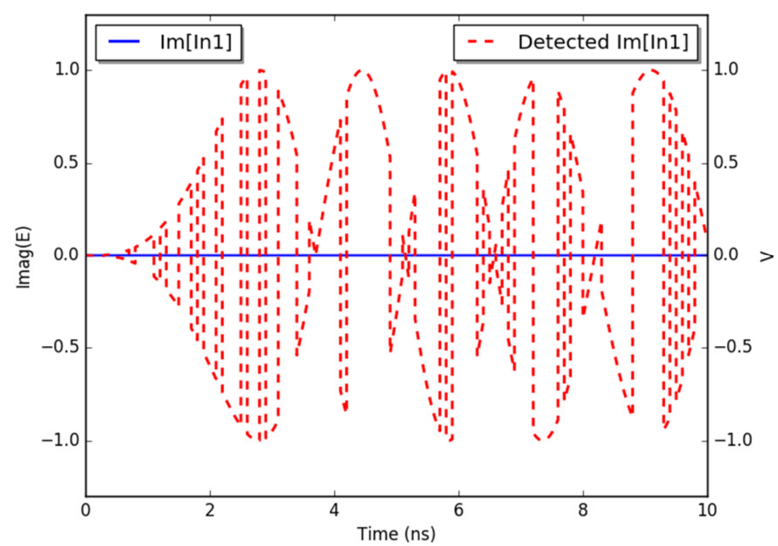
Simulation results – no PLL

Without the active phase correction of the PLL a constant frequency difference between the local oscillator and the carrier signal detected I and Q do not have the correct phase (pi or –pi for BPSK). The constant frequency difference results in the rotation of the constellation diagram



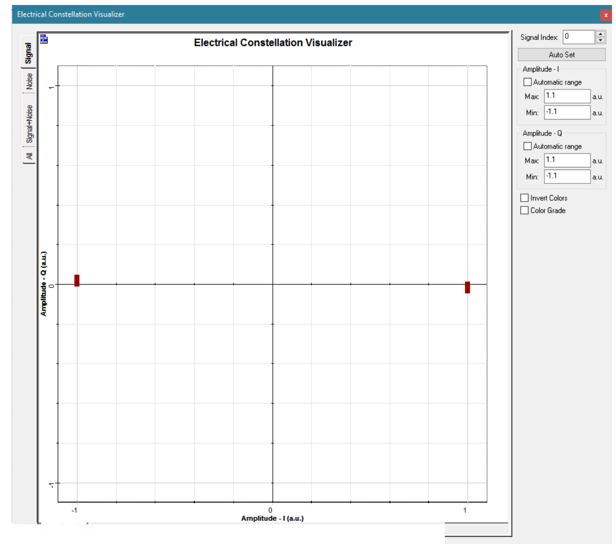
Phase Locked Loop OFF



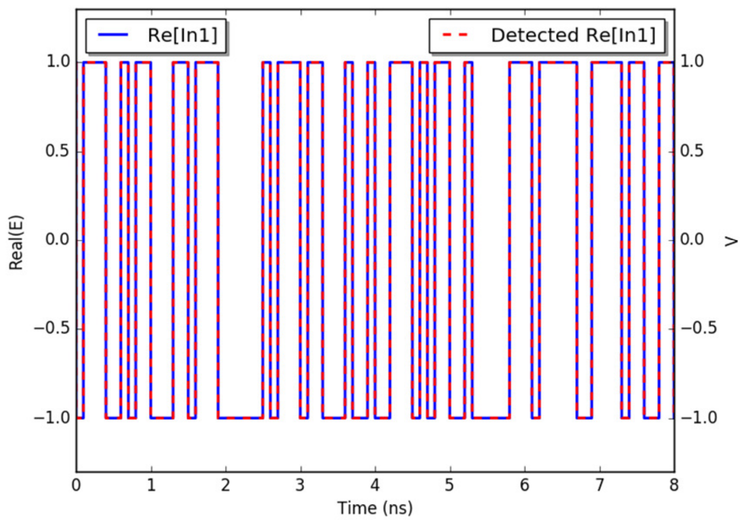


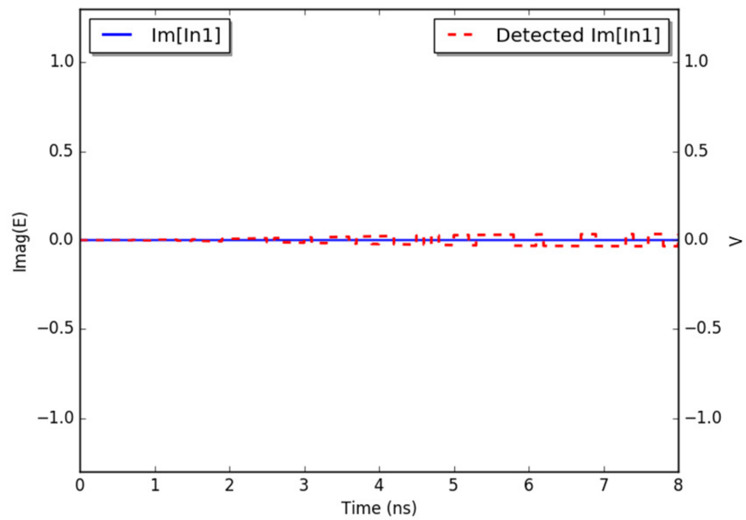
Simulation results – PLL on

When the PLL is activated the frequency/phase of the local oscillator tracks the frequency/phase of the carrier signal. Therefore the detected I and Q have the right phase and the constellation diagram does not rotate



Phase Locked Loop ON





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