OPTICAL PHASE-LOCKED LOOP

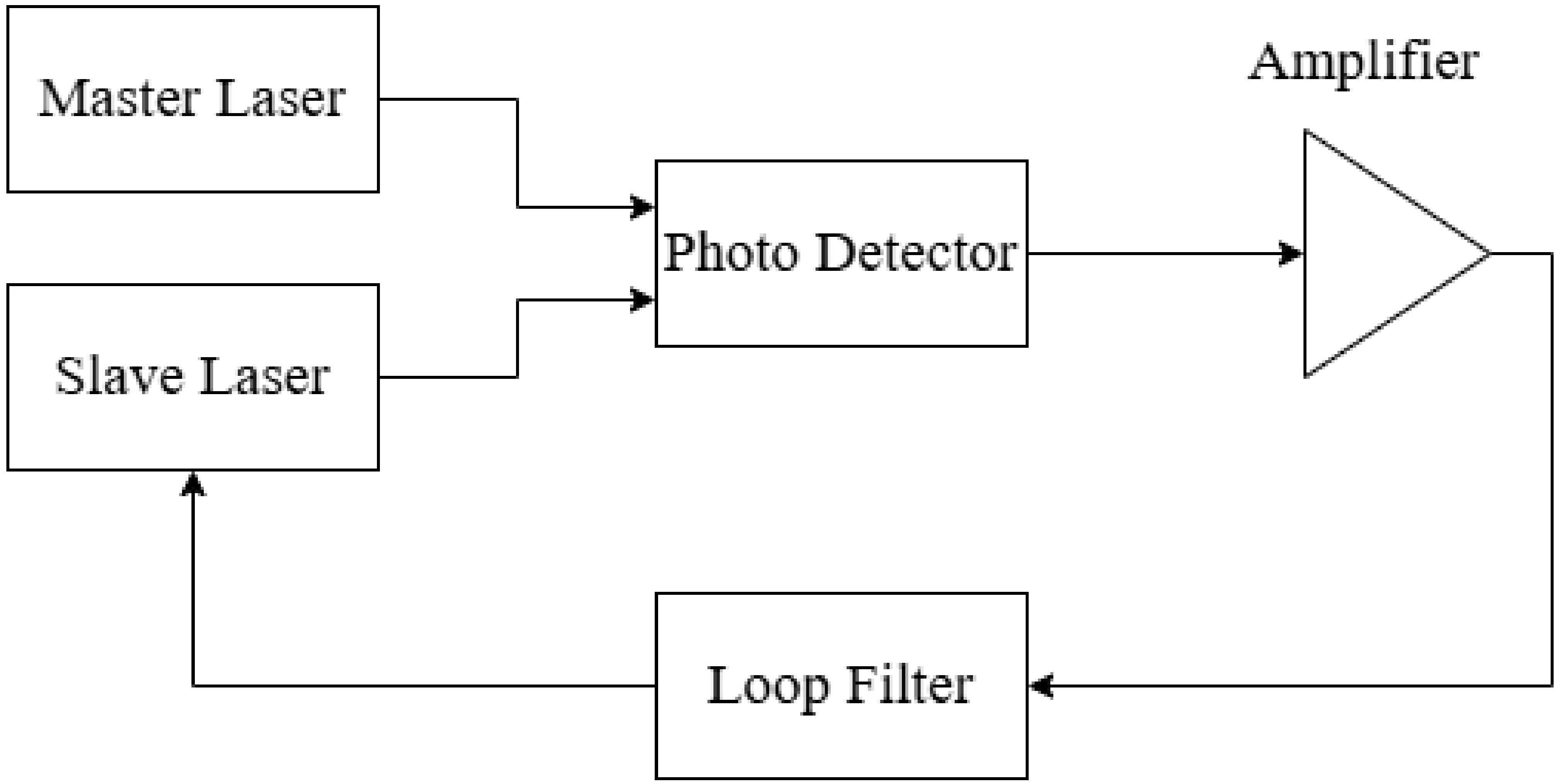
Vasilis Banakos (AM: 1100950)
Violeta Megari (AM: 1100938)

PROJECT'S GOAL

- Study & analysis of the working principle of optical Phase-Locked Loop (oPLL)
- Familiarization with VPIphotonics simulation tool
- Design of an optoelectronic swept-frequency laser
- Testing of the designed system using a VPI demo
- Design and testing of the system using python

OPLL WORKING PRINCIPLE

An oPLL is a negative feedback system which provides closed-loop control over the phase of a slave laser based on the reference phase of a master slave.



Main components:

- Master & slave laser
- Photodetector (PD)
- Interferometer and coupler
- Amplifier
- Loop filter

*Heterodyne oPLLs also exist and in these a mixer with an RF offset input follows the amplifier.

OPTOELECTRONIC SFL

SFL: Swept-Frequency Laser

Based on the oPLL's working principle, the SFL is a feedback system that enables closed loop control over the instantaneous frequency of a chirped semiconductor laser (SCL).

Main components:

- SCL with predistortion bias current
- Mach-Zehnder Interferometer (MZI)
- Photodetector (PD)
- RF mixer
- Amplitude controller

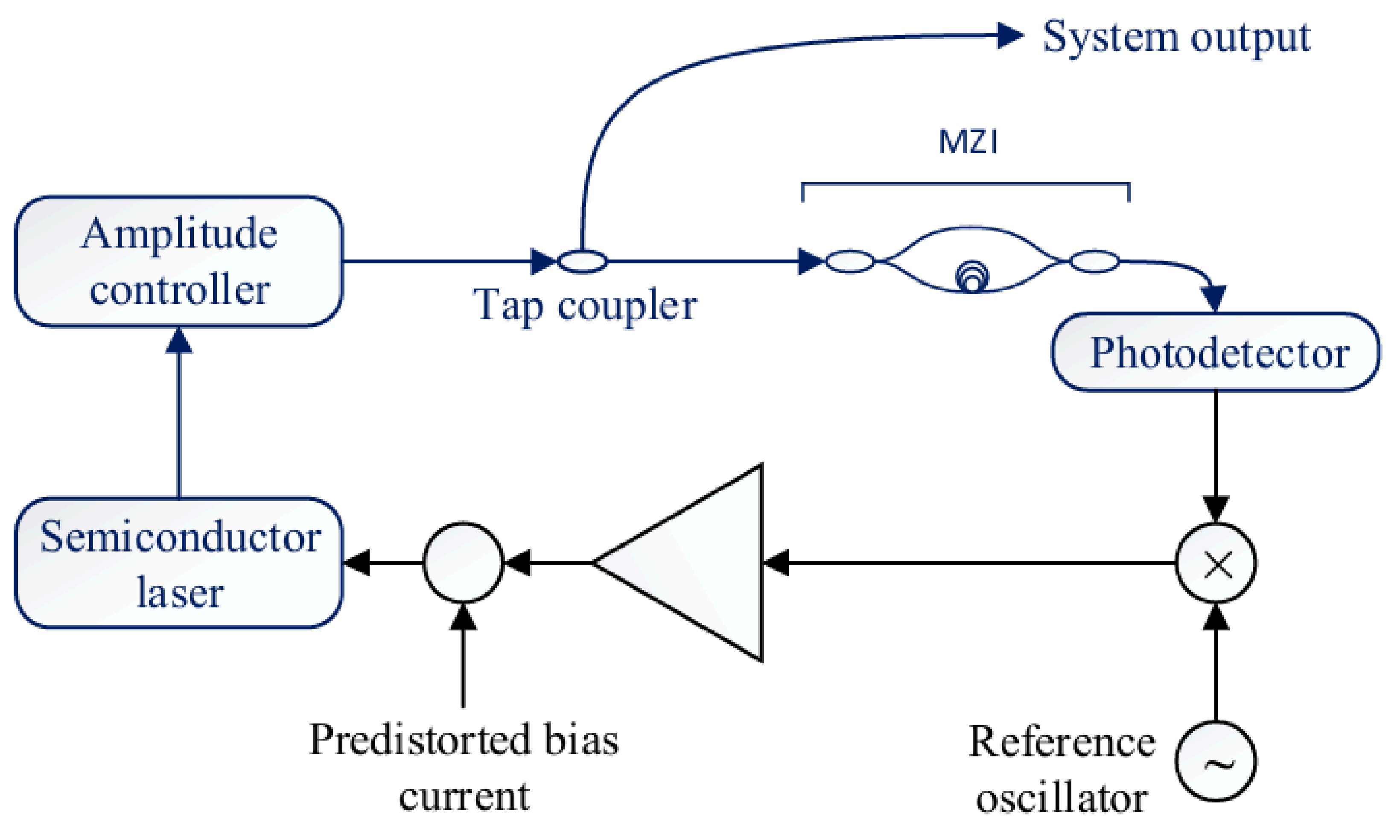


Figure 3.1: Schematic diagram of the SCL-based optoelectronic SFL

ref:[2]

MAIN COMPONENTS

• SEMICONDUCTOR LASER

- acts as a current-controlled oscillator
- instantaneous optical frequency $$\omega_{SCL}(t) = \omega_0 + \int_{-\infty}^{t} K_{SCL}(i(\tau)) \cdot \dot{i}(\tau) d\tau$$
- optical phase $$\phi(t) = \phi_0 + \int_0^t \omega_{SCL}(\tau) d\tau$$
- transfer function $$H_{laser}(s) = \frac{K_{SCL}}{s}$$

MAIN COMPONENTS
• SEMICONDUCTOR LASER

SCL is used but the SFL implementation is actually laser-agnostic.

Pros	Cons
low cost	larger intrinsic noise than other lasers, linewidth ~MHz
relatively easy fabrication	non flat FM response due to thermal and electronic effects
can be frequency tuned with current	presents phase reversal in relation to the modulation signal for frequencies in the range [0.1, 10] MHz

MAIN COMPONENTS
• COUPLER AND MZI

- Tap coupler
  - 90/10 coupler
  - launches small amount of the chirped light into MZI

$$\begin{pmatrix} E_1^{out} \\ E_2^{out} \end{pmatrix} = \begin{pmatrix} \sqrt{0.9} & j\sqrt{0.1} \\ j\sqrt{0.1} & \sqrt{0.9} \end{pmatrix} \begin{pmatrix} E_1^{in} \\ E_2^{in} \end{pmatrix}$$

- MZI
  - differential time delay τ
  - measures the instantaneous chirp slope

$$\begin{pmatrix} E_a(t) \\ E_b(t) \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} E_{in}(t) \\ jE_{in}(t) \end{pmatrix}$$

$$E_{PD}(t) = \frac{1}{\sqrt{2}}(E_a'(t) + jE_b'(t)) = \frac{1}{2}\left(E_{in}(t)e^{j\varphi_a} - E_{in}(t-\tau)e^{j\varphi_b}\right)$$

MAIN COMPONENTS

• PHOTODIODE AND MIXER

- PD
  - generates photocurrent proportional to the incident light's intensity
  - photocurrent's phase is proportional to the instantaneous SCL frequency

$$i_{PD}(t) \propto \cos(\Delta\phi(t)) = \cos(\phi(t) - \phi(t-\tau))$$

- Mixer
  - mixes down the PD's output using a reference frequency

$$i_M(t) \propto cos(\phi(t) - \phi(t-\tau) - \omega_R t - \phi_R)$$

MAIN COMPONENTS
• AMPLITUDE CONTROLLER AND PREDISTORTION

- Predistortion current
  - compensates for the inherently non-linear tuning response of the SCL
  - bias current calculated with a numerical method

- Amplitude controller
  - tuning of the SCL through current results in fluxuations in its intensity
  - keeps SCL’s intensity/power constant

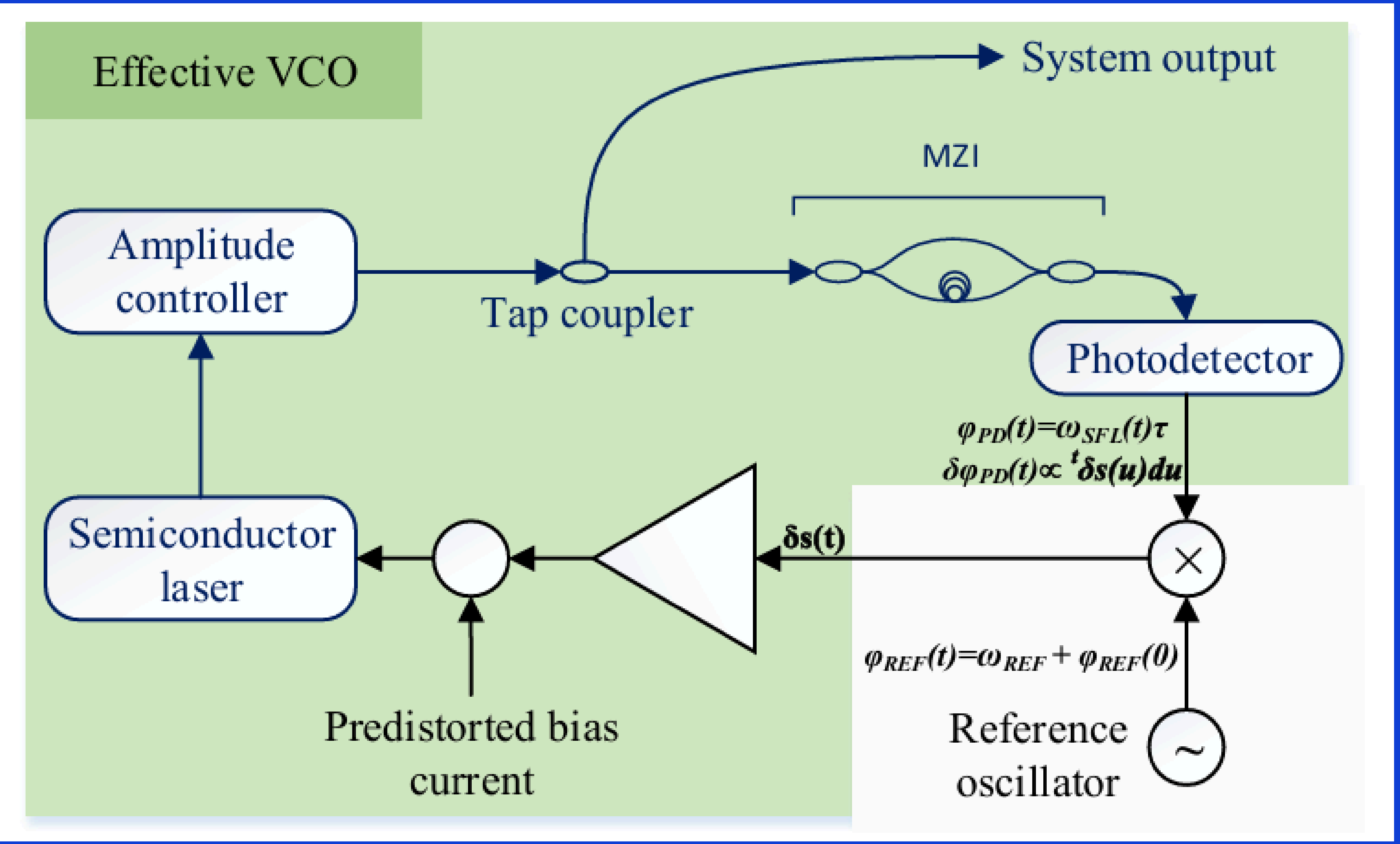
SYSTEM ANALYSIS

- **MZI Difference:** $\Delta\Phi(s) = \Phi_s(s)(1 - e^{-s\tau})$
- **Laser (Plant):** $\Phi_s(s) = \frac{K_L}{s} U(s)$
- **Error Signal:** $\Theta_e(s) = \Phi_s(s)(1 - e^{-s\tau}) - \Phi_R(s) - \Phi_{MZ}(s)$
- **Loop Filter:** $U(s) = -K_{PD} F(s) e^{-s\tau_L} \Theta_e(s)$

- open-loop transfer function $$L(s) = \frac{K}{s} F(s) e^{-s\tau_L}(1 - e^{-s\tau})$$
- closed-loop transfer function $$\Phi_s(s) = \frac{\Phi_n(s)}{1 + L(s)} + \frac{\frac{K}{s} F(s) e^{-s\tau_L}(\Phi_R(s) + \Phi_{MZ}(s))}{1 + L(s)}$$

ALTERNATIVE VIEW

- The system operates as an effective VCO



- The SFL locks the phase of the effective VCO to the phase of the reference oscillator

- chirp rate $\xi^L = \frac{\omega_{REF}}{\tau}$

- initial lock frequency $\omega_0^L = \frac{\phi_{REF}}{\tau} + n\frac{2\pi}{\tau}$

ref:[2]

- MZI's FSR=2π/τ → should be large enough to obtain repeatable chirps

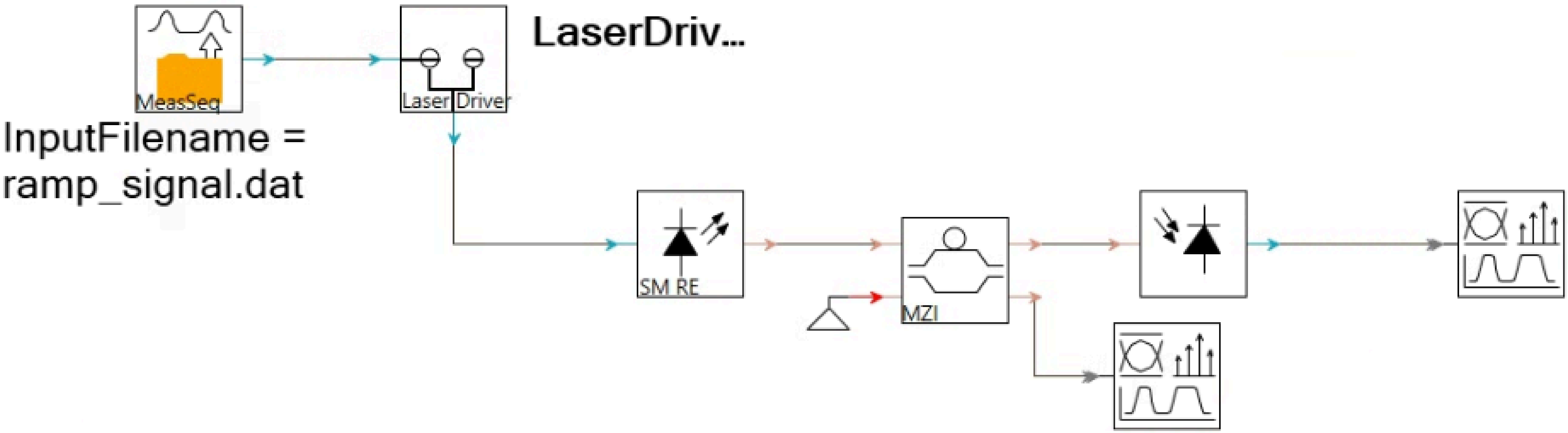
PREDISTORTION CALCULATION

- predistortion: current added to the SCL to compensate for non-linear frequency response

$$\frac{d\omega_{PD}}{dt} = \frac{di}{dt} \times F_{dist}(i)$$

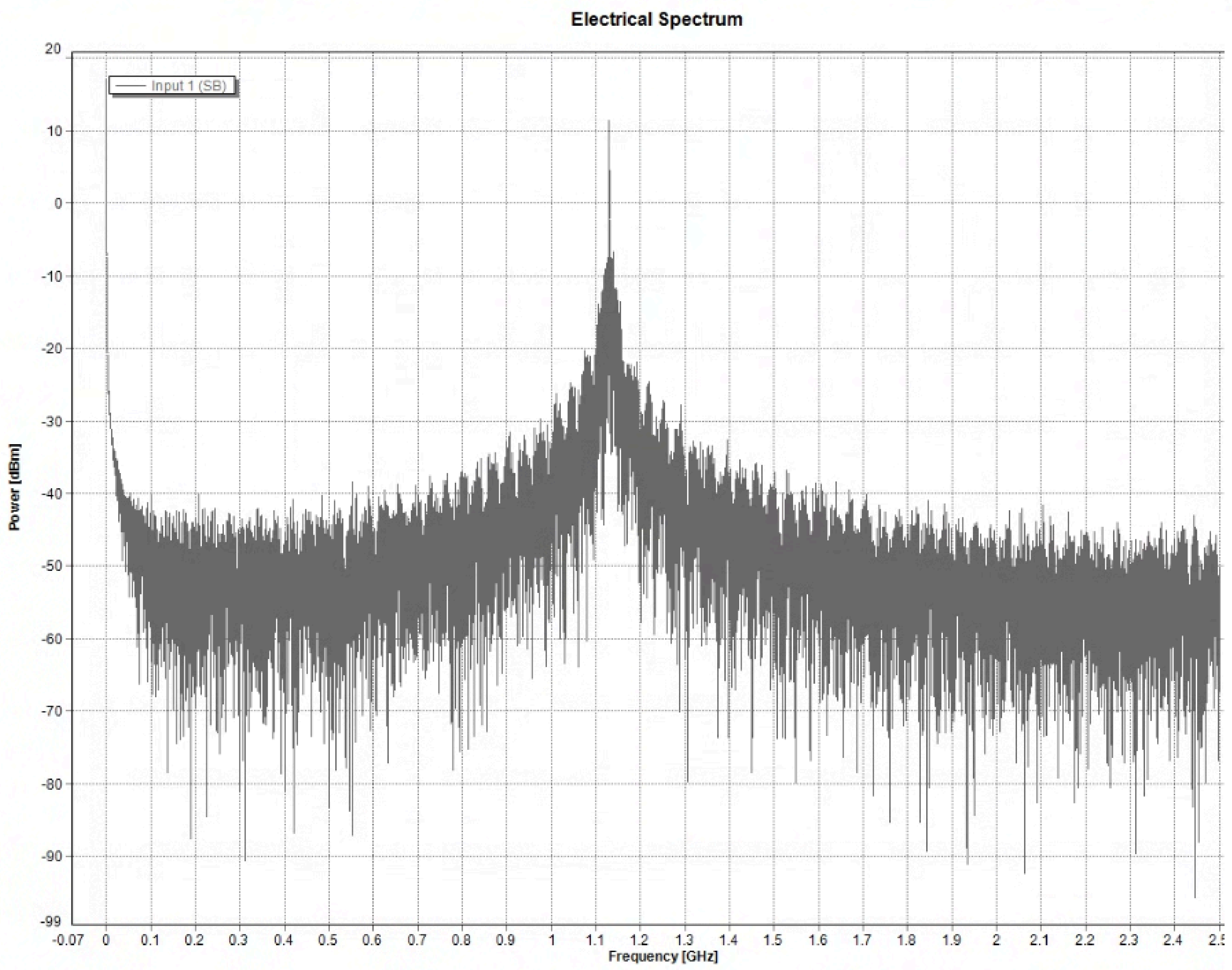
- calculation through a numerical method:
  - apply test current ramp
  - measure PD's frequency and calculate Fdist(i)
  - calculate di/dt to achieve the desired frequency
  - numerically integrate di/dt to obtain new current ramp
  - repeat 3-4 times until sufficiently flat response is achieved

PREDISTORTION IN VPI

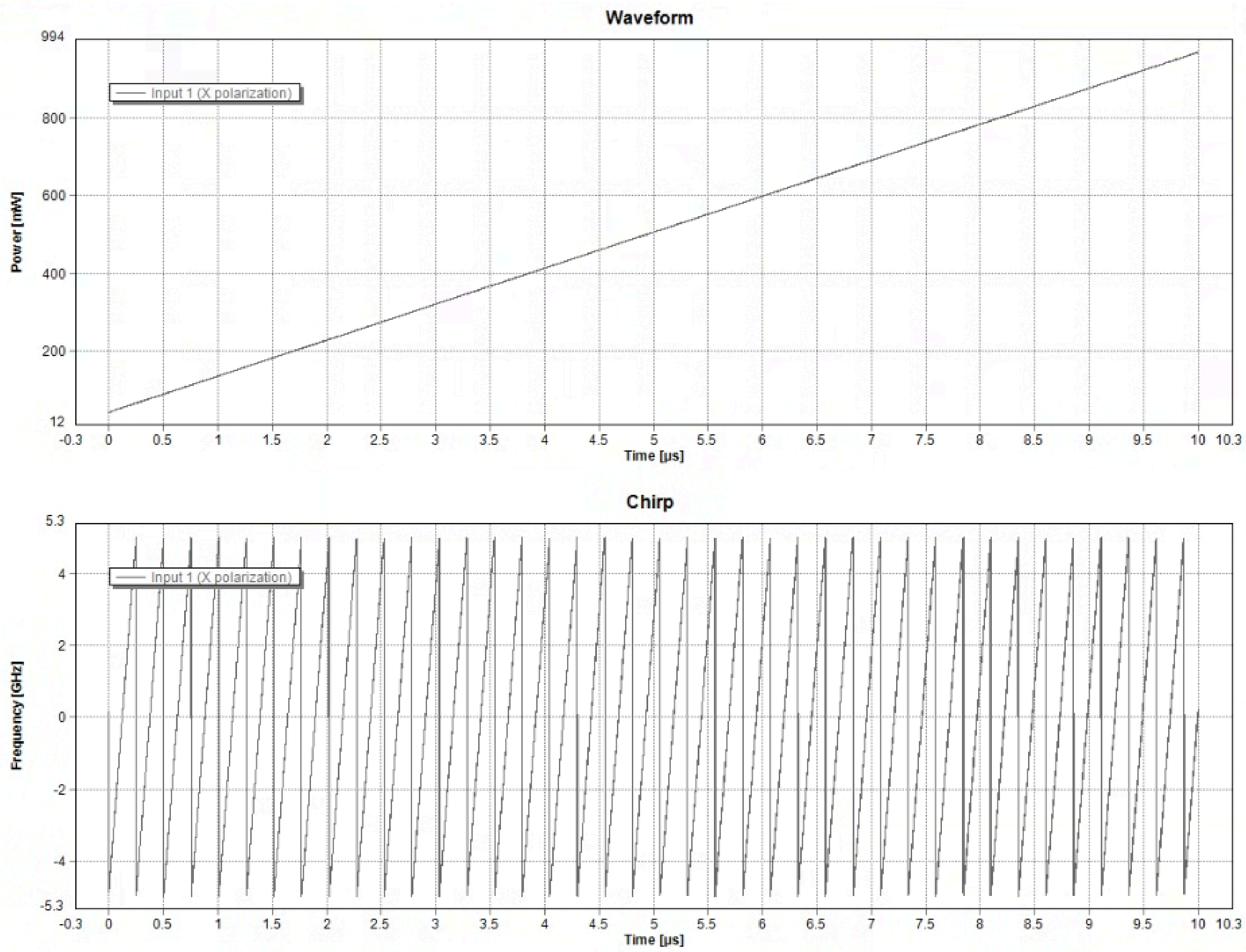


ramp_signal.dat is a dat file containing values for the applied current ramp generated from python code based on the system's configurations

PREDISTORTION IN VPI



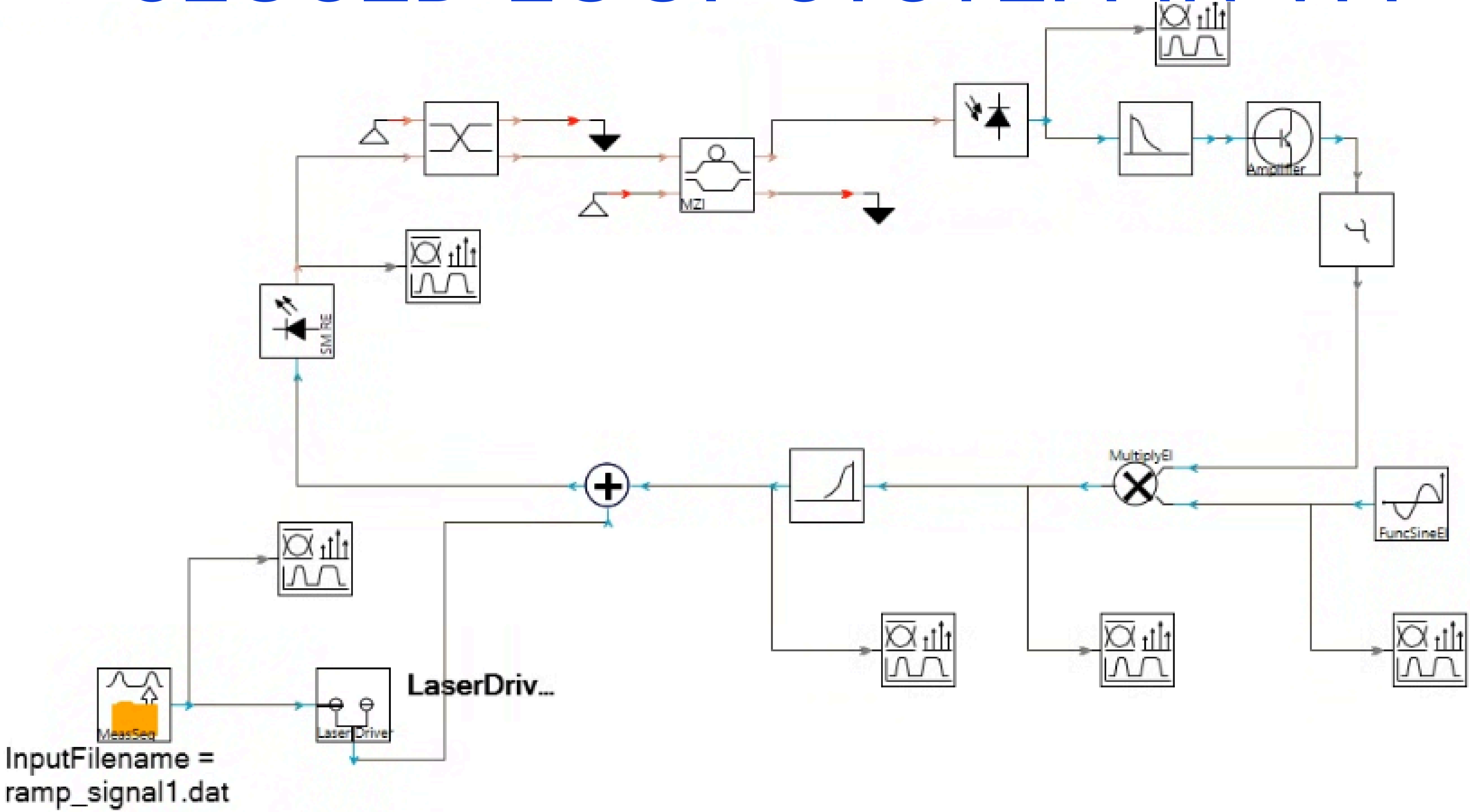
photodiode output



laser output

It can be observed that the chosen laser block has an already sufficiently linear response and thus more numerical iterations are omitted.

CLOSED-LOOP SYSTEM IN VPI



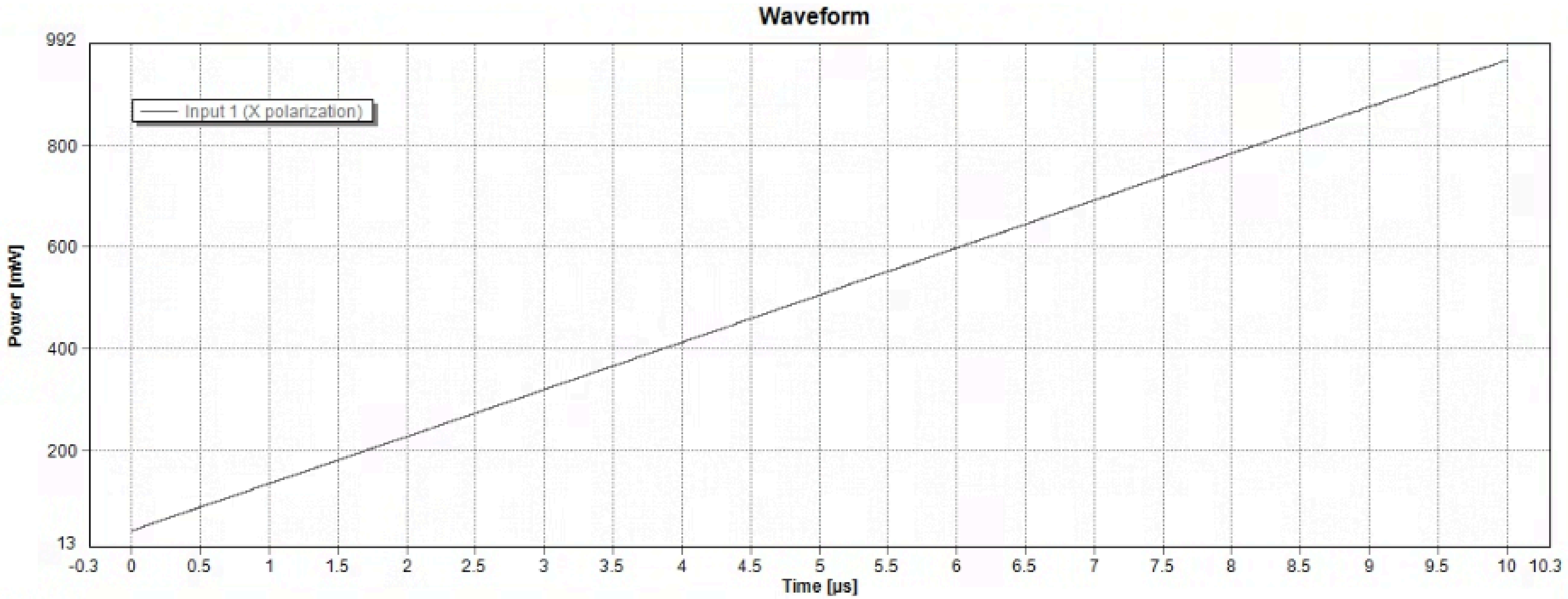
CLOSED-LOOP SYSTEM IN VPI
PARAMETERS

System	
SymbolRate	5e9
NumberOfSymbols	64
BitsPerSymbol	1
BitRateDefault	SymbolRate*BitsPerSymbol
Simulation Control	
TimeWindow	1e-5
SamplesPerSymbol	1
SampleRateDefault	SymbolRate*SamplesPerSymbol
GreatestPrimeFactorLimit	2
BoundaryConditions	Aperiodic
InBandNoiseBins	OFF
LogicalInformation	OFF
SampleModeBandwidth	SymbolRate*SamplesPerSymbol
SampleModeCenterFreq...	193.1e12

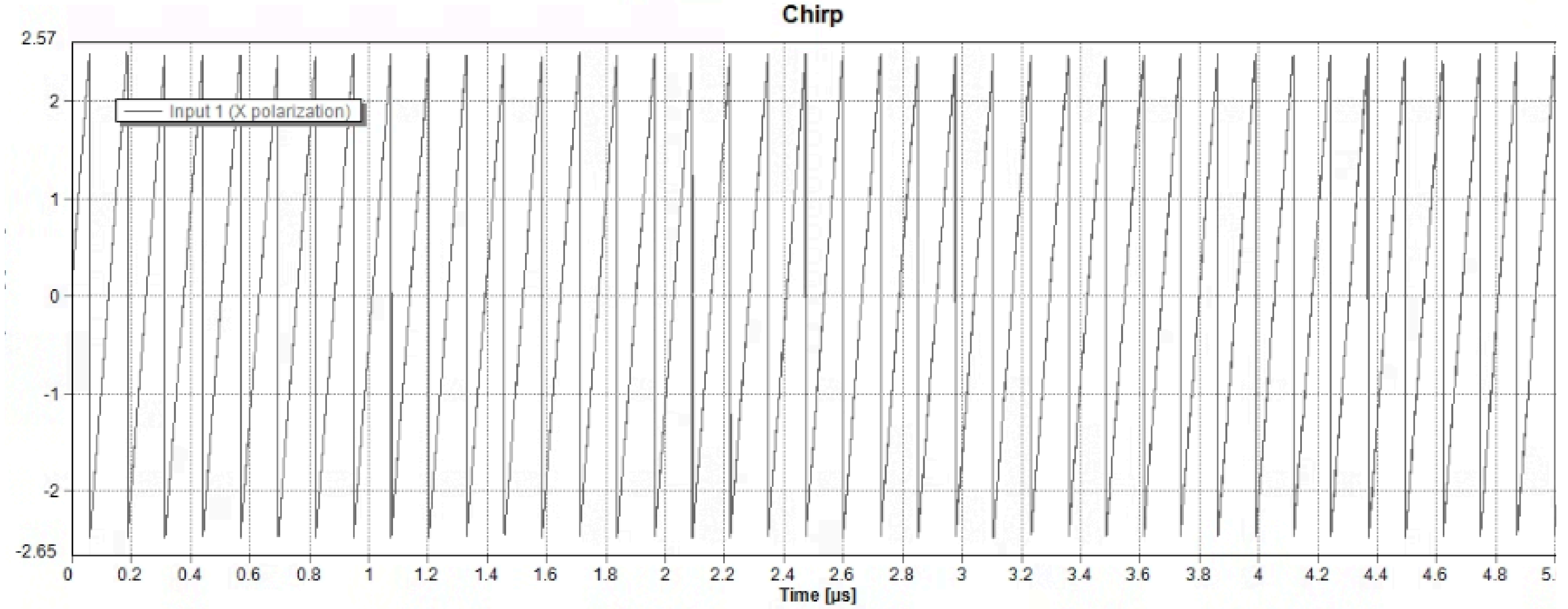
The chosen parameters are:

- sample rate = 160 GHz
- time window = 10 μs
- τ = 28.6 ns
- fref = 1.126 GHz
- chirp slope $\xi = 3.94 \times 10^{16}$ Hz/s

VPI RESULTS
CLOSED-LOOP SYSTEM

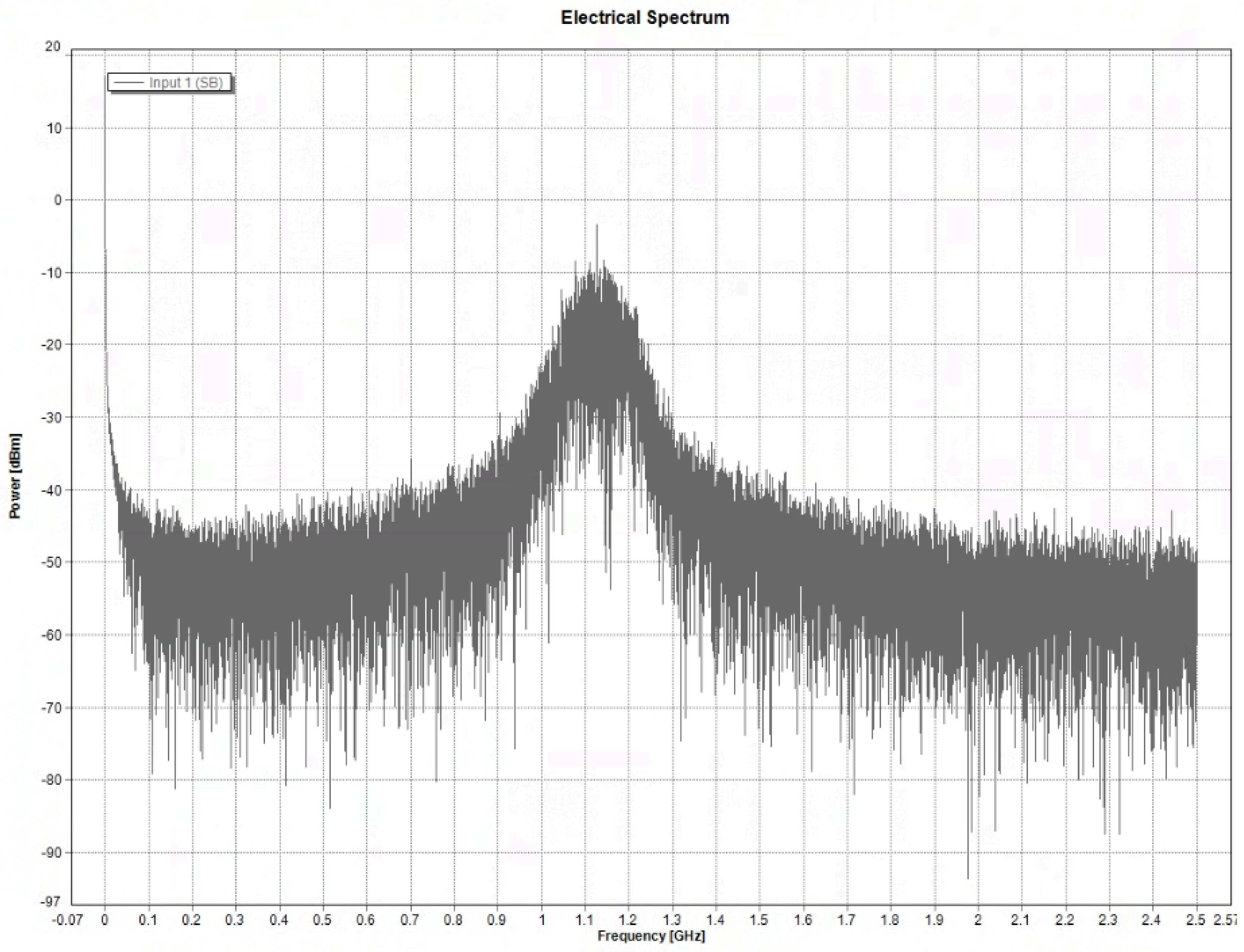


laser output power

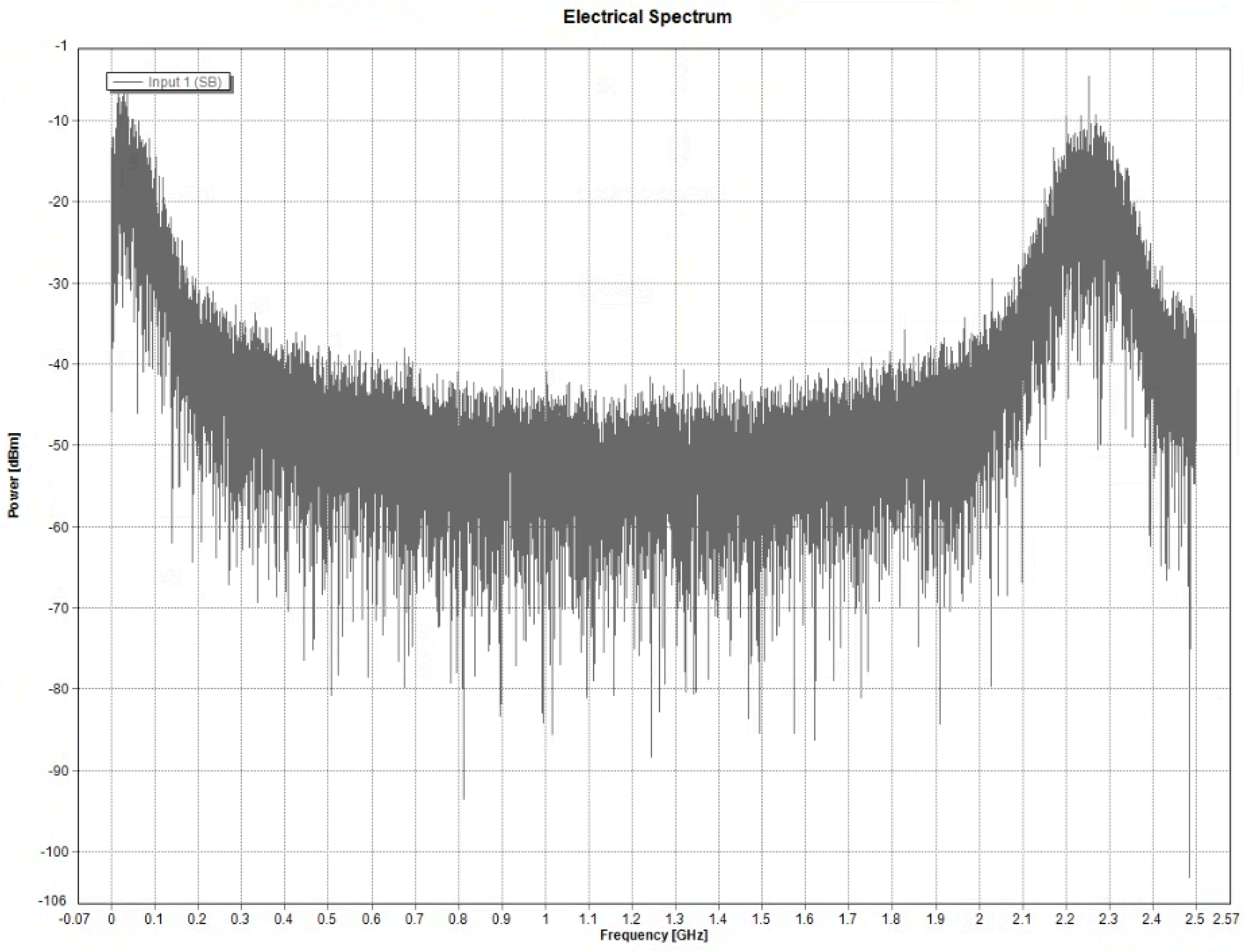


laser output

VPI RESULTS
CLOSED-LOOP SYSTEM



photodiode output



mixer output

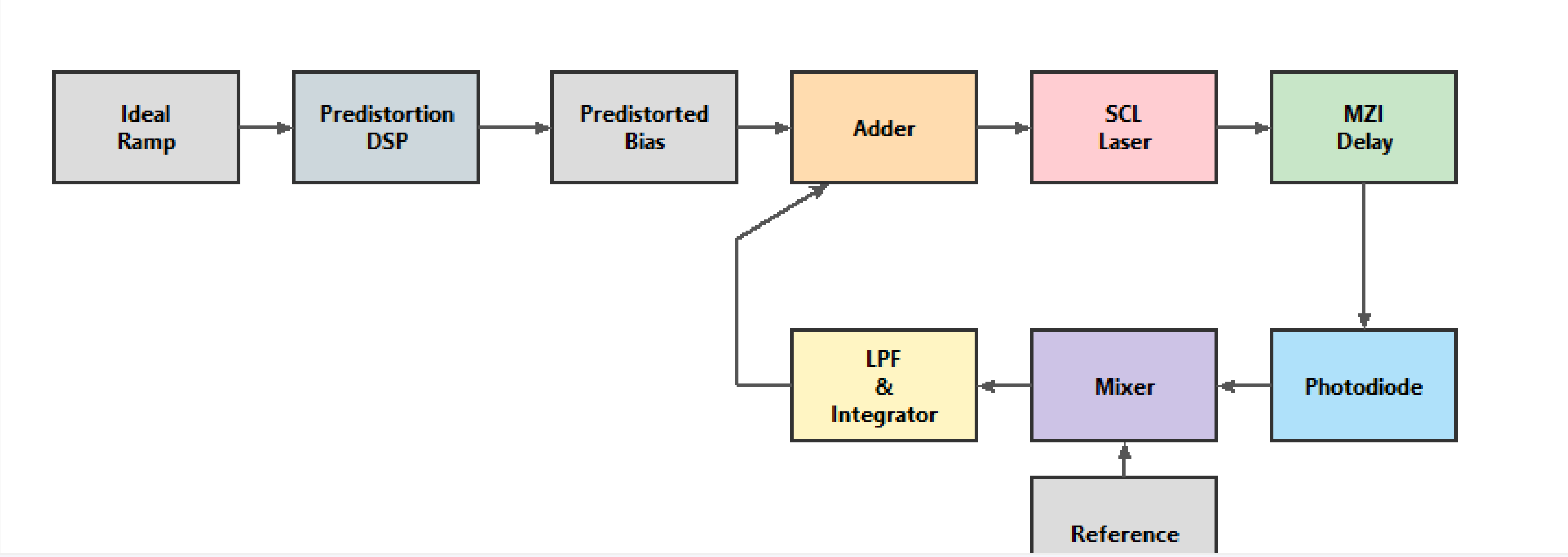
It can be observed from the mixer's output that the system is in lock

ALTERNATIVE REALISATION

PYTHON SIMULATION

Two-Stage Optoelectronic SFL Simulator

Left-Click to Probe Signals | Right-Click to View Math Equations



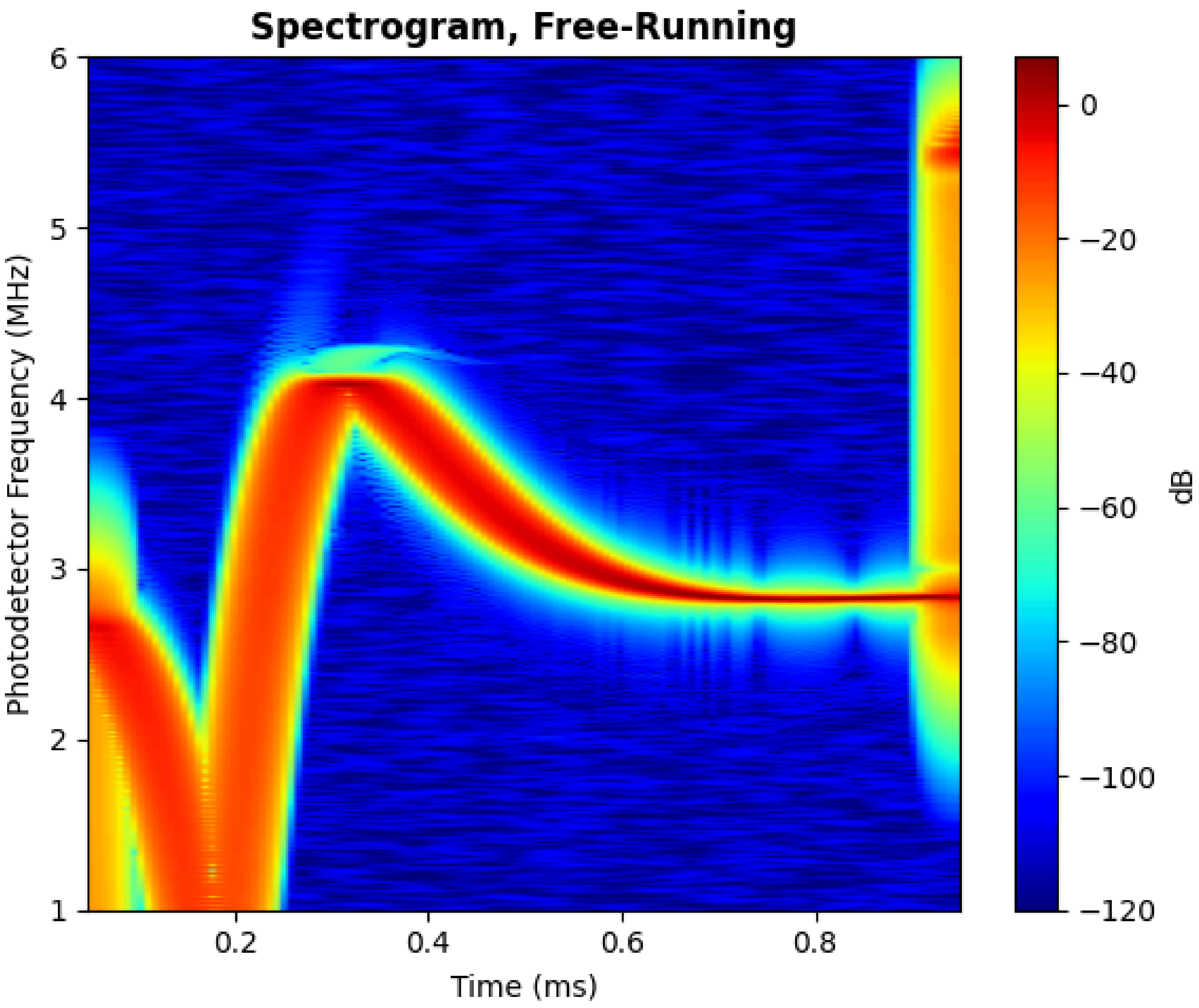
Thesis Project Parameters (DFB SCL)

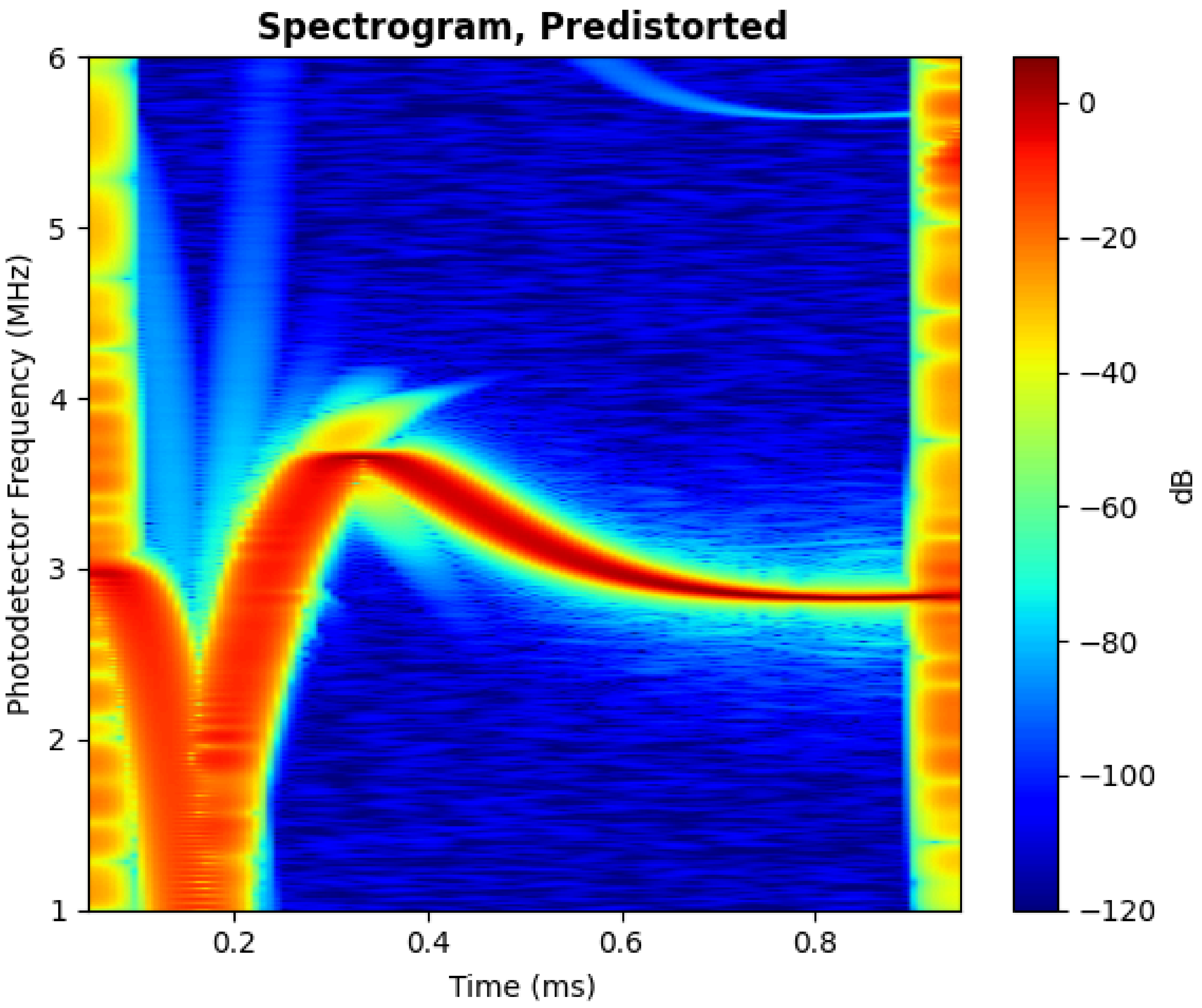
Time Window (μs):	1000.0	Sweep BW (GHz):	100.0	MZI Delay τ (ns):	28.6
Ref Freq (MHz):	2.86	Predistort Iterations:	5	Thermal Sag Mag (GHz):	25.0
Thermal Time Const (μs):	300.0	Integrator Loop Gain:	2e-6	Elec. Cable Delay (ns):	0.0
PD Bandwidth (GHz):	10.0	Laser Linewidth (MHz):	0.0		

1. CALCULATE PREDISTORTION

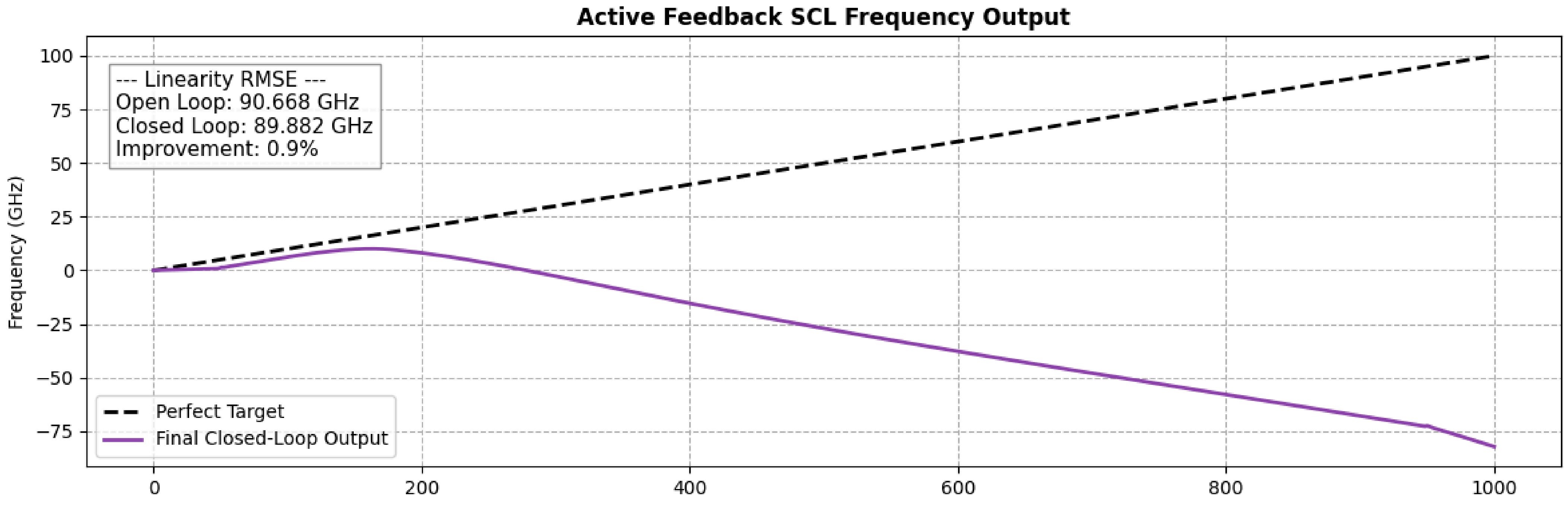
2. SIMULATE CLOSED LOOP

RESULTS(HIGLY NON LINEAR)



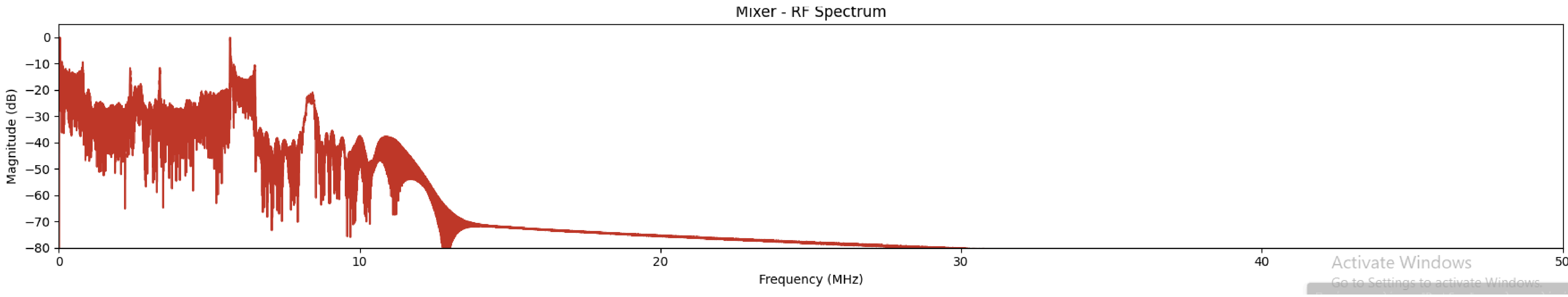


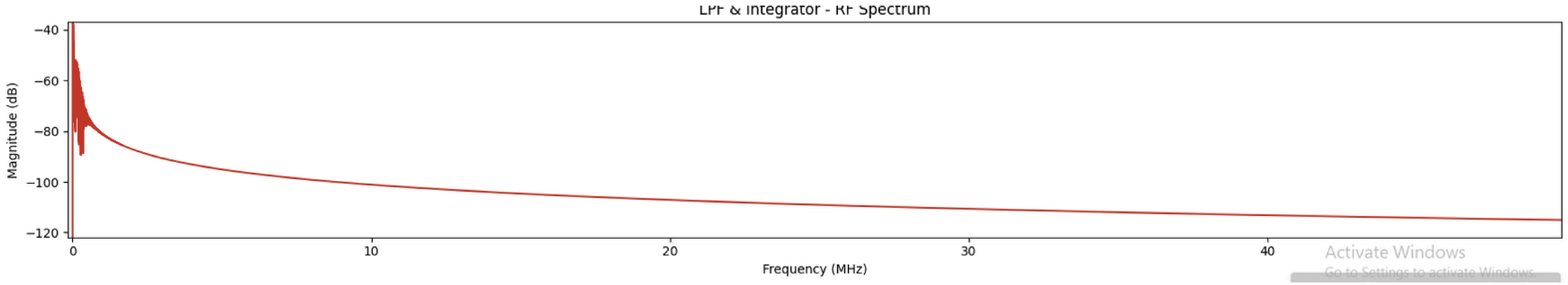
RESULTS(HIGLY NON LINEAR)



SCL FREQUENCY-TIME

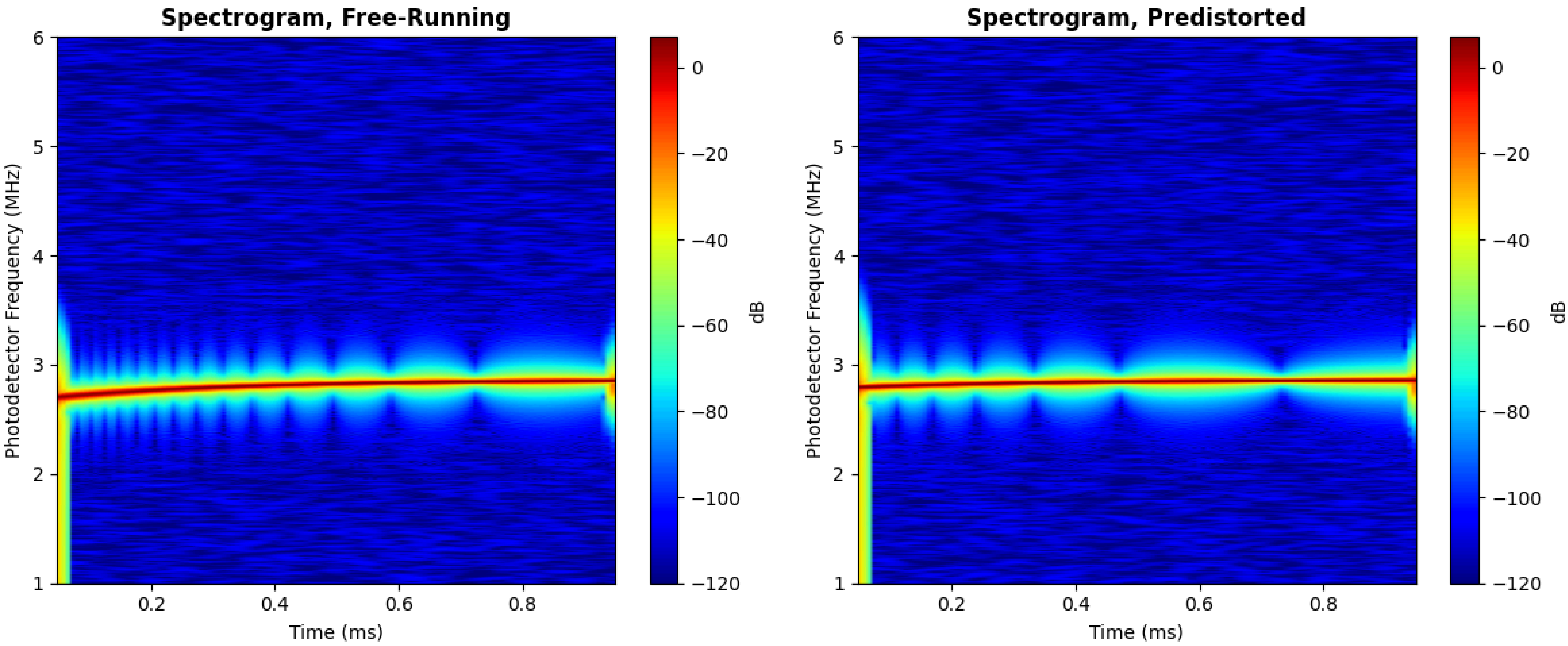
MIXER



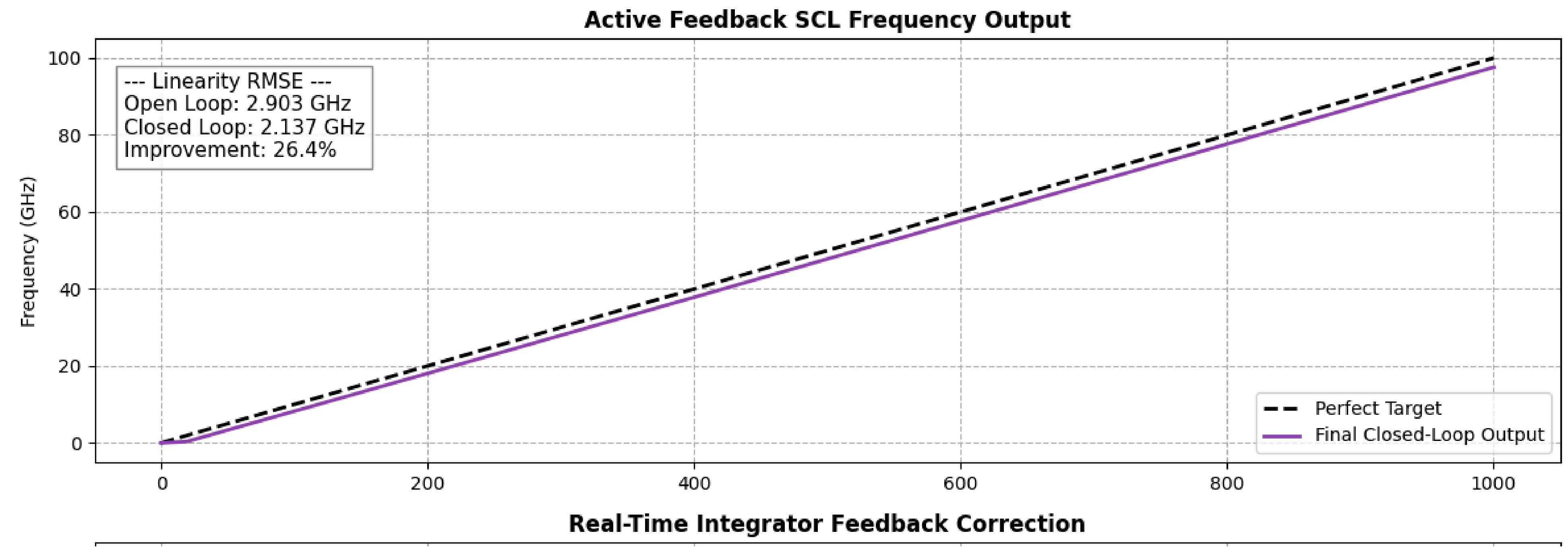


FEEDBACK SIGNAL

RESULTS(HIGLY LINEAR LEASER)

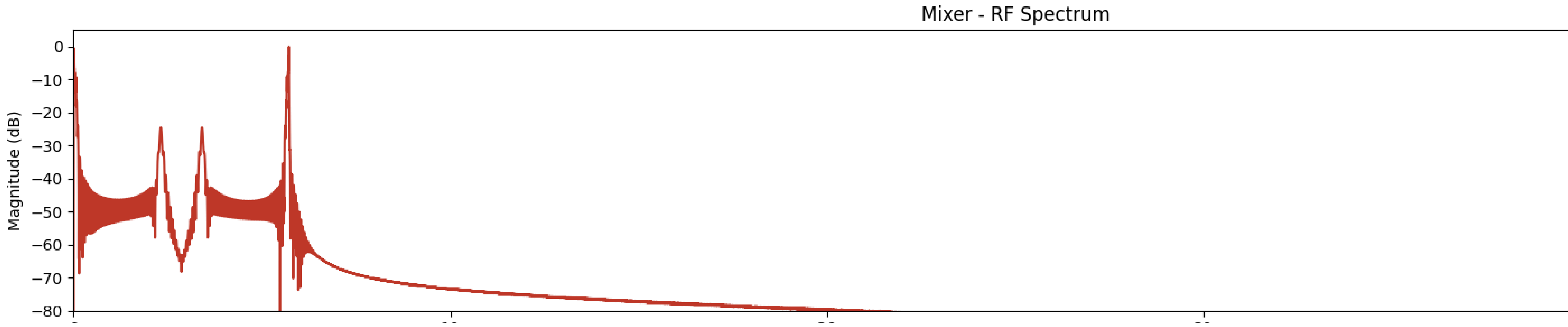


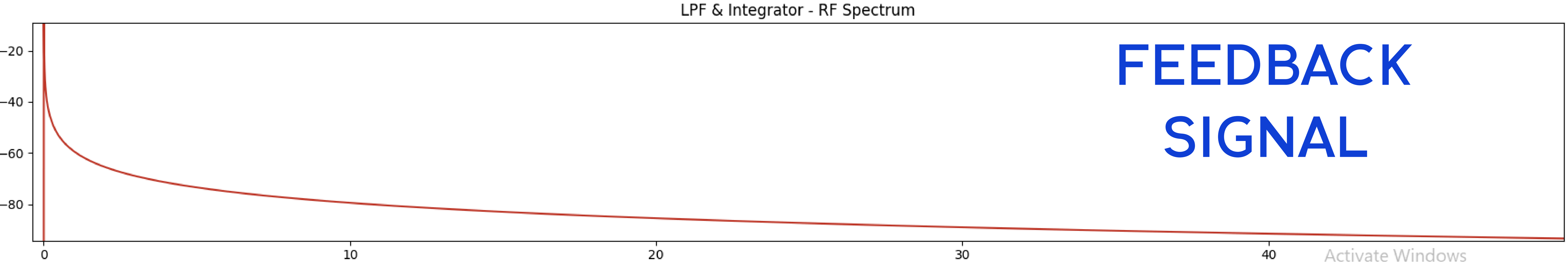
RESULTS(HIGLY LINEAR LEASER)



SCL FREQUENCY-TIME

MIXER





FEEDBACK SIGNAL

IMPLEMENTATION & FUTURE WORK

Future work can include:

- design of the amplitude controller
- noise performance analysis
- generation of different shapes of chirp (triangular for example)
- use of a different kind of laser
- testing of the SFL inside another system

This system can be applied and tested in different applications such as

- ranging & 3D imaging
- FMCW reflectometry
    - LiDAR
    - biomedical imaging

REFERENCES

[1]Arseny Vasilyev, 2013. *The Optoelectronic Swept-Frequency Laser and Its Applications in Ranging, Three-Dimensional Imaging, and Coherent Beam Combining of Chirped-Seed Amplifiers*. PhD thesis, California Institute of Technology

[2]Naresh Satyan, 2011. *Optoelectronic Control of the Phase and Frequency of Semiconductor Lasers*. PhD thesis, California Institute of Technology

[3]Phillip Sandborn, 2019. *FMCW Lidar: Scaling to the Chip-Level and Improving Phase-Noise-Limited Performance.* PhD thesis, University of California at Berkeley

[4]Dimitrios Vrachatis, 2025. *Study of Photonic Circuits for Phase and Polarization Locking for Coherent Optical Communication Systems*. Diploma thesis, University of Patras.

[5]Zhu, J.F. and Chen, L.G. (2021) *Frequency Sweep Linearization for Semiconductor Laser Using a Feedback Loop Based on Amplitude-Frequency Response*. Optics and Photonics Journal, 11, 273-283. https://doi.org/10.4236/opj.2021.118017

[6]Gong Zhang, Zhihuan Ding, Kuankuan Wang, Chun Jiang, Jiajun Lou, Qiaoyin Lu, and Weihua Guo, *Demonstration of high output power DBR laser integrated with SOA for the FMCW LiDAR system*. Opt. Express 30, 2599-2609 (2022)

THANK YOU